Advanced Radio Access Techniques in LTE

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Abstract

Since the end of the 90' mobile communication has been an important part of our life. Since the end of the 2000s the demand on the broadband data transmission has grown, and this resulted the introduction of the new technologies like LTE. In Hungary the LTE frequency bands and permissions has been realized by 29th September 2014, and since then the biggest provider has more than 450 000 subscriber for the new technology[1].

While in GSM the maximum achievable downlink data rate is around 500kbps,in LTE release 10. the maximum peak downlink data rate is 3 Gbps [2]. One key factor in this huge increase was the development of the radio access network (RAN). By applying a better multiple access method, and implementing a lot of new solutions were these enhancements achieved.

In the first part of this essay, I will explain the methods used in the eUTRAN (Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network) that is the RAN in LTE. I show the multiple access method, and I will explain the uplink and downlink data transmission: the defined physical channels and they roles, the coding and modulation techniques, and the synchronization and reference signals. I will also reflect on and compare with the solutions used in GSM.

In the second part, I will expound the MIMO technology which is has an important role in increasing the achievable data rate. Besides the explanation of spatial diversity, I will also introduce the aim of spatial multiplexing. After this part, that covers theory, I will list the transmission modes of LTE release 10 (that is also called LTE-A as “Advanced”) which includes MIMO methods as well. At the end of the section I will review the requirements that these modes stand against the user equipment (UE) and the base station (called evolved NodeB - eNB).

1 Advances of the eUTRAN architecture

In this section I will show the main properties of the eUTRAN. Increasing the available data rate has been a permanent goal in the telecommunication standard development. As shown in the abstract, 4G standard resulted a huge increase in theoretical maximal throughput compared to 2G systems. To achieve such an increase, the RAN had to be drastically changed, because it is one of the main limits of the throughput. However, since both eUTRAN, and GERAN are RAN-s they have to solve similar problems concerning radio wave propagation (concerning 800 – 2600 MHz).

In this section I will introduce the eUTRANs main features and solutions in LTE rel. 8. and rel. 10. At the end of this section, I will refer on the solutions applied in GERAN.

1.1 LTE downlink

1.1.1 Frame structure and OFDMA

Orthogonal frequency division multiple access (OFDMA) is a multiple access scheme, that utilizes the orthogonal frequency division multiplexing (OFDM) as transmission scheme. Here the available transmission band is segmented into many narrowband subcarriers in frequency domain and into time slots in time domain. The multiple access is implemented by the appropriate allocation of this frequency and time domain elements.

In LTE this units are not allocated element wise. Groups are formed in time and frequency as well. The *radio frame* in LTE is 10ms long, and consists of ten 1 ms long *subframe*. Each subframe consists of two 0.5 ms long *slot*s. Slots are the smallest unit in time domain, that can be scheduled to one user.

In the LTE Rel. 8. standard frequency domain duplex (FDD) and time domain duplex (TDD) methods are also defined. In the previous one the uplink and downlink communication is separeted in different frequency bands, while in the latter one, the subframes are scheduled to be uplink, downlink, and special subframes (shared between uplink and downlink control information).

The number of symbols in one time slot depends on the length of the cyclic prefix (CP). The possible CP prefix lengths are: 16.7µs or 4.8µs. According to this, one time slot consists of 6 or 7 symbols. In each cases the lengths of the symbols are equal. Defining two possible CP allows the operation in larger delay spread channel, without introducing to much overhead at normal circumstances.

The carrier spacing in LTE is 15 kHz. According to the OFDM requirements, the carrier spacing is the reciprocal of the symbol length. According to the terminology, one symbol length on one carrier is called *resource element* (RE), and the group of symbols in 12 neighboring elements in one time slot is called resource block (RB). So depending on CP length, the number of symbols in one RB is: 84 or 72.

In LTE Rel 10. the: supported carrier bandwidths are: 1.4, 3, 5, 10, 15, and 20 MHz. This carriers can be allocated in various frequency bands. Besides some bands used in GSM and UMTS, the 832-862 MHz UL/ 791-821 MHz DL and the 2500-2570 MHz UL / 2620-2690 MHz DL bands are also available (In Hungary the realization of this bands has been done by 29th September 2014).

LTE rel. 10 introduces carrier aggregation which enables the communication of one UE simultaneously on more carriers. The future goal is to allow the aggregation of 5 carriers, which enables the allocation of maximally 100 MHz to one UE. Three type of carrier aggregation are distinguished: intra-band contiguous, intra-band non-contiguous, and inter-band, which refer to the position of the aggregated carriers in the frequency domain. In LTE Rel. 10 the aggregation of 2 carriers is enabled in downlink, no carrier aggregation is enabled in uplink [3].

In GSM, the TDMA FDMA system is more rigid. There are two bands assigned for operation. (900 MHz and 1800 MHz GSM bands). Only FDD is supported. The carrier spacing is 200kHz. Each carrier is divided into time frames of length 4.615 ms, which consists of 8 time slot. Each slot consists of 148 bit, including 114 data bits and 26 bit long train for channel estimation, and a 30.5 µs guard time (8.25 bit long). In circuit switched mode, each time slot is allocated to one user. Concerning one carrier, including each 148 bit but neglecting guard period, the throughput is 256,54 kbps, which that can be triplicated using 8PSK modulation instead if GMSK[4].

A similar rough calculation in LTE concerning 13 RB-s (195 kHz) results 78 symbol/slot or 91 symbol/slot that is 156 ksymbol/s or 182 ksymbol/s (depending on CP length). This corresponds to 312-936 kbps or 364-4092 kbps throughput, depending on the modulation (QPSK 16QAM, 64QAM, 256QAM). But as far as in GSM only one carrier can be assigned to one UE, in LTE one UE can simultaneously use more RBs. An other reason which this computations are a bit confusing for, is that they do not say anything about the circumstances (e.g. signal to interference and noise ratio) at which these throughputs can be guaranteed.

1.1.2 Physical channels

In eUTRAN several types of channel coding, and modulation is available. The set possible solution depends on whether data, or control information, or channel information is sent. To distinguish this data, physical channels are defined, which are different kind of channel coding and modulation available for. Here I will introduce the available physical channels they roles in communication and the available coding and modulation techniques for each[5].

Physical Broadcast Channel (PBCH)

PBCH broadcasts the broadcast transport channel (BCH), and contains the information needed by the UE to initiate connection with the eNB (using so-called main information block – MIB). To allow the decoding this channel whiteout prior information, the channel has a dedicated place in frequency and time domains: it is broadcasted on the middle 6 RB of the transmission bandwidth, in the first four symbols of the second slot of the #0 subframe.

Among some other information, the MIB contains the actual carrier bandwidth. The information about the number of transmission antenna ports used in the downlink control data transmission is implicitly broadcasted on the PBCH: the scrambling of the BCH CRC depends on it. There are three possible transmission mode and scrambling variation, by doing each CRC check, the actual antenna configuration can be determined.

By the PBCH convolutional code, and QPSK modulation are used.

Physical Downlink Control Channel (PDCCH) [6]

The content of PDCCH depends on whether the actual message is a downlink or uplink resource assignment, or a power control command. To support all possible contents, different data formats are defined, called downlink control information format (DCI). Resource assignment, power control information for uplink channels, and modulation and coding schemes are usually part of most of the formats. However, information regarding PDSCH transmission mode are different in different DCI formats.

In PDCCH convolutional code width constraint length 7 and coding rate 1/3 is applied. There is a rate matching procedure after encoding which sorts out the code bits for transmission (this algorithm has a puncturing role in case of the assigned transmission resources are “to few”). Here is also QPSK modulation applied.

In PDCCH common, and UE specific information is transmitted. The latter one is sorted out by UEs during decoding, using their C-RNTI identifiers, which are unique in the cell. PDCCH is interleaved across first three symbols of the subframe.

Physical downlink shared channel (PDSCH)

This channel is used for downlink data transmission. More accurately the *downlink shared transport channel* and the *paging transport channel* are allocated on PDSCH. The transport channels are grouped in transport blocks (TB), and encoded before being sent to physical layer. The same turbo code is used here as in WCDMA but with a different interleaver. If the size of the TB is bigger than 6144 bits, than it is further divided into code blocks (CB), which are individually encoded. After encoding, a 24 bit long CRC is added to the TB, or every CBs. Concerning PDSCH, QPSK, 16-QAM, and 64-QAM modulation schemes are available. After channel coding, a rate matching algorithm is applied here as well[7].

The information regarding CB or TB size, and modulation scheme can be extracted from the signaled number of RBs and the actual modulation and coding scheme (sent in PDCCH). PDSCH is interleaved from the second third or fourth symbol of the subframe.

Physical Multicast Channel (PMCH)

The *multicast transport channel* (MCH) is allocated on PMCH, which is used for multimedia broadcast and multicast transmission. The same channel encoding and rate matching methods are applied, as by DL-SCH, and the same modulation schemes are available as by PDSCH. PDSCH is interleaved from the third or fourth symbol of the subframe.

Physical hybrid ARQ indicator channel (PHAICH)

In LTE, hybrid automatic repeat request (HARQ) is applied both in uplink and downlink direction. This means that after channel decoding, the receiver decides whether the decoding was successful or not, and send back an ACK or NACK message to the receiver. PHICH is a dedicated ARQ channel in response to UL transmission. 1/3 repetition code and BPSK modulation is applied. PHICH is sent on the firs, or on the first three symbols of the subframe.

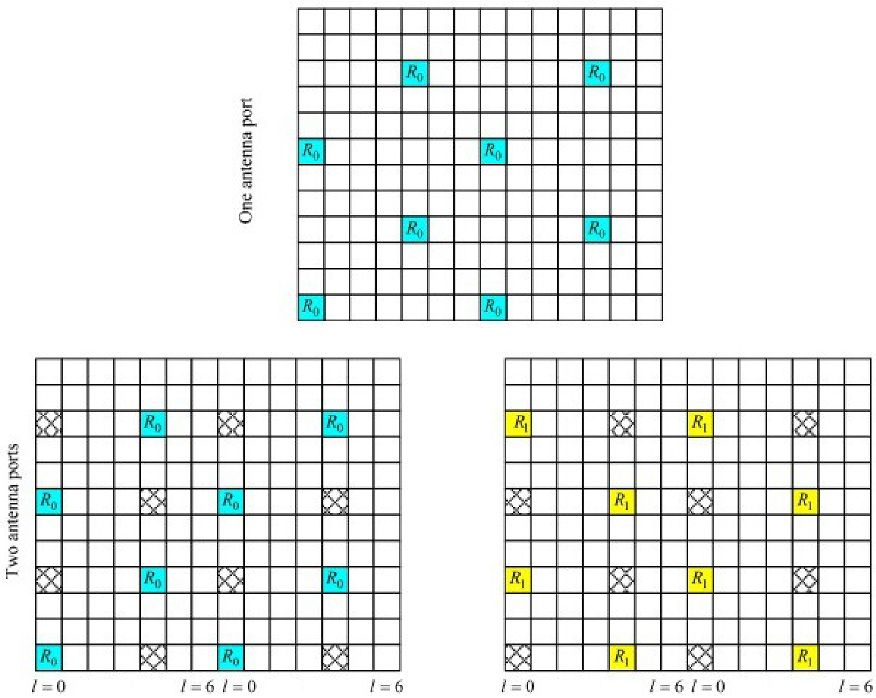
Physical Control Format Indicator Channel (PCFICH)

Since the physical data channels and control channels can be dynamically allocated, the actual allocation scheme must be signaled. This information is transmitted on PCFICH. PCFICH is transmitted on the first symbol of the subframe. A block code with 1/16 coding rate, and QPSK modulation is applied.

1.1.3 Signaling: synchronization and channel estimation

There are two synchronization signals: primary (PSS) and secondary synchronization signals. (SSS). PSS and SSS are symbol sequences in the frequency domain, in the middle 6 RB of the transmission bandwidth. The frequency synchronization and symbol timing synchronization is done by the UE through scanning the frequency band, and searching the PSS (there is 3 possible PSS). After PSS is found, SSS will be extracted (there is 170 possible), and this two synchronization signals gives the physical layer ID of the cell. This determines the reference signals used by the cell, and knowing this, the decoding of PDCH will be possible. Both PSS and SSS are sent twice in one radio frame on two consecutive symbols: on the 5^{th} (SSS) and 6^{th} (PSS) symbols of the #0 and #5 subframes.

Reference signals (RS) are mainly used for channel estimation. Providing predefined pilot signal with predefined frequency and time domain allocation allows the receiver the channel estimation. Here I will introduce cell-specific RS, and UE-specific RS. Cell-specific RS are required for the common control channels and PDSCH, if no UE-specific RS is defined. The mapping of the reference signals is based on the number of antenna ports used by the eNB, since while one antenna port transmits reference signals, the other ports are not transmitting. On the 1. Figure reference signal mapping for one and two antenna portsare shown in two consecutive RB.



1. Figure: RS mapping for one and two antenna port mode. One the two RB of one subframe are shown. The vertical axis denotes frequency domain and the horizontal axis denotes the frequency domain. It is important, that in two port mode, when RS-s are transmitted,then the other port transmits nothing

UE- specific RS-s are used, by multiple antenna port transmission when non-cell-specific precoding is used. Precoding determines how the symbols are mapped on the antenna ports. The UE-specific RSs are precoded with the same method as data symbols, and this allows the receiver to guess the precoding rule[8].

1.2 LTE uplink

1.2.1 Multiple access in uplink, and SC-FDMA

Knowing that TDD is supported in LTE, it is obvious that the uplink time and frequency allocation scheme must fit in the previously introduced downlink scheme. According to this, the *RB, RE, subframe, slot* have the same bandwidths/duration as in the downlink case. Similarly, one slot is divided into 6 or 7 symbols depending on the CP length (same values as in downlink).

The main difference is that, in uplink *single-carrier frequency division multiple access* (SC-FDMA) is used instead of OFDM. So the symbols in a slot are not OFDM, but SC-FDMA symbols. The SC-FDMA frequency domain allocation is similar to OFDM, but an additional FFT transformation is introduced before the resource block mapping process (and an additional IFFT is required in the demodulation chain after channel equalization)[9]. The reason for this seemingly meaningless modification is the high *peak to average power ratio* (PAPR) demand of the OFDM. This means that the maximal transmitter power is higher with 20-30 dB than the average. This is inappropriate for handhold devices. The SC-FDMA has a much lower PAPR and that is why it is applied in uplink, even though the higher receiver and transmitter complexity it results[10].

1.2.2 Uplink signaling

There are two RSs in uplink: *demodulation reference signals* (DM RS), and *sounding reference signals* (SRS).

DM RS are used by the eNB for channel estimation. The allocation of DM RS is different in *physical uplink shared channel* (PUSCH) and in *physical uplink control channel* (PUCCH). In the former one, DM RS is sent in every slot, on the middle symbol, which results 14.3% or 16.6% overhead. In PUCCH, where the delay is more critical, the DM RS maximal overhead is 42.3%. But here the modulation and reference signaling is is combined (the method will be shown in the HIV section). The DM RSs are Zadoff-Chu sequences.

SRS is used by the eNB to adjust the timing and the transmission power of the UEs also in cases when the UE has no data for transmission.

1.2.3 Uplink physical channels

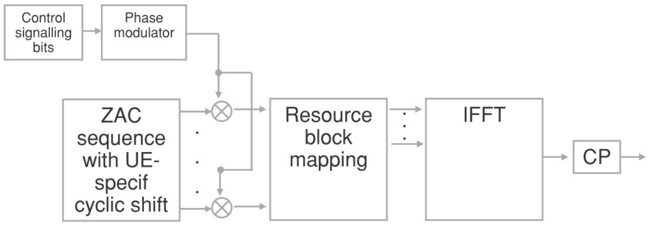
The uplink resources are used to transmit data, and control information, and to allow connection establishment for the UE. Different physical channels are defined to provide appropriate solutions for all of the different purposes. Unlike in downlink, in uplink control information might be sent through the uplink data channel as well. The more detailed description of these channels can be found below.

Physical Uplink Control Channel (PUCCH)

The control information sent on this channel are the following: *channel quality indicator* (CQI), it contains the preferred modulation and coding scheme in downlink; *precoding matrix indication* (PMI), which indicates the preferred precoding in MIMO downlink; *rank indicator* (RI), which denotes the preferred number of data streams in downlink MIMO, ACK/NACK, (ARQ feedback), *scheduling request* (SR), that is a claim for additional PUSCH resources in the near future.

Since the control information needs significantly less throughput, than the data channel, but requires more reliable transmission with shorter delay, the PUCCH differs significantly from PUSCH. *Frequency division multiplexing* (FDM), and *code division multiplexing* (CDM) is used, to reduce the fading, and to allow multiple access.

Two contiguous group of RBs (at least 1-1 RBs) are assigned for PUCCH on both sides of the available transmission bandwidth. The FDM is done between these band since the fist slot of the PUCCH subframe is sent on the lower band and the second slot is sent on the upper band or, reversed. CDM is applied inside this bands. Zadoff-Chu sequences are used for multiplexing several USs in one band. These are the same type of signals used by DM RS, but these sequences has zero periodic auto-correlation, and near zero periodic cross-correlation, which makes them appropriate for CDM. The cyclically shifted version of the same Zadoff-Chu sequences are assigned to the UEs. The multiplexing, reference signaling, and data transfer is simultaneously done with these signals. The available throughput of PDCCH is 1,2,20,21,22, or 48 bit/subframe, which is significantly less than PUSCH throughput. The modulator for the 1 and 2 bit/subframe cases are shown on the picture. IBPSK or QPSK modulation is available in this channel,



2. Figure: PUCCH modulation in the 1 and 2 bit/subframe case, from Krouk, Semenov: Modulation and Coding techniques, picture 11.1141.

Physical Uplink Shared Channel (PUSCH)

In this channel the known subframe-slot-symbol structure is used. The middle symbol in every slot is dedicated to RS transmission. A significant difference compared to uplink is that on PUSCH control information can be sent if no PUCCH resource is assigned to the UE. Thus the different streams need to be multiplexed before the SC-FDMA block: data, CQI/PMI, RI ACK/NACK are coded and the complex symbols are constructed independently, and these symbols are multiplexed. The output of the multiplexer is connected to the FFT the stage of the SC-FDMA block. The same modulation technique is used on every sources which can be QPSK 16 QAM or 64 QAM.

Random access channel (RACH)

This channel allows the UE to initiate unscheduled connection with the eNB. For example when an idle UE initiates radio control connection, then it uses the RACH. The main role of this channel is to allow signaling of the UEs, since when these signals are received, the eNB allocates uplink and downlink resources for the UE, and the communication continues in these channels.

This signaling is solved by sending preambles on the marked RACH subframe. Zadoff-Chu sequences are used as preambles, and there is 64 sequences for the UEs to chose from. The the low cross correlation of these sequences decrease the probability of collision. The duration of the preamble sequence is 800µs and a CP and guard period is concatenated before and after the preamble (the latter one is needed to avoid the distortion of the next subframe). There are more preamble format defined for FDD and TDD to adapt to different environment.

1.3 Control and data transmission in GSM[4]

Regarding GSM, the goal is roughly the same as in LTE: data transmission, to which several overhead must be enclosed, containing the control information. The synchronization method is also similar, first the UE synchronizes to the base station, identifies it, and after processing some basic information, the UE can initiate connection, which finally enables data transmission.

The control channels and their tasks are listed in the 1. Table. The similarity of this list and the physical channels of LTE is obvious.

	Control channels	**Main tasks**
Broadcast channels (all downlink)	Frequency correction channel (FCCH)	frequency synchronization
	Synchronization channel (SCH)	frame synch.
	Broadcast control channel (BCH)	channel assignment
Common control channels	Paging channel (PCH downlink)	paging
	Access grant channel (ACH, downlink)	rand. access response
	Random access channel (RACH uplink)	connection initiation by UE
Dedicated control chaxnnels (bi-directional)	Stand-alone dedicated control channel (SDCCH)	auth. initial data transfer
	Slow associated control channel (SACH)	power and timing adv. control
	Fast associated control channel(FACH)	handoff requests,

1. Table: GSM control channels

The main difference stems from the different multiple access method. In GSM the control signaling adapts to the time frame and time slot structure of the GSM's TDMA system. The time frames are arranged in 26 or 52 frame long multiframes, and some frames of the multiframe are allocated to them in the following manner:

1) there are dedicated time slots on specified frequencies for SDCCH
2) SACCH is sent on every 13^{th} and on some 26^{th} channel
3) channels for FACCH can be allocated before use by setting the F-bits in the slot
4) every #0 slot of each frame are allocated for other control information: for FCH, SCH, BCCH, PCH and ACH in downlink and for RACH in uplink. The type of the downlink slot cyclically varies with and 52 frame long periodicity.

2 MIMO

Phenomenons fading and multipath propagation have always caused problems in mobile communication. The simple model of two path propagation above flat surface also predicts, that fading must also be handled in the case of multipath propagation environment.

If it was possible to „choose” from propagation paths, then the error probability caused by fading would decrease. The spatial diversity allows this, through the application of multiple receive and/or multiple transmit antennas. In this construction every different transmit and receive antenna pair has it own channel characteristic. If the transmit and receive antennas are placed properly, than the these characteristics will probably be „different enough”, which allows to reduce the effect of fading through selection or combination of signals of different channels (e.g. the signal with the highest amplitude is chosen).The abbreviation MIMO means Multiple Input Multiple Output which refer to the plurality of transmit and receive antennas concerning radio communication.

Besides the reduction of fading, the MIMO antenna systems might be used to enhance the data rate. If the different channels are independent, then it is possible to transmit different symbols on different transmit antennas simultaneously so, that each interleaved symbols can be decoded on the receiver side, assumed that the channel characteristics of all channels are known.

To allow the application of spatial multiplexing and more efficient types of spatial diversity, a suitable channel estimation is needed. This should enable the estimation of each channel, which requires dedicated time slots (and subcarriers) for the reference signals of each transmit antenna. In LTE it is provided through an appropriate reference signal mapping (a sample is shown on 1. Figure).

2.1 Spatial diversity, space time coding

When we want to describe mobile radio links in built -up areas, we have to consider the effects of multipath propagation, like fading and dispersion. The additive white Gaussian noise is not good for this purpose. There are two well known channel models for the narrowband case (when we can neglect dispersion):

1) Rician fading: one of the path is a line of sight path,(typically used in the outskirts)

2) Rayleigh fading: none of the paths is a line of sight path, (typically used in highly built up areas).

In the latter case, the connection between the transmitted and received baseband signals can be written up with equation (1) [12]:

$$y_t = h x_t + \eta \tag{1}$$

Where:

y_t : the received symbol

x_t : the transmitted symbol

h : fading coefficient, a complex Gaussian variable

η : additive white Gaussian noise at the receiver

It can be seen from (1), that the channel constant might attenuates, or distorts the transmitted symbol. With the usage of more receive and/or transmit antennas, we increase the probability of having an appropriate channel. A simple case is, when we have one transmit and two receive antennas, the strategy of combining these two received signal is that we always select the signal with the higher amplitude.

The goal of spatial diversity is to reduce the error probability on the channels loaded with fading. There are complex methods to exploit the opportunities of spatial diversity Two of them will be shown here. It is important to mention, that these techniques requires channel estimation and compensation as well.

2.2 Space Time Block Codes (STBC)

With STBC we redistribute the symbols not only among the transmit antennas, but we also rearrange their chronological sequence. More precisely, we have *k* complex symbols: $x_1 \dots x_k$, which must be sent during a time period of length *T* (measured in time slot length, $T \geq k$). Let us assume, that we have *N* transmitter and *M* receive antennas. The space time code defines how these symbols are redistributed in space (transmit antennas) and time. This can be described with a matrix:

$$G=\begin{pmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,N} \\ \cdots & & & \\ \cdots & g_{i,j} & \cdots & \\ g_{T,1} & \cdots & & g_{T,N} \end{pmatrix} \tag{2}$$

Where the rows indicate the consecutive time slots, and the columns indicate the antennas. The $g_{i,j}$ elements of the code matrix **G** are the linear combinations of symbols $x_1 \ldots x_k$ and their complex conjugates. In the two methods shown here, the elements of **G** are are the symbols themselves, or the complex conjugates, so the code matrix **G** is same as the actual signal matrix **X** of the actual transmission period (with length T).

The channel constants can be denoted with a matrix **H** of N rows and M columns, where the $h_{i,j}$ element of the matrix is the fading coefficient between the i^{th} transmit antenna and the j^{th} receive antenna. With this notation the received symbols can be written in the form of a (T*M)-matrix **R**:

$$R=X*H+N \tag{3}$$

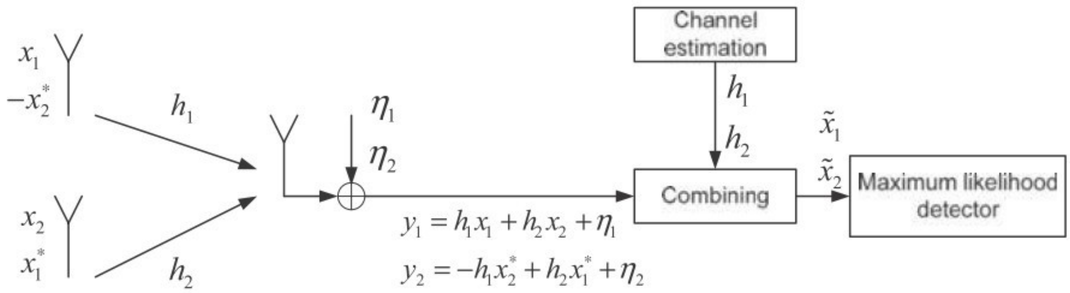
Where **N** is the (T*M) matrix of noise ($n_{i,j}$ is the additive white Gaussian noise at the j^{th} receiving antenna in the i^{th} time slot). So the received signal at the m^{th} antenna in time slot t is [12]:

$$r_{t,m}=\sum_{i=1}^{N} h_{i,m}*x_{t,i}+n_{t,m} \tag{4}$$

One of the simplest schemes for 2 transmit and arbitrary number of receive antennas were proposed by Almouti:

$$G=\begin{pmatrix} x_1 & x_2 \\ -x_2 & x_1 \end{pmatrix} \tag{5}$$

Concerning the arrangement with one receive antenna, and assuming, that the propagation constants do not change during the two time slots, the received signals are:



3. Figure: Transmit diversity with two transmitter and one receiver antennas. The denoted transmitted and received symbols corresponds to the Almouti code.; from Krouk, Semenov: Modulation and Coding techniques, Fig. 8.6

$$y_1=h_1x_1+h_2x_2+n_1 \tag{6}$$

$$y_2=-h_1x_2+h_2x_1 \tag{7}$$

From this, the x_1 and x_2 estimates of the transmitted x_1 and x_2 signals are computed as:

$$\tilde{x}_1=h_1y_1+h_2y_2=\left(h_1\right)^2x_1+h_1h_2x_2+h_1n_1-h_2h_1x_2+\left(h_2\right)^2x_1+h_2n_2=\left(\left(h_1\right)^2+\left(h_2\right)^2\right)x_1+h_1n_1+h_2n_2 \tag{8}$$

$$\tilde{x}_2=h_2y_1-h_1y_2= \ \ldots \ =\left(\left(h_1\right)^2+\left(h_2\right)^2\right)x_2+h_2n_1-h_1n_2 \tag{9}$$

This method can be generalized for arbitrary number (M) of receive antennas: the estimation must be done for every M antennas and the M-M estimations of each symbols must be summed[13].

One important property of STBCs are code rate (R) which is defined here as $R = k/T$. It is a measure of the efficiency of the code. One other aspect is that how does the coding process decrease the error probability through increasing the redundancy in the original stream. This probability is desired by the *coding gain*, concerning traditional error correcting codes, but in the in the case of STBCs, the usage of multiple paths provide an additional source of redundancy, this is called *diversity gain*. In [14] there is an exact definition of coding and diversity gain, Here I only want to show that the diversity gain is defined as (10) :

$$\mathrm{div.gain} = M * \mathrm{rank}\left[C^{(i)} - C^{(j)}\right] \leq N * M \tag{10}$$

Where $C^{(i)}$ $C^{(j)}$ any signal matrixes of the code, and $i \neq j$. Maximum diversity gain can be achieved e.g. by orthogonal STBCs. In this case, the columns of the are orthogonal.

2.2.1 Space Frequency Block Codes (SFBC) – diversity in LTE [15]

Space frequency block codes are similar to STBCs, but instead of arranging the symbols in space and time, they arrange them in space and frequency. So instead of arranging the *k* symbols among *N* antennas and *T* time slot, the symbols are transmitted during one time slot, but every transmit antennas transmit in *F* frequency band (sub-carriers) simultaneously. So we can use the matrix notation used in the previous section, the difference is that one row of **R**, **G**, **X**, **N** matrixes corresponds to one carrier, and the number of rows equals *F* instead of *T*. But an important difference is that the fading constants changes depending on the carrier frequency as well. This results, that the during decoding of a particular symbol the interference caused by other symbols can not be canceled perfectly, even if perfect channel estimation is available.

The OFDM modulation applied in LTE is an optimal framework for space frequency block coding, since the several number of subcarriers allows the frequency domain arrangement of symbols. The SFBC used is an Almouti code in the frequency domain. The code matrixes for two and four transmit antennas are shown in 2. and 3. Tables. It can be seen from these tables, that the four transmit antenna SFBC is two consecutive two antenna SFBC, which results, that the two modes have similar properties.

	Antenna 1	Antenna 2
OFDM subcarrier 1	x_1	$-x_2^*$
OFDM sc. 2	x_2	x_1^*

2. Table: Two transmit antenna

	Antenna1	Antenna 2	Antenna 3	Antenna 4
OFDM sc. 1	x_1	-	$-x_2^*$	-
OFDM sc. 2	x_2	-	x_1^*	-
OFDM sc. 3	-	x_3	-	$-x_4^*$
OFDM sc. 4	-	x_4	-	x_3^*

3. Table: Four transmit antenna

Assuming two transmit and one receive antennas, the received signals and the estimations of the transmitted signals can be written as follows:

$$y_1 = h_1^1 x_1 - h_2^1 x_2 \tag{11}$$

$$y_2 = h_1^2 x_2 + h_2^2 x_1 \tag{12}$$

$$\tilde{x}_1 = h_1^{1*} y_1 + h_2^2 y_2 = \ldots = \left(\left(h_1^1\right)^2 + \left(h_2^2\right)^2\right) x_1 + \left(h_1^{2*} h_2^2 - h_1^{1*} h_2^1\right) x_2 + h_1 n_1 + h_2 n_2 \tag{13}$$

$$\tilde{x}_2 = -h_2^1 y_1 + h_1^2 y_2 = \ldots = \left(\left(h_2^1\right)^2 + \left(h_1^2\right)^2\right) x_2 + \left(h_1^{2*} h_2^2 - h_1^{1*} h_2^1\right) x_1 - h_2^1 n_1 + h_1^2 n_2 \tag{14}$$

Here the upper index of the fading constants denotes the subcarrier, and the lower index denotes the transmit antenna. The difference between STBC and SFBC is that in the latter case the distortion caused by the other symbol can not be canceled. The reason for it is the frequency selective fading. But it was shown in [15] that if the two subcarriers are close to each other in the frequency domain, than the correlation between the fading constants of the two paths are independent of the subcarrier:

$$\mathrm{E}\left(h_1^{2*}h_2^2\right)=\mathrm{E}\left(h_1^{1*}h_2^1\right) \tag{15}$$

and this results, that the distortion caused by interference does not decreases the average SINR.

2.3 Spatial multiplexing

While the coding rate is always less than, or equals to one considering space time codes, it is possible to increase the data rate by using the MIMO architecture. Of course it reduces the diversity gain, but for example in ideal channels with high signal to noise ratio, the additional redundancy provided by space time codes is not necessary.

In the case of spatial multiplexing, the transmit data symbols are distributed among the *N* transmit antennas with a demultiplexer, and this way *N* consecutive symbols are transmitted simultaneously. The strategy of this distribution is called precoding in LTE. This architecture also allows the usage of *N* different (but synchronized) UEs to transmit simultaneously. Spatial multiplexing does not applies code matrixes, so the vector of transmitted symbols must be estimated from the received vector. The decoding of the received signal is usually an iterative process: firstly the most probable symbol (s_i) is detected, and after that the received vector (**r**) is corrected according to this estimation: $\mathbf{r}^{(2)}=\mathbf{r}-\mathbf{h}_{\mathbf{i}*}s_i$. The second symbol is estimated from this corrected vector, and after that and $\mathbf{r}^{(2)}$ is corrected to allow the proper estimation of the third symbol. And this procedure carries on.

The are several spatial multiplexing architectures that are already worked out. Two examples are V-BLAST (Vertical -Bell Labs layered Space-Time architectures) and D-BLAST (Diagonal BLAST), which describe the decoding method (and the precoding, concerning D-BLAST).

2.4 Transmission Modes – the various MIMO solutions of LTE

In LTE technology both spatial multiplexing and spatial diversity are implemented. In Release 10 two *uplink transmission modes* and nine *downlink transmission modes* are defined, which define the properties of the actually used data transmission technique. The main characteristics of transmission modes are:

1) the number of input data streams called transmission layers
2) the used antenna ports
3) the precoding scheme

In LTE, the precoding means the distribution weighting of incoming symbols between/on antenna ports. Antenna and antenna port need to be distinguished because of the possibility of using antenna arrays, which must be controlled differently compared to independent antennas. There are predefined code matrixes known by the eNB and the UE as well, but from Release 9 onwards arbitrary precoding is possible in downlink through the use of UE-specific reference signals.

2.4.1 Downlink transmission modes [8]:

1) **Single transmit antenna:** SISO or SIMO operation (antenna port 0).
2) **Transmit diversity**
   In transmit diversity transmission with two or four transmit antennas is allowed. The code matrix of these two modes are seen in 2. and 3. Tables.Transmit diversity is the default MIMO operating mode, it is the fallback mode of some other transmission modes.
3) **Open loop spatial multiplexing with cyclic delay diversity**
   In this mode two or four transmission layers are multiplexed on two or four transmit antennas. This mode might be used, when there is no feedback regarding the channel situation (no precoding information is included), or the channel characteristics changes rapidly. For example by high velocity user- equipments. By two transmit antenna the precoding matrix signed with PMI = 0 (Precoding Matrix Indicator) is used, while by four antenna the precoding matrix is periodically switched.
4) **Closed loop spatial multiplexing (CL-SM)**
   This mode supports up to four spatial layers multiplexed among two or four transmit antennas. Through the channel information carried by cell specific reference signals, the UE chooses the most appropriate precoding matrix and sends back its PMI to the base station.

5) **Multi-user MIMO**
This mode is similar to closed loop spatial multiplexing, but here the different spatial layers are assigned two different UEs. So the usage of MIMO does affects the UEs data rate, but increases the overall network data rate.
6) **Closed loop spatial multiplexing using a single transmission layer:**
In this mode the application of MIMO does not increases the data rate at all. Precoding is applied to realize a simple beamforming method. Two or four antennas can be used.
7) **Single-antenna port transmission with UE specific reference signals (beamforming)**
Here the common channels are sent with an antenna beam that covers the whole cell, while the user equipment specific data are sent with a narrow beam. User equipment specific reference signals are sent to the handset, from one antenna port. The user equipment sees only one transmit antennas. To implement this mode, beamforming capability is required on the transmitter side, and the eNB must determine the appropriate beam for every UE.
8) **Dual-layer beamforming:**
This mode has been added with the introduction of Rel 9. UE-specific reference signals are used. This transmission methods allows the combination of two transmission layer spatial multiplexing with beamforming. This method requires distinguishing of the reference signals of the two spatial layers.
9) **8 layer transmission**
This is the new transmission mode of LTE-A. In this mode up to eight layers can be used, so up to eight physical transmit antennas are needed, this leads to up to 8×8 MIMO configurations. The number of used layers may be defined dynamically. It allows multi-user and single-user MIMO as well. In this method user equipment specific reference signals are added before the precoding, andon the UE side, the precoding method information is extracted using the precoded reference signals. This results, that in this mode arbitrary precoding matrix can be used, not only the predefined precoding matrixes.

2.4.2 Uplink transmission modes

In uplink direction there are two transmission modes: **single transmit antenna mode** and **closed loop spatial multiplexing**. These modes are similar to the corresponding downlink modes. The new feature in release 10 is the 4 transmit antenna port transmission in the closed loop spatial multiplexing mode.

2.4.3 MIMO requirement against eNB and UE

Supporting all of the above listed transmission modes is not required, since it requires more complex transceivers and more antennas both on the eNB and on the UE side.

Transmission modes 7- 9 requires antenna arrays on the eNB. According to my experiences I acquired as trainee at Magyar Telekom from 2013 September to 2014 September, in Hungary, antenna arrays are hardly ever used. In my opinion the main causes are, that there is no demand for such high data rate that can be achieved with this modes, and that the service provider want firstly develop a good LTE coverage in the whole country, and the throughput enhancement provided by these modes are subsidiary.

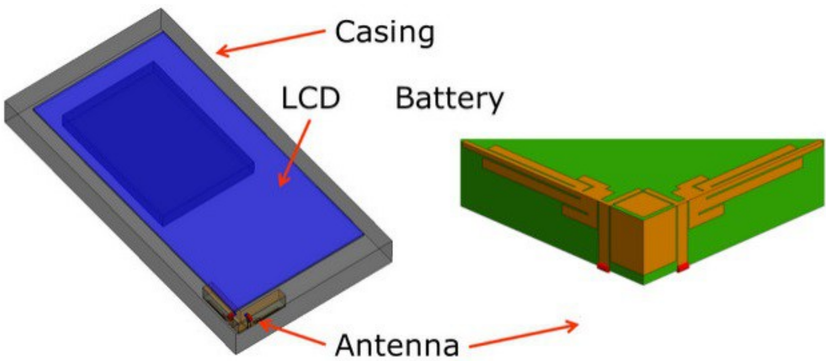
The usage of 4 transmit antennas on the eNB side is also rare. The main reason for this is the shortage on antenna places in the antenna towers (there are three technology, and several bands, and the application of one multiband is not always suitable). Usually, cross polarized multiband and single band antennas are used which allows the two transmit antenna modes.

The abilities of the UEs also vary. The supported downlink transport layer number, the supported downlink and uplink modulation schemes, the maximum number of transport block bits per transmission time interval, and several other capabilities might differ. *UE categories* are defined manage this capabilities. These are classes which stand different requirements against the UEs, and each UE must fit in at least one of these categories. The UE radio access parameters and the properties of the different UE categories are defined in transcript ETSI TS 136 306 V12.3.0 (2015-02).

3 Summary

In this essay I reviewed the radio access technology used in LTE. The multiple access methods and the physical channel related solutions were emphasized. At some point I also compared the appropriate GSM and LTE solutions.

In the second section I showed the MIMO based radio access technologies. This are important features of LTE since it provides throughput increase without increasing the transmission bandwidth. This is a nice solution, cause it exploits the multipath propagation, which effect are basically meant to be harmful.



4. Figure: Possibble 2 UE MIMO antenna with two antenna port, EM Software & Systems–S.A, http://www.feko.info/applications/white-papers/design-and-optimisation-of-an-lte-mobile-phone-antenna

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