LTE Theory and Planning Fundamentals

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1 Scope

This document is intended to provide a basic understanding of LTE (Long Term Evolution) radio aspects together with a set of fundamental radio network features supporting the radio network planning of an LTE system. This document is mainly based on 3GPP specifications and Nokia feature documentation.

It also describes the planning principles for certain LTE areas (PCI, PRACH, PUCCH…) its parameterization and links to additional sources of information.

2 LTE Overview

LTE stands for Long Term Evolution and together with LTE-A represented the next step in mobile radio communications after HSPA. 3GPP is the standardization body behind LTE. The technical specifications for LTE air interface are defined in 3GPP since Release 8 and they can be found in the 36-series (TS 36.xxx). Another name for LTE used in 3GPP is E-UTRA (Evolved-UMTS Terrestrial Radio Access).
LTE requirements were specified in 3GPP TS25.913. Main basic requirements were:

- Peak data rate of 50 / 100 Mbps (uplink / downlink)
- Reduced latency enabling RTT (round trip time) <10 ms
- Packet-optimized
- Improved spectrum efficiency between 2- 4 times higher than Release 6 HSPA
- Frequency flexibility: standard defined 15 FDD and 8 TDD operating bands, the number have been extended over the time
- Bandwidth scalability with allocations of 1.4, 3, 5, 10, 15 and 20 MHz along with carrier aggregation extension (up to 100 MHz)
- Operation in FDD and TDD modes
- Support for inter-working with WCDMA and non-3GPP systems (i.e. WiMAX, 3GPP2, TD-SCDMA)
- Good level of mobility: optimized for low mobile speeds (up to 15km/h) but support also high mobile speeds (up to 350km/h)
- Improved terminal power efficiency

Since it is still early days for 5G, LTE is the most competitive radio technology nowadays by offering high-data-rates with low-latency, improving services, lowering the costs and allowing for spectrum refarming thanks to the frequency and bandwidth flexibility. LTE evolution goes towards 5G direction. See report 'Evolution from LTE to 5G- January 2018'
On Jan 2018, there were 651 commercial LTE networks launched worldwide (Source www.gsacom.com). The deployments are accompanied by LTE-A features and many VoLTE deployments. Further details for LTE-A are covered in Section 9.
As shown in Figure 1, the migration paths for mobile operators towards LTE are multiple which has facilitated the success of the technology. LTE represented a natural and feasible evolution for both 3GPP both non-3GPP based cellular networks. LTE is also open to greenfield operators.

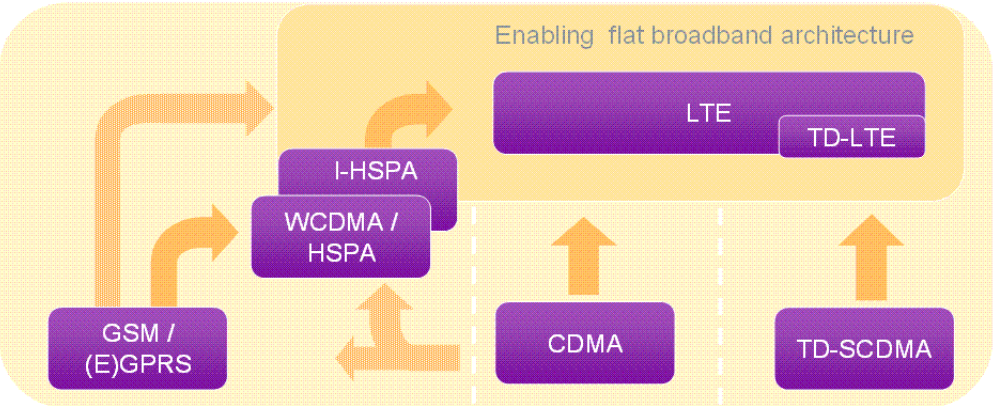


Figure 1: Migration Paths to LTE

3 Architecture

LTE architecture differs from previous UMTS architecture. Principles for LTE architecture design were defined in 3GPP TS25.913. Some of those principles:

- Packet based architecture, although real-time and conversational class traffic should be supported
- It should simplify and minimize the number of interfaces
- It should be designed minimizing the delay variation for traffic requiring low jitter, i.e., TCP/IP
- End to end QoS should be supported for the diverse types of traffic

Before getting into more detail, it is worth mentioning some related concepts:

- LTE or **E-UTRA** refers to the radio access network
- Evolved Packet Core **(EPC)** refers to the core network. The 3GPP name for the core network is System Architecture Evolution (SAE)
- Evolved Packet System **(EPS)** refers to the entire system: E-UTRA plus EPC

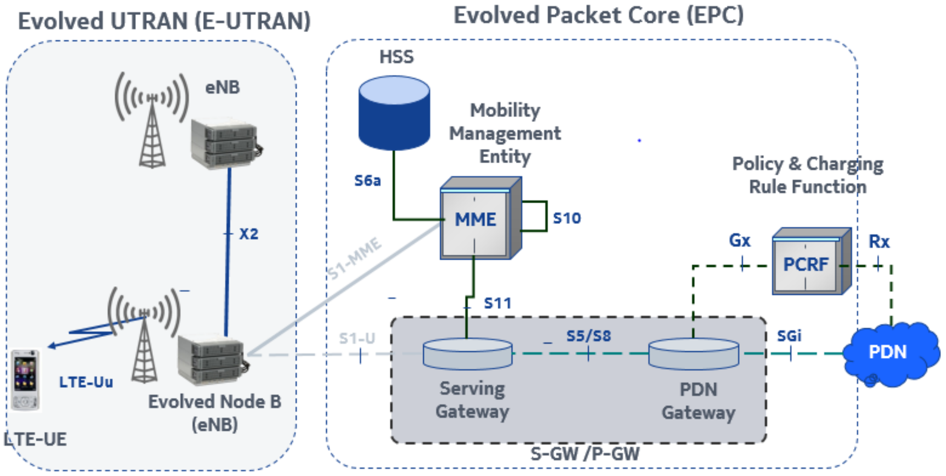


Figure 2: EPS network elements

The LTE / EPC architecture is driven to optimize the system for packet data transfer. There are no circuit switched components.

The network architecture for LTE is called **flat architecture**: there is only a network element in the user plane (the eNodeB) between the radio network and the core network. The RNC is not part of the architecture any more as the eNodeB does the RNC functions. The radio protocols that previously ended in the RNC end in the eNodeB for LTE. Figure 3 shows the network architecture evolution from Release 6 (HSPA) to Release 8 (LTE) and further.

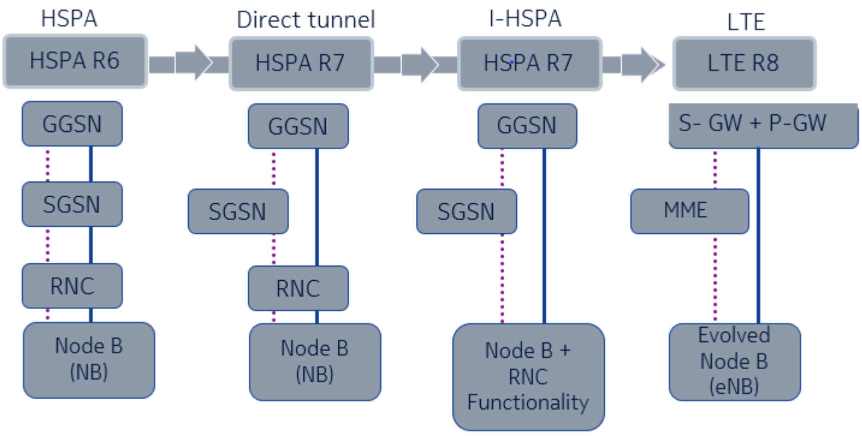


Figure 3: Network Architecture Evolution

This simplification in the architecture not only reduces the costs of the network deployment by using fewer network elements but also allows for shorter round-trip times which is one of the 3GPP requirements for LTE.

3.1.1 Network Elements

Figure 2 shows the network elements within the EPS. As mentioned previously, the eNodeB is the only network element on the radio side, replacing the previous eNodeB / RNC combination from UMTS and providing all the radio management functions. Below, a summary of the **eNodeB functions**:

- Radio Bearer Control: setup, reconfiguration and release
- Admission Control
- Scheduler
- Transmission of Paging messages and of Broadcast information (SIBs)
- Measurement collection and evaluation
- User data routing to the S-GW/P-GW
- MME selection at attach of the UE
- Security: Ciphering and Integrity protection on the radio interface
- IP header (de)compression
- Connection Management Control: UE state management

Core network issues are out of the scope of this document however, a brief description of each of its network elements is given for completeness:

- **Mobility Management Entity (MME):** Pure signaling entity within the EPC. Amongst its main functions:
    - Subscriber attach/detach
    - Tracking area updates
    - Triggering and distribution of paging messages to UE
    - Security and roaming control
    - Authentication, integrity protection

- **Serving Gateway (S-GW):** Manages the user data in the EPC. Receives packet data from the eNodeB and sends packet data to it.

- **Packet Gateway (P-GW or PDN-GW):** Connection between EPC and external Packet data Networks (PDN). Comparable in functionality with the GGSN in 2G/3G networks.
  - IP address allocation for UEs
  - Packet routing / forwarding between S-GW and external data networks
  - Firewall functionality

Note: In Nokia's implementation the S-GW and the P-GW are one unique entity (box).

- **Policy and Charging Rule Function (PCRF):** As the name indicates, it is responsible for implementing the charging policy and for the QoS negotiation with external packet data networks

- **Home Subscriber Server (HSS):** Permanent and central subscriber database containing mobility and service data for each subscriber. It also contains the AuC (authentication center) functionality

3.1.2 Interfaces

Along with the air interface treated in the next section there are two other interfaces of the main interest from the radio point of view:

- **X2 interface:**

Logical interface between eNodeBs since it does not need direct site-to-site connection. It can be routed via core network as well. It is used during inter eNodeB handovers avoiding the involvement of the core network during the handover and forwarding the data between source and target eNodeB. It is also involved in the RRM functions like e.g. exchange of load information between neighboring eNodeBs to facilitate the interference management.

- **S1 interface:**

The S1 interface is divided in two interfaces:

  - **S1-U interface**: User plane interface between the eNodeB and the S-GW. Dedicated only to user data.
  - **S1-MME interface:** Control plane interface between the eNodeB and the MME for the exchange of Non- Access Stratum messages between MME and UE (e.g. paging, tracking area updates, authentication).

4 Air-Interface

One of the main changes in LTE with respect to UMTS is the use of different transmission schemes in the air interface. LTE downlink air interface is based on OFDMA (Orthogonal Frequency Division Multiple Access) whereas the uplink air interface is based on SC-FDMA (Single Carrier-Frequency Division Multiple Access).

4.1 OFDMA

OFDMA is an extension of the OFDM transmission scheme by allowing multiple users. That is, allowing for simultaneous frequency-separated transmissions to / from multiple mobile terminals.

In OFDM the user data is transmitted in parallel across multiple orthogonal narrowband subcarriers. Each subcarrier only transports a part of the whole transmission.

The orthogonal subcarriers are generated with IFFT (Inverse Fast Fourier Transform) processing. The number of subcarriers depends on the available bandwidth as shown in Figure 4. In LTE, they range from less than one hundred to more than one thousand.

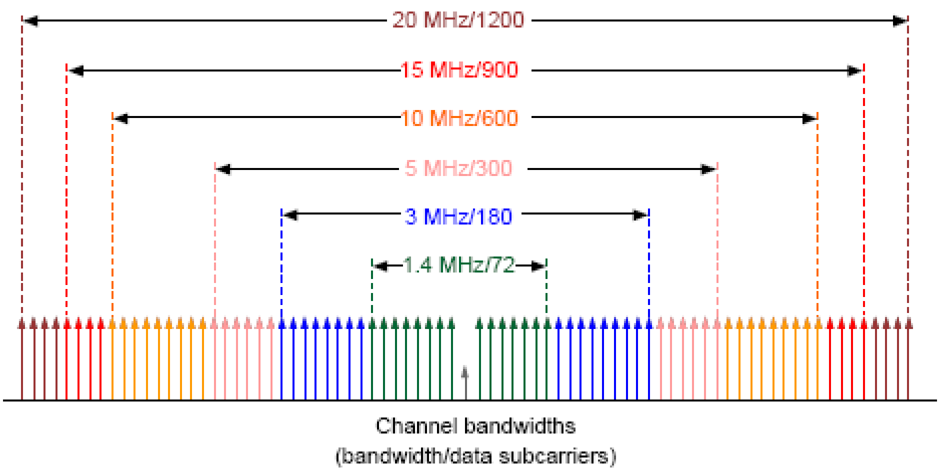


Figure 4: Number of subcarriers for the different bandwidths

The **spacing** between subcarriers is **fixed** in LTE and equivalent to **15 kHz** in the frequency domain.

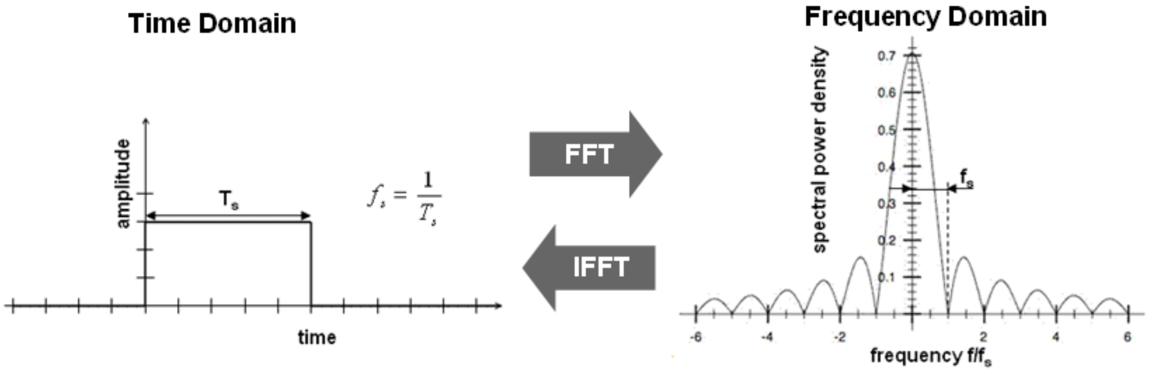


Figure 5: Time and Frequency Domain representation of an OFDM subcarrier

Figure 5 represents a subcarrier in time and frequency domain. A rectangular pulse in time domain corresponds to a sinc-square-shaped spectrum in frequency domain. Although the signal spreads considerably across the spectrum, the spectral power density has null points at multiples of the frequency fs= 1/Ts. Orthogonality means the peaks of a subcarrier intercept the null points of the neighboring subcarriers (frequency domain) and therefore there is no interference between subcarriers.

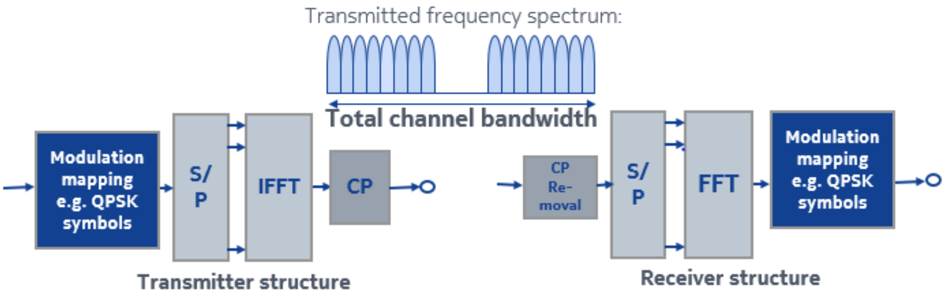


Figure 6: OFDM operation

Figure 6 summarizes at high level the OFDM operation at the transmitter's and receiver's end. User data is modulated according to the different modulation schemes (depending on the radio link conditions).

On the transmitter side, the modulated symbols are interpreted as frequency domain signal and fed into the IFFT algorithm that transforms them into the corresponding time sequence. The number of time symbols is equal to the number of carriers. Then, the cyclic prefix (CP) is inserted. The length of the CP is expressed in the basic time unit Ts and its duration varies for the normal and the extended cyclic prefix (see next page). The bits that define the CP are taken from the end of the symbol and placed as cyclic prefix in front of the symbol (see Figure 7). Finally, the signal is modulated onto the radio carrier and transmitted over the air interface. Inverse operations are carried out on the receiver side i.e., removal of cyclic prefix, FFT to bring the signal back to the frequency domain representation and finally, the symbol de-mapping where the original bit sequence is recovered.

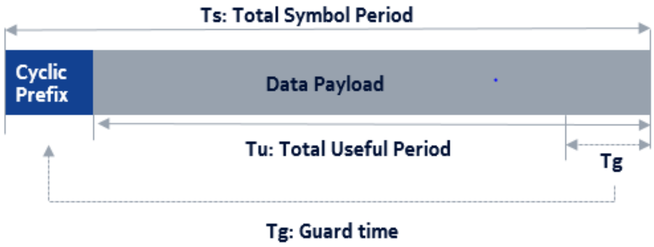


Figure 7: Cyclic Prefix Principle

Cyclic prefixes are used by all modern OFDM systems as a way of fighting against the Inter Symbol Interference (ISI) that may happen in multipath environments where transmitted signals arrive at the receiver with different delays. As previously mentioned, the CP consists of a copy of the last part of a symbol shape for the duration of a guard time and adding it to the beginning of the symbol. This guard time needs to be long enough to capture all the delayed multipath signals and avoid ISI at the receiver. Besides, the CP is used by the receiver to detect the start of symbol due to the high correlation between the CP and the last part of the symbol that precedes so the receiver can start with the decoding.

Using the CP to manage the effects of ISI is possible due to the long symbol duration in OFDM based systems. LTE's typical symbol duration including the CP is around 71.64 µsec. That is considerably longer when compared with GSM 3.69 µsec or 0.26 µsec for WCDMA. Therefore, LTE does not require complex ISI management techniques like other systems.

There are two cyclic prefix options for LTE:

- **Normal cyclic prefix:** For use in small cells or cells with short multipath delay spread. Its length depends on the symbol position within the slot being 5.21 µsec for the CP in symbol 0 and 4.6 µsec for the rest of symbols. The reason for these two different lengths is so that the slot duration is 0.5ms, facilitating at the same time, that the terminal finds the starting point of the slot.
- **Extended cyclic prefix:** For user with large cells or those with long delay profiles. Its length is 16.67µs and it is constant for all symbols in the slot. Extended cyclic prefix appeared at RL15A as part of MBMS feature only. It seems there is not strong will to for regular implementation of extended CP except MBMS solutions in cellular industry at all.

Benefits of OFDMA

OFDM/OFDMA has several benefits over other transmission schemes:

- High spectral efficiency: due to the orthogonality between subcarriers it is possible to pack them closely together (15kHz subcarrier spacing)
- Little interference between subcarriers due to the IFFT/FFT processing (Interference can be introduced by frequency offsets generated by either Doppler or Local Oscillator frequency inaccuracies).
- Robustness in multi-path environments thanks to the cyclic prefix as mentioned before.
- Straightforward support of the operation in different spectrum allocations with different bandwidths just by varying the number of OFDM subcarriers used for transmission.
- Simpler receiver design to support high data rate communications. Detecting a rectangular pulse with cyclic prefix requires less hardware. Free capacity can be used then to implement other performance optimization techniques.

- Easy implementation of MIMO techniques.

Drawbacks of OFDMA

The main disadvantage of OFDM/OFDMA is that the signal has a relatively large peak-to-average power ratio (PAPR). This is due to the nature of OFMA where modulated symbols are transmitted in parallel, each one containing a part of the transmission. The power at a certain point in time is the sum of the powers of all the transmitted symbols for a certain connection, which explains that the differences between peak and average powers can be high.

This issue reduces the power efficiency of the RF amplifier. Expensive transmission amplifiers are needed, especially on the mobile side, to work on a wide range of powers; otherwise the non-linear amplification reduces the orthogonality of the OFDM signal. This is a reason why OFDMA is not optimal for use with mobile or battery-power devices.

Other issue of OFDM/OFDMA systems is that tight spacing of subcarriers may lead to loss of orthogonality due to frequency errors. Doppler may cause inter carrier interference (ICI) and the consequent loss of orthogonality. To cope with the problems caused by close subcarrier spacing, LTE has adopted 15 kHz spacing (mobile WiMAX uses 10KHz spacing).

Note: As shown in Figure 5, the symbol duration and the sub-carrier spacing are tied together. Tsymbol = 1/(fspacing) which allows to maintain the orthogonality.

4.1.1 Subcarrier types

There are several types of subcarriers:

- **Data subcarriers:** Represent most of the subcarriers. They carry the modulated user data signals. The data rate of each data subcarrier depends on the symbol rate and the modulation scheme employed.
- **Null subcarriers.** As the name indicates, nothing is transmitted in these subcarriers. There are two types:

  - **Guard subcarriers:** They are located at the bottom and top of the channel. Their function is to limit the amount of interference caused by the channel and also to limit the adjacent channel interference from neighboring channels. The more guard subcarriers the less the interference but this also reduces the data throughput of the channel.

    In addition, the number of guard subcarriers affects the LTE Tx spectrum mask: the more the guard subcarriers the less the data subcarriers and the 'wider' the Tx spectrum mask will be because there are less subcarriers to cancel out the tails of the sinc signals. LTE Tx spectrum emission mask needs to meet the UMTS spectrum emission mask (from 3GPP specifications) if the same/similar interference is to be caused to the adjacent carriers in both technologies.

  - **DC-subcarrier or null subcarrier**: It is the center subcarrier of the downlink band (0 Hz offset from the channel's center frequency). This subcarrier is not used because it may suffer from high interference (i.e., due to local oscillator leakage). The null subcarrier does not exist in the uplink because a frequency offset of 7.5 kHz is applied.

4.1.2 OFDMA Symbol

The OFDMA symbol is defined in the time and frequency domains:

- **Time domain:** Time period occupied by the modulation symbols on the considered subcarriers. The symbol duration without considering the cyclic prefix is 66.67 µs since the subcarrier spacing is 15 kHz.
- **Frequency domain:** A symbol is made up of subcarriers. Figure 8 shows that each subcarrier only carries information related to a specific modulation symbol. An OFDMA symbol represents all the data being transferred in parallel at a point in time.

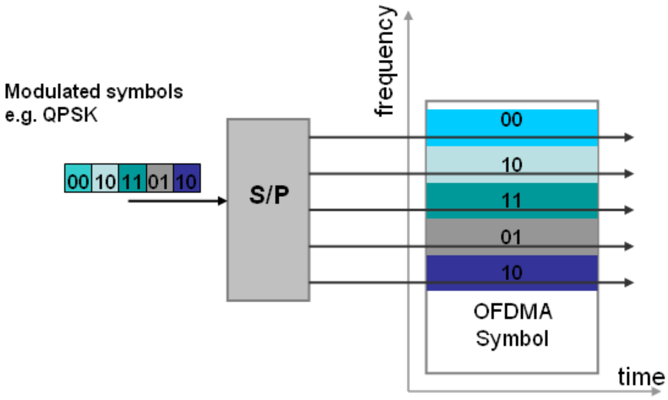


Figure 8: OFDMA symbol

4.1.3 LTE Physical Layer Structure

There are two types of frames defined for LTE: Type 1 frame for FDD and Type 2 frame for TDD.

4.1.3.1 FDD

LTE Type 1 Frame (FDD) is common to both, uplink and downlink. Components and durations are illustrated in Figure 9

- Frame length: 10 ms. In the FDD case, 10 ms frame for UL and 10 ms frame for DL
- 1 Frame = 20 slots of 0.5 ms each
- 1 **slot (s_x)** = 7 **symbols (sy_x)** in the case of normal CP or 6 symbols in case of extended CP
- 1 Frame = 10 **Subframes (SF)** of 1ms each

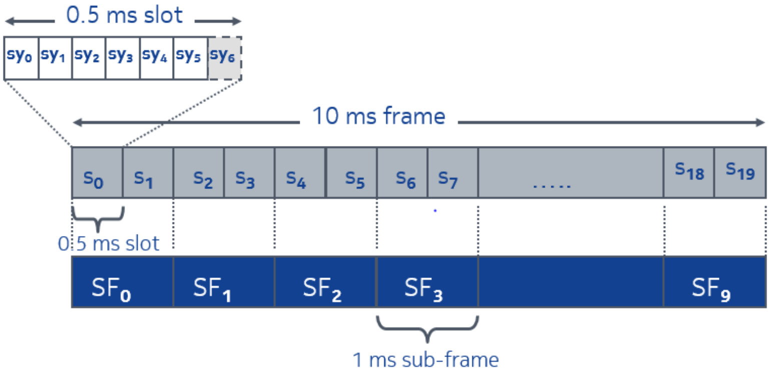


Figure 9: LTE FDD Frame Structure

As shown in Figure 7, the Total symbol duration (Ts) includes the cyclic prefix duration. The extended cyclic prefix duration is equal for all the symbols in the slot (16.67µs). Normal cyclic prefix duration is longer for the first symbol of the slot (5.21 µs). Remaining symbols in the slot have a cyclic prefix duration of 4.7 µs.

The reason why there are fewer symbols per slot in the case where extended CP is used, is that the total symbol duration (with extended CP) is longer and this leaves room for fewer symbols within the 0.5 ms slot.

4.1.3.2 TDD

Type 2 frame is defined for TDD. Type 2 frame shares the same frame structure and the slot duration of Type 1 frame but it contains some TDD specific fields to enable switchovers between UL and DL along with the co-existence with the TD-SCDMA. Figure 10 shows the LTE TDD frame structure:

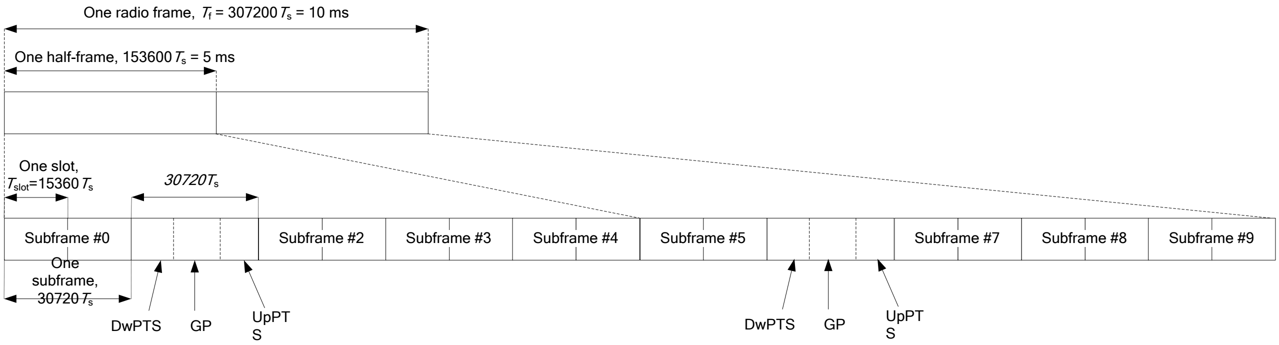


Figure 10: LTE TDD Frame Structure (for 5 ms switch-point periodicity)

Each radio frame of length $T_f = 307200 \cdot T_s = 10\,\text{ms}$ consists of two half-frames of length $153600 \cdot T_s = 5\,\text{ms}$ each. Each half-frame consists of five subframes of length $30720 \cdot T_s = 1\,\text{ms}$. The supported per 3GPP uplink-downlink configurations are listed in Figure 11 where, for each subframe in a radio frame, "D" denotes the subframe is reserved for downlink transmissions, "U" denotes the subframe is reserved for uplink transmissions and "S" denotes a special subframe with the three fields: DwPTS, GP and UpPTS. Uplink-downlink configurations with both 5 ms and 10 ms downlink-to-uplink switch-point periodicity are supported.

DwPTS always contains reference signals and the Control Information, like a regular DL subframe (i.e. PDCCH, PCFICH & PHICH), in the first symbol, deviating from usual PDSCH format. One subsequent symbol is consumed by the Primary Synchronization Channel (P-SCH). Further remaining symbols in the DwPTS can be used for DL data (the exact amount of resources depends on the S subframe configuration, that is, the size of the GP). UpPTS can be configured as 1 symbol or 2 symbols, which can be used for PRACH or SRS. If UpPTS length is 1 symbol, it can be used for Sounding Reference Signal (SRS) only.

Only the TDD DL/UL Configuration 1 and Configuration 2 are supported in Nokia releases up to and including TL17A.

Uplink / Downlink Subframe Configuration	DL to UL Switching Period	Subframe Number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Figure 11: Uplink-downlink configurations

This figure shows that:

- In case of 5 ms downlink-to-uplink switch-point periodicity, the special subframe exists in both half-frames.
- In case of 10 ms downlink-to-uplink switch-point periodicity, the special subframe exists in the first half-frame only.
- Subframes 0 and 5 and DwPTS are always reserved for downlink transmission. UpPTS and the subframe immediately following the special subframe are always reserved for uplink transmission.

Together with the GP, the length of DwPTS and UpPTS can be configured in 10 discrete special subframe formats as shown in Figure 12.

Nokia support is limited to special subframe configurations 3, 4, 5, 6, 7 and 9.

Special Subframe Configuration	Normal Cyclic Prefix in DL		
	DwPTS	Guard Period Normal Cyclic Prefix in UL	UpPTS
0	3 sym	714 µs	1 sym
1	9 sym	285 µs	
2	10 sym	214 µs	
3	11 sym	143 µs	
4	12 sym	71 µs	
5	3 sym	643 µs	2 sym
6	9 sym	214 µs	
7	10 sym	143 µs	
8	11 sym	71 µs	
9	6 sym	429 µs	

Figure 12: Configuration of special subframe (lengths of DwPTS/GP/UpPTS)

4.1.4 Physical Resource Block and Resource Element

A Physical Resource Block (PRB) or Resource Block (RB) is the physical resource used for transmission. Capacity allocation in LTE is based on Physical Resource Blocks.

A PRB is composed of 12 subcarriers in the frequency domain per 1 slot period (0.5 ms) in time domain. Since each subcarrier occupies 15 kHz, a PRB occupies 180 kHz (12 x 15 kHz) in the frequency domain. A different concept is the **scheduling resource block** that is composed of two Physical Resource Blocks (1 ms duration) since the scheduling is done per 1 ms (TTI duration)

A **resource element** (RE) is the theoretical minimum capacity allocation unit. It is formed by 1 subcarrier per 1 symbol.

Figure 13 represents the resource element concept and (physical) resource block concept in the case of normal CP being used (7 symbols per slot). There are 84 (7x 12) resource elements per PRB.

In case of extended CP being used each slot contains 6 symbols and a PRB is composed of 72 (=6 x 12) resource elements.

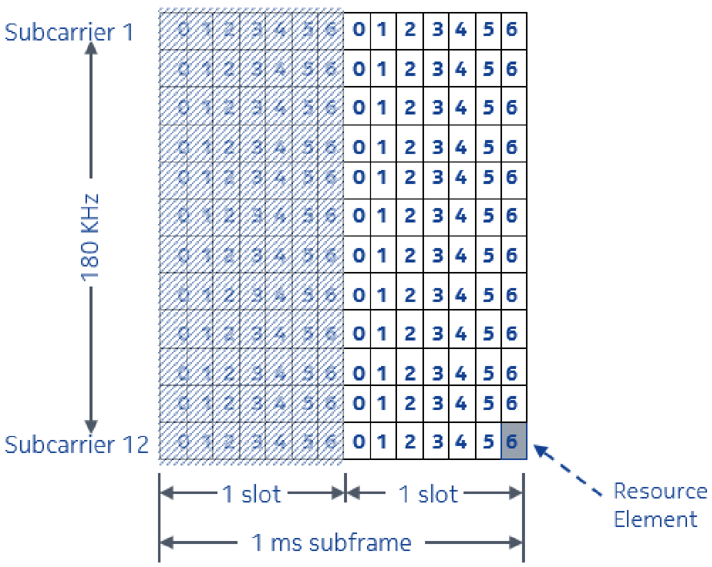


Figure 13: Physical RB and RE concepts

4.1.5 Downlink Resource Allocation

The physical layer specification allows for a downlink carrier to consist of any number of resource blocks, ranging from a minimum of 6 resource blocks up to a maximum of 100 (equivalent to a downlink transmission bandwidth ranging from around 1MHz up to 20MHz). However, only certain bandwidths are specified in the LTE requirements: 1.4, 3, 5, 10, 15 and 20MHz.

Once the bandwidth is known also the number of available resource blocks for scheduling is known. As Figure 14 shows, several users can be allocated per time period. The number of resource blocks assigned to each user will be decided by the scheduler based on the amount of data to be transmitted. The allocation in time domain (although not specified in Figure 14) refers to 2 slots (1ms).

Resource allocation does not need to be continuous in the frequency domain. This is different to the uplink resource allocation as it will be seen in Figure 20 *Uplink Resource Allocation*

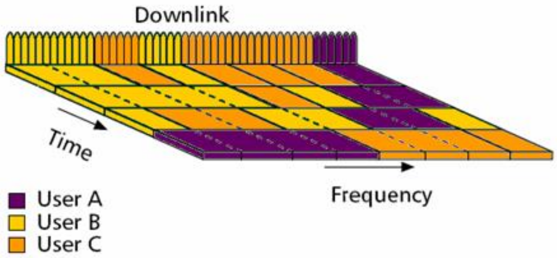


Figure 14: Downlink resource allocation

4.1.6 OFDMA Parameters

A summary of the main OFDMA parameters is presented in this section:

	1.4MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Frame Duration	10ms					
Subcarrier Spacing	15 kHz					
Sampling Rate (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
Data Subcarriers	72	180	300	600	900	1200
Symbols/slot	Normal CP=7, extended CP=6					
CP length	Normal CP=4.69/5.12 µsec, extended CP= 16.67µsec					

Table 1: Summary of main OFDMA parameters

By having a fixed subcarrier spacing (15 kHz) the complexity of a system supporting multiple channel bandwidths is reduced. Additionally, 7.5 kHz subcarrier spacing option is defined for Multimedia Broadcast Multicast systems (MBMS).

To ensure that all signals are received correctly, the receiver sampling rate must be slightly higher than the bandwidth of the signal used to carry it (e.g. for a channel bandwidth of 10 MHz the sampling rate is 15.36 MHz). It is always a factor or multiple of 3.84 to ensure compatibility with WCDMA by using common clocking.

The subcarrier spacing (15 kHz) for the different bandwidths is obtained as: sampling frequency / FFT size. It can be observed that the FFT sizes (equivalent to the number of subcarriers used in the FFT process) vary from 128 in case of 1.4MHz to 2048 in case of 20MHz.

The difference between the subcarriers defined by the FFT size and the subcarriers used for the different bandwidths (shown in Figure 4) determines the number of subcarriers used to protect the system against the ACI (Adjacent Channel Interference), i.e. guard subcarriers or null subcarriers.

4.1.7 Downlink Reference Signals

Reference signals are not subcarriers but *reference* symbols. They do not occupy a whole subcarrier but they are periodically embedded in the stream of data being carried on a data subcarrier. In fact, each reference signal occupies one resource element (see Figure 13: Physical RB and RE concepts).

Reference signals are used for channel estimation (signal quality and strength); therefore, they are similar in functionality to the Pilot signal in WCDMA. There are three types of reference signals defined in downlink for LTE: cell-specific, UE-specific and MBSFN (Multicast Broadcast Single Frequency Network).

Within the context of these planning guidelines, cell specific downlink reference signals are the ones with the most interest. They are transmitted in every downlink subframe spanning across the whole downlink cell bandwidth. Additionally, they are modulated to identify the cell to which they belong.

The position of the reference signals in the time domain is fixed (symbols 0 and 4 for the FDD frame) and in the frequency domain it depends on the Cell ID. Distributing the reference signals in both time and frequency domains allows the UE to complete the channel estimation in both domains.

In the case of downlink multi-antenna transmission (e.g. MIMO) the terminals need to estimate the channel for each transmitting antenna, so reference signals are needed per antenna (see MIMO Mode Control). In these cases, the resource elements allocated to reference signals in one antenna cannot be used in the other antennas (DTX: Discontinuous Transmission-).

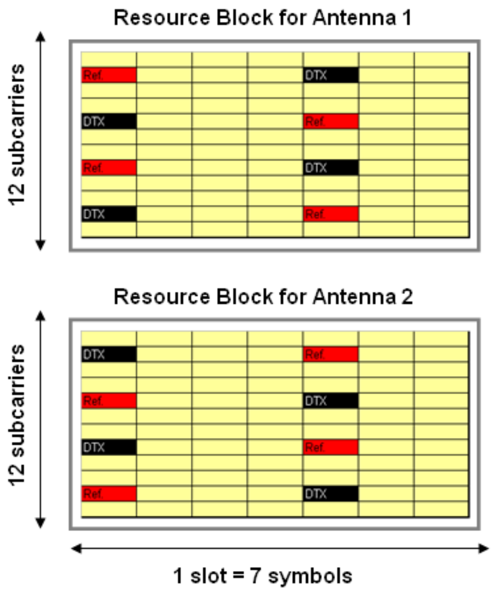


Figure 15: Downlink Reference Signals Example Location (2 Tx antennas case)

4.2 SC-FDMA

Single Carrier-Frequency Division Multiple Access is the technology chosen for the uplink air interface because it does not suffer from high peak-to-average power ratio (PAPR) as OFDMA. SC-FDMA is a more power efficient variation of OFDMA that still employs subcarriers, FFT, cyclic prefix and other OFDM concepts.

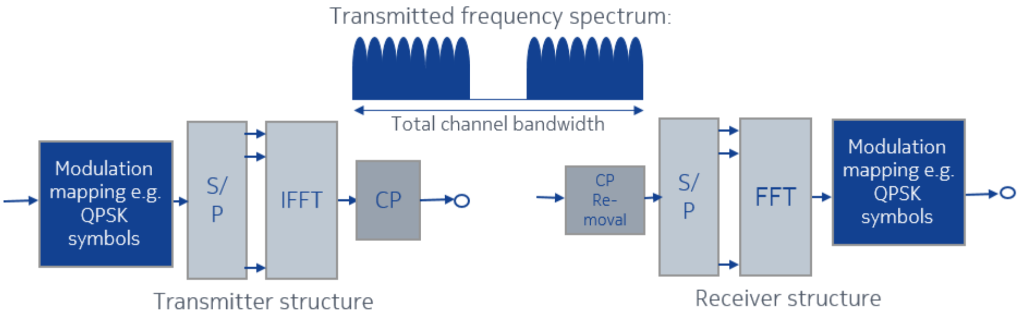


Figure 16: SC-FDMA Operation

Figure 16 shows, at a high level, the SC-FDMA operation. It is similar to the OFDM/OFDMA case. The main difference is that in the case of SC-FDMA there is additional processing before the IFFT: the modulated symbols (interpreted in this case as time signals) are fed to the FFT processing. The outputs are the frequency components of the modulation symbols. Those frequency components are mapped to the allocated inputs of the IFFT and from there, the normal OFDM processing continues.

The additional FFT processing block in SC-FDMA spreads the information of each bit over all the sub-carriers (see Figure 18). In a SC-FDMA signal, each subcarrier used for transmission contains information about all transmitted modulation symbols (thus 'single carrier' name) since input data stream has been spread by the FFT transform over the available subcarriers. In OFDMA each subcarrier only carries information related to specific modulation symbols.

The FFT output size is smaller than the IFFT input size. This is because the granted UL resources to one UE cannot exceed the total resources in the cell. Multiple UEs can be allocated in uplink, each one using different (groups of) subcarriers.

4.2.1 SC-FDMA Symbol

The SC-FDMA symbol has also a definition in the time and frequency domains, same as the OFDMA symbol. However, there are differences as shown in Figure 17 :

- The SC-FDMA symbol duration is the same as the OFDMA symbol duration (66.7µs) but whereas in OFDMA each modulated symbol lasts the whole OFDMA symbol duration (see Figure 8: OFDMA symbol) in SC-FDMA each modulated symbol lasts for '1/n'th of the SC-FDMA symbol (where n is the number of used subcarriers, $1/5^{th}$ in Figure 17 example)
- In OFDMA there is one modulated symbol per subcarrier (see Figure 8: OFDMA symbol). In SC-FDMA each modulated symbol is spread across the used subcarriers.
- In the frequency domain, each OFDMA data symbol occupies 15 kHz and each SC-FDMA data symbol occupies n x 15 kHz bandwidth (see example in Figure 18)

Based on the above points, it can be seen that as the bandwidth increases the modulated symbol duration decreases. Therefore, to double the data rate in case of SC-FDMA the total bandwidth needs to be doubled (as well as the amount of FFT inputs in the transmitter) and the modulated symbol duration is halved.

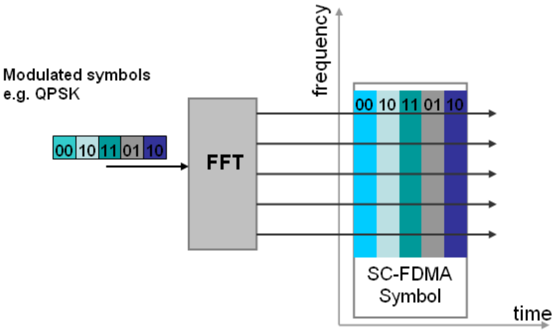


Figure 17: SC-FDMA symbol

Figure 18 illustrates in a comprehensive way the operation of both transmission techniques: Visually, the OFDMA signal is clearly multi-carrier and the SC-FDMA signal looks more like single-carrier. OFDMA and SC-FDMA symbol lengths are the same at 66.7 µs. However, the SC-FDMA symbol contains N "sub-symbols" that represent the modulated data.

The parallel transmission of multiple symbols creates the undesirable high PAPR of OFDMA. By transmitting N data symbols in series at N times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but the PAPR is the same as that used for the original data symbols.

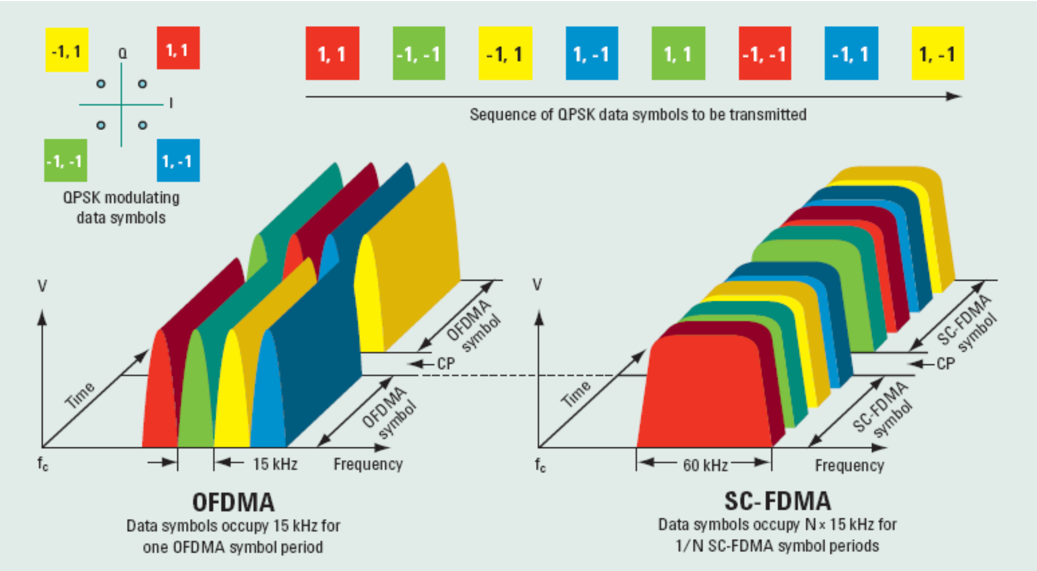


Figure 18: OFDMA and SC-FDMA operation comparison

The cyclic prefix in SC-FDMA is added like in the OFDMA case (refer to Figure 16), however there is no cyclic prefix after each symbol because in SC-FDMA the symbols are much more frequent than in OFDMA. Consequently, in the SC-FDMA case each modulation symbol is not protected by the cyclic prefix and the receiver needs to cope with ISI between cyclic prefixes. The receiver will run the equalizer for a block of symbols until reaching the CP that prevents the further propagation of ISI. Therefore, the SC-FDMA receiver is more complex than the OFDMA receiver.

4.2.2 Uplink Reference Signals

The uplink reference signals are used for channel estimation to help with the data demodulation, channel quality estimation for the uplink scheduling, power control and timing estimation amongst others. Due to the nature of SC-FDMA, they are time-multiplexed with the data symbols. They always occupy symbol number 3 in each slot (first symbol is symbol 0) in the case of normal cyclic prefix and symbol number 4 in the case of extended cyclic prefix. There are two types of reference signals supported in uplink:

- **Demodulation reference signals:** Used for channel estimation and associated with transmissions of uplink data and/or control signaling. They occupy the same bandwidth as used for data/control transmission
- **Sounding reference signals:** Used for channel quality estimation to support scheduling in the uplink in the case of channel aware scheduling. They are not associated to uplink data and/or control transmissions.

4.2.3 Uplink Physical Resource Block

The concept of Physical Resource Block is also valid for uplink: 12 subcarriers in frequency domain by 1 slot in time domain. The demodulation signal, as mentioned before, is always sent in symbol 3 across the whole bandwidth used by the terminal. The remaining resource elements are used for control and data.

The representation of a resource block in the time domain (after the IFFT processing) is shown in Figure 19. Every modulated symbol is spread across the 12 subcarriers.

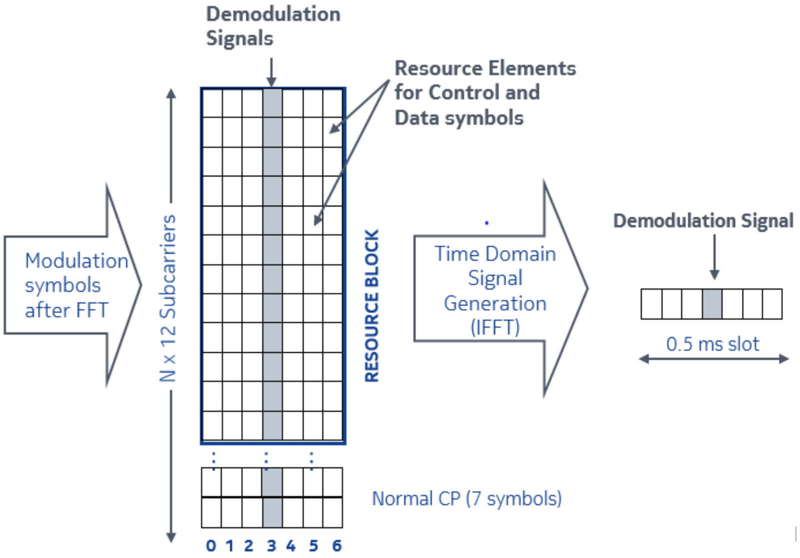


Figure 19: Uplink Resource Block

4.2.4 Uplink Resource Allocation

Uplink resource allocation is also based in PRB as in the downlink. However, due to the SC-FDMA nature, one user is always continuous in frequency. A *'PRB group'* specifies the group of consecutive PRBs which are assigned to a certain UE.

The smallest uplink bandwidth that can be allocated is 12 subcarriers (180 kHz) and the largest is 20 MHz. Terminals are required to be able to receive and transmit up to 20 MHz depending on the frequency band.

It will be the uplink scheduler the entity that will decide, out of the resources available in the frequency and in the time domain, which and how many resources to assign per user.

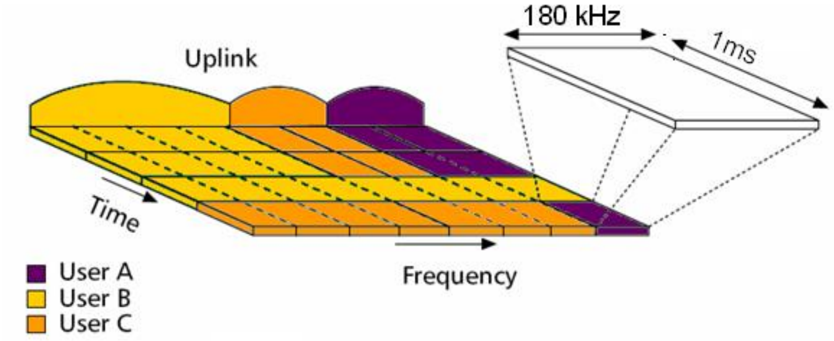


Figure 20: Uplink Resource allocation

5 Radio Resource Management

The scope of the RRM is to:

- Manage and optimize the utilization of the radio resources
- Provide for each service/bearer/user an adequate QoS (if applicable)
- Increase the radio network capacity and maximize the network quality

The RRM framework, implemented in the eNodeB, consists of building blocks and functions as shown in Figure 21.

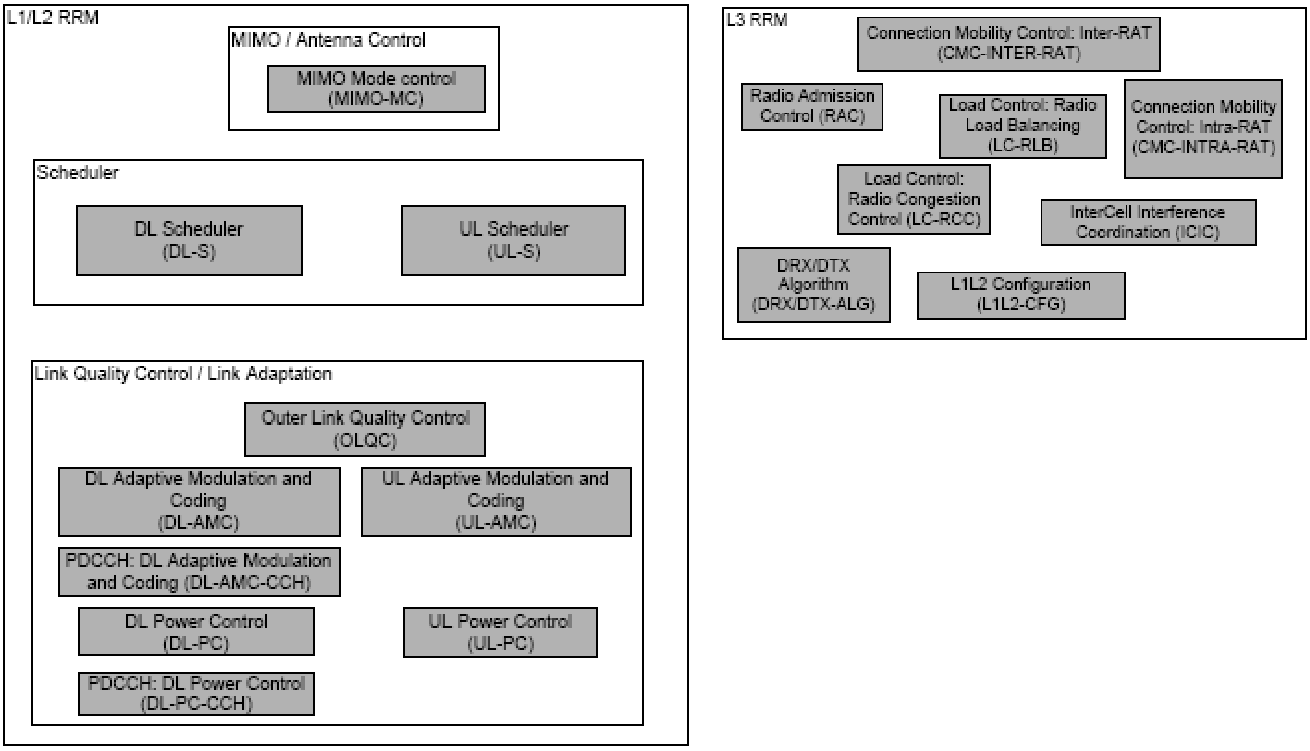


Figure 21: Radio Resource Management Resource Blocks and Functions

5.1 Scheduler

Additional feature information for the scheduler can be found in webNEI for LTE Scheduler

The scheduler is part of the MAC layer of the eNodeB and it is in charge of the assignment of the available uplink and downlink resources in the time and frequency domains (note that in HSPA, scheduling is in the time and code domains only).

The idea behind the scheduler is to take advantage of the channel variations amongst terminals by avoiding assigning resources when the channel conditions are bad (frequencies are suffering from fading) and scheduling transmissions to a UE under good channel conditions instead. The frequency domain scheduling benefits are potentially higher the larger the bandwidth because it is more likely that more fading occurs in these cases.

The most common type of scheduling is **dynamic scheduling**, that is, the downlink assignment messages for the allocation of downlink transmission resources and the uplink grant messages for the allocation of uplink transmission resources are valid per TTI (subframe). Each 1 ms TTI the eNodeB makes a scheduling decision and sends it to a set of terminals.

Additionally, **persistent scheduling** can be defined. In this case radio resources are allocated to a UE for a longer time period than one TTI (subframe) reducing the overhead considerably since there is no need for specific downlink assignment messages or uplink grant messages per TTI. Persistent scheduling is useful for VoIP (VoLTE) cases where data packets are small, periodic and semi-predictable.

Persistent scheduling can be combined with dynamic scheduling into semi persistent scheduler (SPS). Persistent scheduling is used to allocate periodic resources which are intended for the first transmission of transport blocks. Dynamic scheduling is used to allocate resources for re-transmissions, as and when required. SPS is suitable for applications like VoLTE because the packets arrive periodically, i.e. VoLTE packets arrive once every 20 ms. The use of persistent scheduling reduces the PDCCH capacity requirement because it is no longer necessary to make individual resource allocations for every packet transmission. Semi persistent scheduler is implemented in Nokia for TDD branch with feature LTE1929 TDD UL Semi-Persistent Scheduling. It is currently not implemented for FDD.

Feature LTE815 allows also **prescheduling of resources**. The feature allows for a faster allocation of UL resources for a UE who no longer has data in the buffer to send and has no ongoing Scheduling Request. UE can send small packets such as a ping packet of 32-byte size immediately without adding latency for a resource request via SRI / resource grant cycle. Main advantage is feasibility to demonstrate very low ping latency ~10ms.

In the case of LTE, downlink and uplink scheduling are separated so scheduling decisions can be taken independently. In both cases, scheduling is done in a fair manner and is cell based: each cell has a separate scheduler and the UE only follows the scheduling commands form the serving cell.

5.1.1 Downlink Scheduler

The DL scheduler is responsible for the assignment of the DL physical resources (PRBs) in the **time and frequency domains**. It utilizes proportional fair approach and grants specific higher priority for common channels, control information and HARQ retransmissions.

The DL scheduler is channel aware: the frequency resources are assigned considering the quality of the link between the UE and the eNodeB. DL scheduler also supports MIMO transmissions.

Interactions of DL scheduler with other RRM functions

- **The Radio Admission Control (RAC)** admits or rejects signaling and data radio bearer requests. Upon admission, the RAC provides to the DL scheduler all the relevant information e.g. data rate and priorities. RAC also informs the DL scheduler about radio bearer releases.
- **Adaptive Modulation and Coding (AMC)** provides the modulation and coding scheme on TTI basis for UEs which are scheduled on the shared channel. It also provides the CQI (Channel Quality Indicator) values in which the DL scheduler bases the frequency domain scheduling.
- The **DL HARQ** entity (UE specific) provides to the DL scheduler with the ACK/NACK information for a particular transmitted transport block of a UE, the current number of transmission and the HARQ process status. The DL HARQ entity itself takes from the DL scheduler the allocated number of PRBs

and the MCS (or transport block size) for a particular UE as well as the required HARQ process information.

- The **MIMO mode control** information is used to indicate to the DL scheduler whether one or two code words should be scheduled for a particular UE.
- Downlink scheduler must be able to insert gaps in DL scheduling of a UE in order to allow for UE performing inter-RAT measurements. Measurement gap activation and deactivation is controlled by **connection mobility control functionality**

Downlink scheduler algorithm

The DL scheduler algorithm performs three different tasks as shown in Figure 22.

First, it determines which PRBs are available and can be allocated to UEs. Second, out of the available PRB, it evaluates which are needed for common channels (i.e. system information broadcast - SIB -, paging and random-access procedure). Finally, in the last step, the UEs (bearers) are allocated into the remaining PRBs.

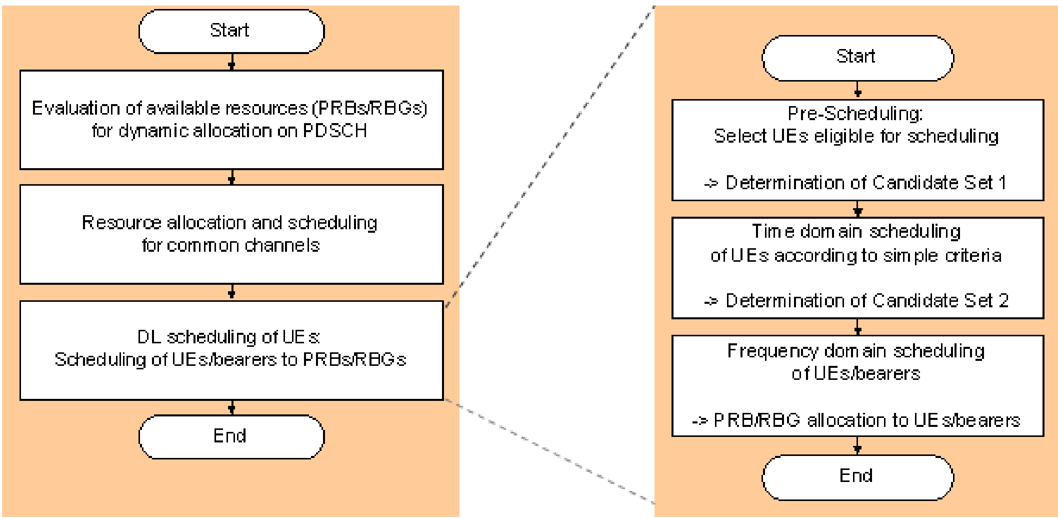


Figure 22: DL scheduler algorithm

The scheduling of UEs (bearers) into PRBs is done in three steps:

- **Pre-scheduling:** For each UE the scheduler evaluates if there is data for transmission depending on the buffer fill levels.
- **Time domain scheduling:** How many UEs are allocated per TTI scheduled. It depends on the LNCEL parameter, ***maxNumUeDl***, with a default value that depends on the Channel Bandwidth: 1.4MHz, 3MHz or 5 MHz -> 7, 10MHz ->14, 15MHz -> 17, 20 MHz -> 20.
- **Frequency domain scheduling:** How many PRBs and in which location are allocated for each scheduled UE.

5.1.2 Uplink Scheduler

The UL scheduler is responsible for the assignment of the UL physical resources (PRBs) in the **time and frequency domains**. In order to do this, the UL scheduler evaluates first what are the available physical resources per transmission time interval (TTI = 1 ms) and then, selects the UEs that will be scheduled in the next TTI. The result of the UL scheduler evaluation is sent by means of grants to the appropriate UEs via the L1/L2 Control Signaling in DL.

UL scheduler works with the buffer status report (BSR) i.e. users are scheduled depending on the amount of data in their buffer. Scheduler works in time and frequency domain with additional inputs like power control headroom. Due to synchronous HARQ operation in uplink, users with pending HARQ retransmissions will always be scheduled.

Similarly, to the Downlink Scheduler it also works in several steps:

1. **Pre-scheduling:** Evaluation of physical resources available for PUSCH (i.e. PRBs used for PUCCH and PRACH are not considered/used by PUSCH). Reservation of resources needed for RACH Msg.3 to disable the resources allocated for dynamic scheduling. Evaluation of users that can be scheduled based on UEs DRX/DTX mode, UL channel synchronisation, data in the buffer, HARQ retransmissions.
2. **Time domain scheduling:** Fair criterion (equal throughput) using minimum bit rate. Prioritization of signalling data and HARQ retransmissions through vendor parameters **prioSrbUl** LNCEL; 1….100, default 10 and **prioHarqUl** LNCEL; 1…100, default 100. Determination of the set of UEs for frequency domain scheduling.
3. **Frequency domain scheduling:** Allocation of selected UEs (output of Time Domain scheduling) to PRBs. The algorithms for UL Frequency Domain scheduling are defined based on ***ulsFdPrbAssignAlg*** parameter:

    - **Round Robin** (***ulsFdPrbAssignAlg*** =0). UEs are assigned PRBs in an equally fair manner until they are sufficient for the service or the PRBs of the cell are exhausted. Based on weights defined in user QCI (LTE9 Service Differentiation feature).
    - **Exhaustive scheduler** (***ulsFdPrbAssignAlg*** =1): Assigns the priority sequence defined by the Time Domain scheduler as many physical resources as possible to the UEs until the number of PRBs are sufficient for the service or the resources of the cell are exhaust
    - **Mixed scheduler (*ulsFdPrbAssignAlg* =2):** The scheduler is a joint FD scheduler which assigns the PRBs for SRB and GBR bearers by the exhaustive FD scheduler and the PRBs for the nonGBR bearers by the Round Robin FD scheduler to the UEs.

The maximum number of UEs which can be scheduled per TTI time frame is restricted by LNCEL parameter ***maxNumUeUl***. The value depends upon the channel bandwidth.

When assigning PRBs to a UE, the UL scheduler takes into account the buffered data volumes of the data radio bearers (DRB) and of the signaling radio bearers (SRB). Since the scheduling decisions are performed by the eNodeB and the buffer is in the UE, the UE needs to report the buffer data volume. This reporting is done for each logical channel group (it cannot be on a bearer bases). The UE is responsible for selecting from which radio bearer(s) the data is taken. The task/bearer prioritisation for the UL scheduler is as follows:

- Hybrid ARQ (HARQ) retransmissions. Note: In case of HARQ retransmissions they will use the same MCS, the same rate matching and the same number of PRBs but may use different PRBs in the frequency domain.
- Random access procedure
- Scheduling request
- Signaling radio bearer
- Data radio bearer

Interactions of UL scheduler with other RRM functions

- **Radio Admission Control (RAC):** RAC informs the UL scheduler whenever a data or signaling radio bearer is setup or released. RAC also provides the minimum and maximum bit rates of the data radio bearers whenever they are setup.
- **Link Adaptation:** UL Adaptive modulation and Coding (AMC) provides per UE the Modulation and Coding Scheme (MCS) and the maximum number of PRBs. UL scheduler provides an indication to the UL AMC for each UE scheduled in the next TTI as well as the amount of PRB which is assigned to the UE. For the DL AMC, the UL scheduler provides a list of UEs scheduled in the next TTI.

UL scheduler algorithm

The UL scheduler is divided in two main functions:

- The evaluation of the resources that can be used for UL data transfer in the next TTI (step 1 in Figure 23)
- The scheduling algorithm that assigns the available resources to the UE (step 2 in Figure 23)

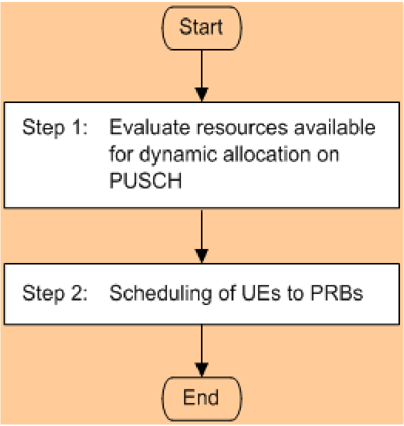


Figure 23: UL Scheduler algorithm

The PRBs available for UL scheduling are those which are not used for signaling or by the random access procedure.

Scheduling for the available PRBs is done in the time and frequency domain. In time domain, the UEs to be scheduled are prioritized. The maximum number of UEs that can be scheduled per TTI is determined by a configurable parameter: ***maxNumUeUl***. After the decision of how many UEs will be scheduled per TTI the frequency domain scheduling determines the PRBs that will be assigned to those UEs.

5.1.2.1 UL Scheduler Types

There are three types of UL scheduler in Nokia implementation: Channel unaware scheduler (CUS), channel aware scheduler (CAS) and Interference Aware Scheduler (IAS). A performance comparison of these schedulers can be found in webNEI under UL schedulers analysis.

In early releases, UL Scheduler was channel unaware. In channel unaware scheduling a random function (blind hopping) decides the position of the PRB groups within each TTI. The PRB groups are evenly distributed over the allowed frequency range: if not all of the PRBs are assigned and some physical resources are left over, the unassigned PRBs are considered as physical resources of 'virtual' UEs and the hopping algorithm handles the unassigned PRBs in the same manner as the allocated PRBs.

Interference Aware Scheduler (IAS) was introduced after channel unaware scheduler. The scheduler divides UL resources into 3 categories as per the interference scenario and this information is taken into account during the scheduling process. The scheduler does not require UL probe signal from UE.

Finally, the channel aware scheduler for UL was introduced. The scheduler uses UL measurements of sounding signal transmitted by UE.

5.1.3 Power Control

Power control in uplink is based on the slow uplink power control scheme that is a combination of open loop power control and closed loop power control. In downlink, power control works towards flat spectral density over the bandwidth with possibility to boost certain elements if needed (e.g. reference elements). Both directions are supported via adjustable parameters. Power Control for LTE is standardized within 3GPP in TS 36. 213. A briefing on the topic is available in webNEI under LTE UL Power Control

5.1.3.1 Uplink Power Control

Power control is a mean to improve the cell edge behavior (improve bit rates and have reliable control plane operation), to reduce inter-cell interference and to reduce the UE power consumption. In the LTE UL, the performance of the system heavily depends on the power control scheme. The scope of UL power is UE level, that is, it is performed independently for each UE in a cell.

LTE power control requirements are less stringent than for WCDMA. Power control in WCDMA was designed for radio link adaptation under continuous transmission in circuit-switched services. In LTE, there is already fast scheduling of UEs (1 ms, TTI). So, whereas the power control in WCDMA is periodic with a frequency of 1500 Hz (every 0.67 ms loop delay) with power steps of +-1 dB in LTE it is possible to have larger power steps with lower frequencies (5 ms minimum loop delay) and it does not need to be periodic. This is why it is called 'slow' power control.

The slow uplink power control scheme is applied separately by using different parameter sets for the different uplink physical channels: PUSCH (physical uplink shared channel) and PUCCH (physical uplink control channel) and for the sounding reference signal (SRS). The standard (3GPP TS36.213) specifies a fractional power control scheme for PUSCH with the option to disable it and revert it to a conventional power control scheme. This contrasts with PUCCH where it specifies a conventional PC scheme.

Conventional PC schemes try to maintain a constant SINR at the receiver so the UE increases the Tx power to fully compensate for increases in the path loss. Fractional PC schemes, allow the received SINR to decrease as the path loss increases so the UE Tx power increases at a lower rate when compared to a conventional power control scheme and consequently, it increases the average cell throughputs by reducing the inter-cell interference. Parameter α is used to configure the use of fractional power control. It has a big impact on the maximum UE achievable throughput in UL, as well as the aggregated UL cell throughput

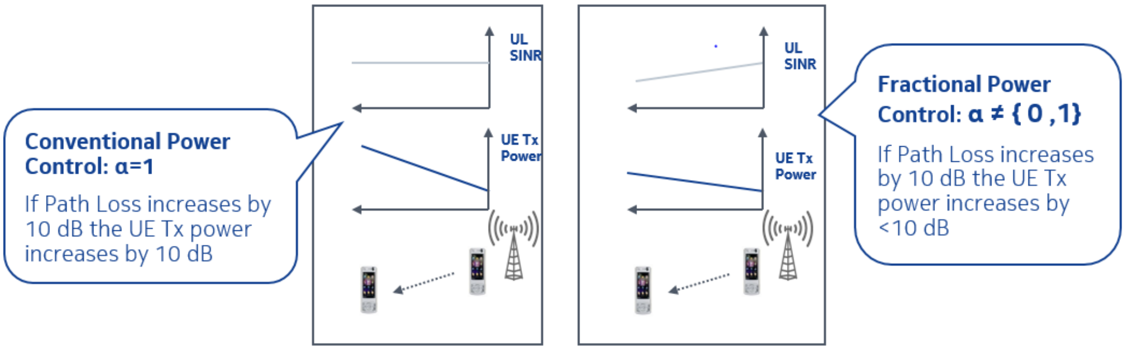


Figure 24: Conventional PC Scheme vs. Fractional PC Scheme

Slow UL power control combines two components:

- Open loop power control calculated at the UE
- Closed loop power control corrections transmitted by the eNodeB

The **open loop power control** is performed independently by the UE and compensates for long-term channel variations (e.g. path loss and shadowing). It is based on path loss measurements, broadcasted parameters and RRC signaled parameters from the eNodeB. However, open loop power control suffers from errors in UE path loss measurements so closed loop power control is used.

The **closed loop power control** is less sensitive to errors in measurements because it is based on interactions between UE and eNodeB. The eNodeB performs UL level and quality measurements. Based on these measurements (weighed and averaged) the eNodeB sends power correction commands to the UE to maintain, increase or decrease the transmit power.

The UE uses the closed loop power correction values on top of the open loop component to calculate its total uplink transmit power.

Open loop power control is a basic functionality. Closed loop power control functionality can be enabled / disabled although the best way of operation is when both (open and closed power control) are combined. There can be an overall cell throughput gain of ~20% when using both open and closed power control compared to using only open loop power control.

The uplink transmit power of the PUSCH in each sub frame is defined by the formula on the Figure 25. It consists of an open loop and a closed loop power control component as mentioned above. The factional power control scheme is part of the open loop component.

$$P_{PUSCH}(i) = \min\{P_{CMAX}, 10\log_{10}(M_{PUSCH}(i)) + P_{0\_PUSCH}(j) + \alpha(j) \cdot PL + \Delta_{TF}(i) + f(i)\} [dBm]$$

Figure 25: PUSCH PC formula

- **M_{PUSCH}**: Represents the PUSCH bandwidth during sub-frame. The UE Tx Power is increased proportionally to the number of allocated RBs. Remaining terms of the formula are per RB
- **P_{0_PUSCH}**: eNodeB received power per RB when assuming path loss 0 dB. Depends on α:
- **P_{0_PUSCH}** is small when α=1 (conventional PC scheme) to allow for sufficient UE transmit power headroom for when the path loss increases, i.e. the UE Tx power should fully compensate the path loss when fractional power control is disabled.
- **P_{0_PUSCH}** increases as the value of α decreases because less UE Tx transmit power headroom is required for when the path loss increases. **P_{0_PUSCH}** is maximum when α=0, i.e. the UE transmits as its maximum capability irrespectively of the path loss.
- **PL**: Downlink path loss calculated by the UE using a combination of RSRP measurements and knowledge of the reference signal (RS) transmit power, i.e. PL= RS transmit power – RSRP measurement.
- **α (j)**: Used to configure the fractional power control. Same variable as the one used by the eNodeB when calculating **P_{0_PUSCH}**
- **Delta_TF**: It links the UE Tx power to the MCS. Increases the UE Tx power to achieve the required SINR when transmitting a large number of bits per RE (high MCS)
- **f(i)**: Makes use of feedback from the eNodeB. Feedback are TPC (Transmit Power Control commands) send via PDCCH to instruct the UE to increase or decrease its transmit power

Slow UL power control procedure

- In UL, the total UE power is accumulated only on the subcarriers that are used for transmission. The UE controls its total output power to keep the transmitted power spectral density (PSD) constant and independent of the allocated transmit bandwidth (number of PRBs)
- While there is no feedback from the eNodeB (no UL power control commands) the UE performs open loop power control based on path loss measurements, system parameters and RRC signaling. This is important for the start of the data transfer.
- Started the data transfer, the UE receives the power control commands from the eNodeB and corrects the power spectral density.

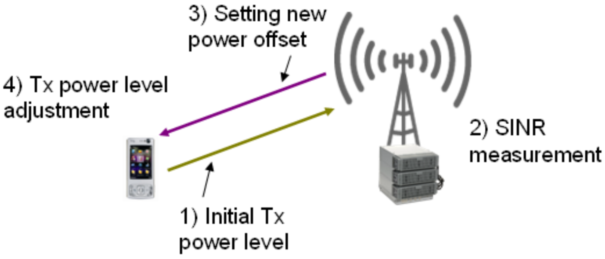


Figure 26: Slow UL power control procedure

The main evolution step of LTE Power Control happened with the introduction of the Interference Aware UL Power Control (LTE1336) representing an alternative for Closed Loop UL Power Control for PUSCH/SRS.

UL power control might lead to high UE power on cell edge which would lead to high interference in an interference limited scenario. It is desirable therefore to compromise UL power a bit in advantage of a bit better average cell throughput for everyone.

The feature implements a kind of deal between cells in an interference limited cluster. Cell border UEs are toned down. The action results in lower interference. Reduced interference helps to restore the loss in link quality caused by reducing UL power. This gives overall average cell throughput improvement.

System level simulations have shown average cell throughput improvement 14%-20% in comparison with the open loop power control in clusters with 500m inter-site distance.

In general, the increase of UL power brings additional useful signal for own cell UEs, however it adds additional interference for neighboring cells and the reduction of UL power decreases the useful signal but also lowers the interference. Nokia research created the algorithm which achieves higher throughput in a complete range of cells, at reduced UL power settings (especially for cell-edge UEs).

5.1.3.2 Downlink Power Control

In downlink, the total eNodeB Tx power is shared equally between all PRBs and subcarriers available in the given channel bandwidth. This is called 'flat power allocation' since each subcarrier is transmitted with the same and constant power independently of the resource occupation. There possibility of boosting the power of certain subcarriers, e.g. control channels, is under study but it is not standardized by 3GPP.

Note that for an eNodeB with the same total Tx power, the power per subcarrier will be higher in smaller bandwidths than in larger bandwidths and consequently, under the same conditions, the downlink coverage will be higher for smaller bandwidths than for larger ones.

DL power control is supported by means of adjustable parameters. It is possible to reduce the cell power (via parameter) to obtain a flat power spectral density for the control of the coverage. In case of multiple transmit antennas (i.e. MIMO) the power is given per transmit antenna.

Power for different physical channels can be handled separately with different parameter settings for each channel (PDSCH – Physical Downlink Shared Channel-, control channels, reference signals, synch channel and common channels).

5.1.4 Admission Control

Admission control is one of the main functions of the L3 RRC (Radio Resource Control) control plane and is implemented in the eNodeB.

The task of RAC (Radio admission control) is to admit or to reject the requests for establishment of Radio Bearers (RB). Reasons for requesting radio bearers are a paging event, a handover request or a user request for establishing a call. Each of those requests is evaluated with respect to the current cell load and the effect the new bearer can have on existing connections. The scope of RAC is cell level.

Radio Bearers in case of cell access due to handover (HO) are handled by the target cell as 'all or nothing', this is, either both Signaling Radio Bearer (SRB) **AND** Data Radio Bearer (DRB) are admitted or the UE is rejected. The DRB establishment requests for HO have higher priority than those for normal access.

Admission control evolved from admitting all SRBs by default to limit the SRB and give different admission priorities for UEs accessing the cell via HO depending on the HO cause. Later on, smart admission control (LTE 497) was introduced which is based on measurement based estimations for bearers with guaranteed bit rate. This is for bearers with QCI 1,2,3,4. The feature works usually together with the Allocation and Retention Priority (LTE534) which introduces preemption possibilities in case of resource shortage.

RAC interacts with the Scheduler by informing it every time a new bearer is set up or released.

5.1.5 Link Adaptation (Adaptive modulation and coding: AMC)

Link adaptation is a fundamental function of the air interface for efficient data transfer. It dynamically adjusts the data rate for each user based on the channel conditions to improve the system capacity and the coverage reliability. It is closely related to the modulation and coding scheme used. This is why the terms Link adaptation and adaptive modulation and coding are used together.

In downlink, the eNodeB decides the modulation and coding scheme based on the downlink channel condition by considering the CQI (channel quality indicator) reports that the UE sends in uplink. This CQI reporting can be done per TTI period and that is why it is also called Fast AMC. The CQI is an indication of the data rate that can be supported by the downlink channel based on the SINR and the characteristics of the UE's receiver.

- If SINR is good then higher modulation and coding schemes (MCS) can be used which implies more bits per symbol are sent and higher throughputs are achieved.
- If SINR is poor then lower order MCS (i.e. QPSK) should be used which implies fewer bits per modulated symbol are sent and although the achieved throughputs are lower the communication is more robust because it has higher tolerance to interference.

In uplink, the eNodeB also controls which modulation and coding schemes are used. The main difference with the downlink is that link adaptation is not based on CQI reports, but instead the eNodeB can directly estimate the uplink data rates by channel sounding, i.e. using the sounding reference signals (SRS). In

Nokia's implementation, the UL link adaptation is based on the BLER after 1st transmission. Additionally, link adaptation can be switched on/off.

The uplink link adaptation interacts with the uplink power control by informing about the selected MCS and getting information about the UE Power Headroom so the uplink AMC can calculate the maximum allowed number of uplink PRBs per TTI for UL scheduling. These interactions are result driven to reduce the signaling load in the eNodeB internal interfaces (i.e. the delivery of MCS is delivered to PC when the data transfer starts and when changes in the MCS are reported)

Modulation and coding rates are constant over the allocated frequency resources for a given user but they can change on the time domain on TTI basis (both, for uplink and downlink transmissions).

The 3GPP standard defines the following options for **modulation and coding schemes**: QPSK, 16QAM and 64QAM in both directions along with 256QAM possibility for DL. 64 QAM is mandatory in downlink but in uplink is only mandatory for the UEs with highest categories (Class 5, 8 and 13 in 3GPP Rel.12).

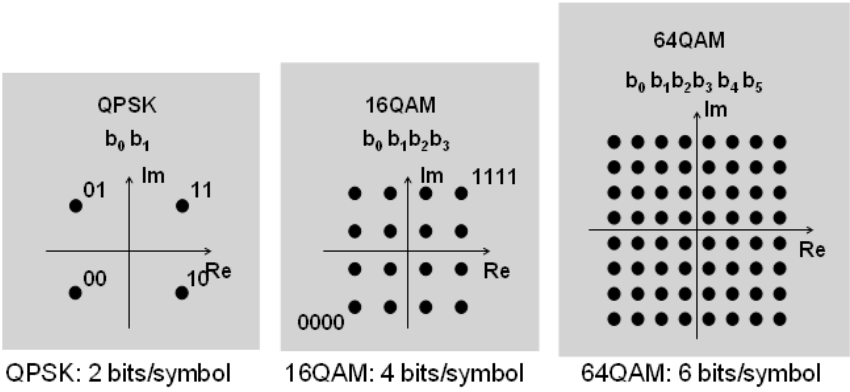


Figure 27: Basic Modulation and Coding Schemes defined by 3GPP for LTE

Note that the different physical channels can only use certain modulation and coding schemes as on the Table 2.

Physical Channel	MCS
PDSCH, PMCH	QPSK, 16QAM, 64QAM, 256QAM
PBCH	QPSK
PDCCH (PCFICH, PHICH)	QPSK
PUSCH	QPSK, 16QAM, 64QAM
PUCCH	BPSK and/or QPSK

Table 2: Allowed MCS per Physical Channel

5.1.5.1 Downlink link adaptation procedure

Additional information to the one presented in this section can be found in webNEI [LTE Link Adaptation Principles].

The link adaptation procedure is different for the downlink data channel (PDSCH) and for the downlink control channel (PDCCH):

AMC for Downlink Data Channel (PDSCH)

The initial modulation and coding scheme is provided by an O&M parameter and it is set as the default MCS. If dynamic DL AMC is not activated, the default MCS is always used.

In case the dynamic link adaptation is activated, HARQ retransmissions are handled differently from initial transmissions. For a HARQ retransmission the same MCS must be used as for the corresponding initial transmission. The MCS determined for an initial transmission therefore has to be remembered as long as HARQ retransmissions are performed for the same block of data.

For an initial transmission, the DL link adaptation determines the MCS considering the available channel state information, PRB allocation as determined by the downlink scheduler and optionally, potential limitations in the available/allowed amount of data for the considered TTI if indicated by the scheduler

The average channel state is determined from the CQI information corresponding to the PRBs assigned (or considered for being assigned) by the scheduler.

The averaged CQI is mapped to an MCS level considering if the downlink scheduler indicates a bit rate limit (throughput). The MCS selected cannot pass that limit.

It is possible to enable/disable the use of 64QAM and 16QAM modulation. This limitation also needs to be considered by the link adaptation.

If no new CQI values are received for a UE and the UE is scheduled, the MCS is calculated based on the latest available CQI information or the default MCS is used depending on how 'old' the available CQI information is.

According to 3GPP, the same MCS is used for all resource blocks allocated to a single user in the frequency domain. However, the channel quality may be different for the resource blocks of the same UE within a TTI. In downlink, the set of resource blocks being allocated to a UE is determined step-by-step depending on the UEs channel quality as well as all the other UE's channels quality. For each allocation step the set of RB changes so the MCS for the UE needs to be calculated again. Once scheduling and link adaptation are finalized, the MCS corresponding to the exact set of RBs allocated to the UE is known and it is the same MCS for all RBs.

DL link adaptation supports transmit diversity (single stream of data transmission) and MIMO 2x2 spatial multiplexing (two data streams) as well as the higher MIMO schemes up to 4x4 if used. DL link adaptation actions are determined dynamically by MIMO Mode Control.

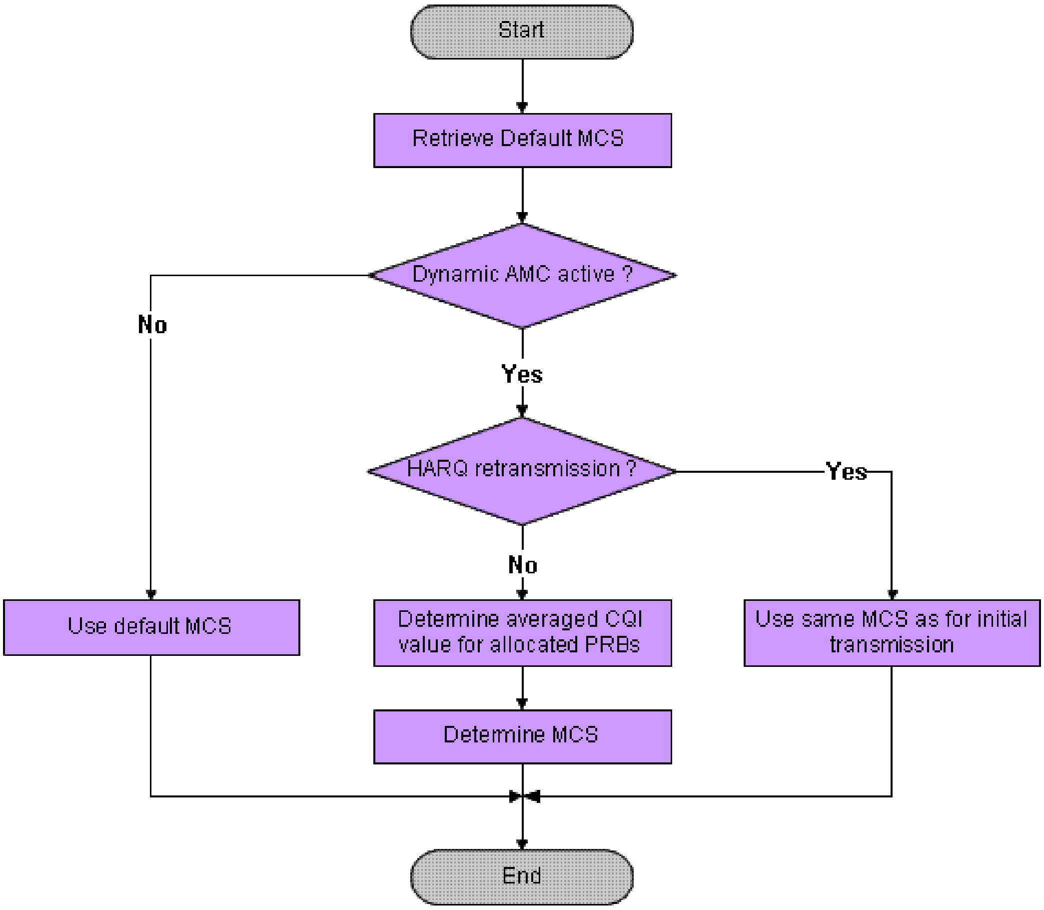


Figure 28: DL link adaptation procedure

AMC for Downlink Control Channel (PDCCH)

Link Adaptation/AMC for downlink control channel (PDCCH) was originally a UE specific adaptive solution (non-payload based). The QPSK modulation is mandatory, but the code rate and aggregation level is selected based on CQI reports which means a more efficient usage of the PDCCH resources based on the channel condition. Lately, further improvement was introduced as usage based PDCCH region adaptation, i.e. the region is sized on demand instead of fixed setting.

5.1.5.2 Uplink link adaptation procedure

UL Link adaptation have been based on BLER and on the Power Control Headroom (PHR) from the first releases. It works on a per UE basis: The Link adaptation adapts the optimum MCS according to UE specific link quality. It is called slow AMC because the update rates vary from 10ms-100ms and it is not linked to the UL scheduler nor to the UL power control. Transmission bandwidth changes are based on the power control headroom in parallel way. Consequently, it is a robust and stable AMC solution. In addition, the UL link adaptation is also independent from the UL L1 physical measurements and their accuracy. However, to avoid cases of low and high BLER situations, the slow AMC is implemented together with an outer loop link adaptation (OLLA). In this case, two adjustable BLER thresholds are defined allowing for fast MCS downgrade/upgrade in case of long update periods and very poor or excellent radio conditions:

- If BLER goes above a MAX BLER threshold (poor radio conditions) there is an ***'Emergency Downgrade'*** of the MCS into a lower one.

- If BLER goes below a MIN BLER threshold (good radio conditions) there is a ***'Fast Upgrade'*** of the MCS into a higher one.

With the 'Emergency Downgrade' and the 'Fast Upgrade' functionalities a configurable O&M target BLER is maintained. All the UL link adaptation strategy can be configured via parameters.

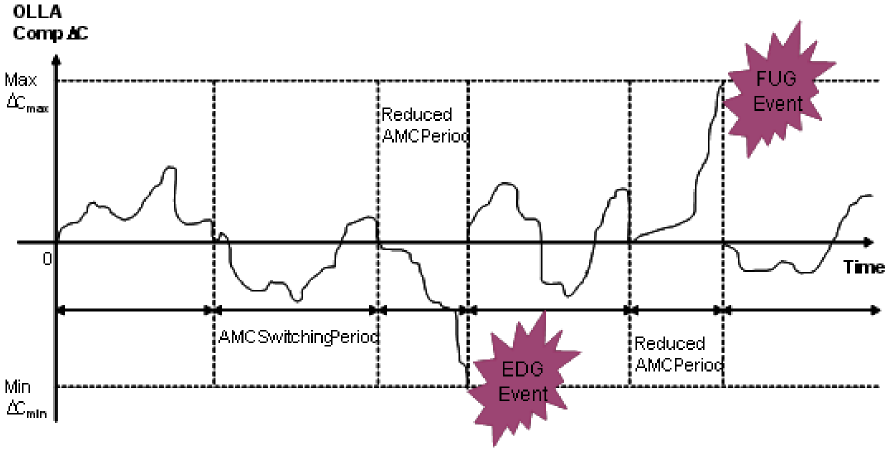


Figure 29: Emergency Downgrade (EDG) and Fast Upgrade (FUG)

The interactions with UL power control and Scheduler are **result driven**, i.e. to keep signaling load on eNodeB internal interfaces low, the MCS is reported at the start of data transfer and only when there are changes of MCS.

The original Link Adaptation (described above) appears to be quite conservative and thus 2 evolution steps have been introduced in form of features:

Feature Extended-Uplink Link Adaptation (LTE1034) introduced the coordination between Adaptive Transmission Bandwidth (ATB) and outer loop link adaptation with suppression of the slow AMC. ATB is dependent on Power HeadRoom (PHR, means how much UE transmission power is available to overcome additional UL attenuation) and BLER as well. ATB reduces UL transmission bandwidth in case of UL power shortage, which improves UL SINR at eNB receiver.

The feature Fast Uplink Link Adaptation (F-ULA, LTE1495) with modified algorithms (ATB, AMC and OLLA) takes into account measurements SRS and DM-RS in addition of BLER and PHR. The link adaptation evolution steps are on the Figure 30

The F-ULA algorithm provides better throughput than previous LA methods, it improves cell average and cell edge throughput after the events as handover, call setup, etc. There is faster MCS ramp-up starting from the (low) initial MCS (mainly users in good radio conditions should benefit from this effect). Link adaptation is able to better follow the varying radio conditions (both users with good and bad radio conditions should benefit from this effect).

Exemplary gains from Morse-system dynamic simulations (F-ULA vs. E-ULA) are 26% on mean cell throughput and 3% on cell edge UE throughput.

Link Adaptation		UL LA	E-ULA	F-ULA
AMC	ILLA	Slow AMC	Not used with E-ULA	Fast AMC SINR based
	OLLA	OLLA	OLLA unchanged	Modified OLLA
ATB		Slow ATB - PHR based	New ATB - PHR and BLER based	Modified ATB
Parameter activation		LNCEL:ulamcEnable = True LNCEL:ulatbEnable = True	LNCEL:actUlLnkAdp = eUlLa	LNCEL:actUlLnkAdp = fUlLa
Comment			OLLA and ATB synchronization	F-AMC core integrates all functional blocks

Figure 30: Evolution of Nokia's UL Link Adaptation

5.1.6 Connection Mobility Control

Connection Mobility Control is one of the basic functionalities of the RRM. As the name suggests, it refers to handovers. Handovers in LTE are:

- **Lossless**: Packets are forwarded from the source to the target.
- **Network controlled:** The target cell is selected by the network not by the UE. The handover control is in the e-UTRAN not in the Core network.
- **UE-assisted:** Measurements are made and reported by the UE to the network although it is the network (eNodeB) which triggers those measurements.
- **Late path switch**: Only when the handover is successful, the packet core is involved.

Handover Types

Handover types are defined based on the frequency and the technology. Within LTE, the following types are defined:

- **Intra-LTE (or Intra-RAT) handovers**:
  - Intra frequency handovers, that is, handovers within the same frequency band. There are two scenarios:
    - Intra-eNodeB handover (i.e. inter sector)
    - Inter-eNodeB handover (i.e. inter site)

    In both cases the HO can happen via the X2 interface or via the S1 interface. The downlink data forwarding over X2 is applied for lossless data path switching.
  - Inter-frequency handovers that allow service continuity for LTE deployments in different frequency bands and for LTE deployments within one frequency band but with different center frequencies.

Inter frequency handovers also include those between TD LTE and FD LTE as part of inter-frequency handovers.

- **Inter-RAT handovers**:

These are the handovers to other radio access technologies (RAT). The scope of these HOs is to provide continuous PS coverage.

- LTE HO to/from WCDMA
- LTE NACC to/from GSM
- LTE HO to/from HRPD (3GPP2)

Mobility Requirements

Mobility requirements are based on 3GPP 25.915:

- Optimized performance (in terms of delay and packet loss) is required for low mobile speeds 0….15 km/h
- High performance for mobile speeds between 15…120 km/h
- Mobility maintained for mobile speeds 120….250/350/500 km/h depending on the frequency band.
- Voice and other real-time services via the PS domain must have a handover performance better or equal than GERAN

Nokia Releases support high performance intra and inter-system handover, seamless and lossless via data forwarding over X2. There is also specific support for high mobility (up to 250…350 km/h)

Basic handover scenario (Reference 3GPP TS36.300)

Figure 31 illustrates the basic HO signaling in the case where neither the MME nor the S-GW change. The HO procedure does not involve the EPC, i.e. the preparation messages are exchanged between eNodeBs. The release of the resources at the source side after HO completion is triggered by the eNodeB.

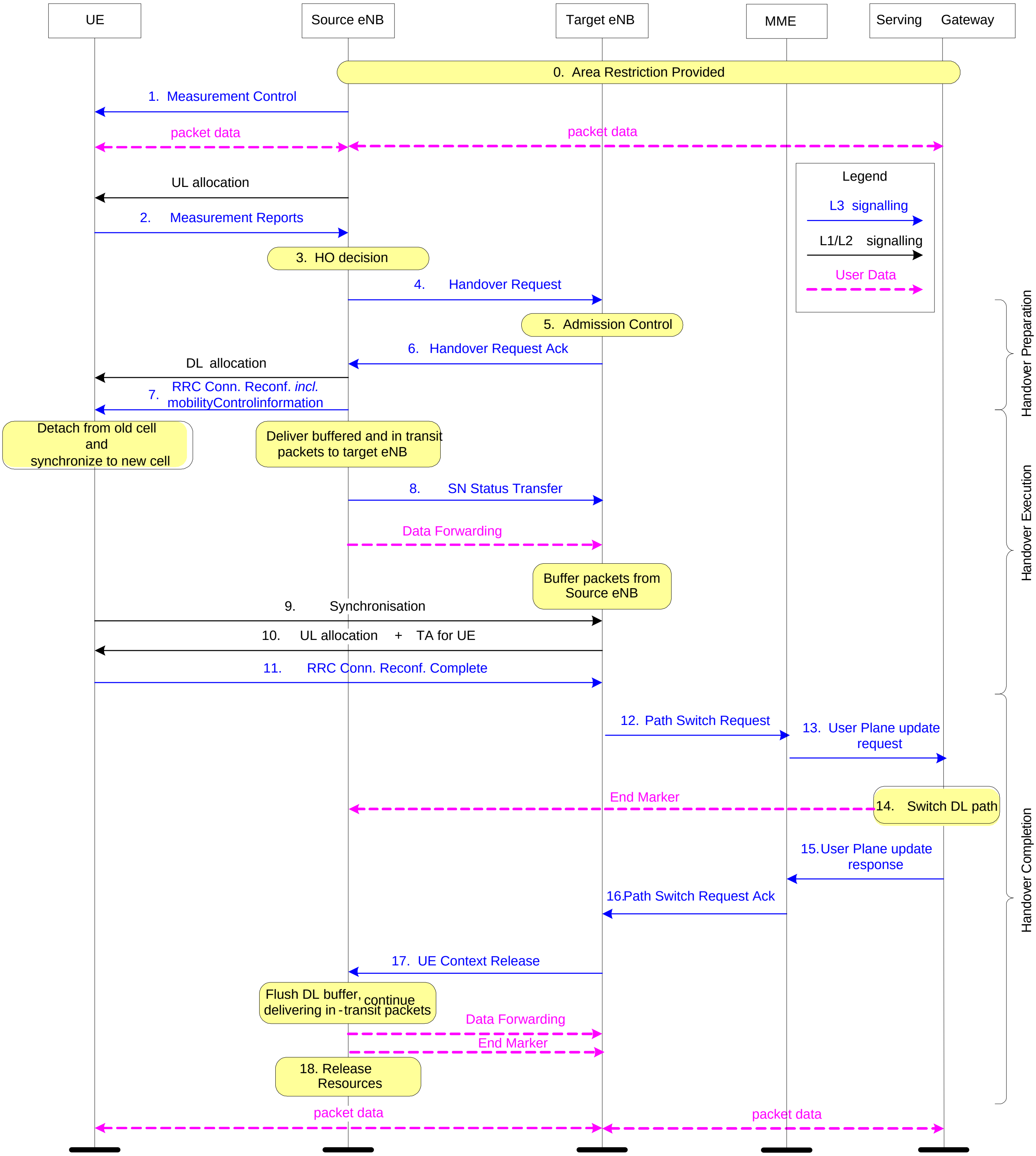


Figure 31: Basic HO process (Intra-MME/S-GW)

The source eNodeB contains information about the roaming (area) restrictions for the concerned UE. Based on those restrictions the source eNodeB configures the UE measurement procedures.

After receiving the Measurement Control message from the source eNodeB, the UE is triggered to send measurement Reports to the eNodeB.

The source eNodeB takes a HO decision based on the contents of those measurement reports. If the eNodeB decides to proceed with the HO then it issues a '*handover request message*' to the target eNodeB passing the necessary information to prepare the HO at the target side (e.g. the UE X2 and UE S1 signaling references that enable the eNodeB to address the source eNodeB and the EPC respectively).

The target eNodeB may perform admission control depending on the EPS (Evolved Packet System) Bearer QoS and it configures the required resources based on that bearer. After preparing the HO with L1/L2 it sends a *'handover request ack'* to the source eNodeB.

As soon as the source eNodeB receives the *'handover request ack'* the data forwarding from the source to the target eNodeB may be initiated. The target eNodeB buffers those packets.

The source eNodeB sends the *'handover command'* message to the UE that it starts synchronization and the random-access process with the target cell. The network will respond with the UL allocation and timing advance.

When the UE has accessed the target cell, it sends the *'handover confirm'* message to the target eNodeB to indicate that the procedure has been completed by the UE. The target eNodeB starts to send data to the UE.

Once the handover is completed it is necessary to involve the core to inform the UE has changed cell. This is done when the target eNodeB sends a *'path switch request'* message to the MME, which in turn, after receiving this message, sends a *'user plane update request'* to the Serving Gateway (S-GW).

The S-GW switches the downlink data path to the target eNodeB, releases the resources towards the source eNodeB and sends a *'user plane update response'* to the MME that confirms the path switch to the target eNodeB with the *'path switch ack'* message.

Finally, the target eNodeB sends the *'release resource'* message to the source eNodeB to inform the success of HO and trigger the release of resources in the source eNodeB.

5.1.6.1 Handovers within Nokia implementation

Note: For more information on mobility topics including multi-vendor refer to the Multi-Layer Mobility Strategy proposal wiki page and to the Neighbor Planning wiki page

Handover decisions are made in the eNodeB based on DL measurements that the UE provides to the eNodeB by means of event triggered or periodic reporting. The reasons for handover are typically 'better cell HO' (A3 case) and 'coverage HO (A5 or B2 case). Such handovers provide UE with optimal cell and RAT from RF point of view, when UE is connected to the best server and so it generates minimum interference. Additional handovers types support load balancing.

In the Inter RAT handover towards WCDMA, measurements of WCDMA are started and if proper inter-RAT neighbor cells are detected, a handover is initiated. Note that the reason for inter-RAT HO to WCDMA in this case is coverage (not better cell).

Assumptions:

- Downlink measurements are sufficient for Measurement control and HO decision. UL measurements are not considered in RL16A.
- RSRP (Reference Signal Received Power) is considered for the HO algorithm. RSRQ (Reference Signal Received Quality) based mobility feature (LTE1198) allows to trigger reporting and handovers based

on RSRQ. Event triggered measurement report is sent by the UE according to the eNodeB measurement control message.

Handover Algorithm

The HO algorithm handles the UE in RRC_CONNECTED mode only. If the UE is in RRC_IDLE then the UE decides autonomously about cell reselection.

The HO algorithm triggers the UE to provide measurements via the *Measurement Configuration*. The measurement configuration consists of a list of measurement objects. According the related control parameters (thresholds, offsets, timers) which are transmitted to the UE by Measurement Configuration, the UE performs measurements and sends event based or periodic measurement results to the eNodeB.

Depending on the RSRP of the serving cell different objects are measured as shown schematically in Table 3: Measurements might be activated by RSRQ as well.

RSRP of serving cell	Measurement activities in UE
rsrp(s) > Th1	no measurement except serving cell,
Th1 > rsrp(s) > Th2	intra-frequency measurement
rsrp(s) < Th2	intra-frequency measurement + interRAT measurement

Table 3: Measurement activities in UE based on the RSRP of serving cell, LTE Intra-frequency case

Th1 and Th2 are thresholds set via O&M parameters.

In case of inter-frequency or another RAT involvement, the Th2 might be configured as RSRP or RSRQ or both. Measurement activation of particular layers can be then triggered either by dedicated RSRP thresholds or monitoring of all these layers can be triggered by one common RSRQ based threshold as per the Figure 32.

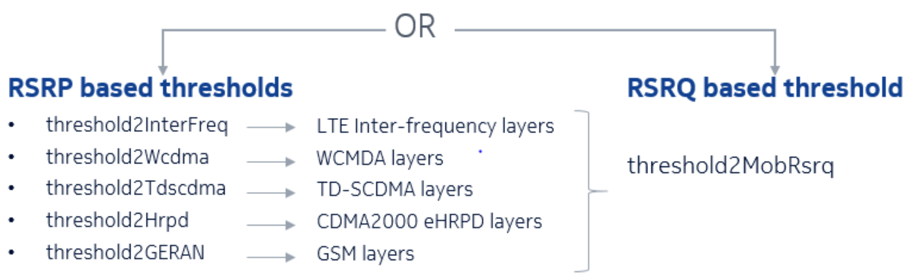


Figure 32: RSRP and RSRQ based Threshold2 measurement activation

Measurement deactivation of all so far measured LTE inter-frequency/inter-RAT layers is triggered if both RSRP level and RSRQ quality of serving cell are above particular RSRP and RSRQ thresholds as per the Figure 33.

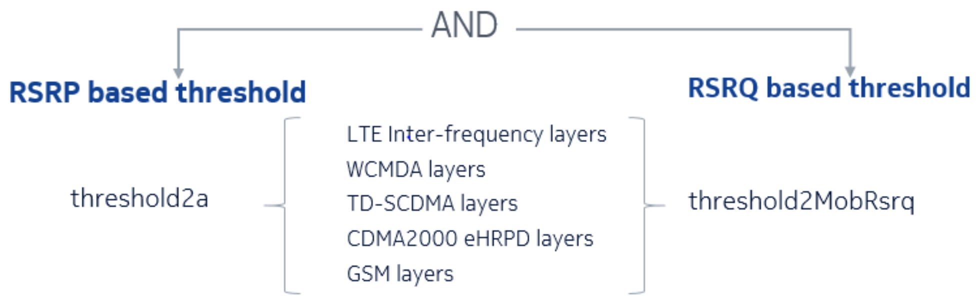


Figure 33: RSRP and RSRQ based Threshold2a measurement deactivation

When the RSRP of the serving cell becomes better than Th2a, then Inter-RAT measurements are de-activated. Th2a is similar to Th2, but to prevent ping-pong effects it is necessary that the value of Th2a is higher than Th2.

The measurement reporting events are:

- Event A1: Serving becomes better than threshold
- Event A2: Serving becomes worse than threshold
- Event A3: Neighbor becomes amount of offset better than serving
- Event A4: Neighbor becomes better than absolute threshold
- Event A5: Serving becomes worse than absolute threshold1 and inter RAT neighbor becomes better than threshold2 (coverage type of handover)
- Event B1: Inter RAT neighbor becomes better than threshold
- Event B2: Serving becomes worse than threshold1 and inter RAT neighbor becomes better than threshold2 (coverage type of handover)

The events are fully described in 3GPP TS 36.331, Chapter 5.5.

5.1.7 MIMO Mode Control

One of the initial design requirements for LTE was to be able to achieve peak data rates of 100Mbps in downlink and 50 Mbps in uplink. Those thresholds assume two receive antennas in the terminal for the downlink capability and one transmit antenna in the terminal for the uplink capability. Therefore, to be able to achieve those peak throughputs in downlink it is necessary to use multiple antennas, which in case of LTE is supported at the eNodeB and at the terminal as a basic part of the specifications.

The term MIMO (Multiple Input Multiple Output) is generally used to indicate the use of multiple antennas, e.g. the maximum (marketing) peak throughput figures for LTE were 172.8 Mbps downlink and 56.8 Mbps uplink for a 20 MHz bandwidth using **2x2 SM MIMO in downlink** (2 transmit antennas in the eNodeB and 2 receive antennas at the UE, 2 parallel streams) and **single stream in uplink** (1 transmit antenna at the UE).

It is possible to achieve even higher peak data rates in downlink by using 4x4 SM MIMO (4 transmit antennas in the eNodeB and 4 receive antennas in the terminal, 4 parallel streams) with feature LTE1987. Note that 4x2 MIMO (feature LTE568, DL Adaptive Closed Loop MIMO 4x2) improves cell edge user throughput, but cannot exceed peak throughput of 2x2 SM of MIMO due to maximum of 2 parallel streams along with additional reference symbol overhead.

There is little consistency between different sources of information about what is meant by the term MIMO. As previously mentioned, strictly speaking, the term refers to all cases of multiple transmit and multiple receive antennas. However, in this document and being in line with Nokia features, MIMO refers to the spatial multiplexing case. Transmit diversity (although using 2 transmit antennas) is not referred as MIMO but simply as transmit diversity. It is good practice to specify exactly Div MIMO or SM MIMO to avoid misunderstandings.

Nokia implementation (based on LTE specifications) supports the following multi-antenna transmission schemes in addition to single antenna transmission:

- Transmit diversity (2x2, 4x2 or 4x4)
- Open loop spatial multiplexing (Open Loop MIMO)
- Dynamic Open Loop MIMO: PDSCH are transmitted using either Single Stream Downlink Transmit Diversity or Dual Stream MIMO with spatial multiplexing depending on radio conditions
- Closed Loop spatial multiplexing (Closed Loop MIMO, 2x2, 4x2, or 4x4).

The above MIMO cases use the Downlink Reference Signals for channel estimation. There is one downlink reference signal for each transmit antenna or, more exactly for each **antenna port** as defined by the 3GPP meaning that what is referred to does not necessarily correspond to a single physical antenna. An antenna port is defined by the presence of an *antenna-port-specific reference signal*. If identical reference signals are transmitted from several physical antennas the UE does not differentiate between them and all the antennas can be seen as a single antenna port. There are however various transmission mode configurations for the 4x4 schemes possible – either as TM4 mode (common reference symbols used for PDSCH and CQI estimation) or TM9 mode (side common reference symbols there are demodulation reference signals for PDSCH channel estimation along with additional CSI-RS symbols introduced for CQI estimation).

5.1.7.1 Transmit Diversity

In the case of two transmit antennas (antenna ports) the LTE transmit diversity is based on Space Frequency Block Coding (SFBC) which means that two consecutive modulation symbols S1 and S2 are mapped directly onto adjacent subcarriers on the first antenna port. The second antenna port transmits the swapped and transformed symbols –S2* and S1*.

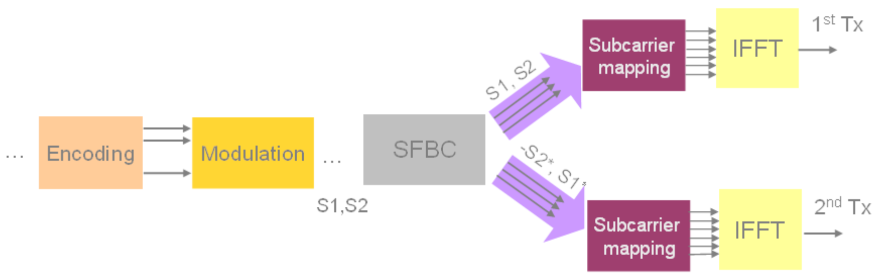


Figure 34: Two antennas Transmit Diversity

As it can be seen in Figure 34 with transmit diversity, only a **single data stream** is transmitted through the two antenna ports. Each symbol is transmitted twice: once per antenna. The diversity is achieved by mapping the symbols into different subcarriers (frequency domain). It is possible to use also 4Tx-2Rx

Diversity which improve cell edge user throughput. The scheme is part of LTE568 (DL Adaptive Closed Loop MIMO 4x2) feature.

Transmit diversity is the only multi-antenna transmission scheme that can be applied to all physical channels (see Figure 37). However, synchronization signals are transmitted only on the 1st antenna.

5.1.7.2 Spatial Multiplexing (MIMO)

With spatial multiplexing, multiple streams or 'layers' are transmitted in parallel which implies higher data rates for a given bandwidth. In general, LTE spatial multiplexing allows for the transmission of a variable number of layers up to a maximum that equals the number of antenna ports. As mentioned before, it is also known as MIMO. MIMO 2x2 refers to the case of 2 antenna ports and 2 layers. In this case, the peak rates are double compared to 1 Tx antenna. MIMO 4x2 (4 Tx ports and 2 Rx ports on DL) obviously cannot exceed maximum throughput of SM 2x2, but it improves total cell and cell edge throughput. Four antenna ports and up to four layers is also defined by 3GPP (MIMO 4x4) and the feature is part of FL16 release.

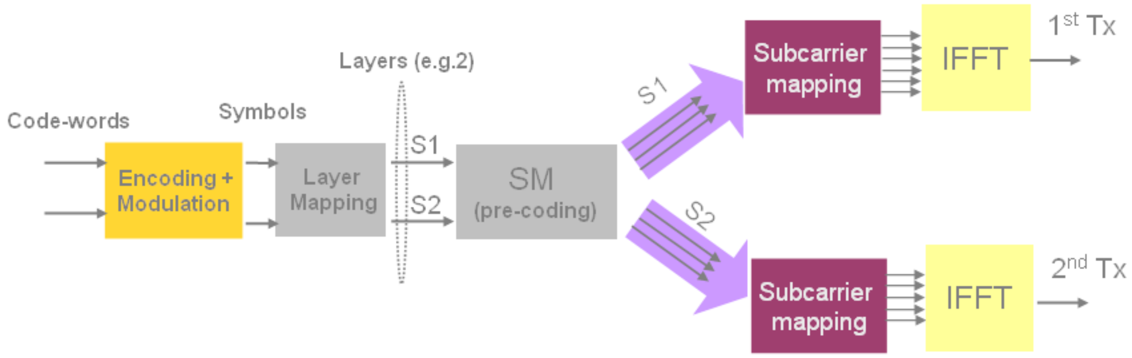


Figure 35: Two antennas Spatial Multiplexing (MIMO)

LTE Spatial Multiplexing may operate in two different modes: open loop spatial multiplexing (open loop MIMO) or closed loop spatial multiplexing (closed loop MIMO). The difference between both modes is that in the case of closed loop MIMO there is more feedback from the UE than in the case of open loop MIMO.

- **Closed Loop MIMO**

LTE spatial multiplexing uses codebook-based pre-coding, so for each combination of antennas (ports) and number of layers a set of pre-coder matrices are defined in the 3GPP standard. The UE decides on a suitable **rank (number of layers)** and the corresponding pre-coder matrix. This decision is based on measurements on the downlink reference signals of the different antennas.

First step is the mapping of the symbols of the **code-words (transport blocks)** into layers. In case of MIMO 2x2, two code-words are mapped into 2 antenna layers that is also the number of antenna ports.

After layer mapping, one symbol from each layer (S1 and S2 in Figure 35) is linearly combined and mapped to the antenna ports. The combining/mapping is done using a pre-coder matrix. For the case of 2 antenna ports and 2 layers there are two possible pre-coding matrices:

$$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad \frac{1}{2}\begin{bmatrix} 1 & 1 \\ +j & -j \end{bmatrix}$$

Figure 36: Pre- coding matrices for two antenna ports and two layers

The terminal may report a recommended number of layers **(Rank Indication, RI)** and the recommended pre-coder matrix **(Pre-Coder Matrix Indication, PMI)** corresponding to the number of layers based on the estimates of the downlink channel condition (downlink reference signal measurements). In this way, the terminal is assisting the network in selecting a suitable pre-coder matrix and that is why it is called closed loop MIMO. If the network does not follow the terminal recommendation when transmitting to the UE then it needs to inform the terminal about the pre-coding matrix used in the next downlink transmission.

- **Open Loop MIMO**

The open loop spatial multiplexing does not consider any pre-coder recommended feedback from the UE (PMI). Pre-coding is still done but because the pre-coding matrices vary in a pre-determined way it is not necessary for the pre-coding matrix information to be provided to the terminal. Open loop MIMO is suitable for high-mobility scenarios and cases where the additional overhead associated with closed-loop MIMO is not justifiable.

Another name for open loop MIMO is **large- delay CDD**. This is because the overall pre-coding matrix introduces Cyclic Delay Diversity (CDD) in the layer domain. In the case of two layers, the first layer works as with the single antenna transmission but the CDD operation introduces a delay of certain number of samples (linear phase shift) on the second layer. The signals of both antennas are sent at the same time, so at the receiver, the frequency selectivity increases. It is a way of increasing diversity against fading.

In this case, it is called large-delay because the cyclic delay is very large (for two layers the delay is equal to half of the block length).

Spatial multiplexing (open and closed loop MIMO) only applies to the downlink data channel (see Figure 37).

5.1.7.3 MIMO Mode Control Functionality

The MIMO Mode Control Functionality, part of RRM, is provided by the eNodeB. It works **only in downlink** (uplink is not affected) and it switches between the above transmission modes plus the single Tx mode (1x1 Single Input Single output - SISO - or 1x2 Single Input Multiple Output - SIMO -).

Figure below shows that only the data channel can be configured to use Open or closed loop MIMO. Synch signals cannot use MIMO or Tx Diversity and the control channels can only use transmit diversity.

		Transmit Diversity	Spatial Multiplexing (MIMO)
Synch signals	P-Syn		
	P-Syn		
Control Channels	PBCH	OK	
	PDCCH	OK	
	PHICH	OK	
	PCFICH	OK	
Data Channel	PDSCH	OK	OK

Figure 37: Multiple antenna transmission modes vs. DL channels

MIMO Mode Control affects only the DL direction. UL is always a SIMO 1x2 or higher (1x4, LTE72 feature, 4-way RX Diversity) with Rx diversity by MRC (Maximum Ratio Combining) at the eNodeB receiver. Another possibility is to use Interference rejection combining (IRC) for 2Rx Paths (LTE979) or for 4Rx paths (LTE980). IRC algorithm is suitable for removing dominant interferers coming from a few directions (corelated interference). IRC cannot remove uncorrelated interference.

In downlink, the antenna mode can be:

- A **semi-static scheme**: The selection between open loop MIMO (spatial multiplexing), transmit diversity and single Tx mode is done via an O&M parameter. Suitable for laboratory measurements or tests.
- **Dynamic Downlink Open Loop MIMO**: The selection between transmit diversity or spatial multiplexing is done dynamically for each UE depending on the radio conditions and based on O&M thresholds. The CQI and rank measurements from the UE are taken into account. The UE capabilities are also taken into account, i.e. UEs that are non MIMO capable should only use transmit diversity. This is also applicable to the previous semi-static scheme, i.e. if spatial multiplexing is commanded for the whole cell, non MIMO capable UEs are still served with transmit diversity.
- Other RRM functions like Scheduler, DL PC, DL AMC, OLQC, etc. are dynamically informed (event driven) about the MIMO mode decision. The Dynamic Switching feature can be enabled/disabled by means of O&M.
- **Dynamic Downlink Closed Loop MIMO:** The selection between transmit diversity or spatial multiplexing is done dynamically for each UE depending on the radio conditions and the reported Precoding Matrix Indicator (PMI) and based on O&M thresholds. The CQI, rank and PMI measurements from the UE are taken into account. As per the Open Loop MIMO, the UE capabilities (if UE supports MIMO or not) are taken into account.

Other RRM functions like Scheduler, DL AMC, OLQC etc. are dynamically informed (event driven) about the MIMO mode decision and the selected DL PMI. Algorithm decisions are controlled via O&M configurable thresholds. These thresholds can be configured differently for closed loop adaptive MIMO and open Loop MIMO Switch.

5.1.7.4 Beamforming Features

Beamforming features are tight to TDD system due to natural usage of the radio channel reciprocity. However, massive MIMO (LTE 2666) opens beamforming also for FDD systems. Beamforming can be categorized as either user specific or fixed beam. User specific beamforming allows the antenna gain pattern of the eNodeB to follow individual UE around the cell. This approach is complex and difficult to achieve in practice. The fixed beam (GOB) approach to beamforming divides the cell into a number of segments. Relatively narrow fixed beams are then used to provide coverage across those segments. Figure 38 illustrates the basic principal of antenna beamforming for system interference reduction.

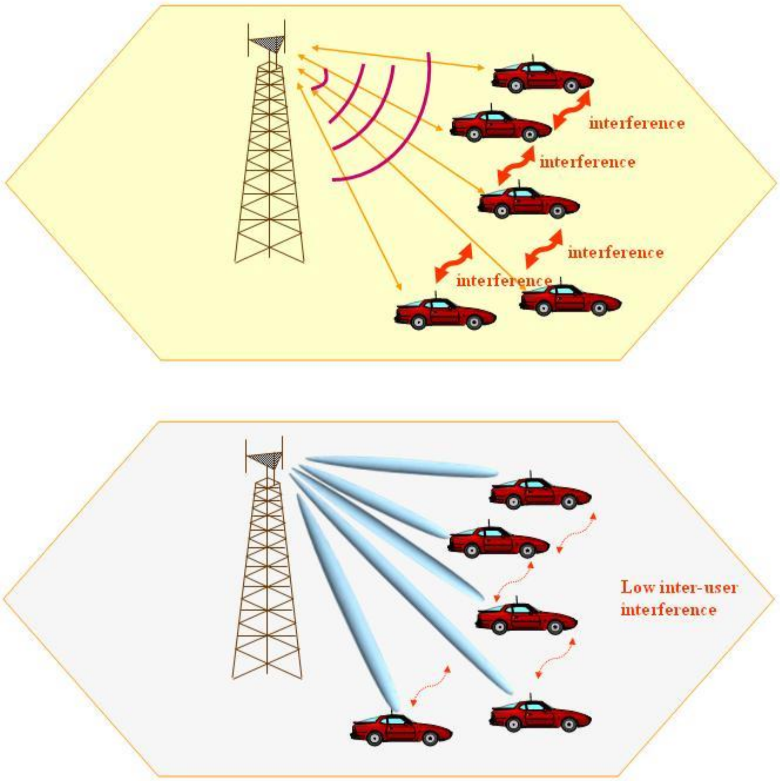


Figure 38: System interference reduced by antenna beamforming

For example, a cell belonging to a 3 sector site typically provides 120 degrees of coverage, which could be divided between 8 fixed beams of 15 degrees. The signals belonging to individual connections are then transmitted and received over a relatively narrow beam width. This helps to reduce the level of interference in the system, increasing both service coverage and system capacity. Figure 39 shows the example of 8 antenna element (4 column X-pol antennas) beamforming illustration.

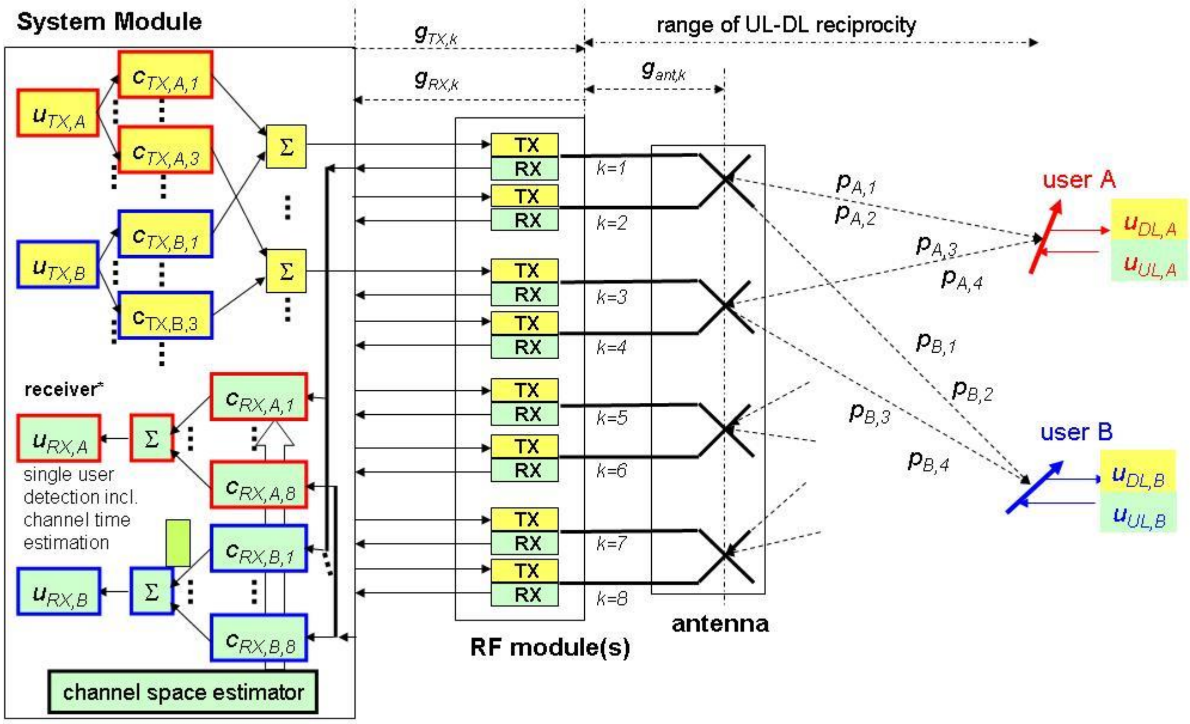


Figure 39: 8 antenna element beamforming

Since beamforming is related to the physical position of the UE, the required update rate for the antenna phasing is much lower than the rates needed to support MIMO precoding. Thus, beamforming has a lower uplink signaling overhead than MIMO. The most advanced form of multiple antenna techniques is probably the combination of beamforming with MIMO in LTE. In this mode MIMO techniques could be used on sets of antennas, each of which comprises a beamforming array. Given that beamforming with only two antennas has limited gains, the advantage of combining beamforming and MIMO will not be realized unless there are many antennas. In the China market, antenna beamforming technology was already adopted in the TD-SCDMA network by China Mobile. Most of the smart antenna system in the TD-SCDMA network are 6-pipe or 8-pipe, which allows for the reuse of the antenna system.

The eNodeBs are able to support TM7 (Transmission mode 7, beamforming, EBB algorithm), with 8 antennas supported for uplink, and 8 antennas supported for downlink. The UE is able get higher throughput at the cell edge. The antenna array is a 2x4 antenna array, i.e. dual polarized 4 elements ULA (Uniform Linear Array); the bandwidth is limited at 20MHz only.

If the eNodeB is configured as TM1~TM6, the eNodeB will not support transmission of UE specific reference signals, for UL eNodeB will provide 8 antenna MRC support, for DL eNodeB will provide sector beamforming (radiating to the whole cell, i.e. as if no BF would be applied) support. If the eNB is configured as TM7, default DL transmission for each UE is TX diversity over sector beamforming.

Beamforming require certain capabilities from UE side. Therefore, eNodeB checks if the UE is capable to receive UE specific reference signals during UE access as first step.

Step2: if the UE is not able to receive UE specific reference signals, then TX diversity is selected over sector beamforming for DL transmission, DCI format is 1A.

Step3: if the UE is able to receive UE specific reference signals, then the eNodeB will let the UE send sounding signals.

Step4: the eNodeB calculates the weighting vector according to the received sounding signal.

Step5: when the weighting vector is ready, the eNodeB sends the PDCCH with DCI format 1 and sends PDSCH, then DL beamforming is selected, physical antenna 0,1,2,3,4,5,6,7 is mapped to antenna port 5, PDSCH is transmitted over antenna port 5, and UE specific reference signal is transmitted over antenna port 5.

- Virtual Antenna Port and Physical Antenna Port Mapping

eNodeB shall support 8 antennas, which are half-lambda spaced and +45/-45 X-polarized. Existing 2 antenna MIMO mode shall be able to work on 8 antenna array via sector beam. Long-term beamforming (LTBF) is based on average channel knowledge measured from uplink sounding.

Multiple antenna elements in dual-polarized 4+4 antenna array shall be mapped to 3GPP defined antenna ports. The same encoded data and reference signal shall be transmitted on the antenna elements mapping to the same virtual antenna port.

3GPP defined antenna ports 0, 1, and 5 shall be supported. Physical antenna 0,1,2,3 is mapped to virtual antenna port 0 group. Physical antenna 4,5,6,7 is mapped to virtual antenna port 1 group. Physical antenna 0,1,2,3,4,5,6,7 is mapped to virtual antenna port 5 group.

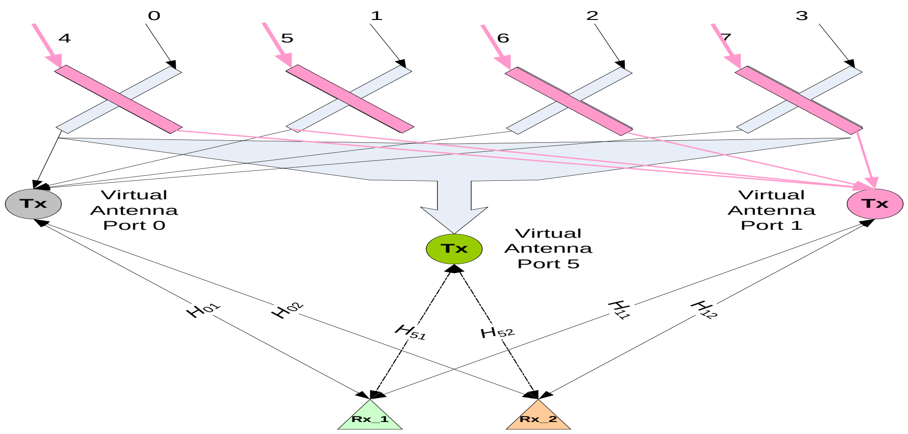


Figure 40: Virtual antenna port and physical antenna port mapping

- Beam in Dual-polarized 4+4 Antenna Array

There are: sector beam, SFBC + sector beam, two codeword Large Delay CDD and Close Loop Spatial Multiplexing beam and Single Antenna Port 5 Transmission beam in Dual-Polarized 4+4 Antenna Array. Figure 41 to Figure 44 shows the detailed configurations.

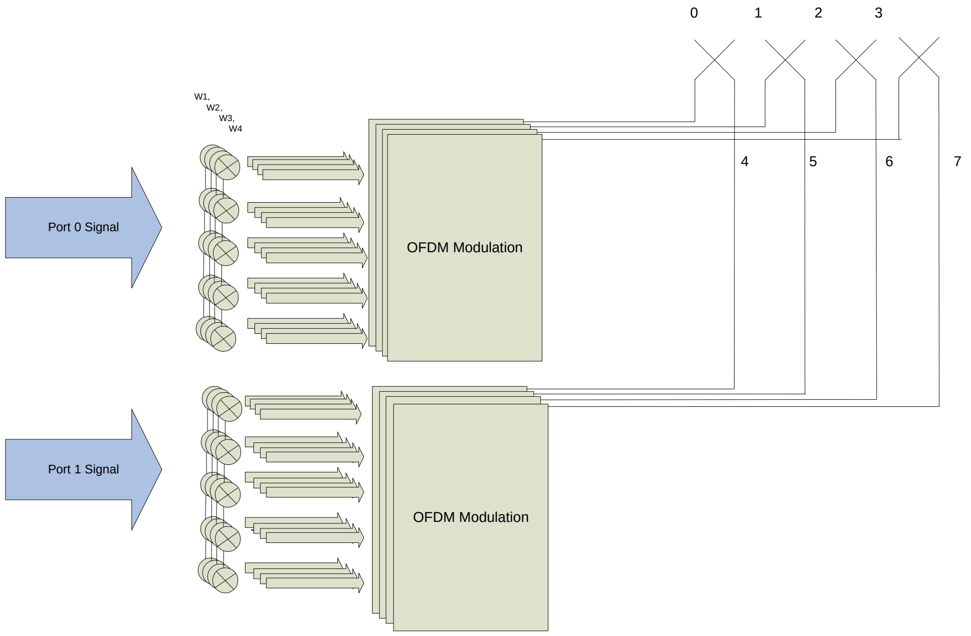


Figure 41: Sector beam for virtual antenna port 0/1 in dual polarized 4+4 antenna array

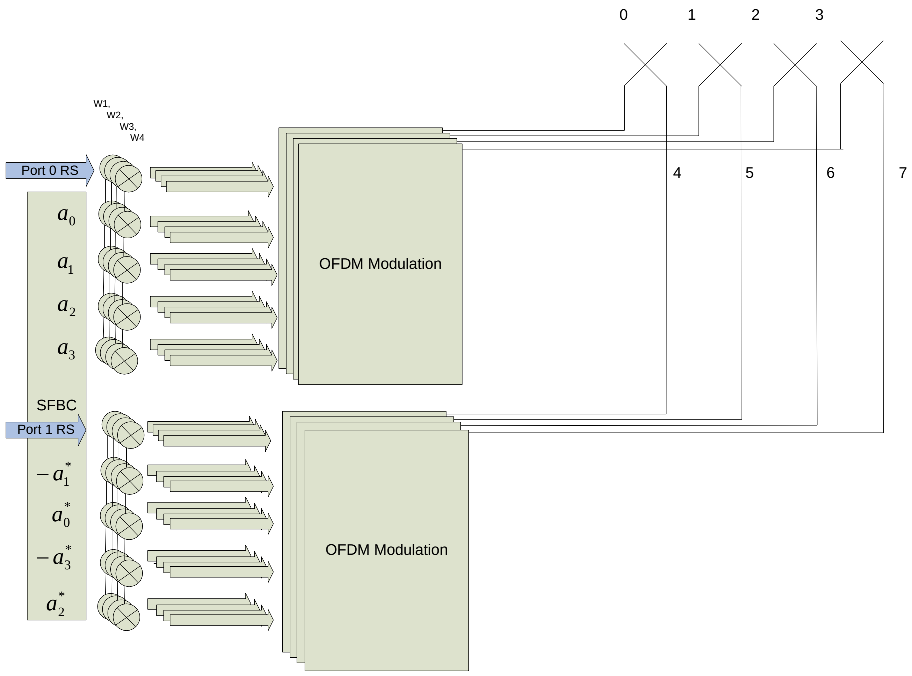


Figure 42: SFBC+ Sector Beam in Dual-Polarized 4+4 Antenna Array

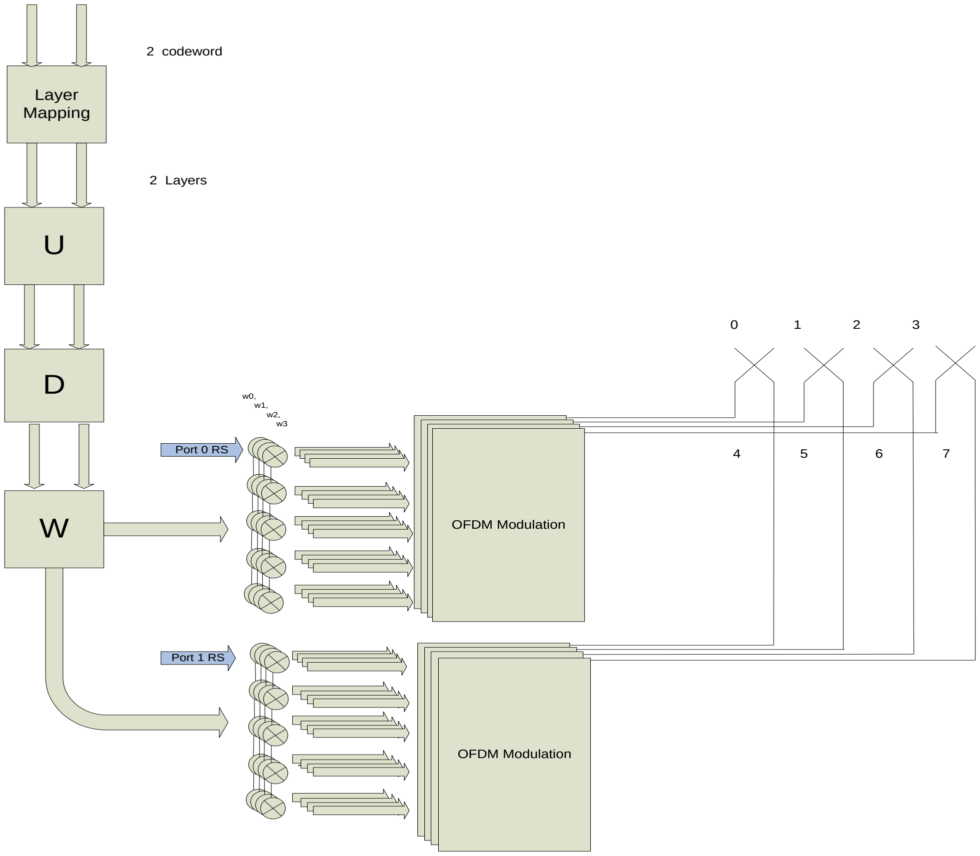


Figure 43: Two codeword Large Delay CDD and Close loop Spatial Multiplexing in Dual-Polarized 4+4 Antenna Array

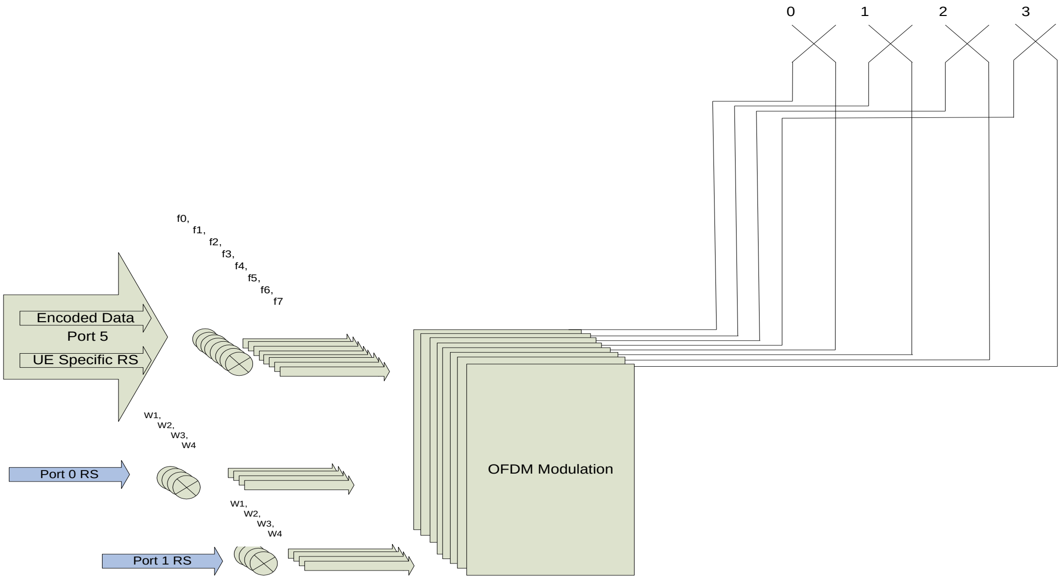


Figure 44: Single Antenna Port 5 Transmission in Dual-Polarized 4+4 Antenna Array

- Transmission Schemes for Different Channel

		Single Antenna Port + Sector Beam	TxDiv + Sector Beam	Beamforming
Control Channels	PBCH	N/A	√	N/A
	PDCCH	N/A	√	N/A
	PHICH	N/A	√	N/A
	PCFICH	N/A	√	N/A
Data Channels	PDSCH	N/A	* Note 1	* Note 2
Sych Signals	PSS	Via Antenna Port 0 *	√	N/A
	SSS	Via Antenna Port 0 *	√	N/A
Ref. Signal	Cell Specific RS	Via Antenna Port 0,1 *	√	N/A
	UE Specific RS	N/A	N/A	√

Table 4: Transmission Schemes for different channel

- Via virtual antenna port 0

  Signal is transmitted on the physical antennas 0, 1, 2, 3, which maps to virtual antenna port 0
- Via virtual antenna port 0,1
  - RS Signal on virtual antenna port 0 shall be transmitted on corresponding mapping physical antennas (0, 1, 2, 3)
  - RS Signal on virtual antenna port 1 shall be transmitted on corresponding mapping physical antennas (4, 5, 6, 7)
- Note 1:
  - TxDiv+Sector Beam is used for SRB0(CCCH), BCCH and PCCH.
  - For SRB1(DCCH), TxDiv is used before the first DRB is set up.
- Note 2
  - For SRB1(DCCH), DRB (DTCH) shall use single antenna port 5 transmission scheme.

Single stream beamforming (SS-BF) is associated with feature LTE493. SS-BF is specified for TM7 in 3GPP release 8.

This feature introduces main beamforming design, which performs best with quad cross-polar panels (four half-lambda spaced cross-polar elements.

There are different approaches to realize weight estimates:

- In LTBF (Long Term Beamforming), the channel is averaged over frequency and time. LTBF is therefore not frequency selective (fast fading plays no role) and has a low demand of CSI. SVD (Singular Vector Decomposition) technique is used to compute the eigenvectors and the whole available power is allocated to the dominant eigenvector. For this reason, LTBF performs best when the whole energy is received from or transmitted into a single direction.
- STBF (Short Term Beamforming) is quite sensitive to fast changing conditions.

Feature LTE 541 is associated with dual stream beamforming (DS-BF). DS-BF is specified for TM8 in 3GPP release 9.

The principle of dual stream beamforming is very similar to standard 2x2 MIMO. In case of quad cross-polar panels, four elements with the same polarization (e.g. +45deg) transmit one stream and another four with different polarization (e.g. -45deg) transmit the other data stream to the same terminal. These two beams can be regarded as two virtual antennas and transmit different data streams simultaneously.

Due to the second stream the user throughput can be doubled with dual stream beamforming as compared to single stream beamforming (assuming good channel conditions).

As in the case of SS-BF, in DS-BF, the eNB is assumed to be equipped with an 8 pipe RRU and an array of 4 cross-polarized antennas: 4 elements of the same polarization generate a UE specific beam, the other 4 elements generate another UE specific beam to the same UE (multi user MIMO is not supported). With dual stream beamforming, two code words are transmitted simultaneously in beamforming mode. Compared with single stream beamforming, one additional code word is weighted by a vector and combined with the first precoded code word to form the transmitted data for each antenna. A total of two weighting vectors should be derived for dual stream beamforming.

The figure below outlines the calculation of the antenna weights:

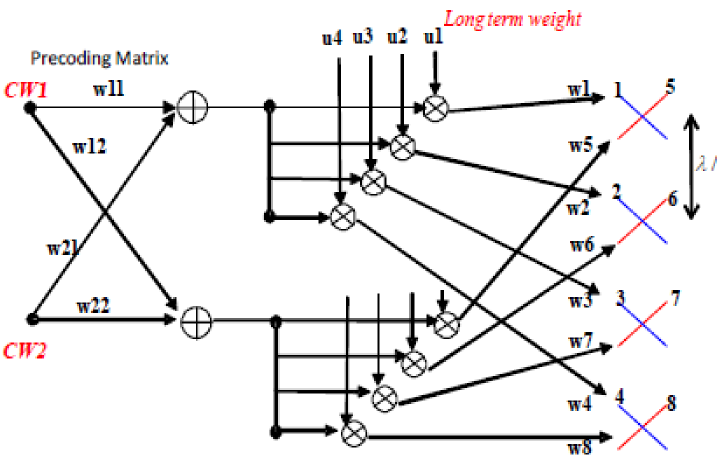


Figure 45: Calculation of the antenna weights

Dual stream beamforming (feature LTE541) introduces 3 beamforming algorithms comprising 2 steps each, as seen in the table below:

- Calculation of "long term weights": all 3 algorithms use long term beamforming (LTBF) for the calculation of the long-term weights u1 to u4 in the above figure. The same set of weights is used for both polarizations. In single stream beamforming (LTE493), LTBF was applied to all 8 antennas.
- Calculation of "precoding matrix (PM)": the 3 algorithms only differ with respect to this step. However, "Hybrid BF" (which is a combination of long term and short-term beamforming) is the target algorithm and the other 2 algorithms are used as fallback.

Details are given in the table below:

feature	RL	# antennas		# streams	beamforming		MIMO scheme (over 2 logical antennas)	cell average factor versus LTE493
		physical	logical		long term weights	BF algorithm		
LTE493	RL15	8 (4 + 4)	1	1	LTBF over 8 antennas of both polarizations (8x8 covariance matrix)	LTBF	- (single logical antenna)	1.00
LTE541	RL25	8 (4 + 4)	2	dynamic (1 or 2)	LTBF over 4 antennas of a polarization (4x4 covariance matrix)	Hybrid BF (default)	"continous PM" calculated via STBF (based on instantaneous channel estimation)	1.23
						PMI + LTBF (fallback for invalid weighting vectors but valid PMI feedback)	PM based on PMI reports and code book (3GPP 6.3.4.2.3 of 36.211)	-
						Unitary LTBF (fallback for invalid weighting vectors and invalid PMI feedback)	PM is a random unitary matrix	-
2x2 MIMO	RL15	2 (1 + 1)	2	dynamic (1 or 2)	-	-	dynamic CL MIMO	0.98

Table 5: Overview of Beamforming Methods

Within the table above, the "cell average factor versus LTE493" column denotes the estimated capacity gain which can be achieved, assuming LTE493 as the reference. This estimated capacity gain is also incorporated in the dimensioning tool. No gain factor is implemented for the fallback solutions.

As with single stream beamforming, the UE specific channel sounding via SRS is used for UL channel estimation and consecutive generation of DL weights, which are applied to PDSCH and dedicated reference signal (DRS). Beside the 3 new BF algorithms, LTE541 will support

- adaptive switching between SS-BF and DS-BF based on the UE's reported RI and CQI
- fallback to Tx diversity in case of high channel variations (e. g. for fast UEs)

Dual stream beamforming is backward compatible, i.e. both 3GPP R8 and R9 terminals are supported. UE capability specified in 3GPP 36.306 is considered. FSM3 hardware is required to support this feature.

With regards to antenna ports, dual stream beamforming supports two DRS antenna ports, port 7 and 8. When a user is scheduled with two code words, these two ports are used simultaneously, which brings the possibility to provide higher throughput with regards to transmission mode 7 on port 5. Ports 7 and 8 are mutually orthogonal.

With transmission mode 8, the UE is able to transmit over Tx diversity (using ports 0 and 1), single stream beamforming (using port 7 or 8), and dual stream beamforming (using ports 7 and 8).

The 8x2 SU MIMO with transmission mode 9 (TM9) feature provides MIMO over 8 Tx pipes and 2 Rx UE antennas with closed-loop channel state information (CSI) feedback. TM9 is 3GPP Rel-10 compliant. This feature can provide more accurate channel feedback based on 8 port CSI-RS, relaxing the strict sounding requirement of TM7/8. (The additional overhead of CSI-RS is very low.)

During the initial access phase, TM2 is used as the default transmission mode. Then, if the cell specific parameter of transmission mode is set to TM9, then Rel-10 UEs will work in transmission mode 9. Non-TM9 UEs will still be served using TM8, TM7 or TM2, depending on the UE capabilities.

The following summarizes some of the differences between the 3GPP transmission modes:

- TM1, TM2, TM3, TM4 (TM5 and TM6 not supported by Nokia)
  - PDSCH channel estimation based on Common Reference Signals (CRS)
  - CQI report based on CRS
  - Closed loop precoding based on CRS, reported by PMI
- TM7 (Single Stream Beamforming – LTE493)
  - PDSCH channel estimation based on Dedicated Reference Signals (DRS)
  - CQI report based on CRS
  - Open loop, non-codebook precoding (beamforming)
  - Channel feedback using sounding reference signals (SRS) and UL/DL reciprocity in TDD LTE
- TM8 (Dual Stream Beamforming – LTE541)
  - PDSCH channel estimation based on Demodulation Reference Signals (DM-RS)
  - CQI report based on CRS
  - Open loop, non-codebook precoding (beamforming)
  - Channel feedback using sounding reference signals (SRS) and UL/DL reciprocity in TDD LTE
- TM9 (8x2 SU MIMO TM9 – LTE1543, 8x2 MU MIMO TM9 – LTE1787, 4x4 DL SU MIMO with TM9 – LTE1987, 8x4 DL SU MIMO with TM9 – LTE2068)
  - PDSCH channel estimation based on Demodulation Reference Signals (DM-RS)
  - CQI report based on Channel State Information Reference Signals (CSI-RS)
  - Closed loop precoding based on CSI-RS
  - CSI-RS is configured to each Rel10 UE via RRC reconfiguration

Compared to LTE541 (TM8-based Dual Stream Beamforming), LTE1543 allows for higher average throughput and cell edge DL throughput. (Peak throughput is not changed with respect to LTE541). Based on link level simulations, TM9 increased the average DL cell throughput by 14.4% and the cell edge throughput by 95%, compared to TM8. Differences between LTE541 and LTE1543 are illustrated in the following figure.

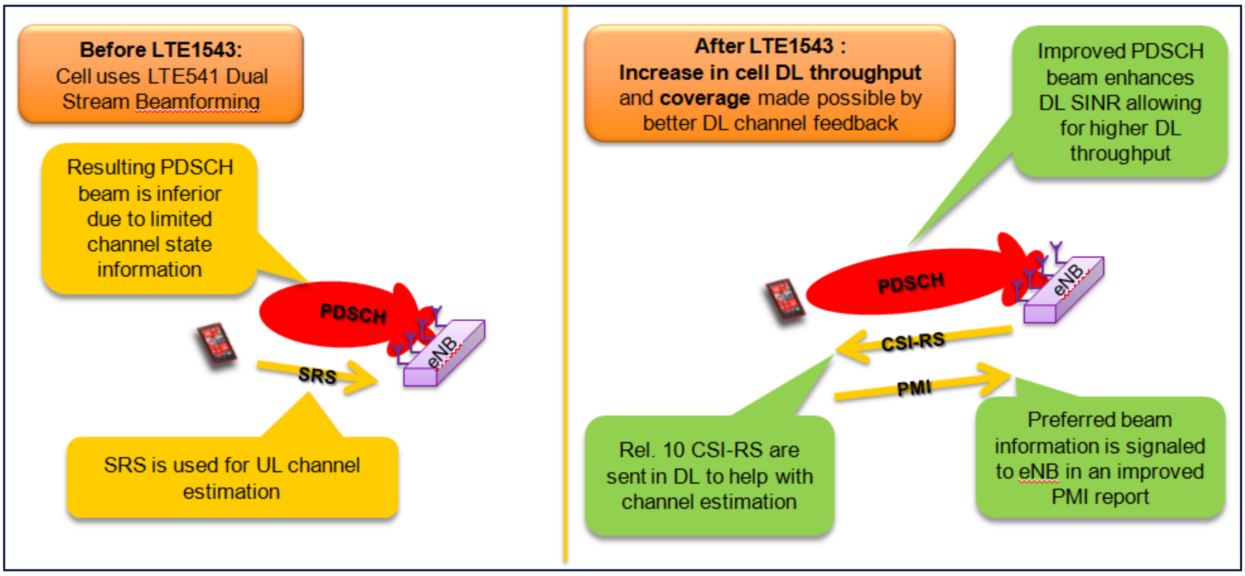


Figure 46: LTE1543 Improvements over LTE541

Multiuser MIMO (also known as Virtual MIMO, V-MIMO) allows pairs of UEs with appropriate radio conditions to be scheduled on the same time and frequency radio resources. Contrary to the DL, 3GPP Rel. 8 and 9 do not standardize single user MIMO in the UL. The UE is able to transmit only one stream of data. Scheduling UEs on the same resources (MU-MIMO) is still possible given the standard definition.

The MU-MIMO scheme enables MIMO capacity gains on low-cost terminals with a single Tx antenna.

Figure 47: Multiuser MIMO versus Single User MIMO

LTE1545 (UL Multi-user MIMO) is implemented for advanced 8 Rx UL MU-MIMO receivers, which are based on the MRC (Maximum Ratio Combining) algorithm. A new receiver type is needed for MU-MIMO, since earlier UL receivers assume single UE operation. The MU-MIMO receiver only pairs UEs that will benefit from MU-MIMO. MU-MIMO UE pairing candidates are chosen from among the UEs that are to be scheduled in the same TTI. Pairing criterions are based on radio conditions of the individual UEs and potential pairs. The final pairing decision is made based on the joint throughput-to-average metric (Max-PF metric). MU-MIMO UE pairs are assigned the same number of PRBs and the same position in the frequency domain. Also, pairing decisions are done in every TTI.

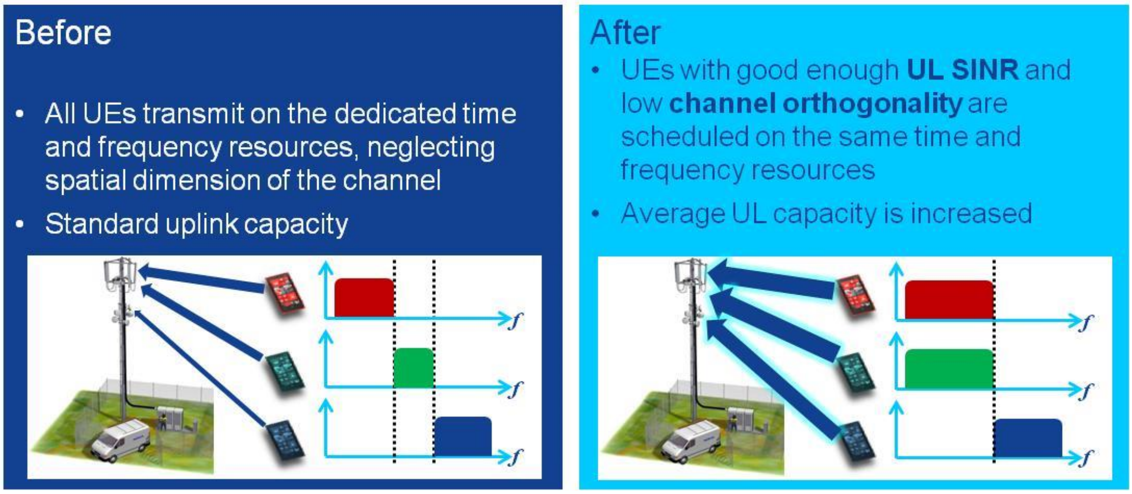


Figure 48: LTE1545 Before and After Comparison

The MRC receiver that is used for MU-MIMO reception does not help to cancel interferers. Interference can be expected from the paired UEs. LTE1545 addresses this issue by only pairing UEs with channel orthogonality that is above a certain threshold (set within the parameters). Higher channel orthogonality leads to less interference between the paired UEs. Note that channel orthogonality is obtained from SRS soundings, so SRS sounding must be enabled.

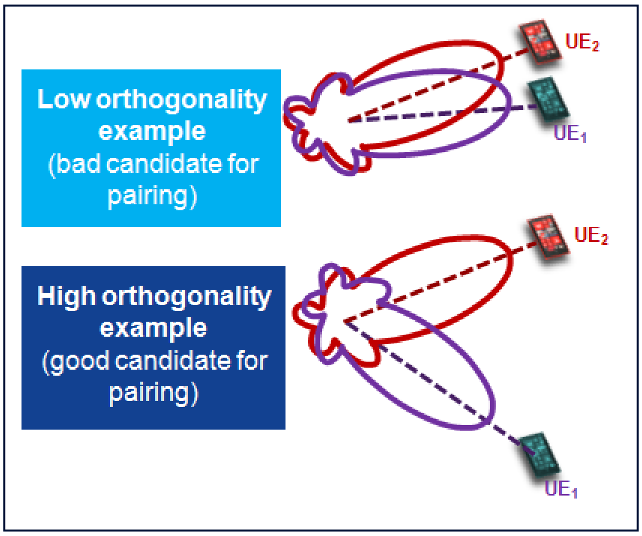


Figure 49: LTE1545 Use of Channel Orthogonality in UE Pairing

The UE pairing procedure impacts the UL scheduling and Fast Uplink Adaptation (F-ULA) algorithms. The time domain scheduling step (TD scheduling) is not changed by MU-MIMO. The pool of UEs to be scheduled in TTI is not changed and the Candidate Set 2 is the same as for SU-MIMO.

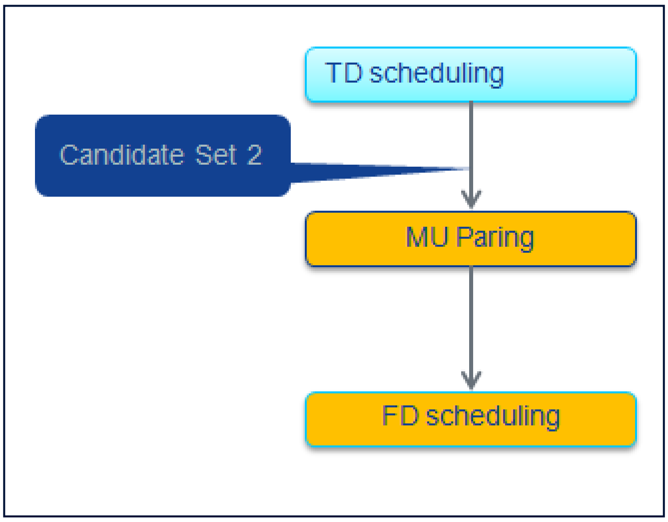


Figure 50: UE Pairing Process

In the MU pairing step, it is decided how the UEs will be paired, using the following checks:

1. Retransmission check
   - retransmission UEs are not considered for pairing so as not to compromise the BLER
2. TTI bundling check
   - UEs using TTI bundling are excluded from MU-MIMO pairing. They are believed to be cell edge UEs for which MU mode is not recommended
3. SINR check
   - Only the UEs with wideband SINR above the threshold (ulMuMimoSinrThreshold) can be paired. Scheduling UEs in the same resources will generally decrease their SINR, as paired UEs will interfere with one another.
4. Orthogonality check
   - Only the UE pairs with an orthogonality metric above the threshold (ulMuMimoOrthThreshold) are considered for pairing. (Pairs with high orthogonality will interfere with each other less than those with low orthogonality.)
5. Joint Max-PF metric check
   - Max-PF (Proportional Fair) metric is used to finally decide how the pairs will be formed. The PF metric is a ratio of achievable throughput based on the radio conditions to throughput that was achieved by the UE in the past. Joint PF metric for the pair is the sum of the individual PF metrics of the UEs from that pair. UE pairs with maximum joint PF metric will be paired.

In the frequency domain scheduling step (FD scheduling), PRB assignment and frequency domain position of MU-MIMO pairs is decided. Since MU-MIMO also modifies the Fast Uplink Adaptation (F-ULA) algorithm, which works closely with the FD scheduling, it impacts both algorithms. (F-ULA takes care of the adaptation of the MCS to the existing link conditions of the UE.)

The LTE 1545 UL MU-MIMO 8RX feature could double the UL peak cell throughput. However, there is no increase in the UE peak throughput. In real radio conditions, over 20% average capacity increase can be expected. (System level simulation results show a mean cell throughput increase of ~27%.) Cell edge UEs benefit indirectly, since they get more scheduling opportunities. As cell-center users obtain sufficient data throughput via the MU-MIMO scheme, it allows for more transmission opportunities for cell edge users. (System level simulation results have shown a cell edge throughput increase of 22%.)

With this feature, the same radio resources can be allocated by the eNB for two UEs simultaneously, which increases average UE throughput and average cell throughput and it may improve cell edge throughput as well. It can only apply to UEs in TM8 and TM9 transmission modes. It allows for transmission modes TM8 and TM9 to be paired in combination (TM8–TM8, TM8-TM9, TM9-TM9). The pairing is based on channel correlation between two users (best conditions when correlation is low). This feature is applicable for 8 TX (X-pol) antenna systems.

To differentiate the two paired UEs, LTE1787 (TM9 with 8TX MU-MIMO and up to 2 layers overall) uses different antenna ports, as seen in the following figure.

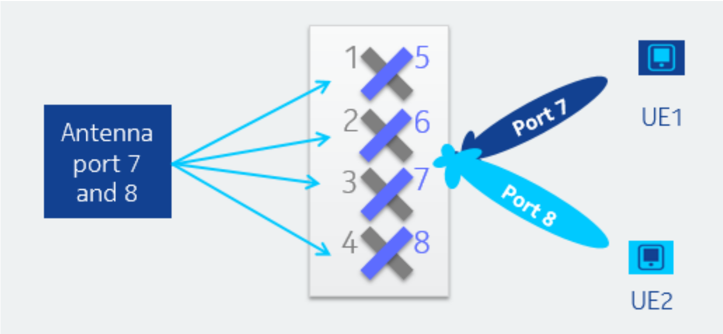


Figure 51: LTE1787 Antenna Pairing

This feature works best in cells with a high ratio of TM8 and TM9 capable UEs, since it allows for more pairing of UEs.SU

This feature extends the MIMO functionality of the LTE BTS to include 4x4 MIMO. The functionality of the feature includes:

- Support of new UE-types with integrated 4Rx antennas to support MIMO 4x4, based on TM9 with up to four spatial multiplexing layers
- Support of TM9 in addition to TM4, depending on the capabilities of the UEs
- Selection of an optimum transmission mode, TM4 or TM9, depending on the UE category and UE MIMO capability and other related features including carrier aggregation
- Optimum coordination of non-TM9-capable UEs with TM9-based CSI-RS transmissions and optimum interworking between TM4 and TM9

This feature improves the peak throughput by extending the usage of MIMO transmission schemes from 4x2 MIMO to 4x4 MIMO, using TM9 or TM4. This allows spatial multiplexing with four layers instead of two, which potentially may double the throughput for the UEs, under specific radio conditions.

LTE2068 extends the MIMO functionality of the LTE BTS to include 8x4 MIMO. The functionality of the feature includes:

- Up to four spatial multiplexing layers in downlink using TM9

- Dynamic switching between 1-4 spatial layers for TM9 UEs, based on RI/PMI reports from the UEs
- Pre-configured 8 port CSI-RS resource allocation and dynamic CSI-RS on/off switch, based on the availability of TM9 UEs in the network
- 4Rx UEs (category 5 and higher, 3GPP Rel. 10 UE capabilities) with up to four spatial multiplexing layers and TM9
- UE's capability based transmission mode configuration and codebook restriction of TM9 to four layers

This feature provides higher downlink peak rates for end users with category 5 or higher UEs supporting spatial multiplexing of up to four layers, depending on the radio conditions.

5.1.7.5 Summary of Transmission Modes

The following figure provides a summary of the transmission modes and the associated 3GPP release.

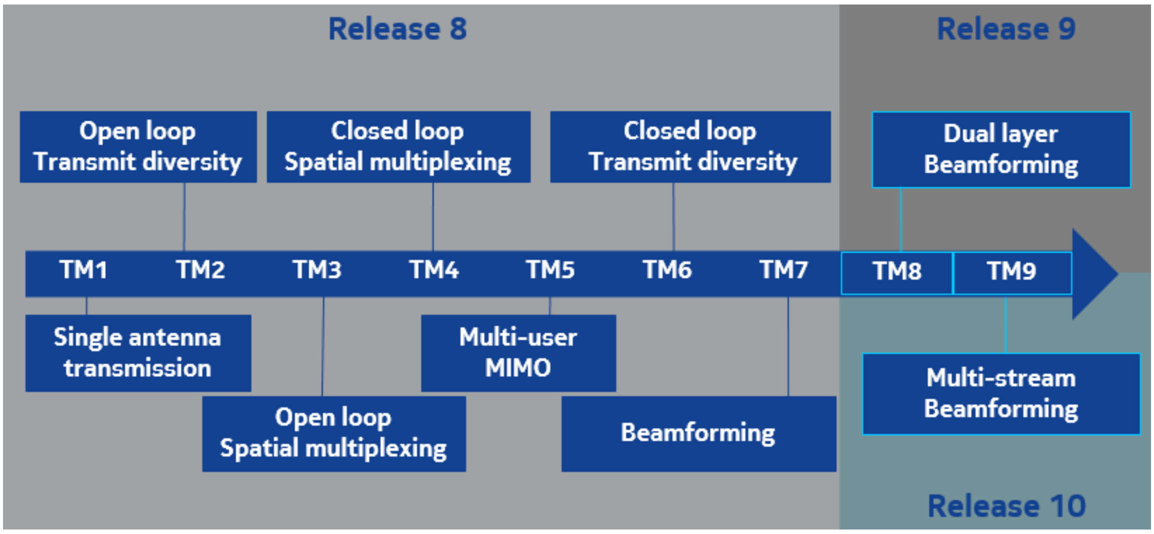


Figure 52: Transmission Modes

5.1.8 Outer Link Quality Control (OLQC)

OLQC is another function of the RRM only for the downlink direction. It is used to compensate for CQI measurement errors. The basic algorithm is captured on feature LTE 1035.

It controls the link adaptation in such a way that a certain target block error ratio (BLER) is achieved for the 1st transmission of a transport block. The function is needed to compensate to a certain degree for errors in the link adaptation. Some of those errors can be:

- CQI estimation error of the UE
- CQI reporting error
- Time delay between CQI measurement and the reception of the subsequent data block
- Errors due to CQI averaging of PRBs

Outer Link Quality control adds a CQI offset to the CQI reports that are provided by the UE. The corrected CQI report is provided them to the link adaptation for further processing. The CQI offset is controlled by the ACK/NACK responses for the initial transmission of each transport block provided by the DL HARQ.

The full set of link adaptation features can be found in Section5.1.5

6 Planning Topics

6.1 Physical Cell ID (PCI) Planning

Note: Refer to the LTE Outdoor RF Design Guidelines for additional information on the topic.

Nokia Recommendations

- The isolation between cells which are assigned the same physical layer cell identity should be maximized and should be sufficiently great to ensure that UE never simultaneously receive the same identity from more than a single cell.
- Whenever possible, cells belonging to the same eNodeB should be allocated identities from within the same group.
- Specific physical layer cell identities should be excluded from the plan to allow for future network expansion.
- There should be some level of co-ordination across international borders when allocating physical layer cell identities.
- Better to avoid CellIDs with identical values mod 3 among neighbor cells on the same site to distinguish PSS as per the text below

Background

There are 504 unique physical layer cell identities. These identities are organised in 168 groups of 3. A physical layer cell identity is thus uniquely defined by a number N_{ID1} in the range of 0 to 167, representing the physical layer cell identity group, and a number N_{ID2} in the range of 0 to 2, representing the identity within the group, i.e. physical layer cell identity = 3× N_{ID1} + N_{ID2}.

The value of N_{ID2} (0 to 2) defines the Primary Synchronisation Signal (PSS) sequence, whereas the value of N_{ID1} (0 to 167) defines the Secondary Synchronisation Signal (SSS) sequence. The UE can thus deduce the Physical Layer Cell Identity during the cell synchronisation procedure.

As per 3GPP 36211 the sequence $d(n)$ for the primary synchronization signal is generated from a frequency-domain Zadoff-Chu sequence according to

$$d_u(n) = \begin{cases} e^{-j\frac{\pi u n(n+1)}{63}} & n = 0,1,...,30 \\ e^{-j\frac{\pi u(n+1)(n+2)}{63}} & n = 31,32,...,61 \end{cases}$$

$N_{\mathrm{ID}}^{(2)}$	**Root index** u
0	25
1	29
2	34

Aiming to avoid same PSS sequence among neighbours (of the same site), CellIDs with identical values mod 3 should not be allocated for neighbors (PCImod3 rule). Different sites in FDD are not frame synchronized and so the PSS sequence with neighbors from other sites may or may not overlap. The probability of such overlap is low.

The Physical Layer Cell Identity has an impact upon the physical allocation of resource elements of the reference signal and the set of physical channels. Figure 53 illustrates the impact upon the allocation of resource elements to the reference signal. All physical layer cell identities within adjacent groups have a different allocation of resource elements to the reference signal. The allocation pattern repeats every 6th physical layer cell identity (every 2nd physical layer cell identity group). Thus, in case PCImod3 rule cannot be followed there is good to allocate different PCImod6 per site (PCImod6 rule)

In case PCI mod3 and PCImod6 rule cannot be followed from some reason, it is benefitial to check PCI mod30 rule. In case of problems with the PCI mod30 rule (having 2 or more different PCI same modullo 30 on the same site), let use grpAssigPUSCH parameter to eliminate this problem and differentiate between UL DM RS (UL reference demodulation sequences) in neighbour cells.

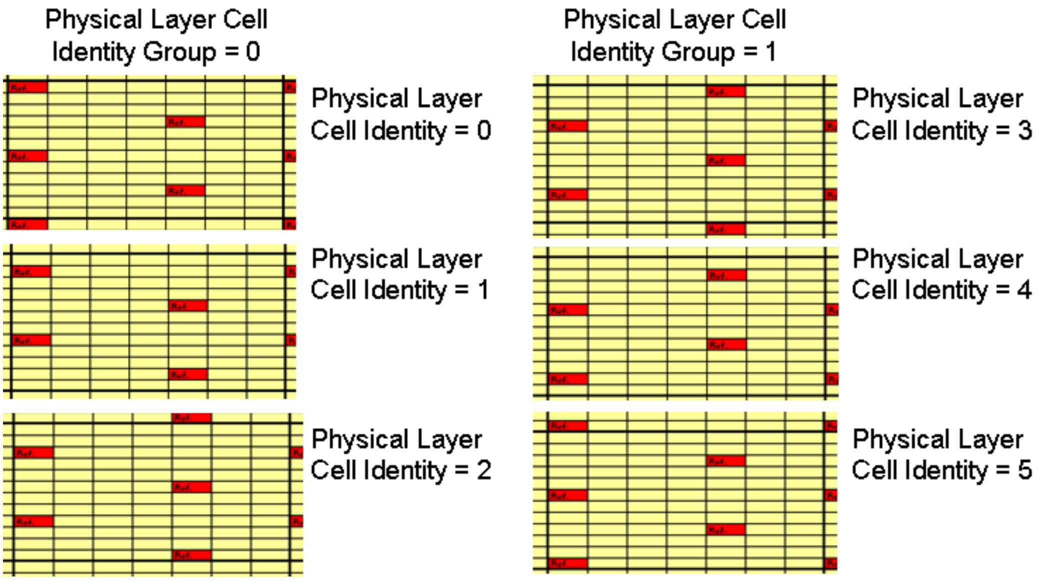


Figure 53: Impact of Physical Layer Cell Identity upon position of Reference Signal

6.2 Tracking Area Planning

Nokia Recommendations

- Tracking area size should be reduced subsequently if the paging load becomes high.
- Existing 2G and 3G location area and routing area boundaries should be used as a basis for defining LTE tracking area boundaries.
- Tracking areas should not run close to and parallel to major roads nor railways. Likewise, boundaries should not traverse dense subscriber areas.
- Cells which are located at a tracking area boundary and which experience large numbers of updates should be monitored to evaluate the impact of the update procedures.
- There might be specific requirements to coordinate Tracking Area Code planning with Location Area Code planning in case of SG mobility during CS fallback (CSFB) or in case of cell reselection towards 2G/3G.
- Nokia however definitely recommends using different Location Areas Identities in LTE (4G) access than in the 2G or 3G. Reason is MSS pooling concept. The concept requires that LTE (4G) Location Area identities are separated from 2G and 3G Location Area Identities.

Background

Tracking Areas (TA) represent the LTE equivalent to Routing Areas. LTE does not have a circuit switched domain so does not require Location Areas. TA are used for Evolved Packet System (EPS) Mobility

Management (EMM). UE are responsible for registering themselves within specific TA. System Information Block 1 (SIB 1) broadcasts the TA to which a cell belongs. SIB 1 is broadcast once every 80 ms. An eNodeB can include cells which belong to different tracking areas and a single cell can belong to more than one TA. A single TA can span multiple MME or can be within a single MME area.

The Access Stratum within the UE passes the TA to the non-Access Stratum within the UE before using it within a registration procedure. Once a UE is registered within a specific TA then paging messages are broadcast across all cells belonging to that TA. UE are allocated an s-TMSI once registered within a TA. The s-TMSI is allocated by the MME and uniquely identifies a UE within a TA. Within the s-TMSI, one field contains the identity of the MME that allocated the s-TMSI. This is necessary to ensure that the s-TMSI remains unique in a tracking area which spans multiple MME.

The normal TA updating procedure is used when a UE moves into another TA within which it is not registered. UE can be registered within more than a single TA so updates are not necessarily required at every boundary. The periodic TA updating procedure is used to periodically notify the availability of the UE to the network.

The Tracking Area Identity (TAI) is constructed from a concatenation of the Mobile Country Code (MCC), Mobile Network Code (MNC) and Tracking Area Code (TAC), i.e. a concatenation of the PLMN identity and the TAC. A single cell can belong to a maximum of 6 PLMN so can have a maximum of 6 TAI (all based upon the same TAC). The TAC has a length of 16 bits, allowing 65,536 TAI per PLMN.

A specific case is the SG based mobility case (e.g. CSFB procedure or cell re-selection to 2G/3G). When UE makes a combined EPS/IMSI attach or combined EPS/IMSI Tracking Area Update Request, it receives a Location Area Code from MME inside of the Attach/TAU Accept message. In case of CSFB MOC LAC is needed when MSC is paging a UE over SGs interface as MME maps LAC received from MSC to TAC and sends the paging to eNBs over S1AP. Therefore, a mapping table between Location Area Identity – Tracking Area Identity must be configured at MME. MSS pooling concept requires that LTE (4G) Location Area identities are separated from 2G and 3G Location Area Identities.

The main drawback associated with large TAs is an increased paging load. 3GPP TS 36.331 specifies that a single paging message can accommodate a maximum of 16 paging records. Nokia implementation supports the maximum of 16 paging records per paging message but limits the number of paging messages to 1 per 10 ms radio frame. The configuration with 1 paging occasion per 10ms means that the paging channel is able to support 1600 pages per second. Paging collisions as well as substantial S1 processing at eNB are likely to be experienced once the paging load reaches about 500 pages per second. Therefore, it is recommended to split paging area if the paging load appears to be around 500 pages/second.

Alternative view on the TA size is through the MME load. MME have to send messages to each and any eNB inside the TA. The limitation works in a way more eNB per TA – less users feasible to page at the same time. Such direct impact is in case of no use of stepwise paging, where the whole TA or even TA list if used is paged in the first step. Stepwise paging should not be used in case of CSFB to ensure minimum delay for CS services. MME could serve several hundred of eNB suppose there is good paging success rate. This is possible due to good protection of IPDU overload. There could be short random bursts of overload, but the MME will recover by itself after the overload burst has passed.

The main benefit associated with large TAs is a reduced requirement for TA updates resulting from mobility. TA updates generate signaling and increase the probability of a UE missing a paging message. Paging messages may be missed because there is a delay between a UE crossing a TA boundary and that UE registering with the new TA, i.e. paging messages could be broadcast across the old TA after the UE has moved into a new TA.

Operators who have existing 2G or 3G networks can plan their TA boundaries to coincide with their Routing Area (RA) or Location Area (LA) boundaries. LA and RA boundaries used for the 2G and 3G systems are likely to be relatively mature and may have already been optimized in terms of their locations. Existing 2G or 3G counter data can be used to estimate the quantity of paging which is likely to be experienced across a specific TA.

TA boundaries should not run close to and parallel to major roads nor railways otherwise there is a risk of relatively large numbers of updates. Likewise, boundaries should not traverse dense subscriber areas. Cells located at a TA boundary and which experience large numbers of updates should be monitored to evaluate the impact of the update procedures.

TA boundaries should be accounted for during the cluster identification task associated with pre-launch optimization. Clusters checks should be defined such that TA boundaries are crossed during drive tests. This helps to verify that the update procedures are successful and do not have a significant impact upon services.

LTE counters should be monitored subsequent to launching the network to ensure that the paging load does not become too high. If the paging load approaches 500 pages per second then a reduction in TA size should be considered.

It is good to have reasonable size of TA to prevent explosive paging load and so to have time to measure paging load and decrease the tracking area if needed

Let’s take example TA = 40 eNodeB --> 120 cells,

Let’s have 1000 UE/Cell and 15Pages/UE/hour ---> 1.800.000 pages/hour

So Paging load is 1.800.000/3.600 = 500 pages/second which is the number when one should start to think how to split/redesign the TA

6.3 eNodeB and Cell Identity Planning

Nokia Recommendations

- The short eNodeB-ID should be used for macrocell networks which include more than a single cell per eNodeB.
- The long eNodeB-Id should only be used for network deployments based upon very large numbers of single cell eNodeB (picocell and Femto networks).
- The cells belonging to an eNodeB should be numbered sequentially as 0, 1, 2.

Background

The E-UTRAN Cell Global Identifier (ECGI) is specified within 3GPP TS 36.300. It is used to identify cells globally, and is constructed from the MCC, MNC and E-UTRAN Cell Identifier (ECI). The ECI is used to identify cells within the PLMN. The MCC, MNC and ECI are broadcasted within SIB 1. The ECI has a fixed length of 28 bits and contains the eNodeB Identifier (eNB-Id).

The eNB-Id is used to identify an eNodeB within a PLMN. The eNB-Id can have a length of either 20 bits (short length) or 28 bits (long length). The long length allows up 20,268,435,456 eNodeB to be addressed per PLMN but limits each eNodeB to having a single cell. The short length allows up to 1,048,576 eNodeB to be addressed per PLMN and allows up to 256 cells per eNodeB. The short eNB-ID is appropriate for macrocell networks which include more than a single cell per eNB. The long eNB-ID is appropriate for picocell and femto networks which are based upon large numbers of eNodeB with only a single cell per eNodeB.

The construction of the ECGI from the MCC, MNC and ECI as per 3GPP is illustrated in Figure 54.

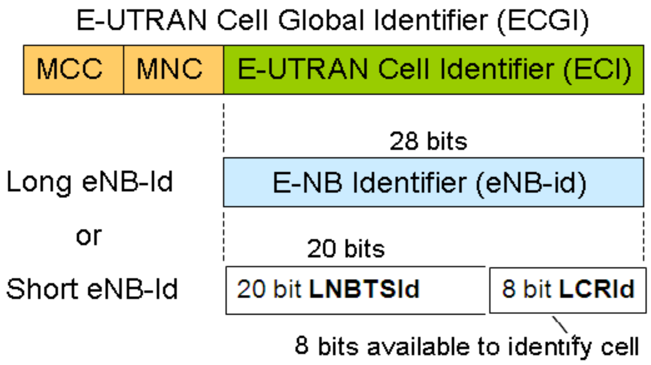


Figure 54: Construction of E-UTRAN Cell Global Identifier (ECGI)

It is also possible to construct a Global eNodeB identifier from the MCC, MNC and eNB-Id. Nokia implementation works with short eNB-ID and EGCI is compiled by the system from following two individual parameters on binary string level

- LNBTS: lnBtsId Range: 0…1048575
- LNCEL: lcrId   Range: 0….255

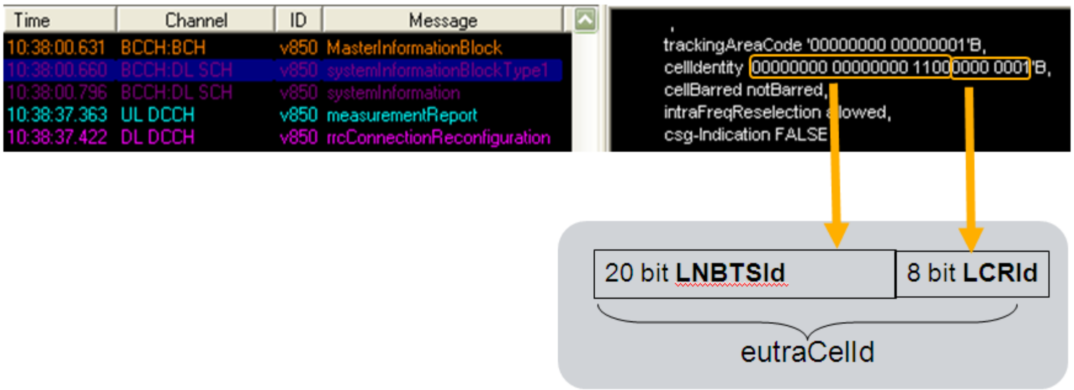


Figure 55: E-UTRAN Cell Identifier (ECI, Short eNB)

The assignment of the both parts (lnBtsId & lcrId) is done by the system during the creation of relevant objects (CELL and LNBTS)

In general, the short eNB-Id should be used rather than the long eNB-Id. This provides support for over 1 million eNodeB within the PLMN and allows multiple cells per eNodeB. The long eNB-Id should only be used for network deployments based upon very large numbers of single cell eNodeB (picocell and femto networks). The cells belonging to an eNodeB can be numbered sequentially as 0, 1, 2. Nokia implementation includes two parameters associated with eNodeB and cell identity planning. These parameters are shown in Table 6.

Parameter	Object	Range	Default
lnbtsId	LNBTS	0...1048575, step 1	Not Applicable
lcrId	LNCEL	0 to 255	Not Applicable

Table 6: eNodeB and cell identity parameters

6.4 MME Area Planning

Nokia Recommendations

- MME planning should account for the equipment capability in terms of maximum subscribers, maximum bearers, maximum transaction rate and maximum eNodeBs.
- The initial plan should not fully load each MME but should allow some margin for traffic growth.
- MME boundaries should be planned to avoid areas of dense traffic.
- MME boundaries should be planned to minimize the requirement for inter-MME mobility.

Background

Mobility Management Engines (MME) are control plane nodes within the Evolved Packet Core (EPC). They are responsible for control plane traffic handling, session management, mobility management and paging. MME planning involves identifying the group of eNodeB to be parented by each MME. The capability of the Nokia Flexi Network Server MME is presented in Table 7.

Maximum Subscribers	24 000 000
Maximum Bearers	48 000 000
Maximum Transaction Rate (Nokia mix of 3GPP MME signalling procedures)	60 000 per second
Maximum eNodeB	40 000

Table 7: MME capability for Nokia Flexi Network Server - MME release NS16 (maximum configuration asc per the NS Datasheet)

A relatively large number of eNodeB can be connected to each MME. The MME requirement is likely to be determined by the number of subscribers. This means that MME planning must account for the distribution of subscribers. The number of subscribers within an area should be estimated and then associated with a specific MME. The initial plan should not fully load each MME but should allow some margin for traffic growth.

MME boundaries should be planned to avoid areas of dense traffic. They should also be planned to minimize the requirement for inter-MME mobility, e.g. if possible, avoid planning an MME boundary across a motorway.

6.5 FDD PRACH Planning Principles

Note: Refer to the LTE Outdoor RF Design Guidelines, the LTE FDD Optimization Guidelines and in the LTE FDD Capacity Solutions Guide for more information on the topic.

Nokia Recommendations

- Unlike in WCDMA where preambles are just randomly taken from a pool of preambles in LTE it is necessary the radio planner selects the preamble format for each cell.
- There are four possible preamble formats. Selection of one or the other is based on the maximum estimated cell range.
- Typical preamble format will be 'Preamble Format 0', allowing for cell sizes up to 15km. Other preamble formats (1, 3 in Nokia implementation) allow for larger cell ranges.
- Preamble format is broadcasted as part of the system information (SIB2).

Background

Random access is a basic procedure within cellular technologies so the terminal establishes uplink synchronization and starts the uplink transmission. In LTE, the random access is used for several purposes, some of them:

- Initial access when establishing a radio link (RRC_IDLE to RRC_CONNECTED)
- To re-establish a radio link after a radio link failure
- During the handover process to establish uplink synchronization to the target cell

Random access process is described in Figure 56. Before starting the random access process, the UE has already acquired downlink synchronization. The UE selects randomly a preamble from a list of parameters broadcasted in BCCH (SIB2) and transmits it in the PRACH with an initial power result of a basic downlink pathloss estimation. If the random access attempt is unsuccessful (there is no answer from the eNB) the UE makes a retry with higher power level. However, in LTE there is no need for several preamble transmissions attempts as in WCDMA since preamble and data transmissions from other terminals in the cell are orthogonal (lower intracell interference) and the initial power can be set such that the first random access is likely to be successful which has a positive impact in the delay.

Upon the reception of the preamble the eNB calculates the power adjustment for initial UE transmission, the delay between eNB and the UE and assigns a UL capacity grant so the UE can send the information.

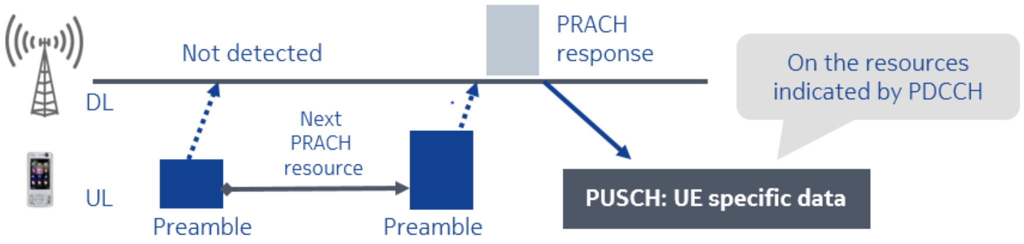


Figure 56: Overview of Random Access Procedure

The PRACH only carries preambles (no additional signaling or user data like in WCDMA Rel.99). In each cell there are 64 preamble sequences available. They are grouped in subsets and the set of sequences within each subset is signaled as part of the system information. The terminal randomly selects one sequence in one of the subsets during the random access process. The subset from which the preamble sequence is selected depends on the amount of data the terminal would like to transmit on PUSCH. Therefore, based on the preamble the eNodeB has some orientation about the amount of uplink resources to be granted to the terminal.

The preamble consists of two parts: the preamble sequence and the cyclic prefix. In addition, there is a guard time used during the preamble transmission to account for the timing uncertainty (due to lack of uplink synchronization) and avoid interference with other subframes not used for random access.

Based on the duration of the cyclic prefix and the preamble sequence 4 different preamble formats are defined in LTE FDD. They are also valid for TDD although there is an additional format available for TDD.

6.5.1 Planning

The radio network planner needs to select the appropriate preamble format based upon the cell range. The typical preamble format is Configuration 0 that allows for maximum cell ranges of up to 15km. Formats with longer guard times are suitable for larger cell ranges which is the case for configurations 1-3. See Table 8 below.

The preamble configuration used in a cell is signaled as part of the system information (SIB2)

Preamble Format	Cyclic Prefix Length	Sequence Length	Guard Time	Total Length	Guard Time Equiv. Dist.	Typical Max. Cell Range
0	0.10 ms	0.8 ms	0.10 ms	1 ms	30 km	15 km
1	0.68 ms	0.8 ms	0.52 ms	2 ms	156 km	78 km
2	0.20 ms	1.6 ms	0.20 ms	2 ms	60 km	30 km
3	0.68 ms	1.6 ms	0.72 ms	3 ms	216 km	108 km

Table 8: Preamble formats for PRACH (Nokia have implemented 0,1,3)

When it comes to PRACH planning/optimization the principle is: PRACH configuration from two cells should not be identical within the PRACH re-use distance.The PRACH of two cells can be separated by:

- Time (prachConfIndex)
- Frequency (prachFreqOff)
- Sequence (prachCS and rootSeqIndex)

1. Time (prachConfIndex)

The number of times the PRACH slot is scheduled per frame and the slot number employed are defined by the parameter ***prachConfIndex.*** Additionally, this parameter implicitly defines the preamble format.

Figure 57 shows the possible values of prachConfIndex for Formats 0, 1 and 3. Each ***prachConfIndex*** indicates in which system frame number (SFN) and in which sub frame(s) there will be PRACH resources. Note than only ***prachConfIndex*** values of 3…8, &19….24 and 51……56 are supported currently. 51 to 53 are for very large cells with normal density. 54 to 56 are for very large cells with high number of attempts.

Config. Index	Preamble Format	SFN	Subframe Numbers	Config. Index	Preamble Format	SFN	Subframe Numbers
0	0	Even	1	32	2	Even	1
1	0	Even	4	33	2	Even	4
2	0	Even	7	34	2	Even	7
3	0	Any	1	35	2	Any	1
4	0	Any	4	36	2	Any	4
5	0	Any	7	37	2	Any	7
6	0	Any	1, 6	38	2	Any	1, 6
7	0	Any	2, 7	39	2	Any	2, 7
8	0	Any	3, 8	40	2	Any	3, 8

9	0	Any	1, 4, 7
10	0	Any	2, 5, 8
11	0	Any	3, 6, 9
12	0	Any	0, 2 , 4, 6, 8
13	0	Any	1, 3, 5, 7, 9
14	0	Any	0 to 9
15	0	Even	9
16	1	Even	1
17	1	Even	4
18	1	Even	7
19	1	Any	1
20	1	Any	4
21	1	Any	7
22	1	Any	1, 6
23	1	Any	2, 7
24	1	Any	3, 8
25	1	Any	1, 4, 7
26	1	Any	2, 5, 8
27	1	Any	3, 6, 9
28	1	Any	0, 2 , 4, 6, 8
29	1	Any	1, 3, 5, 7, 9
30			
31	1	Even	9

41	2	Any	1, 4, 7
42	2	Any	2, 5, 8
43	2	Any	3, 6, 9
44	2	Any	0, 2 , 4, 6, 8
45	2	Any	1, 3, 5, 7, 9
46			
47	2	Even	9
48	3	Even	1
49	3	Even	4
50	3	Even	7
51	3	Any	1
52	3	Any	4
53	3	Any	7
54	3	Any	1, 6
55	3	Any	2, 7
56	3	Any	3, 8
57	3	Any	1, 4, 7
58	3	Any	2, 5, 8
59	3	Any	3, 6, 9
60			
61			
62			
63	3	Even	9

Figure 57: Extract of the random access preamble configurations table (3GPP TS36.211)

Current recommendation is to set the ***prachConfIndex*** **to the same value for cells belonging to the same site**. By doing this though, the PRACH allocations in one cell will interfere with PRACH allocations in other cells of the site.

Alternative approach as per the reference varies the prachConfIndex parameter for the cells belonging to the same site (so there is potential for PUSCH – PRACH interference between sectors), but it simplifies the root sequence planning by allocating the same root sequence to each sector

Simulations have shown that PRACH-PRACH interference is preferred to PRACH-PUSCH interference (i.e. this would be the case when allocating different ***prachConfIndex*** to the cells of the same eNodeB). The reason for this is that the PUSCH Rx power (SINR) can be very high compared to PRACH SINR in the neighbor cell and hence effectively swamp the PRACH preambles and/or resulting in misdetections (ghost RACH)

Figure 58 shows (simulation results) the relation between SNR PUSCH and the required PRACH SNR for a probability of misdetection (Pmd) of 1%, i.e., the probability that a preamble is not detected by the eNodeB.

Figure 59 shows (simulation results) the relation between SNR PUSCH and the false alarm rate i.e. the probability that a preamble is falsely detected due to noise or interference even when no such preamble was transmitted.

Up to a SNR ~0 the degradation is acceptable: ~1% for false alarm rate and req. PRACH SNR loss of 3dB. The degradation could be tolerable up to a PUSCH SNR of 4dB (switching point from QPSK to 16AQM PUSCH) with 5% false alarm and ~6 dB req. SNR loss. In any case, higher PUSCH SNR has a strong (& negative) impact over the PRACH detection.

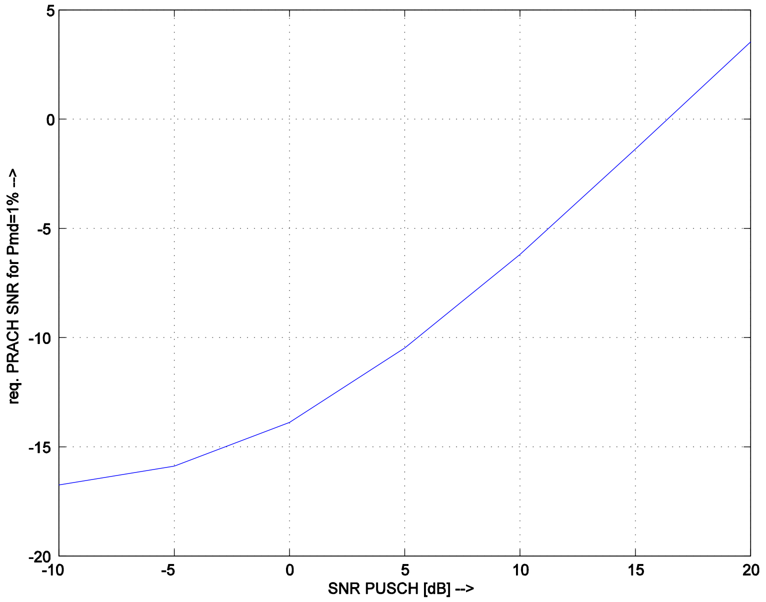


Figure 58: Simulation results for SNR PUSCH vs. req. PRACH SINR

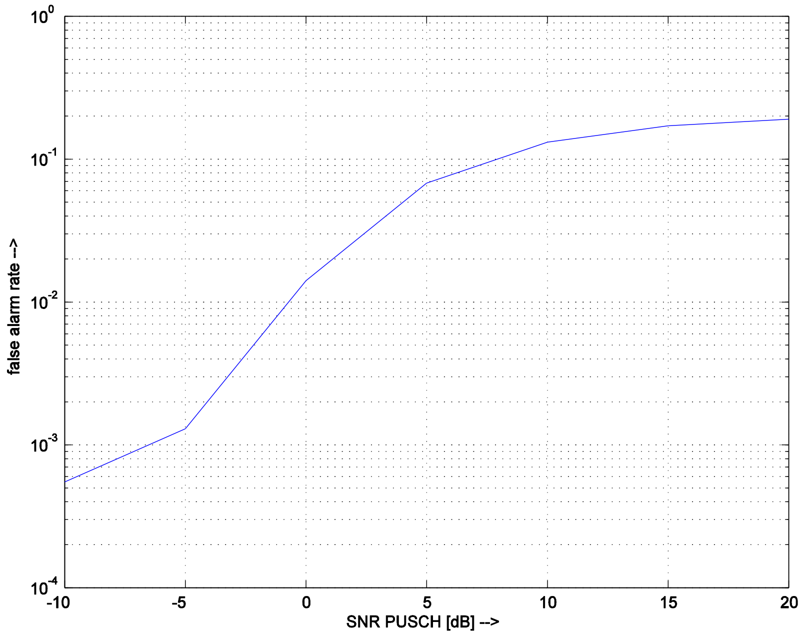


Figure 59: Simulation Results SNR PUSCH vs. False Alarm Rate

2. Frequency (PrachFreqOff)

Every time the PRACH is scheduled, the UL scheduler will reserve 6 PRBs for this purpose. The location of these PRBs is defined by the parameter *prachfreqOffset*.

If PRACH area is placed at the lower border of UL frequency band then:

- PRACH-Frequency Offset= roundup [PUCCH resources/2]

If PRACH area is placed at the upper border of the UL frequency band then:

- PRACH-Frequency Offset= NRB -6- roundup [PUCCH resources/2]

There are two preconditions:

- The PRACH area shall not overlap with the PUCCH area
- The scheduler can handle only one PUSCH area. It is better to have only one PUSCH area instead of two (i.e. definitely do not locate the PRACH somewhere to the middle of the frequency band).

Therefore, there are only two possibilities for frequency separation, either at the lower or at the upper edge of the PUSCH area. Two possibilities are not enough for a separation of the PRACH in a complete network. Anyhow *prachFreqOff* can be used in case of problems as an alternative/add-on, however this will also generate PRACH to neighbor cells PUSCH interference.

There is an automatic check implemented in BTS Site Manager for PUCCH and PRACH area overlapping avoidance. However, since this automatic check does not look for the possibility of setting prachFreqOff with a gap between PRACH and PUCCH, it is recommended to verify it manually. (PUSCH PRBs between PRACH and PUCCH cannot be allocated by single UE.) The ideal PRACH location is on the boundary between PUCCH and PUSH region. Thus, PRACH offset depends on PUCCH resources and the PUCCH resources can be calculated with the PUCCH Capacity Tool for FDD.

Every cell requires 64 preamble signatures. PRACH preambles are generated from Constant Amplitude Zero-Auto-Correlation Zadoff-Chu Codes. The sequences generated from a cyclic shift of a single root sequence are orthogonal. Sequences obtained from cyclic shifts of different root sequences are not orthogonal. Therefore, orthogonal sequences obtained by cyclically shifting a single root sequence should be favored over non-orthogonal sequences; additional ZC root sequences should be used only when the required number of sequences (64) cannot be generated by cyclic shifts of a single root sequence. Furthermore, processing power of eNodeB is increasing with additional root sequences. The cyclic shift dimensioning is therefore important in the RACH design.

3. Sequence

The parameter ***PrachCs*** defines the Preamble cyclic shift which is used for preamble generation. The configuration determines how many cyclic shifts are needed to generate the preamble. The table below illustrates the cell range for different values of ***PrachCs*** for the normal set.

NCs Configuration (PrachCs)	Size of Cyclic Shift	Signatures per root Sequence	#Root Sequence required per cell	Cell Range (km)
1	13	64	1	0.76
2	15	55	2	1.04
3	18	46	2	1.47
4	22	38	2	2.04
5	26	32	2	2.62
6	32	26	3	3.48
7	38	22	3	4.33
8	46	18	4	5.48
9	59	14	5	7.34
10	76	11	6	9.77
11	93	9	8	12.2
12	119	7	10	15.92
13	167	5	13	22.78
14	279	3	22	38.8
15	419	2	32	58.83
0	839	1	64	118.9

Table 9: Cell ranges vs Preamble cyclic Shifts (PrachCs)

The column signatures per root sequence indicate how many signatures are in the zero-correlation zone, additionally the table shows how many root sequence indices are required for that specific ***PrachCs*** configuration and the respective maximum cell range. As explained above, two cells that are assigned the same root sequence could interfere each other and potentially lead to ghost RACH's, therefore the set of logical root sequence index assigned to each cell should be planned in a way to avoid re-use in neighbor sites.

The table highlights how the intra-cell interference is optimized with respect to cell size: the smaller the cell size, the larger the number of orthogonal signatures and the better the detection performance.

The relationship between cell size and the required number of ZC root sequences allows for some system optimization. In general, the eNodeB should configure *NCS(prachCs) independently in* each cell, because the expected inter-cell interference and load (user density) increases as cell size decreases; therefore, smaller cells need more protection from co-preamble interference than larger cells.

6.5.2 Features and tools for planning

MUSA tool is used for the Root Sequence Index (RSI) Planning. There is also the option for automated planning/optimization of the PRACH using the EdenNet PRACH Optimization Module (based on features LTE581 PRACH Management and LTE962 RACH Optimization):

- PRACH Management (LTE581) – Provides automatic assignment of PRACH parameters during **the initial eNB auto-configuration process** using NetAct Optimizer (i.e. PRACH auto planning). Parameters: *prachConfIndex, prachFreqOff, prachCS, rootSeqIndex*. Assignment done for all cells of an eNB considering own cell data and configuration data from 'surrounding' eNodeBs.

- Automatic Optimization of RACH parameter assignments (LTE962) - for network performance increase during operation. The feature Optimize PRACH / RACH parameters same as the feature LTE581, i.e. *prachConfIndex, prachFreqOff, prachCS, rootSeqIndex,* but the process include performance measurements. LTE 962 thus it can set PRACH format/ PRACH position, and PRACH density. It could detect, visualize and remove PRACH/RACH inconsistencies, PRACH/RACH collisions based on configuration data of eNBs as e.g. geo-location, and operator selectable scope.

6.6 TDD PRACH Planning Principles

Note: Refer to the LTE Outdoor RF Design Guidelines and the LTE TDD Capacity Solutions Guide for more information on the topic.

Nokia Recommendation

- Unlike in WCDMA where preambles are just randomly taken from a pool of preambles, or in TD-SCDMA where Sync-UL sequences are associated with scrambling code, in LTE the radio planner selects the preamble format for each cell.
- For TD-LTE, there are five possible preamble formats. Selection of a preamble format is based on the maximum estimated cell range, as well as on which formats are supported within a given release.
- Typical preamble format will be 'Preamble Format 0', allowing for cell sizes up to 15km. Preamble formats 1-3 allow for larger cell ranges, while preamble format 4, only used in TDD systems, allows a smaller cell range.
- Only Preamble Formats "0", "1", "2", and "4" are currently supported.
- Preamble format is broadcast as part of the system information (SIB2).
- The PRACH configuration of two cells must be different, within the PRACH reuse distance, to increase the RACH decoding success rate. PRACH transmission can be separated in:
    - Time Domain (using prachConfIndex)
        - The prachConfIndex should be the same for all cells on one site to minimize PRACH to PUSCH interference.
    - Frequency Domain (using prachFreqOff)
        - Typically, the same prachFreqOff configuration is used for all cells (depends on PUCCH resources)
    - Code Domain (using prachCS and rootSeqIndex)
        - The prachCS parameter depends on the range. It is recommended to set this the same for all cells in the network, if making the simplifying assumption that the cell range for all cells is roughly the same.
        - Use different sequences, rootSeqIndex, for all neighboring cells.

There is also an alternate approach which varies the prachConfIndex parameter for the cells belonging to the same site, but uses the same root sequence for each sector.

Background

Random access is a basic procedure within cellular technologies. The terminal establishes uplink synchronization, and then starts the uplink transmission. In LTE, the random access is used for several purposes, such as:

- Initial access when establishing a radio link (RRC_IDLE to RRC_CONNECTED)
- To re-establish a radio link after a radio link failure
- During the handover process to establish uplink synchronization to the target cell

The random access process is described in Figure 56. Before starting the random access process, the UE has already acquired downlink synchronization. The UE selects randomly a preamble from a list of parameters broadcast in BCCH (SIB2) and transmits it in the PRACH with an initial power level based on a basic downlink pathloss estimation. If the random access attempt is unsuccessful, that is there is no answer from the eNB, the UE makes a retry with a higher power level. However, in LTE there is no need for several preamble transmission attempts, as in WCDMA, since preamble and data transmissions from other terminals in the cell are orthogonal. Thus, there is lower intracell interference and the initial power can be set such that the first random access is likely to be successful, which has a positive impact on delay.

Upon the reception of the preamble, the eNB calculates the power adjustment for initial UE transmission, the delay between eNB and the UE, and assigns a UL capacity grant so the UE can send the information.

The PRACH only carries preambles, not additional signaling or user data like in WCDMA Rel. 99. In each cell, there are 64 preamble sequences available. They are grouped in subsets, and the set of sequences within each subset is signaled as part of the system information. The terminal randomly selects one sequence in one of the subsets during the random access process. The subset from which the preamble sequence is selected depends on the amount of data the terminal would like to transmit on PUSCH. Therefore, based on the preamble, the eNB has some information about the amount of uplink resources to be granted to the terminal.

The preamble consists of two parts: the preamble sequence and the cyclic prefix. In addition, there is a guard time used during the preamble transmission.

Based on the duration of the cyclic prefix and the preamble sequence, 5 different preamble formats are defined in TDD LTE. Preamble formats 0-3 are also valid for FDD while preamble format 4 is only valid for TDD on UpPTS.

There are various eNodeB parameters that are related to random access: prachConfIndex, prachFreqOff, PrachCS, and rootSeqIndex. These are explained further in the subsections below.

6.6.1 Planning

The transmission of a random access preamble is restricted to certain time and frequency resources. The physical layer random access preamble consists of a cyclic prefix of length Tcp and a sequence part of length Tseq. The length of Tcp and Tseq depend on the random access configuration, which will determine the preamble format. Different preamble formats are needed to accommodate for different cell ranges.

The radio network planner needs to select the appropriate preamble format based on the cell range. The typical preamble format is Configuration 0, which allows for maximum cell ranges of up to 15 km. Formats with longer guard times are suitable for larger cell ranges, which is the case for configurations 1-3. Format

4 allows for maximum cell ranges of up to 1.4 km, but it improves UL throughput, since more resources can be reserved in normal UL subframes for PUSCH. See Table 10 below.

Preamble formats 2 and 3 employ preamble sequence lengths which are double the size of the ones used for preamble formats 0 and 1, aiming to improve PRACH decoding reliability in higher UL interfered scenarios. Note also that the preamble formats 1, 2, and 3 each require more than one TTI.

The preamble configuration used in a cell is signaled as part of the system information (SIB2)

Preamble Format	Cyclic Prefix Length (us)	Sequence Length (us)	Guard Time (us)	Total Length (us)	Typical Max. Cell Range (km)
0	103.1	800	96.9	1000	14.5
1	684.4	800	515.6	2000	77.3
2	203.1	1600	196.9	2000	29.5
3	684.4	1600	715.6	3000	107.3
4	14.6	133.3	9	150	1.4

Table 10: Preamble formats for PRACH

This table is based on the following information from the 3GPP TS 36.211 document, where Ts is equal to 1 / (15000 x 2048):

Preamble format	T_{CP}	T_{SEQ}
0	$3168 \cdot T_s$	$24576 \cdot T_s$
1	$21024 \cdot T_s$	$24576 \cdot T_s$
2	$6240 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
3	$21024 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
4 (frame structure type 2 only)	$448 \cdot T_s$	$4096 \cdot T_s$

Table 11: Random Access Preamble Parameters

The random access configurations for FDD and TDD are different. For FDD with preamble formats 0-3, there is at most one random access resource per subframe. For TDD with preamble formats 0-4, however, there might be multiple random access resources in an UL subframe (or UpPTS in the case of preamble format 4), depending on the DL/UL configuration.

A general PRACH planning principle is that the PRACH configuration of two cells must be different (within the PRACH reuse distance) to increase the RACH decoding success rate. PRACH transmission can be separated by time (using the prachConfIndex parameter), by frequency (using the prachFreqOff parameter), or by sequence (using the PrachCS and rootSeqIndex parameters).

- With respect to time, it is recommended that the prachConfIndex be set the same for all cells on a site. This helps to minimize PRACH to PUSCH interference, which can occur if PRACH resources are separated in time within an eNB.
- With respect to frequency, it is recommended for simplicity that the same prachFreqOff configuration be used for all cells. The allocation of the PRACH area in frequency should be next to the allocation of the PUCCH area, either at the upper or lower border of the frequency band.

However, the PRACH area should not overlap the PUCCH area. Also, the PRACH area in frequency should avoid separating the PUSCH area, since the scheduler can only handle one PUSCH area.

- Finally, with respect to sequence, it is recommended to use different sequences for all neighbor cells.

As mentioned previously, there is also an alternate approach which varies the prachConfIndex parameter for the cells belonging to the same site, but uses the same root sequence for each sector

1. Time (prachConfIndex)

From 3GPP TS 36.211, the following table provides the PRACH configurations which are allowed for TDD LTE with preamble formats 0-4. The PRACH Configuration Index, along with the information in the following tables, is used to identify the frame for random access attempts, the subframe number in which the PRACH will be found, and the preamble format. The PRACH density indicates how many RACH resources are in a 10 ms frame (i.e. a density of 1 indicates one random access attempt per frame).

It is recommended to set the prachConfIndex to the same value for cells belonging to the same site. By doing this, the PRACH allocations in one cell will interfere with PRACH allocations in other cells of the same site. However, simulations have shown that PRACH-to-PRACH interference is preferable to PRACH-to-PUSCH interference, which would occur if different prachConfIndex values were allocated to the cells of the same eNodeB. The reason for this is that the PUSCH Rx power (SINR) can be very high compared to PRACH SINR in the neighbour cell and hence, effectively swamp the PRACH preambles and/or resulting in misdetections (ghost RACH).

PRACH Configuration Index	Preamble Format	PRACH Density Per 10 ms	Version	PRACH Configuration Index	Preamble Format	PRACH Density Per 10 ms	Version
0	0	0.5	0	32	2	0.5	2
1	0	0.5	1	33	2	1	0
2	0	0.5	2	34	2	1	1
3	0	1	0	35	2	2	0
4	0	1	1	36	2	3	0
5	0	1	2	37	2	4	0
6	0	2	0	38	2	5	0
7	0	2	1	39	2	6	0
8	0	2	2	40	3	0.5	0
9	0	3	0	41	3	0.5	1
10	0	3	1	42	3	0.5	2
11	0	3	2	43	3	1	0
12	0	4	0	44	3	1	1
13	0	4	1	45	3	2	0
14	0	4	2	46	3	3	0
15	0	5	0	47	3	4	0
16	0	5	1	48	4	0.5	0
17	0	5	2	49	4	0.5	1
18	0	6	0	50	4	0.5	2
19	0	6	1	51	4	1	0
20	1	0.5	0	52	4	1	1
21	1	0.5	1	53	4	2	0
22	1	0.5	2	54	4	3	0
23	1	1	0	55	4	4	0
24	1	1	1	56	4	5	0
25	1	2	0	57	4	6	0
26	1	3	0				
27	1	4	0				
28	1	5	0				
29	1	6	0				
30	2	0.5	0				
31	2	0.5	1				

Table 12: TDD LTE Random Access Configurations for Preamble Formats 0-4

PRACH configuration indexes are limited to the set of 3-7, 23-25, 33-35, and 51-53, as shown in gray in the table above and as described in further detail in the following table:

Preamble Format	PRACH Configuration Index
0	3-7 for UL/DL configuration 1; 3, 4, 6 for UL/DL configuration 2
1	23-25 only applicable to UL/DL configuration 1 and special subframe configuration 5
2	33-35 only applicable to UL/DL configuration 1 and special subframe configuration 5
4	51-53 only applicable to supported TDD special subframe configuration 5 & 7

Table 13: TDD LTE PRACH Configuration Limitations

The following table, from 3GPP TS 36.211, provides a mapping of different TDD random access preambles to physical resources (time and frequency). Although 3GPP TS 36.211 defines this mapping for all UL/DL configurations, only configurations 1 and 2 are shown in the table below since these are the only two configurations that are used currently.

	TDD UL/DL Configuration	
PRACH Configuration Index	1	2
0	(0,1,0,1)	(0,1,0,0)
1	(0,2,0,1)	(0,2,0,0)
2	(0,1,1,1)	(0,1,1,0)
3	(0,0,0,1)	(0,0,0,0)
4	(0,0,1,1)	(0,0,1,0)
5	(0,0,0,0)	N/A
6	(0,0,0,1) (0,0,1,1)	(0,0,0,0) (0,0,1,0)
7	(0,0,0,0) (0,0,1,0)	N/A
8	N/A	N/A
9	(0,0,0,1) (0,0,1,1) (0,0,0,0)	(0,0,0,0) (0,0,1,0) (1,0,0,0)
10	(0,0,1,0) (0,0,0,1) (0,0,1,1)	(0,0,1,0) (0,0,0,0) (1,0,1,0)
11	(0,0,0,0) (0,0,1,0) (0,0,0,1)	N/A
12	(0,0,0,1) (0,0,1,1)	(0,0,0,0) (0,0,1,0)

	TDD UL/DL Configuration	
PRACH Configuration Index	1	2
22 / 32	(0,1,1,0)	N/A
23 / 33	(0,0,0,0)	N/A
24 / 34	(0,0,1,0)	N/A
25 / 35	(0,0,0,0) (0,0,1,0)	N/A
26 / 36	(0,0,0,0) (0,0,1,0) (1,0,0,0)	N/A
27 / 37	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0)	N/A
28 / 38	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0)	N/A
29 /39	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0) (2,0,1,0)	N/A

	(0,0,0,0) (0,0,1,0)	(1,0,0,0) (1,0,1,0)
13	N/A	N/A
14	N/A	N/A
15	(0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0) (1,0,0,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0)
16	(0,0,1,1) (0,0,0,0) (0,0,1,0) (0,0,0,1) (1,0,1,1)	(0,0,1,0) (0,0,0,0) (1,0,1,0 (1,0,0,0) (2,0,1,0)
17	(0,0,0,0) (0,0,1,0) (0,0,0,1) (0,0,1,1) (1,0,0,0)	N/A
18	(0,0,0,1) (0,0,1,1) (0,0,0,0) (0,0,1,0) (1,0,0,1) (1,0,1,1)	(0,0,0,0) (0,0,1,0) (1,0,0,0) (1,0,1,0) (2,0,0,0) (2,0,1,0)
19	(0,0,0,0) (0,0,1,0) (0,0,0,1) (0,0,1,1) (1,0,0,0) (1,0,1,0)	N/A
20 / 30	(0,1,0,0)	N/A
21 / 31	(0,2,0,0)	N/A

40	N/A	N/A
41	N/A	N/A
42	N/A	N/A
43	N/A	N/A
44	N/A	N/A
45	N/A	N/A
46	N/A	N/A
47	N/A	N/A
48	(0,1,0,*)	(0,1,0,*)
49	(0,2,0,*)	(0,2,0,*)
50	(0,1,1,*)	(0,1,1,*)
51	(0,0,0,*)	(0,0,0,*)
52	(0,0,1,*)	(0,0,1,*)
53	(0,0,0,*) (0,0,1,*)	(0,0,0,*) (0,0,1,*)
54	(0,0,0,*) (0,0,1,*) (1,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*)
55	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*)
56	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*)
57	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)	(0,0,0,*) (0,0,1,*) (1,0,0,*) (1,0,1,*) (2,0,0,*) (2,0,1,*)

Table 14: TDD LTE Random Access Preamble Mapping in Time and Frequency
*** denotes UpPTS**

Within this random access preamble mapping table, there are four values given for each row and UL/DL configuration. These four values are described in the 3GPP TD 36.211 document as follows: (f_{RA}, t^0_{RA}, t^1_{RA}, t^2_{RA}). These values provide the time and frequency mapping as follows:

- f_{RA} is the random access preamble frequency resource index within the considered time instance
- t^0_{RA} indicates the reoccurrence of the resource: where 0, 1, and 2 indicates whether the resource is reoccurring in all radio frames, in even radio frames, or in odd radio frames, respectively

- t^1_{RA} indicates whether the random access resource is located in the first half frame (indicated with a “0”) or in the second half frame (indicated with a “1”).
- t^2_{RA} provides the uplink subframe number where the preamble starts, counting from 0 at the first uplink subframe between 2 consecutive downlink-to-uplink switch points, with the exception of preamble 4, which is always transmitted in UpPTS.

As previously mentioned, preamble format 0 is typically used. From the previous two tables, it shows that for Preamble 0, the PRACH configuration index is 3 to 7 for TD-LTE frame configuration 1, or 3, 4, or 6 for TD-LTE frame configuration 2. Also, based on

Table 14, for PRACH configuration indexes 3-7, f_{RA} is always 0 (i.e. the random access preamble frequency resource index within the considered time instance). Similarly, for this set of PRACH configuration indexes, t^0_{RA} is always 0, indicating that the resource is reoccurring in all radio frames. For this set of PRACH configuration indexes, t^1_{RA} is either 0 or 1 depending on whether the random access resource is located in the first or second half frame. Finally, for this set of PRACH configuration indexes, the t^2_{RA} is always 0 for TD-LTE frame configuration 2, so the preamble will start in the first uplink subframe between 2 consecutive downlink-to-uplink switch points. However, for TD-LTE frame configuration 1, t^2_{RA} is 0 for PRACH configuration indexes of 5 and 7, but it is 1 for PRACH configuration indexes of 3, 4, or 6 (indicating that the preamble will start in the second uplink subframe between 2 consecutive downlink-to-uplink switch points).

2. Frequency (prachFreqOff)

The PRACH frequency offset parameter, prachFreqOff, indicates the first PRB available for the PRACH in the UL frequency band. The PRACH area, which occupies 6 PRBs, should be next to the PUCCH area, either at the upper or lower border of the frequency planning band, in order to maximize the PUSCH area. However, the PRACH area should not overlap the PUCCH area. Additionally, the PRACH area should avoid separating the PUSCH area, since the scheduler can only handle one PUSCH area.

Therefore, the setting of the prachFreqOff parameter is based on the PUCCH region and depends on how many PUCCH resources are available and whether the PRACH area will be placed at the lower or upper border of the UL frequency band, as shown below.

- If the PRACH area is placed at the lower border of UL frequency band, the prachFreqOff parameter is calculated as:
  prachFreqOff = roundup [PUCCH resources/2]
- If the PRACH area is placed at the upper border of UL frequency band, the prachFreqOff parameter is calculated as:
  prachFreqOff = # of RBs – 6 – roundup [PUCCH resources/2]

Calculation of prachFreqOff is done automatically with the tool PUCCH Capacity Calculation for TDD

3. Sequence (prachCS and rootSeqIndex)

Once the preamble format and frequency have been decided, the preamble signature planning has to be performed. There are 64 preambles available in each cell. PRACH preambles are generated from Constant

Amplitude Zero-Auto-Correlation Zadoff-Chu Codes. The sequences generated from a cyclic shift of a single root sequence are orthogonal. Sequences obtained from cyclic shifts of different root sequences are not orthogonal. Therefore, orthogonal sequences obtained by cyclically shifting a single root sequence should be favored over non-orthogonal sequences; additional ZC root sequences should be used only when the required number of sequences (64) cannot be generated by cyclic shifts of a single root sequence. Furthermore, processing power used by the eNodeB increases with additional root sequences. The cyclic shift dimensioning is therefore very important in the RACH design.

The parameter ***PrachCs*** defines the Preamble cyclic shift which is used for preamble generation. The configuration determines how many cyclic shifts are needed to generate the preamble. The tables below illustrate the cell range for different values of ***PrachCs*** for the normal set. Cyclic shift and cell range values associated with Preamble Formats 0-3 are shown in Table 15, while values associated with Preamble Format 4 are shown in Table 16.

The *PrachCs* parameter is selected based on the cell range. If all cells in the network are assumed to have the same cell range, then *PrachCs* is the same for the whole network. For example, assuming a preamble format of 0 and an estimated cell range of 15 km, the PrachCS would be 12.

Ncs Configuration (PrachCs)	Number of Cyclic Shifts (Ncs)	Signatures per root sequence	# of root sequences per cell	Supportable Cell Size, km *
1	13	64	1	0.8
2	15	55	2	1
3	18	46	2	1.5
4	22	38	2	2
5	26	32	2	2.6
6	32	26	3	3.5
7	38	22	3	4.3
8	46	18	4	5.5
9	59	14	5	7.3
10	76	11	6	9.8
11	93	9	8	12.2
12	119	7	10	15.9
13	167	5	13	22.8
14	279	3	22	38.8
15	419	2	32	58.8
0	839	1	64	118.9

Table 15: Cell ranges vs. Preamble Cyclic Shifts (PrachCs) for Preamble Formats 0-3
*** assumes 5.2 microsecond delay spread and 2 guard samples**

Ncs Configuration (PrachCs)	Number of Cyclic Shifts (Ncs)	Signatures per root sequence	# of root sequences per cell	Supportable Cell Size, km	Supportable Cell Size, km (assuming 5.2us delay spread)
0	2	69	1	0.29	n/a
1	4	34	2	0.58	n/a
2	6	23	3	0.86	0.08
3	8	17	4	1.15	0.37
4	10	13	5	1.44	0.66
5	12	11	6	1.73	0.95
6	15	9	8	2.16	1.38

Table 16: Cell ranges vs. Preamble Cyclic Shifts (PrachCs) For Preamble Format 4

Within these tables, the cyclic shift values correspond to information found in tables 5.7.2-2 and 5.7.2-3 in the 3GPP TS 36.211 document. The PrachCS defines the number of cyclic shifts (in terms of number of samples) used to generate multiple preamble sequences from a single root sequence. The column "Signatures per root sequence" indicates how many signatures are in the zero correlation zone. The signatures per root sequence values are calculated by taking the random access preamble sequence length and dividing it by the number of cyclic shifts:

Signatures per root sequence = rounddown [preamble sequence length/# of cyclic shifts]

The root sequence length varies depending on the Preamble format, as seen in the following table (copied from the 3GPP TS 36.211 document, table 5.7.2-1).

Preamble Format	Random Access Preamble Sequence Length
0 – 3	839
4	139

Table 17: Random Access Preamble Sequence Length

For example, assuming a random access preamble format of 0 and a PrachCS of 12, the number of cyclic shifts is 119 and the number of signatures per root sequence is 7 [i.e. round down (839/119)].

Sixty-four preambles are transmitted in the PRACH frame. If one root sequence is not enough to generate all 64 preambles, then more root sequences are necessary. To ensure having 64 preamble sequences within the cell, it is necessary to determine the number of root sequences required, which is calculated by taking 64 preamble sequences divided by the number of signatures per root sequence:

root sequences required per cell = roundup [64 / # of signatures per root sequence]

Using the same example as before with a random access preamble format of 0 and a PrachCS of 12, the number of cyclic shifts is 119, the number of signatures per root sequence is 7 and the number of root sequences per cell is 10 [i.e. roundup(64/7)].

The supportable cell range is based on the number of cyclic shifts and the random access sequence length per preamble format. For example, with preamble format 4, the random access preamble sequence length is 139 (see Table 17) and 133.3 microseconds (see

Table 11). The cell range is then calculated by:

Cell range for preamble format 4 (m)
= Ncs * (133.3 * 10^{-6} sec/139) * (3*10^8 m/sec) / 2
if Ncs = 6, then cell range = 6*(133.3 * 10^{-6} sec/139) * (3*10^8 m/sec) / 2 = 863 m

If a delay spread of 5.2 microseconds is factored into the range then the distance is reduced by ½ * delay spread * speed of light. In the case where Ncs =6, the distance including the delay spread would be 863 – [½ * (5.2 *10^{-6}) * (3*10^8 m/sec)] = 83 m

Please note that the cell ranges shown in Table 15, preamble formats 0-3, include both a 5.2 microsecond delay and 2 guard samples. For example,
Cell range for preamble 0 = (Ncs – guard samples) * (800 * 10^{-6} sec/839) * (3*10^8 m/sec) / 2

Table 15 and Table 16 show how many root sequence indices are required for that specific PrachCs configuration and the respective maximum cell range. As explained above, two cells that are assigned the same root sequence could interfere with each other and potentially lead to ghost RACH's. Therefore, the set of logical root sequence indexes assigned to each cell should be planned, avoiding re-use in neighboring sites.

These tables highlight how the intra-cell interference is optimized with respect to cell size. The smaller the cell size, the larger the number of orthogonal signatures, and the better the detection performance.

The relationship between cell size and the required number of ZC root sequences allows for some system optimization. In general, the eNodeB should configure ***NCS (prachCs)*** *independently* in each cell, because the expected inter-cell interference and load (user density) increases as cell size decreases. Therefore, smaller cells need more protection from co-preamble interference than larger cells.

The rootSeqIndex parameter points to the first root sequence to be used when generating the set of 64 preamble sequences. Each logical rootSeqIndex is associated with a single physical root sequence number. In case more than one root sequence is necessary, the next consecutive numbers are selected until the full set is generated. It is recommended to use a different rootSeqIndex across neighboring cells to ensure that neighboring cells will use different preamble sequences.

Within the 3GPP TS 36.211 document, there are tables showing the mapping of logical root sequence numbers to physical root sequence numbers for random access preamble formats 0-3 and format 4 (Table 5.7.2-4 and 5.7.2-5 within this document, respectively). These tables are also copied below for reference.

Logical root sequence number	Physical root sequence number u (in increasing order of the corresponding logical sequence number)
0–23	129, 710, 140, 699, 120, 719, 210, 629, 168, 671, 84, 755, 105, 734, 93, 746, 70, 769, 60, 779 2, 837, 1, 838
24–29	56, 783, 112, 727, 148, 691
30–35	80, 759, 42, 797, 40, 799
36–41	35, 804, 73, 766, 146, 693
42–51	31, 808, 28, 811, 30, 809, 27, 812, 29, 810
52–63	24, 815, 48, 791, 68, 771, 74, 765, 178, 661, 136, 703
64–75	86, 753, 78, 761, 43, 796, 39, 800, 20, 819, 21, 818
76–89	95, 744, 202, 637, 190, 649, 181, 658, 137, 702, 125, 714, 151, 688
90–115	217, 622, 128, 711, 142, 697, 122, 717, 203, 636, 118, 721, 110, 729, 89, 750, 103, 736, 61, 778, 55, 784, 15, 824, 14, 825
116–135	12, 827, 23, 816, 34, 805, 37, 802, 46, 793, 207, 632, 179, 660, 145, 694, 130, 709, 223, 616
136–167	228, 611, 227, 612, 132, 707, 133, 706, 143, 696, 135, 704, 161, 678, 201, 638, 173, 666, 106, 733, 83, 756, 91, 748, 66, 773, 53, 786, 10, 829, 9, 830
168–203	7, 832, 8, 831, 16, 823, 47, 792, 64, 775, 57, 782, 104, 735, 101, 738, 108, 731, 208, 631, 184, 655, 197, 642, 191, 648, 121, 718, 141, 698, 149, 690, 216, 623, 218, 621
204–263	152, 687, 144, 695, 134, 705, 138, 701, 199, 640, 162, 677, 176, 663, 119, 720, 158, 681, 164, 675, 174, 665, 171, 668, 170, 669, 87, 752, 169, 670, 88, 751, 107, 732, 81, 758, 82, 757, 100, 739, 98, 741, 71, 768, 59, 780, 65, 774, 50, 789, 49, 790, 26, 813, 17, 822, 13, 826, 6, 833
264–327	5, 834, 33, 806, 51, 788, 75, 764, 99, 740, 96, 743, 97, 742, 166, 673, 172, 667, 175, 664, 187, 652, 163, 676, 185, 654, 200, 639, 114, 725, 189, 650, 115, 724, 194, 645, 195, 644, 192, 647, 182, 657, 157, 682, 156, 683, 211, 628, 154, 685, 123, 716, 139, 700, 212, 627, 153, 686, 213, 626, 215, 624, 150, 689
328–383	225, 614, 224, 615, 221, 618, 220, 619, 127, 712, 147, 692, 124, 715, 193, 646, 205, 634, 206, 633, 116, 723, 160, 679, 186, 653, 167, 672, 79, 760, 85, 754, 77, 762, 92, 747, 58, 781, 62, 777, 69, 770, 54, 785, 36, 803, 32, 807, 25, 814, 18, 821, 11, 828, 4, 835
384–455	3, 836, 19, 820, 22, 817, 41, 798, 38, 801, 44, 795, 52, 787, 45, 794, 63, 776, 67, 772, 72 767, 76, 763, 94, 745, 102, 737, 90, 749, 109, 730, 165, 674, 111, 728, 209, 630, 204, 635, 117, 722, 188, 651, 159, 680, 198, 641, 113, 726, 183, 656, 180, 659, 177, 662, 196, 643, 155, 684, 214, 625, 126, 713, 131, 708, 219, 620, 222, 617, 226, 613
456–513	230, 609, 232, 607, 262, 577, 252, 587, 418, 421, 416, 423, 413, 426, 411, 428, 376, 463, 395, 444, 283, 556, 285, 554, 379, 460, 390, 449, 363, 476, 384, 455, 388, 451, 386, 453, 361, 478, 387, 452, 360, 479, 310, 529, 354, 485, 328, 511, 315, 524, 337, 502, 349, 490, 335, 504, 324, 515
514–561	323, 516, 320, 519, 334, 505, 359, 480, 295, 544, 385, 454, 292, 547, 291, 548, 381, 458, 399, 440, 380, 459, 397, 442, 369, 470, 377, 462, 410, 429, 407, 432, 281, 558, 414, 425, 247, 592, 277, 562, 271, 568, 272, 567, 264, 575, 259, 580
562–629	237, 602, 239, 600, 244, 595, 243, 596, 275, 564, 278, 561, 250, 589, 246, 593, 417, 422, 248, 591, 394, 445, 393, 446, 370, 469, 365, 474, 300, 539, 299, 540, 364, 475, 362, 477, 298, 541, 312, 527, 313, 526, 314, 525, 353, 486, 352, 487, 343, 496, 327, 512, 350, 489, 326, 513, 319, 520, 332, 507, 333, 506, 348, 491, 347, 492, 322, 517
630–659	330, 509, 338, 501, 341, 498, 340, 499, 342, 497, 301, 538, 366, 473, 401, 438, 371, 468, 408, 431, 375, 464, 249, 590, 269, 570, 238, 601, 234, 605
660–707	257, 582, 273, 566, 255, 584, 254, 585, 245, 594, 251, 588, 412, 427, 372, 467, 282, 557, 403, 436, 396, 443, 392, 447, 391, 448, 382, 457, 389, 450, 294, 545, 297, 542, 311, 528, 344, 495, 345, 494, 318, 521, 331, 508, 325, 514, 321, 518
708–729	346, 493, 339, 500, 351, 488, 306, 533, 289, 550, 400, 439, 378, 461, 374, 465, 415, 424, 270, 569, 241, 598
730–751	231, 608, 260, 579, 268, 571, 276, 563, 409, 430, 398, 441, 290, 549, 304, 535, 308, 531, 358, 481, 316, 523
752–765	293, 546, 288, 551, 284, 555, 368, 471, 253, 586, 256, 583, 263, 576
766–777	242, 597, 274, 565, 402, 437, 383, 456, 357, 482, 329, 510
778–789	317, 522, 307, 532, 286, 553, 287, 552, 266, 573, 261, 578
790–795	236, 603, 303, 536, 356, 483
796–803	355, 484, 405, 434, 404, 435, 406, 433
804–809	235, 604, 267, 572, 302, 537
810–815	309, 530, 265, 574, 233, 606
816–819	367, 472, 296, 543
820–837	336, 503, 305, 534, 373, 466, 280, 559, 279, 560, 419, 420, 240, 599, 258, 581, 229, 610

Table 18: Root Sequence Order for Random Access Preamble Formats 0-3

Logical root sequence number	Physical root sequence number u (in increasing order of the corresponding logical sequence number)																			
0 – 19	1	138	2	137	3	136	4	135	5	134	6	133	7	132	8	131	9	130	10	129
20 – 39	11	128	12	127	13	126	14	125	15	124	16	123	17	122	18	121	19	120	20	119
40 – 59	21	118	22	117	23	116	24	115	25	114	26	113	27	112	28	111	29	110	30	109
60 – 79	31	108	32	107	33	106	34	105	35	104	36	103	37	102	38	101	39	100	40	99
80 – 99	41	98	42	97	43	96	44	95	45	94	46	93	47	92	48	91	49	90	50	89
100 – 119	51	88	52	87	53	86	54	85	55	84	56	83	57	82	58	81	59	80	60	79
120 – 137	61	78	62	77	63	76	64	75	65	74	66	73	67	72	68	71	69	70	-	-
138 – 837	N/A																			

Table 19: Root Sequence Order for Random Access Preamble Format 4

The radio network planner also needs to establish the link budget for PRACH preamble coverage calculation. 3GPP TS 36.141specifies LTE BTS receiver SNR thresholds for 99% correct PRACH detection, for different channel conditions. These specifications from this 3GPP document (Table 8.4.1.5-1 within TS 36.141) are copied in the table below for reference.

Number of RX antennas	Propagation conditions (Annex B)	Frequency offset	SNR [dB]				
			Burst format 0	Burst format 1	Burst format 2	Burst format 3	Burst format 4
2	AWGN	0	-13.9	-13.9	-16.1	-16.2	-6.9
	ETU 70*	270 Hz	-7.4	-7.2	-9.4	-9.5	0.5
4	AWGN	0	-16.6	-16.4	-18.7	-18.5	-9.5
	ETU 70*	270 Hz	-11.5	-11.1	-13.5	-13.3	-4.5
Note*: Not applicable for Local Area BS and Home BS (as defined in 3GPP TS 36.141).							

Table 20: PRACH detection test requirements for Normal Mode

For PRACH format 4 (TDD only), ETU 70 channel conditions, 270 Hz frequency offset, TS 36.141 specifies SNR <= 0.5 dB with two receive antennas, and SNR <= -4.5 dB with four receive antennas. Simulations of Nokia receivers show 99% correct PRACH detection at -2.5 dB and -7 dB for these test conditions. So, the simulated Nokia receiver out-performs the requirements by 3 dB for the two-antenna case, and by 2.5 dB for the four-antenna case. Formats 0-3 are more robust than format 4. However, the short preamble, format 4 performs similarly to PUSCH 64 kbps in terms of coverage. PRACH format 4 does not introduce additional UL overhead, because it can be transmitted only in the UpPTS slot, where no PUSCH allocation is possible.

Also, as mentioned before, an alternate approach varies the prachConfIndex parameter for the cells belonging to the same site (so there is potential for PUSCH – PRACH interference between sectors), but simplifies the root sequence planning by allocating the same root sequence to each sector.

Assume a cell range of 12 km for the 3 cells of an eNodeB.

- **Select a preamble format that can support that cell range.**

Based on the cell range of 12 km and Table 10, Preamble Format 0 is most suitable.

- **Select prachCS**

From Table 15, one can see that a prachCS of 11 is enough to support cell ranges of 12 km. Lower indexes will not support that cell range and higher indexes require more root sequences (more processing power).

- **Select root sequences**

Also from Table 15, it can be seen that with a prachCS of 11 and a cell range of 12 km, 9 signatures per root sequence are available and therefore, 8 root sequences are needed to fulfill the requirement of 64 sequences. Based on this, an example for selecting these sequence numbers would be that for cell 1, select logical root sequence numbers 0-7; for cell2, select logical root sequence numbers 8-15; for cell 3, select logical root sequence numbers 16-23, and so on. From Table 18 one can see that the physical root sequence numbers for cell 1 would be: 129, 710, 140, 699, 120, 719, 210, and 629.

- **Determine prachFreqOff**

The prachFreqOff value depends on the PUCCH resources. Assuming that the PUCCH resources are 6 and that the PRACH area will be located at the lower border of the UL frequency band: prachFreqOff = roundup [PRACCH resources/2] = roundup [6/2] = 3

This value can be the same for all the cells in the network, unless it is not possible to assign different rootSeqIndex values for the different cells.

- **Select prachConfIndex based on cell range**

Based on Table 12 and

Table 13, for Preamble Format 0 and LTE configuration 1, it is possible to have prachConfIndex values ranged from 3 to 7. The same value should be selected for the cells of one site.

Additionally, to facilitate the planning, the prachConfIndex can be the same across the whole network (based on the assumption that the same preamble format is used for all cells in the network).

Assumptions:

LTE frame configuration	1
Cell Range (km)	12
PRACH resources	6

PRACH Planning Parameter Settings:

Preamble Format	0

	eNodeB "A"		
Parameter Name	**cell 1**	**cell 2**	**cell 3**
prachCS	11	11	11
rootSeqIndex	0	8	16
prachFreqOff	3	3	3
prachConfigIndex	3	3	3

6.6.2 Features and tools for planning

MUSA tool is used for the Root Sequence Index (RSI) Planning. There is also the option for automated planning/optimization of the PRACH using the EdenNet PRACH Optimization Module (based on features LTE581 PRACH Management and LTE962 RACH Optimization).

- PRACH Management (LTE581) – Provides automatic assignment of PRACH parameters (prachConfIndex, prachFreqOff, prachCS, rootSeqIndex) during the initial eNB auto-configuration process, using NetAct Optimizer (i.e. PRACH auto planning). Assignment is done for all cells of an eNB considering own cell data and configuration data from surrounding eNBs.

- Automatic Optimization of RACH parameter assignments (LTE962) – optimizes network performance during operation. This feature optimizes PRACH/RACH parameters, as in feature LTE581: prachConfIndex, prachFreqOff, prachCS, rootSeqIndex, but it also includes performance measurements. LTE962 can set PRACH format/PRACH position, and PRACH density. It can detect, visualize and remove PRACH/RACH inconsistencies and PRACH/RACH collisions based on configuration data of eNBs (e.g. Geolocation), and operator selectable scope.

6.7 PUCCH Capacity & Configuration Planning

Note: Additional documentation on PUCCH can be found in the LTE Optimization Guidelines and in the Capacity Solutions Guides (FDD and TDD).

The physical uplink control channel (PUCCH) is used for the transmission of signaling when no simultaneous UL data is being sent

The UE transmits the UCI (Uplink Control Information) over the PUSCH using different Formats. That is: Channel Quality Indicator (CQI), Rank Indication (RI), Precoding Matrix Indicator (PMI), Scheduling Requests (SR) and HARQ acknowledgements. The PUCCH resources are always allocated on the extreme ends of the bandwidth to maximize the number of contiguous PRBs that can be allocated for the PUSCH. Additionally, users will hop between the bandwidth edges (intra sub-frame hopping) in order to provide frequency diversity gain for PUCCH transmissions.

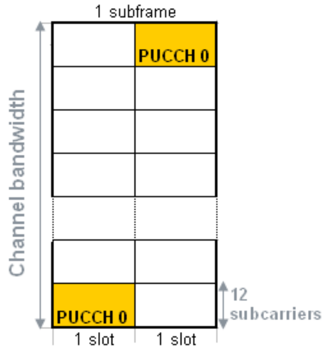


Figure 60: PUCCH hopping

The PUCCH region needs planning in order to get an appropriate balance between control and data traffic resources. It is important to correctly dimension the PUCCH area, not only to avoid unnecessary overheads that reduce the throughput (if more resources than needed are reserved) but also to avoid poor RRC Setup Success Rates (in case insufficient PUCCH resources are reserved to handle the maximum number of active users in the cell).

This section aims to provide a guideline and background on how to correctly dimension the PUCCH region. A tool to dimension the PUCCH has been developed within Nokia (FDD version and TDD version).

Important note: Features LTE1130 (replacement of LTE1808) and LTE2712 allow automatic PUCCH resource allocation adjustment on cell individual level based on real load ongoing in that cell. First feature is changing periodicity of scheduling requests and CQIs based on load whereas the second one handles PUCCH format 3 in dynamic manner to support higher number of UEs with 3 component carriers.

The physical uplink control channel supports multiple formats. Table 21 provides a list of these formats and the type of information that is carried with the different PUCCH formats. Formats 2a and 2b are supported for normal cyclic prefix only.

The outer part of the PUCCH region will be employed to transmit Format 2 type information. This is mainly CQI reports with or without HARQ acknowledgements. This region will be followed by another section in which it is possible to have a mix of Formats 1.x and 2.x. Formats 1 are employed for the transmission of SR's and Ack/Nacks.

Finally, the inner part of the PUCCH region allocates resources dedicated for Formats 1.

PUCCH Format		UCI information
Format 1		Scheduling Request (SR)
Format 1a		1-bit HARQ ACK/NACK with/without SR
Format 1b	FDD (1CC)	2-bit HARQ ACK/NACK with/without SR (This is for MIMO, 1 bit for each transport block)
	FDD (2CC)	4-bit HARQ ACK/NACK with channel selection
	TDD (1CC)	4-bit HARQ ACK/NACK
Format 2		CQI (20 coded bits)
Format 2		CQI and 1 or 2 bit HARQ ACK/NACK - 20 bits - Extended CP only
Format 2a		CQI and 1 bit HARQ ACK/NACK - (20 + 1 coded bits)
Format 2b		CQI and 2 bit HARQ ACK/NACK - (20 + 2 coded bits)
Format 3	FDD(up to 5CC)	up to 10 bit HARQ ACK
	TDD(up to 5CC)	up to 20 bit HARQ ACK
Format 3	FDD(up to 5CC)	11 bit corresponding to 10 bit HARQ ACK and 1 bit positive/negative SR
	TDD(up to 5CC)	21 bit corresponding to 20 bit HARQ ACK and 1 bit positive/negative SR

Table 21: Info carried in the different PUSCH Formats

These regions must be dimensioned keeping in mind the number of active users in the cell. Figure 61 depicts an example of a PUCCH for one frame along with PUCCH dimensioning example without format 3:

Figure 61: Sample PUCCH Region

The number of PRBs dedicated to Formats 2.x is defined by the parameter ***nCqiRb.***

Control information from multiple users can be scheduled on the same PUCCH timeslot by means of using Zadoff-Chu CAZAC codes which will preserve the orthogonality. Since a PUCCH RB spans over 12 sub carriers there will be 12 Cyclic shifts available per PUCCH RB.

From simulations it is not recommended to employ all 12 cyclic shifts since this leads to excessive interference and therefore degradation in performance.

Every UE with a DRB in the cell is required to send CQI reports periodically. For this purpose every UE will require a Format 2.x PUCCH resource assignment. The periodicity of the CQI reports is set by the parameter ***cqiPerNp***.

The total capacity provided exclusively for Format 2.x in a cell will be defined by:

nCqiRb * 12 * cqiPerNp

For the transmission of Formats 1.x a similar approach as for Format 2.x is employed. Cyclic Shifts for orthogonality between users are employed along with Code Division Multiplexing (CDM) increasing the number of users, multiplexed orthogonally on a single PRB. The CDM is limited by the number of reference symbols which are available for the time domain spreading. This leads to a SF=3 for normal cyclic prefix (CP) and a SF=2 for extended cyclic prefix.

The number of resources for PUCCH format 1.x per RB is defined by:

c * 12 / **deltaPucchShift**

Where:

- ***c:***: is the spreading factor (SF) or number of RS signals on PUCCH format 1.x which is 3 for normal CP and 2 for extended CP.
- ***deltaPucchShift*** : is a parameter which defines the maximum number of cyclic shifts allowed for Formats 1.x. Range : 1, 2 and 3

Considering normal cyclic prefix the maximum number of Formats 1.x which can be multiplexed per PRB is 36. Simulation results do not recommend the usage of all 12 cyclic shifts due to the high interference generated therefore it is recommended to set ***deltaPucchShift*** to 2, reducing the maximum number of Formats 1.x per PRB to 18 (according to above formula)

As shown in Table 21 Formats 1.x are employed for different purposes:

- HARQ acknowledgements for Dynamic Scheduling
- HARQ acknowledgements for Semi -Persistent Scheduling
- Repetition of HARQ acknowledgements
- Scheduling Requests

For each of these purposes the UE has to be granted a resource inside the Format 1.x region.

For Scheduling requests, Semi-persistent scheduling Ack/Nacks and Ack/Nack repetition a fixed number of resources is reserved per TTI. This is defined via the parameter n1pucchAn. The exact resource to be employed inside this reserved region for the above use cases is communicated to the UE via explicit signalling. For HARQ acknowledgements of dynamic scheduling, the resource to be used by the UE is a function of the first CCE used for the PDCCH scheduling.

This means that the resources for Formats 1.x can vary between the ranges specified below:

0< Format 1.x Resource range < **n1pucchAn** + Max CCE

The number of Format 1.x resources required has to be dimensioned considering the number RRC connected users per cell and the amount of users scheduled per TTI in the DL

Apart from having dedicated PRBs for Formats 1.x and Formats 2.x there is a possibility of having a mixed format region. In this region the resources per PRB are divided between the 2 Formats. For formats 1.x we can reserve up to 8 Cyclic Shifts per PRB via the parameter ***pucchNAnCs.*** The remaining cyclic shifts can be employed for Formats 2.x considering there are 2 Guard Cyclic shifts as shown in the diagram below:

	Cyclic Shifts	
RB xx	0	Format 1.x
	1	Format 1.x
	2	Format 1.x
	3	Format 1.x
	4	Format 1.x
	5	Format 1.x
	6	Guard
	7	Format 2.x
	8	Format 2.x
	9	Format 2.x
	10	Format 2.x
	11	Guard

Table 22: Mixed region resource allocation for pucchNAnCs =6

If the mixed format region is employed the total capacity for Formats 1.x and Formats 2.x can be calculated as per the equations below:

- Formats 1.x Capacity per PRB =

*{(n1pucchAn - pucchNAnCs * c / deltaPucchShift) * deltaPucchShift] / (c*12)} + roundup (pucchNAnCs / 8)*

- Formats 2.x Capacity per PRB =

*nCqiRb * 12 * cqiPerNp + (12-2- pucchNAnCs)*Roundup(pucchNAnCs /8)*

Summarizing, the maximum PUCCH capacity reserved in a cell for the normal cyclic prefix case (i.e. c=3) is defined by the PUCCH resources for Formats 1.x and Formats 2.x as:

MaxPucchResourceSize = nCqiRb + roundup {[((maxNumOfCce) + n1PucchAn - pucchNAnCs * 3 / deltaPucchShift) * deltaPucchShift] / (3*12)} + roundup (pucchNAnCs / 8)

Each UE will know the physical resource blocks to be used for transmission of PUCCH in slot n_s from the following equations obtained from 3GPP 36.211

$$n_{\mathrm{PRB}} = \begin{cases} \left\lfloor \frac{m}{2} \right\rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 0 \\ N_{\mathrm{RB}}^{\mathrm{UL}} - 1 - \left\lfloor \frac{m}{2} \right\rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 1 \end{cases}$$

Where the variable m depends on the PUCCH format:

- For formats 1, 1a and 1b:

$$m = \begin{cases} N_{\mathrm{RB}}^{(2)} & \text{if } n_{\mathrm{PUCCH}}^{(1)} < c \cdot N_{\mathrm{cs}}^{(1)} / \Delta_{\mathrm{shift}}^{\mathrm{PUCCH}} \\ \left\lfloor \frac{n_{\mathrm{PUCCH}}^{(1)} - c \cdot N_{\mathrm{cs}}^{(1)} / \Delta_{\mathrm{shift}}^{\mathrm{PUCCH}}}{c \cdot N_{\mathrm{sc}}^{\mathrm{RB}} / \Delta_{\mathrm{shift}}^{\mathrm{PUCCH}}} \right\rfloor + N_{\mathrm{RB}}^{(2)} + \left\lceil \frac{N_{\mathrm{cs}}^{(1)}}{8} \right\rceil & \text{otherwise} \end{cases}$$

Where:

$$c = \begin{cases} 3 & \text{normal cyclic prefix} \\ 2 & \text{extended cyclic prefix} \end{cases}$$

$N_{\mathrm{cs}}^{(1)}$: *Number of cyclic shifts reserved for Formats1.x in the mixed region*(pucchnanCS)

$n_{\mathrm{PUCCH}}^{(1)}$: *Cyclic Shift assigned to the UE for Formats1.x*

$\Delta_{\mathrm{shift}}^{\mathrm{PUCCH}}$: *Number of Cyclic Shifts used per RB*(deltapucchshift)

$N_{\mathrm{RB}}^{(2)}$: number of PUCCH resources reserved for formats 2x(nCqiRb)

- Whereas for formats 2, 2a and 2b:

m = round down (Cyclic Shift Assigned for Formats 2.x / 12)

- PUCCH Dimensioning Example

Formats 2.x have to be dimensioned considering the max number of active DRBs that there will be active in a cell. This is defined by the parameters ***maxNumActUE, addAUeRrHo and addAUeTcHo.*** The condition is: maxNumActUE + max (addAUeRrHo, addAUeTcHo) <= maxNumActUE. For the purpose of this example, let's consider maxNumActUE + max (addAUeRrHo, addAUeTcHo) <= 100 for a 10 MHz BW. Note that although recommended values can change in other releases the procedure is the same.

Considering ***cqiPerNp*** =10ms 1 RB for Formats 2.x would be able to handle up to 120 UEs with 12 CS. However, the recommendation is not to use more than 6 Cyclic Shifts (i.e. 60 users in this case). More than a recommendation, the limit of 6 Cyclic Shifts is a practical limitation as the algorithm wouldn't assign more than 6 Cyclic Shifts. This means if we set ***nCqiRb*** =1 we would not have enough capacity. The solution is to increase nCqiRb =2. In case the interference was still high in Format 2.x, it should be possible to continue increasing **nCqiRb** so number of users per slot is reduced further. The algorithm to assign slots for Formats2.x always assigns the slot with lower load first as a way of controlling the interference when there is low number of users per slot.

Initial LTE releases do not support Semi – Persistent scheduling or Ack/Nack repetition which means the number of resources reserved by the parameter ***n1pucchAn*** will be only used for scheduling requests.

Every user in RRC connected mode requires to be assigned a Format1.x resource for scheduling resource requests. The max number of RRC connected users per cell is specified by the parameter ***maxNumRrc***. Let's consider for this example that the maximum value is 100 for the case of 10 MHz bandwidth.

In order to accommodate 100 resources for SR, considering a 10ms SR periodicity (***cellSrPeriod*** =10ms), there would need to be 10 resources reserved per TTI, i.e. ***n1pucchAn*** =10

Dimensioning of the number of Format 1.x resources required for acknowledgements from dynamic scheduling is dependent on the max number of CCEs which are available for the PDCCH scheduling. For this example we will consider a 10 MHz bandwidth with 1 PDCCH symbol per Subframe. This leads to a maximum of 10 CCEs available (see Table 21).

The maximum number of acknowledgements that will be received per TTI depends on the number of UEs which can be scheduled per TTI. This is set by the parameter ***maxNumUeDl***. The maximum value of this parameter depends on the bandwidth and for 10 MHz is 10 UEs.

Considering normal cyclic prefix, maxNumUeDl =10 and deltaPucchShift =2

Max Resources for Format 1.x per PRB = c * 12 / ***deltaPucchShift*** = 18

0< Format 1.x Resource range < ***n1pucchAn*** + Max CCE = 10+10 =20

Number of PRB required for Formats 1.x = Roundup (20/18) = 2

With 2 PRBs for Formats 1.x, we would have in total 36 resources per TTI out of which the first 10 are always reserved for Scheduling Requests according to the parameter ***n1pucchAn*** and the remaining 26 will be employed for acknowledgments of Dynamic Ack/Nack scheduling depending on the position of the first CCE used in the PDCCH scheduling.

As it can be seen with the current configuration chosen a total of 10 CCEs are available, which means in theory we could schedule up to 10 users in the DL per TTI with aggregation level 1. In reality PDCCH will schedule users in UL and DL and with different aggregation levels so with the current configuration it would be difficult to reach the maximum number of simultaneous users per TTI specified by parameter (***maxNumUeDl*** =10). Even if this number would be achieved, the capacity reserved for dynamic Ack/Nacks supports up to 26 users so there would be no problem.

In the above configuration the mixed format region was not employed since no further capacity was required for Formats 2.x, therefore ***pucchNaCs*** =0.

The total PUCCH region for the above given example would be 4 PRBs: 2PRB for Formats 2.x and 2 PRB for Formats 1.x. This information can be used to correctly set the ***prachFreqOff*** which defines the starting PRB for the PRACH. This parameter ranges from 0 to the max UL BW - 6.

In this case it is recommended to set ***prachFreqOff*** to 2, to avoid the overlapping of PUCCH and PRACH regions.

With above given configuration:

- **For formats 2.x:**

m = round down (Cyclic Shift Assigned for Formats 2.x / 12) =2

Since ***nCqiRb***=2, the assigned Cyclic shift format by the eNodeB will always be in the range 0 to 23, which means for that **for formats 2.x m=0 and m=1**

- **For formats 1.x:**

$$m = \begin{cases} 1 & \text{if } n_{\text{PUCCH}}^{(1)} < 18 \\ \left\lfloor \frac{n_{\text{PUCCH}}^{(1)}}{18} \right\rfloor + 1 & \text{otherwise} \end{cases}$$

$$n_{\text{PUCCH}}^{(1)} : \textit{Cyclic Shift assigned to the UE for Formats } 1.x$$

Knowing that the Format 1.x range is delimited to a maximum value of 20, this means that **Formats 1.x will use m=2 and m=3**

The plot below shows the frame structure and the PRB hopping for the different formats 1.x and 2.x for the example configuration (***prachConfIndex***=4).

Note that parameter ***actFlexBbUsage*** can limit the size of PUCCH PRB on 10MHz system bandwidths or lower if set to 'true' (default: false). The parameter only needs to be set to 'true' to configure more than 2 cells with FSMD or more than 3 cells with FSME. This parameter also influences the range of parameters ***maxNumActUE*** and ***maxNumRrc*** necessary to calculate the max number of PUCCH resources.

6.8 PDCCH Capacity & Configuration Planning

In early releases, it was necessary to plan the PDCCH to get appropriate capacity balance between control and data traffic resources but the introduction of feature LTE616 allowed for automated setting of DL capacity based on Usage based Load adaptation.

The feature, Usage based load Adaptation of the PDCCH (LTE 616), has adapted the number of OFDM symbols for PDCCH based on the CCE (control channel elements) load. Additionally, as a second part of the feature, the balance between the DL and the UL PDCCH space may be adapted depending on the current load split. The PDCCH usage will vary depending on the number of users in the cell, radio conditions of the users and amount of UL/DL traffic they generate. The information about number of symbols to be used is broadcasted every TTI via PCFICH. The benefit is that subscribers may experience better downlink throughput in scenarios with low PDCCH but high PDSCH usage.

The functionality of this feature has been verified during single UE cluster drives in which the UE performed simultaneous UL and DL UDP sessions. Figure 62 shows the number of PDCCH symbols used in the different cells vs. the DL SINR conditions measured by the UE. As expected, under good radio conditions, low aggregation levels are employed for UL and DL. As radio conditions worsen the aggregation levels will tend to increase and so will the average number of required PDCCH symbols. In extremely low DL SINR the average PDDCH symbols is just beneath 2, since drives were performed with a single user and 10MHz Bandwidth configurations for all the cells.

The usage of this feature leads to efficient use of Control channel resources (minimizing overhead in low load conditions) and, as previously mentioned, users will experience better downlink throughput in scenarios with low PDCCH but high PDSCH usage. When there are a high number of users, this feature will allow for more users per TTI to exploit gains from the scheduler allocating every UE to part of the band where it best performs

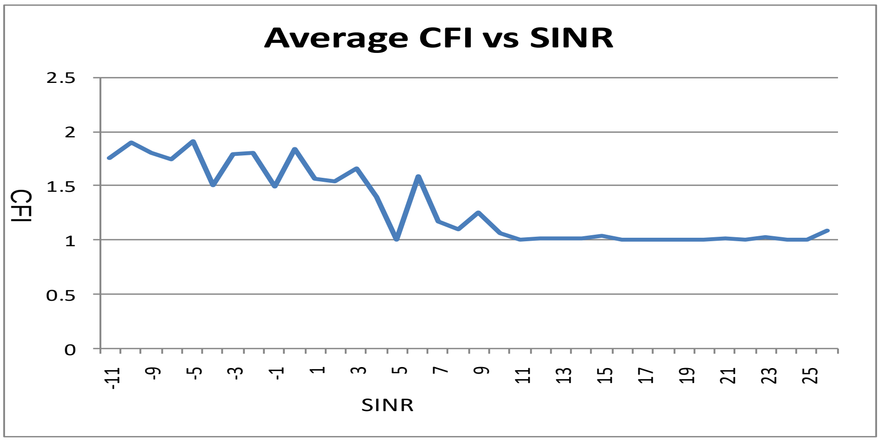


Figure 62: Number of PDCCH Symbols vs. DL SINR (CFI: Control Format Indicator)

Since the UL and DL PDCCH load during the test was approximately constant and equal the additional part of the feature of shifting the split between DL and UL CCE's was not evaluated.

Outer Loop Link Adaptation for PDCCH

Feature (LTE1035) allows for a separate correction to the CQI employed in the PDCCH scheduling in order to employ the PDCCH resources efficiently and target a 1% BLER for this channel.

In order to verify the functionality of this feature drive test data from a cluster drive was employed.

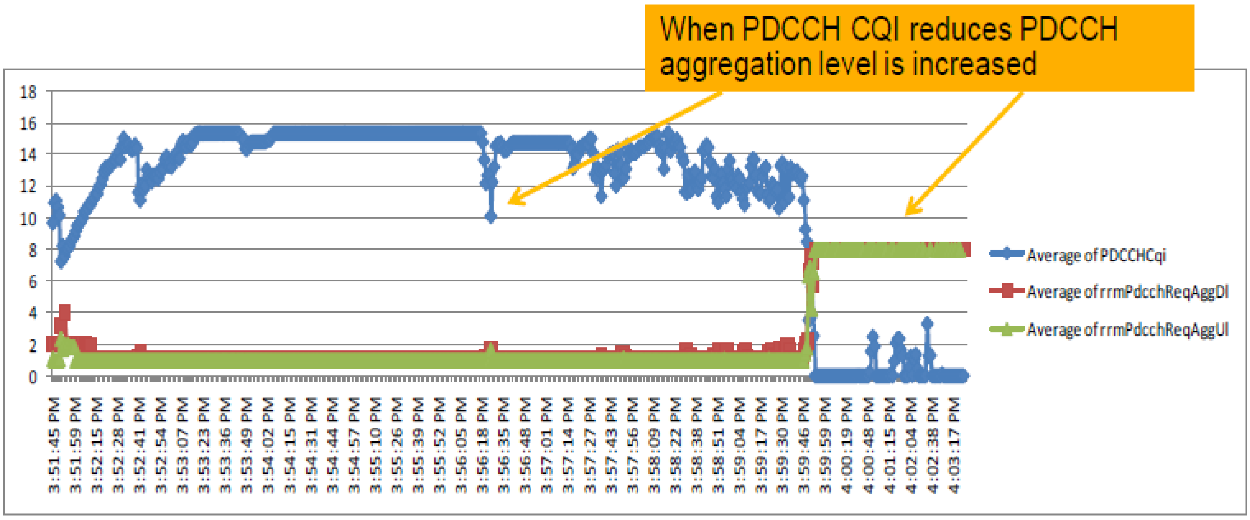


Figure 63: PDCCH CQI and UL & DL PDDCH aggregation levels vs. Time

Figure 63 shows average PDCCH CQI variation along the drive. As shown, the PDCCH CQI decreases, PDCCH LA and PC increase the aggregation level for the UL and DL allocations.

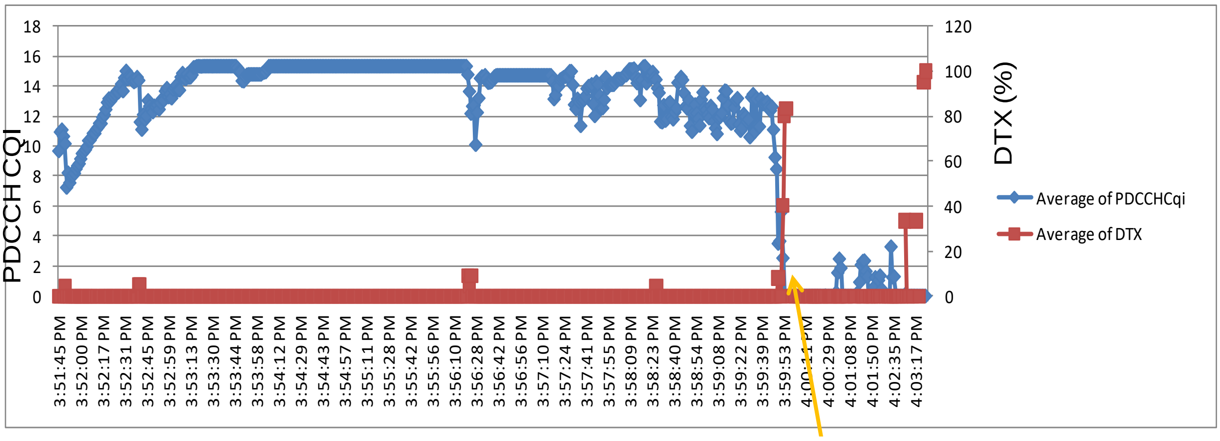


Figure 64: PDCCH CQI and CW1 DTX vs. Time

The purpose of the feature is to obtain a 1% BLER for the PDCCH channel. In order to evaluate the feature, the discontinuous transmission (DTX) for codeword1 was measured at the eNodeB (Figure 64). In case of MIMO, at least Codeword1 (CW1) should be sent every time the UE is granted a turn. The reason to control the DTX is as follows:

The eNodeB sends the PDCCH and DL data (on PDSCH) and then waits for ACK/NACK on the UL. If nothing is detected on the UL (DTX) it can be either due to an UL power issue or to the fact that the UE didn't get the DL data in the first place (i.e. not decoding PDCCH). With throughput tests it is possible to detect if there are UL issues. In the test, there were no UL power issues, so whenever the UE did not send ACK/NACK it meant it couldn't decode the PDCCH.

The PDCCH outer loop algorithm is based on the UL HARQ feedback. As it can be observed in Figure 65 the average PDCCH BLER target was maintained for most of the drive. Some samples of high DTX can be observed during the drive as radio conditions deteriorate. These cause the PDDCH CQI to be significantly reduced leading to aggregation levels of 8 for the UL and the DL. Once the PDCCH CQI is reduced to 0, there is no further correction that can be done, even though the DTX for CW1 is high. This is caused by extremely bad radio conditions of approximately -12 dB DL SINR.

Figure 65 compares the eNB internal metrics for the PDCCH CQI and the PDSCH CQI. The PDCCH CQI is now independent of the PDSCH BLER and will not lead to changes in the PDSCH CQI and as a consequence in the DL MCS.

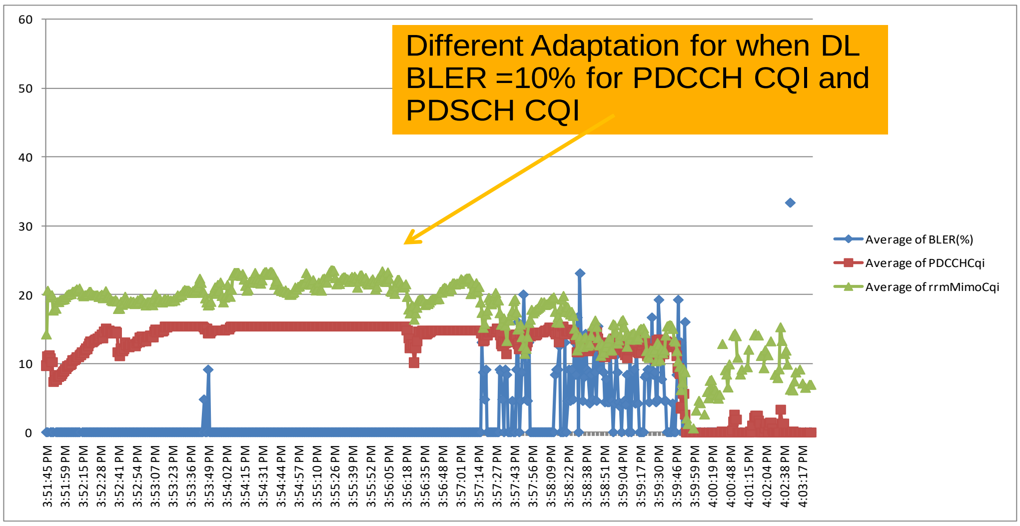


Figure 65: PDCCH CQ vs. PDSCH CQI and PDSCH BLER

6.9 UL DM RS Planning Principles

The UL RS are mostly based on Zadoff- Chu (ZC) Sequences. The sequences used for UL RS are commonly denoted as Extended Zadoff Chu codes and are not of constant amplitude. The **Reference signal sequence** $r_{u,v}^{(\alpha)}(n)$ is **defined by a cyclic shift** α **of a base sequence** $\bar{r}_{u,v}(n)$ according to

$$r_{u,v}^{(\alpha)}(n) = e^{j\alpha n}\bar{r}_{u,v}(n), \quad 0 \le n < M_{\text{sc}}^{\text{RS}}$$

Where $M_{\text{sc}}^{\text{RS}} = mN_{\text{sc}}^{\text{RB}}$ is the length of the reference signal sequence and $1 \le m \le N_{\text{RB}}^{\text{max,UL}}$. Multiple reference signal sequences are defined from a single base sequence through different values of α.

DM RS are employed for PUCCH and PUSCH transmissions. When it comes to PUSCH transmissions the DM RS will span over a number of Resource blocks depending on the allocation provided by the UL scheduler that is why sequences of different lengths are required. **The RS sequences of different length are obtained via cyclic shifts of a base.**

These base sequences $\bar{r}_{u,v}(n)$ are divided into groups of 30 sequences where $u \in \{0,1,\ldots,29\}$ is the group number and v the base sequence within the group. Each group contains sequences for all the possible UL RB allocations (sequence lengths) as shown in Figure 66.

For RB allocations (sequence lengths) of 5 or less there will only be one 1 RS base sequence per group whereas there will be 2 per group for RB allocations of more than 5. The availability of 2 RS base sequences per group for allocation sizes of more than 5 PRBs introduces the possibility of intra sub-frame hopping between sequences of the same group to randomize interference. This can be enabled or disabled via the parameter ***ulSeqHop***. If enabled, it will only apply to allocations of 6 or more PRBs.

Summarizing, the Demodulation Reference Signal is characterised by:

Sequence Group ‘u’:

- Cell specific parameter
- 30 groups each one containing sequences of different lengths (generated as cyclic shifts of one base sequence)
- RL60 brought possibility to use group hopping feature as defined at 3GPP 36.211, i.e. that the sequence group is picked per each slot as per pseudorandom sequence.

Sequence:

- 2 base sequences per group in case of PRB allocations >5 or 1 base sequence per group otherwise

Sequence Length:

- It will be the same as the PRB allocated to the UE i.e. equal to the number of subcarriers used for PUSCH transmission

Cyclic Shift:

- Terminal and cell specific parameter used to generate the sequences of different length.
- The Cyclic shifts generated from the same sequence are not completely orthogonal but have low cross correlation

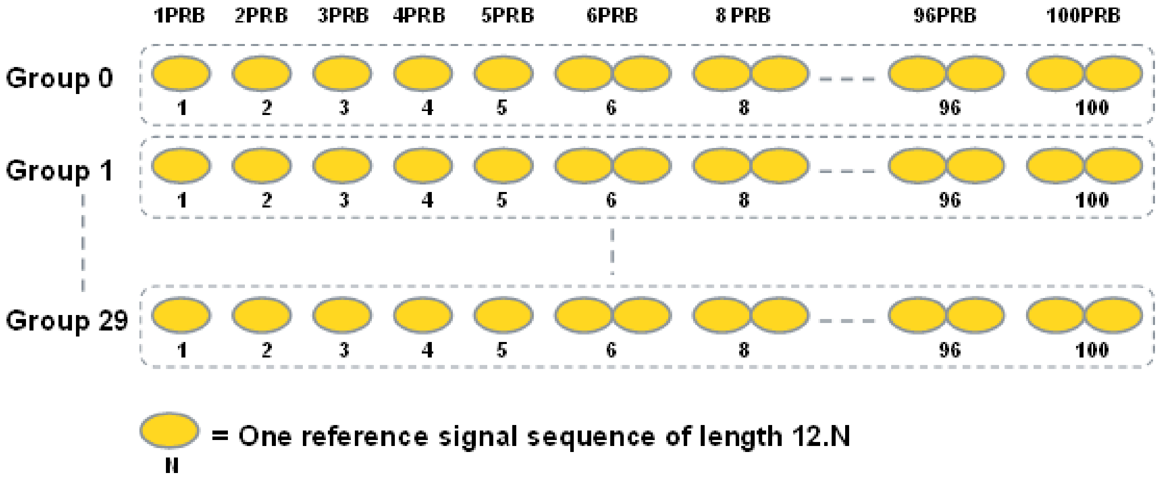


Figure 66: Sequence Groups (u= 0…29) each one containing different reference signal sequences

6.9.1 Need for Planning/Optimizing

In time domain the DM RS occupies always the same slot (i.e. slot 4 in case of normal Cyclic Prefix). In frequency domain the DM RS of a given UE occupies the same PRBs as its PUSCH/PUCH data transmission. Within a certain cell, UL users are separated via FDM (Frequency Division Multiplexing) so there is not DM RS intra cell interference but the DM RS will suffer from interference from neighboring cells. Multi user MIMO is introducing additional complexity, since the eNodeB will have to estimate the channel of different UL users in the same cell from their RS which will no longer be FDM and will span along a different number of RBs.

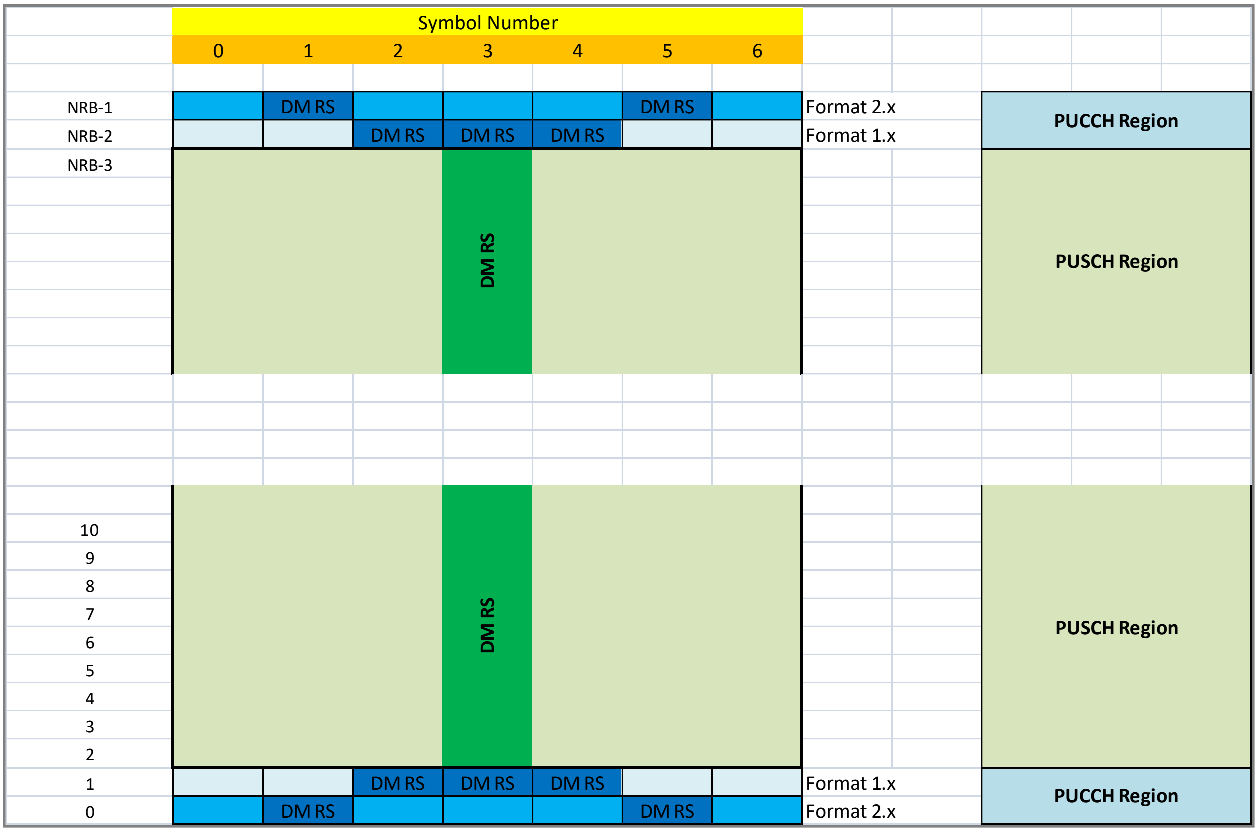


Figure 67: UL DM RS allocation per slot for Normal Cyclic Prefix

In order to randomize the interference and improve the UL channel estimation based on the RS there are 3 hopping techniques which can be implemented:

- UL Sequence Group Hopping
- UL Sequence Hopping
- UL Cyclic Shift Hopping

- ## UL Sequence Group Hopping (LTE801)

With this scheme the UL group sequence used for the DM RS changes from slot to slot based on a hopping pattern which additionally has an offset included based on the cells physical cell ID and a parameter.

Group hopping can be activated with the parameter ***UlGrpHop***. This feature should be activated - set to *true*. As indicated on the previous paragraph the feature adds randomization into the instant group number used from slot to slot, which effectively **means there is no need for specific UL Demodulation sequences planning.**

The sequence-group number u in slot n_s is defined by a group hopping pattern $f_{gh}(n_s)$ and a sequence-shift pattern f_{ss} according to:

$$u = \left(f_{gh}(n_s) + f_{ss}\right) \bmod 30$$

There are 17 different hopping patterns $f_{gh}(n_s)$ defined based on the 504 Physical cell IDs (PCI) and the 30 sequence groups (Round down (504/30) =17). Each of these hopping patterns will have a length of 20 since hopping is performed per slot and there are 20 per frame. Additionally, each of these hopping patterns can be offset by one of the 30 sequence group shift offsets which will be defined via the parameter ***grpAssigPUSCH*** (see formula below)

Note that the PUCCH and PUSCH will employ the same hopping pattern but different sequence shift patterns can be assigned for each one of them based on grpAssigPUSCH parameter (see formula below). If ***grpAssigPUSCH***=0 then PUSCH and PUCCH use the same sequence.

For PUSCH, the sequence-shift pattern f_{ss}^{PUSCH} is given by:

$$f_{ss}^{PUSCH} = \left(f_{ss}^{PUCCH} + \text{grpAssigPUSCH}\right) \bmod 30$$

For PUCCH, the sequence-shift pattern f_{ss}^{PUCCH} is given by:

$$f_{ss}^{PUCCH} = PCI \bmod 30$$

The group number u is given by:

$$u = \left(f_{gh}(n_s) + f_{ss}\right) \bmod 30$$

The group-hopping pattern $f_{gh}(n_s)$ is the same for PUSCH and PUCCH and given by:

$$f_{gh}(n_s) = \begin{cases} 0 & \text{if group hopping is disabled} \\ \left(\sum_{i=0}^{7} c(8n_s + i) \cdot 2^i\right) \bmod 30 & \text{if group hopping is enabled} \end{cases}$$

Where the pseudo-random sequence is: $c(i)$. The pseudo-random sequence generator shall be initialized with $c_{init} = \left\lfloor \frac{PCI}{30} \right\rfloor$ at the beginning of each radio frame.

Note that if group hopping is disabled as it was the case up to RL50 $f_{gh}(n_s)$ = 0, in this case the sequence-group number u in slot n_s is defined by the sequence-shift pattern f_{ss} according to:

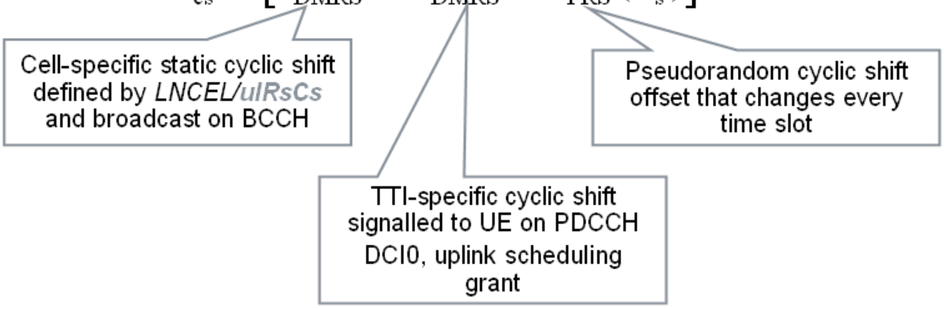
$$u = \left(f_{ss}\right) \bmod 30 = \left((PCI \bmod 30) + \text{grpAssigPUSCH}\right) \bmod 30$$

- UL Cyclic Shift Hopping

UL cyclic shift hopping is always enabled. Cyclic shift hopping is intra sub-frame hopping and helps randomize the interference on PUSCH and PUCCH.

The cyclic shift α in a slot n_s is given as α = 2p n_{cs} /12 with

$$n_{cs} = \left[n_{\mathrm{DMRS}}^{(1)} + n_{\mathrm{DMRS}}^{(2)} + n_{\mathrm{PRS}}(n_s) \right] \bmod 12$$



For PUSCH transmissions, a cell specific cyclic shift $n_{\mathrm{DMRS}}^{(1)}$ communicated to the UE via SIB 2 (3 bits) and defined via ***UlRsCs*** which has a range from 0 to 7 is added on top of the UE specific cyclic shift $n_{\mathrm{DMRS}}^{(2)}$ communicated to the UE during each of its UL grants (3 bits) and on top of a $n_{\mathrm{PRS}}(n_s)$ a slot specific pseudorandom cyclic shift that depends on the PCI, slot number ns and the sequence group 'u' via the ***grpAssigPUSCH*** parameter:

$$n_{\mathrm{PRS}}(n_s) = \sum_{i=0}^{7} c(8N_{\mathrm{symb}}^{\mathrm{UL}} \cdot n_s + i) \cdot 2^i \qquad \text{Where} \quad c_{\mathrm{init}} = \left\lfloor \frac{N_{\mathrm{ID}}^{\mathrm{cell}}}{30} \right\rfloor \cdot 32 + u$$

For PUCCH, one of the 12 CS available is employed by the UE based on the PUCCH resource index the UE was signaled. In order to achieve intra cell interference randomization, the CS used in the second slot is hopped such that UEs which are assigned adjacent cyclic time shifts in the first slot are assigned non-adjacent cyclic time shifts in the second slot.

6.9.2 Sequence Group Planning Recommendation

The principle when planning the UL DM RS (UL Demodulation Reference Signal) is that: UL DM RS needs to be different for the cells of a same eNodeB. It is recommended to enable group hopping feature (LTE801) to relax the planning requirements to ordinary PCI planning.

If the group hopping feature is disabled from whatever reason then there is need for specific UL sequence group planning.

7 LTE UE Categories

LTE system needs to meet the performance requirements indicated in previous sections and LTE terminals (UEs) need to contribute to it. However, since the market for UEs is large and diverse, LTE supports multiple categories of UEs with different capabilities to satisfy various markets with different priorities such as peak data rates, cost and battery life. As an example, some terminals may support high data rates which require bigger amounts of memory for data processing and that translates into higher costs.

LTE system (per 3GPP TS36.306 release 14 – see Figure 68) defines 12 categories of terminals ranging from ‘low-cost’ terminals with similar capabilities to UMTS HSPA up to a very high capability terminals that exceed the peak data rate targets. Some of those terminals defined are not commercially available, as it depends upon chipset makers.

UE Category	Peak rate in Mbps DL/UL	Maximum number of DL-SCH transport block bits received within a TTI (Note 1)	Maximum number of bits of a DL-SCH transport block received within a TTI	Total number of soft channel bits	Maximum number of supported layers for spatial multiplexing in DL	Maximum number of UL-SCH transport block bits transmitted within a TTI	number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM in UL	Total layer 2 buffer size [bytes]
Category 1	10 / 5'	10296	10296	250368	1	5160	5160	No	150 000
Category 2	50 / 25	51024	51024	1237248	2	25456	25456	No	700 000
Category 3	100 / 50	102048	75376	1237248	2	51024	51024	No	1 400 000
Category 4	150 / 50	150752	75376	1827072	2	51024	51024	No	1 900 000
Category 5	300 / 75	299552	149776	3667200	4	75376	75376	Yes	3 500 000
Category 6	300 / 50	301504	149776 (4 layers, 64QAM)	3654144	2 or 4	51024	51024	No	3 300 000
			75376 (2 layers, 64QAM)						
Category 7	300 / 100	301504	149776 (4 layers, 64QAM)	3654144	2 or 4	102048	51024	No	3 800 000
			75376 (2 layers, 64QAM)						
Category 8	3000 / 1500	2998560	299856	35982720	8	1497760	149776	Yes	42 200 000
Category 9	450 / 50	452256	149776 (4 layers, 64QAM)	5481216	2 or 4	51024	51024	No	4 800 000
			75376 (2 layers, 64QAM)						
Category 10	450 / 100	452256	149776 (4 layers, 64QAM)	5481216	2 or 4	102048	51024	No	5 200 000
			75376 (2 layers, 64QAM)						
Category 11	600 / 50	603008	149776 (4 layers, 64QAM)	7308288	2 or 4	51024	51024	No	6 200 000
			195816 (4 layers, 256QAM)						
			75376 (2 layers, 64QAM)						
			97896 (2 layers, 256QAM)						
Category 12	600 / 100	603008	149776 (4 layers, 64QAM)	7308288	2 or 4	102048	51024	No	6 700 000
			195816 (4 layers, 256QAM)						
			75376 (2 layers, 64QAM)						
			97896 (2 layers, 256QAM)						
NOTE 1:In carrier aggregation operation, the DL-SCH processing capability can be shared by the UE with that of MCH received from a serving cell. If the total eNB scheduling for DL-SCH and									

Figure 68: LTE UE categories as per the Release 14

8 VoLTE

VoLTE stands for Voice over LTE. Nokia supports different solutions to handle voice calls in LTE. From the earlier CS Fall Back (CSFB) solutions where no VoIP support is available to the support of full VoIP calls (IMS based) within the LTE network and towards 2G/3G networks. In this case, mobility is handled by Single Radio Voice Call Continuity (SRVCC) solutions. More information on VoLTE can be found in its dedicated wiki page.

VoLTE is implemented on the radio side using set of features. Out of them, TTI bundling is probably the most characteristic.

8.1.1 TTI bundling

TTI bundling mechanism is introduced to enhance uplink VoIP performance in LTE.

TTI bundling (LTE907) allows repeating the same data in multiple TTIs, which effectively increases the TTI length allowing the UE to transmit for a longer time. A single transport block is coded and transmitted in a set of consecutive TTIs. The same hybrid ARQ process number is used in each of the bundled TTIs. The bundled TTIs are treated as a single resource where only a single grant and a single acknowledgement are required. The TTI bundling can be activated with higher layer signaling per UE. The trigger could be, for example, a UE reporting that its transmit power is getting close to the maximum value.

The TTI Bundling feature improves the uplink coverage by transmission of the same transport block in 4 consecutive UL subframes (also known as bundle size). This leads to increased energy per transmitted bit, which improves the UL link budget. Only one UL grant is given for the whole bundle, which leads to reduced PDCCH load.

According to Nokia Link Level simulation results, 4 HARQ transmissions of 4xTTI bundle gives the energy from 16 TTIs, which leads to the gain = 10xlog10(16/4)=3.59dB.

9 LTE Advanced

LTE Advanced was introduced in 3GPP Release 10 and it is also known as Advanced E-UTRA (LTE-A). It operates in spectrum allocations of different sizes including wider spectrum allocations than those having been associated already with release 8 E-UTRA, e.g. up to 100 MHz The focus is upon contiguous blocks of spectrum but the aggregation of smaller non-contiguous blocks is considered as well.

Carrier Aggregation is the main feature for LTE-A.

Table 23 presents the main technical objectives for LTE Advanced. These have been extracted from 3GPP Technical Report 36.913.

	Uplink	Downlink
Target Peak Data Rate	500+ Mbps	1+ Gbps
Idle Mode to Connected Mode Transition Time	< 50 ms	
User Plane Latency	Reduced relative to LTE Release 8	Reduced relative to LTE Release 8
Peak Spectrum Efficiency (based upon throughput of single connection)	15 bps/Hz Assuming antenna configuration is 4x4 or less	30 bps/Hz Assuming antenna configuration is 8x8 or less
Average Spectrum Efficiency (based upon aggregate throughput of all connections)	2.0 bps/Hz/cell for 2x4 antenna 1.2 bps/Hz/cell for 1x2 antenna	3.7 bps/Hz/cell for 4x4 antenna 2.6 bps/Hz/cell for 4x2 antenna 2.4 bps/Hz/cell for 2x2 antenna
Cell Edge User Throughput (based upon 10 users uniform-randomly dropped in the cell)	0.07 bps/Hz/cell/user for 2x4 antenna 0.04 bps/Hz/cell/user for 1x2 antenna	0.12 bps/Hz/cell/user for 4x4 antenna 0.09 bps/Hz/cell/user for 4x2 antenna 0.07 bps/Hz/cell/user for 2x2 antenna
Mobility	Mobile speeds of up to 350 km/hr should be supported, with potential support for up to 500 km/hr	

Table 23: Main technical requirements for LTE Advanced (3GPP TR 36.913)

9.1 Carrier Aggregation

Primary aim of the feature is to boost mean and peak user throughput via sending the user data simultaneously over two or more carriers. Carrier Aggregation concept can be seen from the Figure 69. Nokia supports several component carriers in DL and up to two component carriers in UL.

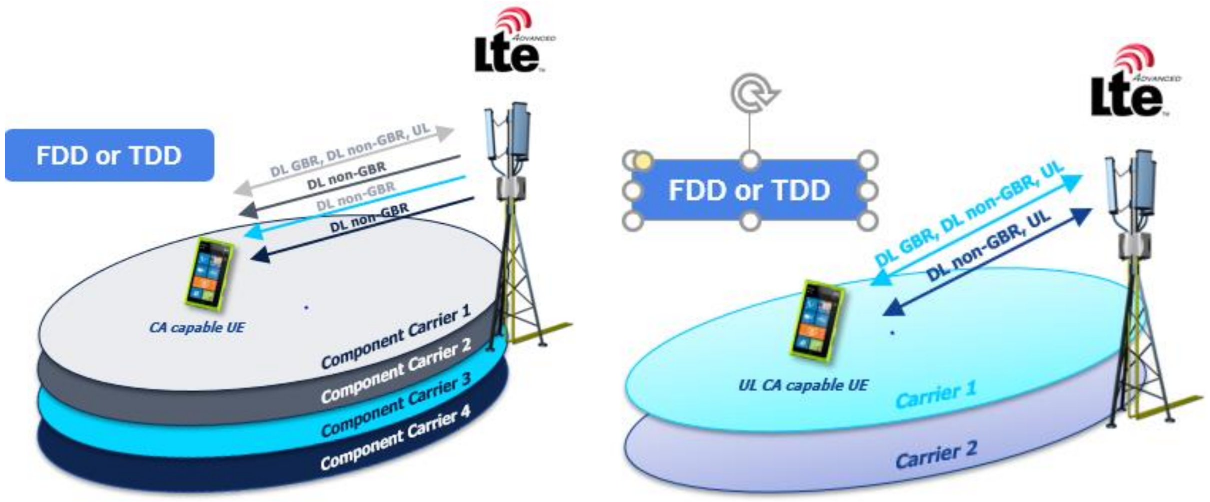


Figure 69: LTE carrier aggregation concept

Carrier aggregation can combine up to 5 20MHz carriers on DL and 2 20MHz carriers in DL. One carrier out of those combined serve as primary one to carry control information for all instantly combined carriers. Primary carrier can carry GBR and nonGBR bearers, while the secondary carrier(s) are for non GBR traffic only. Note that the assignment of primary and secondary carriers is specific for each UE, i.e. other UE might use carriers in opposite order.

Carrier aggregation should be understood as a scheduling feature. The feature allows effective use of fragmented spectrum as well. Carrier aggregation is supported by CA capable UE and combination of carriers (along with bandwidths) defined by 3GPP (TS 36.101).

CA might use frequencies from unlicensed bands as secondary ones to boost user plane throughput but the control channels and signaling are only carried on the licensed frequencies.

Note: more information about the Carrier Aggregation topic and the Nokia features available can be found in the Carrier Aggregation Wiki page.

10 Comparison between UMTS and LTE

The scope for LTE, as defined in the 3GPP standard, was to become a high-data rate, low-latency and packet-optimized radio access technology. This implied certain changes when compared with previous UMTS:

- New air interface transmission techniques (OFDMA and SC-FDMA):

The OFDM techniques split the available spectrum into hundreds and even thousands of orthogonal narrowband carriers. The high spectral efficiency of OFDM is increased further in LTE thanks to the possibility of using higher order modulation schemes such as 64QAM or 256QAM, sophisticated FEC (Forward Error Correction) schemes such as convolutional coding and turbo coding and additional ratio techniques like MIMO. Another effect of the LTE solution is no own cell interference compare to WCDMA based solutions with famous non-orthogonality effects.

The fact that LTE has **higher spectral efficiency** allows operators to increase the number of customers with less cost of delivery per bit.

The radio performance improves significantly with respect to UMTS allowing for **higher data rates**. The (theoretical) peak data rates are 300 and 75 Mbps (20 MHz bandwidth) in downlink and uplink respectively.

HSPA is evolving by also using 64QAM and MIMO since 3GPP Release 7 (RU20: HSPA +). However, the improvements in overall performance for LTE are higher due to the use of OFDM instead of WCDMA and through more complex MIMO antenna configurations. The nature of OFDM makes it **simpler to implement MIMO techniques** than with WCDMA.

- Frequency Domain Scheduling:

In UMTS where a single wideband carrier is transmitted it is not possible to assign resources only to certain frequency parts. Therefore, every fading gap within the channel will affect the data. In LTE, thanks to the nature of OFDMA, it is possible to avoid allocating resources to those parts of the channel where the conditions are bad (fading). Within LTE, in addition to the time domain scheduling it is possible to schedule resources in the frequency domain which translates into capacity gains of up to 40%. Note that in HSPA only time domain scheduling is possible.

- Bandwidth and frequency flexibility:

OFDM makes it simpler to provide different channel bandwidths (ranging from 1.4 MHz to 20 MHz) versus the 5 MHz bandwidth in WCDMA based system. Higher bandwidths allow for higher cell throughputs and facilitate the spectrum re-farming so migration is easy. For the operators, LTE presents the possibility of more efficient use of the subcarriers.

- Same multiple access techniques for FDD and TDD in LTE:

As part of the requirements, LTE can be deployed in paired or unpaired spectrum. Therefore, it supports FDD and TDD deployments. The same requirements were part of the 3GPP specifications for UMTS but in that case, it was done by using two different radio technologies: WCDMA/HSPA for FDD and TD-CDMA/TD-

SCDMA for TDD. Consequently, terminals capable of both FDD and TDD operations in UMTS are uncommon.

In case of LTE, both operations use the same radio access technology (OFDMA in downlink and SC-FDMA in uplink) and because of it, there is a considerable harmonization between FDD-LTE and TDD-LTE.

- Flat and packet based architecture:

The Evolved Packet Core (EPC) is based on TCP/IP protocols like most of fixed data networks and provides 'DSL-like' services including voice, video, rich media and messaging. The evolution to the packet based architecture allows for better interworking with other fixed and wireless networks. The flat architecture concept was explained in Section 3.

- No soft / softer HO:

In case of LTE there is no need or requirement for soft HO (or macro diversity). Soft handover is applied to dedicated channels but not in shared channels (like HSDPA). Additionally, it was defined as an RNC feature in UMTS. In LTE there is no RNC, no need for Iur and no need for additional Iub capacity for multiple transmissions. These are significant changes regarding the network definition and operation.

Mobility in LTE is handled via the S1 and the X2 interfaces. Handover via X2 interface is triggered by default unless there is no X2 interface established or the eNodeB is configured to use the S1-handover.

- No need for neighbor planning:

If the quality of the serving cell is below a configured threshold the UE starts searching periodically for candidate neighbour cells. Cells can be any combination of intra-frequency, inter-frequency and inter-RAT cells and the search is done following a defined priority. Once the candidate neighbour cells are identified they are periodically measured over a certain period of time. Note that although the UE measures and reports neighbours it is the eNodeB which makes the handover decision .

Based on the above procedure, it is clear that the UE is responsible for identifying the neighbouring cells so in LTE, mobility does not rely upon neighbour lists. Therefore, there is no need for neighbour list planning .

Although no neighbour planning is necessary, the UE can still be provided with neighbour cell specific measurement offsets to make a neighbour appear more attractive. The UE can also be provided with RF carriers upon which to search for neighbours.

- Reduced UE power consumption:

One of the reasons why SC-FDMA was selected in UL instead of OFDMA was its reduced Peak to Average Power Ratio (PAPR) when compared to OFDMA. This improves the power amplifier efficiency of the terminal and reduces the HW requirements. This has positive impact for UL power budget size.

Table 24 provides a high level comparison between UMTS and LTE. This table compares the two technologies as defined by 3GPP rather the features supported by Nokia.

	UMTS	LTE

Channel Bandwidth	5, 10 MHz (with dual cell)	1.4, 3, 5, 10, 15, 20 MHz
Multiple Access Scheme	WCDMA	OFDMA (DL), SC-FDMA (UL)
Frequency Re-use Pattern	Re-use of 1	Re-use of 1
Uplink Modulation Schemes	BPSK, 4PAM	QPSK, 16QAM, 64QAM
Downlink Modulation Schemes	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Uplink MIMO	None	None
Downlink MIMO	2x2	2x2, 4x4
Peak Uplink Throughput in 10 MHz, 16QAM, coding rate 1	23 Mbps	28 Mbps (dependant upon control channel assumptions)
Peak Downlink Throughput in 10 MHz with 2x2 MIMO, 64QAM, coding rate 1	84 Mbps	~86 Mbps (dependant upon control channel assumptions)
Peak Uplink Throughput	23 Mbps (10 MHz channel)	85.5 Mbps (20 MHz, coding rate 1, 64QAM)
Peak Downlink Throughput	84 Mbps (10 MHz channel)	325 Mbps (20 MHz, coding rate 1, 64QAM, 4x4 MIMO)
Minimum Round-Trip Time	< 30 ms	< 10 ms
Soft Handover Support	DCH and E-DCH, not HS-DSCH	None
Adaptive Modulation	Yes (HSDPA, HSUPA)	Yes
L1 re-transmissions	Yes (HSDPA, HSUPA)	Yes
BTS based Scheduling	Time/Codes (HSDPA, HSUPA)	Time/Subcarriers
Fast Power Control	DCH and E-DCH, not HS-DSCH	None
Core Network Domains	CS, PS	PS
Flat Architecture	No (includes RNC)	Yes (excludes RNC)
Neighbor Planning Required	Yes	No
Scrambling Code Planning Required	Yes	No
Physical Layer Cell Identity Planning Required	No	Yes

Table 24: Summary Comparison between UMTS and LTE

The capability of UMTS is evolving throughout the various releases of the 3GPP specifications. For example, the use of either 64QAM or MIMO was introduced within the release 7 version of the specifications. The use of both 64QAM and MIMO was introduced within the release 8 version of the specifications. Historically, UMTS was limited to a 5 MHz channel bandwidth whereas the Release 8 version of the specifications introduces the pairing of two 5 MHz channels to effectively provide a 10 MHz channel bandwidth. This was limited to HSDPA within the release 8 version of the specifications but is extended to HSUPA in the release 9 version. This evolution of the UMTS specifications allows UMTS to remain competitive to certain extent with LTE although LTE has the fundamental key advantages of 20 MHz channel bandwidth (plus CA in effects) without own cell interference and a flat architecture.