

# Practical Introduction to LTE for Radio Planners

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This white paper reviews basics of radio planning for 3GPP LTE. Both coverage-limited and interference-limited scenarios are considered. For the coverage-limited scenario LTE link budget is compared to that of 3GPP Release 8 HSPA+ with 2x2 MIMO. It is shown that, given the same 5MHz bandwidth, both systems have similar cell ranges but, for a given target bit rate, there exists an optimum LTE system bandwidth that maximizes cell range in both uplink and downlink. For the interference-limited scenario (with random uncoordinated interference) we illustrate the relationship between average network load, cell edge target throughput and cell range, as well as the notion of interference margin for cell range dimensioning. Impact of base station antenna configurations on dual-stream Multiple-Input Multiple-Output (MIMO) performance is demonstrated by means of a real-world measurement example. Finally, the impact of advanced LTE radio resource management features are briefly reviewed.

## 1. INTRODUCTION

This white paper introduces LTE from the perspective of radio network planning. The paper is mainly targeted for readers with earlier experience in radio planning and mobile communications. Some prior knowledge of radio engineering and LTE is assumed as principles of OFDMA and SC-FDMA, as described in 3GPP LTE specifications, will not be reviewed in this paper. Instead the reader is referred to well-known literature references [1–3]. The most important LTE radio interface parameter are summarized in Table 1 for the convenience of the reader.

### Abbreviations

BCCH	Broadcast Channel
CQI	Channel Quality Feedback
HARQ	Hybrid Automatic Repeat Request
HS-DSCH	HSDPA Downlink Shared Channel
LTE	Long Term Evolution
PDSCH	Physical Downlink Shared Channel
PRB	Physical Resource Block
PUSCH	Physical Uplink Shared Channel
SCH	Synchronization Channel
SINR	Signal-to-Interference-Noise-Ratio
TTI	Transmission Time Interval

## 2. LTE COVERAGE IN NOISE-LIMITED SCENARIO

### 2.1. Definition of average SINR

Probably the most useful performance metric for LTE radio planner is the average signal-to-interference-and-noise ratio,  $SINR_{ave}$ , defined as

$$SINR_{ave} = \frac{S}{I + N}, \quad (1)$$

where  $S$  is the average received signal power,  $I$  is the average interference power, and  $N$  is the noise power. In practical measurement analysis, the sample averages should be taken over small-scale fading of  $S$  and  $I$  and over a large number of HARQ retransmissions (several hundreds of TTIs, preferably). The average interference power can be further decomposed as

$$I = I_{own} + I_{other}, \quad (2)$$

where  $I_{own}$  and  $I_{other}$  are the average own-cell and other-cell interference power. In case of HSPA,  $I_{own} = (1 - \alpha)P_{own}$  with  $\alpha \in [0, 1]$  denoting the average channel multipath orthogonality factor and  $P_{own}$  denoting the own-cell transmit power. In LTE, orthogonality is often assumed unity for simplicity, even though in reality the following nonidealities may result in non-negligible own-signal interference in LTE:

Table 1  
Summary of main LTE radio interface parameters

Quantity	LTE DL	LTE UL
System bandwidth	1.4, 3, 5, 10, 15, 20MHz	1.4, 3, 5, 10, 15, 20MHz
Multiple access	OFDMA	single carrier FDMA
Cyclic prefix	4.7 microsec / 16.7 microsec	4.7 microsec / 16.7 microsec
Modulation	QPSK, 16QAM, 64 QAM	QPSK, 16QAM (64 QAM for Cat5 UE)
Channel coding*	turbo coding	turbo coding
HARQ	8 processes, 3 retransm./proc	8 processes, 3 retransm./proc
Power control	none <sup>‡</sup>	cell-specific and UE-specific
Handover	hard, network-triggered	hard, network-triggered
Num of Tx antennas	1, 2, 4 <sup>‡</sup>	1 <sup>‡</sup>
Num of Rx antennas	arbitrary	$\geq 2$
Transmit diversity	Space-Frequency Block Code	transmit antenna selection diversity
Beamforming	3GPP codebook or proprietary	none
Spatial multiplexing	open-loop, closed-loop	none <sup>†</sup>
PRB allocation per TTI	distributed or contiguous	contiguous <sup>‡</sup>

\* For PDSCH and PUSCH. For L1/L2 control and common channels other coding schemes can be used.

‡ Downlink Reference Signal power boosting has been specified by 3GPP

‡ With UE-specific reference signals (vendor-specific beamforming) arbitrary number of Tx antennas.

‡ For simultaneous transmission. Transmit antenna selection is possible with RF switching.

† Multiuser MIMO possible in UL in 3GPP Release 8.

‡ Intra-TTI and inter-TTI frequency hopping is possible in UL.

- Inter-symbol interference due to multipath power exceeding cyclic prefix length
- Inter-carrier interference due to Doppler spread (large UE speed)
- Transmit signal waveform distortion due to transmitter nonlinearities, measured in terms of Error Vector Magnitude

In both LTE and HSPA the effective value of  $\alpha$  depends on the multipath channel and receiver implementation. For HSDPA with receiver equalizer,  $\alpha > 0.9$  can be assumed in most cases. In this paper,  $\alpha = 1$  is assumed for LTE and hence  $I_{own} = 0$ . The impact of  $\alpha < 1$  can be seen only at high  $SINR_{ave}$ ; at low  $SINR_{ave}$  noise power dominates the denominator of (1) over interference power, for both HSDPA and LTE.

In the remainder of the paper, we drop the subscript and denote average signal-to-interference-ratio simply with SINR.

## 2.2. LTE versus HSPA+ coverage in noise-limited scenario

In Table 2 link budgets of LTE and HSPA+ are compared. Both systems have 5 MHz system bandwidth,  $2T_x \times 2R_x$  MIMO antenna system, and equal antenna and RF characteristics for fair comparison. Note that the link budget is carrier-frequency independent, as it is given in terms of maximum path loss, not cell range. A single cell in isolation is assumed ( $I = 0$ ).

The following differences in link budgets can be seen:

- In HSDPA, L1/L2 control and pilot channel overhead is a fraction of the total

downlink transmit power (typically about 20%). In LTE, L1/L2 control channels consume a fraction of DL OFDM symbols, 30% overhead in time/frequency resource element usage is assumed in Table 2, corresponding to three symbols wide L1/L2 control channel region.

- For a given bit rate target, required SINR is slightly different for LTE and HSPA+. However, in the noise-limited regime the difference in target SINR is typically small, less than 2 dBs.
- The noise bandwidth is about 5MHz for HSPA+ UL and DL, as well as LTE DL. For LTE UL, however, the noise bandwidth depends on the number of allocated physical resource blocks (frequency allocation), since symbols are detected in time-domain and noise is accumulated only over the actual occupied bandwidth.

While HSPA+ and LTE have similar performance in terms of coverage, the same is not true for system-level capacity under network interference, where LTE has advantage over HSPA+ due to more advanced radio features, such as multiuser-MIMO, frequency-domain scheduling and inter-cell interference coordination.

### 2.3. Optimizing LTE system bandwidth for coverage

In this section it is shown that, for a given target bit rate, there is an optimum system bandwidth in DL and UL in terms of optimizing coverage.

*Downlink (Fig. 1):* Consider a fixed rate of information transmission for a fixed transmit power. As the number of allocated Physical Resource Blocks (PRBs) becomes larger, code rate decreases and coding gain in turn increases. Therefore, for a fixed DL system bandwidth it pays off to use as many PRBs as possible to minimize required SINR<sup>1</sup>. On the other hand, if one

<sup>1</sup>One PRB is a contiguous chunk of 12 subcarriers, or 180kHz, in frequency domain.

is allowed to use the system bandwidth as a design parameter, there exists an optimum system bandwidth for a given target bit rate. This is due to the fact that, assuming fixed total transmit power, transmit power per PRB (power density) increases as system bandwidth is reduced. This is illustrated in Figure 1. For bit rate target of 128 kbps, the optimum bandwidth is 1.4 MHz, while for 512 kbps and 1Mbps target bit rate, it is 3 and 5MHz, respectively.

*Uplink (Fig. 2):* There is an optimum system bandwidth in the uplink, too, as illustrated in Figure 2. The difference to downlink is that the noise bandwidth equals actual instantaneous scheduled UL bandwidth, which may be less than the system bandwidth. From Fig. 2, it can be seen that for bit rates  $\leq 256$ kbps the optimum number of PRBs is about 3 – 5, meaning that 1.4MHz system bandwidth (6 PRBs) would be sufficient for optimal coverage. For bit rates above 2Mbps, system bandwidth of 5MHz or more is needed in order for system bandwidth not to limit receive sensitivity (UL coverage).

In practice, control and common channel coverage should be taken into account, too. Simulation results in [1] indicate that for low bit rate services uplink random access channel coverage may be the limiting factor, instead of the PDSCH/PUSCH considered here.

## 3. LTE IN INTERFERENCE-LIMITED SCENARIO

A somewhat simplified engineering view on SINR under non-negligible other cell interference is presented in this section. In particular, interference is here characterized only by its average power, whereas (as in HSDPA) it is in fact very bursty when examined at TTI level. Therefore, the interplay of HARQ and interference (traffic) time correlation is completely neglected in the sequel, for the sake of potential radio planning insights.

Table 2

Link budget comparison in coverage-limited scenario, a single user at cell edge for 2x2 LTE and 2x2 HSPA+, 5 MHz LTE bandwidth. Target bit rate: 1Mbps DL, 128Mbps UL.

Quantity	LTE DL	HSDPA	LTE UL	HSUPA
Transmit power*	46 dBm	45 dBm <sup>b</sup>	23 dBm <sup>†</sup>	24 dBm
Antenna + feeder gain	15 dB	15 dB	-3 dB	-3 dB
MHA gain	-	-	2 dB	2 dB
Rx Noise Figure	7 dB	7 dB	2 dB	2 dB
SNR target	-4 dB <sup>‡</sup>	-5 dB <sup>‡</sup>	-12 dB <sup>‡</sup>	-13 dB <sup>◇</sup>
RX sensitivity	-105 dBm <sup>‡</sup>	-105 dBm	-117 dBm	-118 dBm
Max path loss	164 dB	163 dB	154 dB	156 dB

\* Sum power of two transmit antennas

<sup>b</sup> max HS-DSCH power 42 dBm per antenna

<sup>†</sup> Category 3 LTE terminal

<sup>‡</sup> All bandwidth allocated for the single user in DL and UL.

<sup>◇</sup>  $E_b/N_0$  target of 2dB for 128 kbps, processing gain of 15 dB .

<sup>‡</sup> UL and DL noise bandwidth is 5MHz.

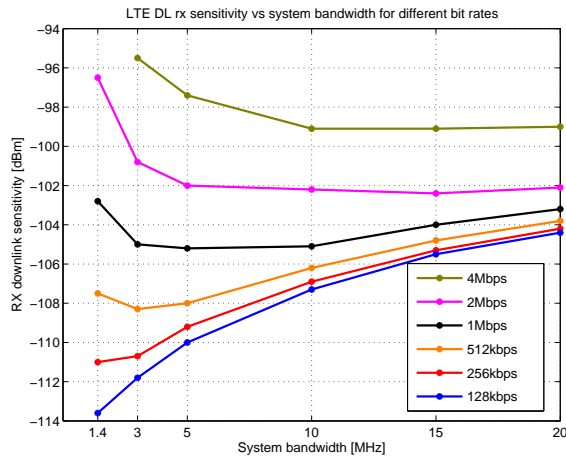


Figure 1. LTE downlink sensitivity versus system bandwidth for different bitrates, channel unaware scheduling. Total system bandwidth is allocated to a single user.

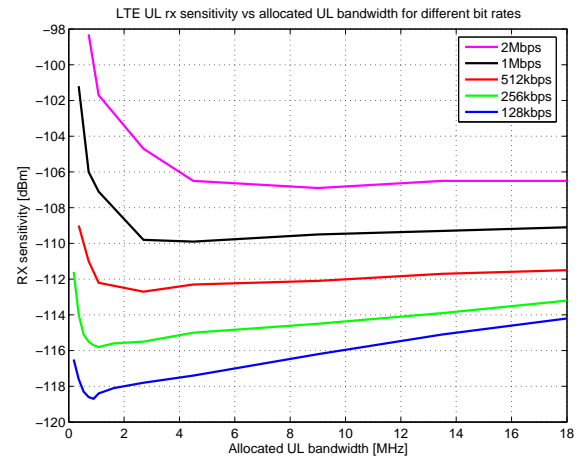


Figure 2. LTE uplink sensitivity versus allocated bandwidth for different bitrates, channel unaware scheduling.

### 3.1. SINR under random (uncoordinated) interference

At cell edge, the interference from  $K$  neighbouring cells can be written as ( $I = I_{other}$ )

$$I = \sum_{k=1}^K \gamma_k I_{max,k} \quad (3)$$

$$= \gamma I_{max}, \quad (4)$$

where  $I_{max} = \sum_{k=1}^K I_{max,k}$  is the maximum interference power at cell edge, and  $\gamma_k$  is the sub-carrier activity factor of the  $k$ th cell. We assume that the average cell load is equal for all cells, in other words,  $\gamma_k = \gamma$ , for all  $k$ .

Signal-to-Interference-and-Noise ratio can be written as a function of SNR, SIR and cell load  $\gamma$  as

$$\text{SINR} = \frac{S}{I + N} \quad (5)$$

$$= \frac{S}{\gamma I_{max} + N} \quad (6)$$

$$= \frac{1}{\frac{\gamma}{\text{SIR}_{min}} + \frac{1}{\text{SNR}}}, \quad (7)$$

where  $\text{SIR}_{min} = \frac{S}{I_{max}}$  and  $\text{SNR} = \frac{S}{N}$ . We again emphasize that all quantities are average values, where the averaging is over small-scale fading of  $S$  and  $I$ . The value of  $\text{SIR}_{min}$  depends on network geometry and antenna configuration (but not on cell range) and is in practice determined from system simulations or network measurements. Typical values are  $\text{SIR}_{min} = -4 \dots -1$  dB. The interference is here implicitly modelled as Gaussian noise, as is the common practice. It always applies that  $\text{SINR} < \gamma^{-1} \text{SIR}_{min}$  and  $\text{SINR} < \text{SNR}$ . Therefore, without inter-cell interference coordination or intelligent channel-aware scheduling, throughput is limited by other-cell interference.

The relation of SINR and SNR is shown in Fig. 3 for different values of network load,  $\gamma$ . It can be seen that even a low network load will saturate SINR, and hence throughput.

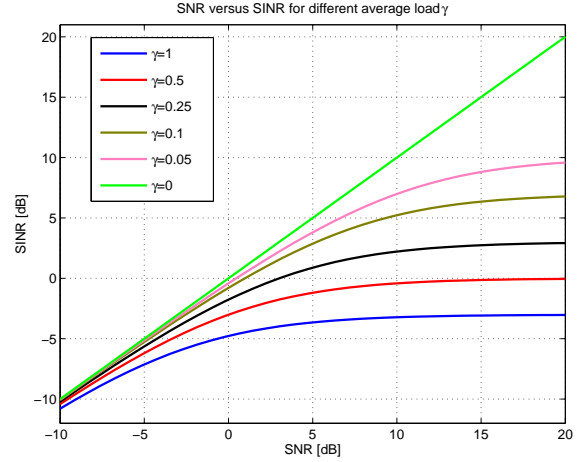


Figure 3. Cell edge SINR versus SNR for different network average loads ( $\gamma$ ),  $\text{SIR}_{min} = -3$  dB.

### 3.2. Link budget with non-negligible interference: Interference Margin

The link budget in Table 2 assumed that interference power is negligible, i.e.,  $\text{SNR} \gg \frac{\text{SIR}_{min}}{\gamma}$  in Eq. (7). When this is not the case, target SNR in the noise-limited link budget must be substituted with the modified SNR target

$$\text{SNR}_{\text{intf}} = \text{SINR} + \text{NR}, \quad [\text{dB}] \quad (8)$$

where NR denotes noise power rise due to interference, and SINR is derived from the throughput target. Cell range can then be solved in the usual manner from  $\text{SNR}_{\text{intf}}$  where the received signal power,  $S$ , is a function of path loss (cell range) and effective isotropic transmit power. What remains to be done is to obtain an expression for the noise rise. Before doing so, it is useful to note, again, that SINR can at cell edge never exceed  $\frac{\text{SIR}_{min}}{\gamma}$  in Eq. (7). As  $\text{SINR} \rightarrow \frac{\text{SIR}_{min}}{\gamma}$ , SNR must in turn increase in order to keep SINR less than its upper limit. Therefore, one sees that the noise rise in Eq. (8) will be huge when the target SINR approaches  $\frac{\text{SIR}_{min}}{\gamma}$ , hence drastically

shrinking the cell size.

Graphically, the same concept can be seen in Fig. 3 where the noise rise is the difference between the noise-limited case ( $\gamma = 0$ ) and loaded case, see Eq. (8). For example, with 100% load the noise rise is 23dB at SNR = 20dB. As SINR approaches  $SIR_{min} = -3$  dB, large increase in SNR is required for diminishing gains in SINR, and therefore cell edge throughput.

To derive formula for the noise rise, we first define in linear scale

$$NR = \frac{I + N}{N} \quad (9)$$

$$= \frac{SNR}{SINR}. \quad (10)$$

Substituting,  $SNR = NR \cdot SINR$  in Eq. (7) and solving for NR results in

$$NR = \frac{1}{1 - \gamma \frac{SINR}{SIR_{min}}}. \quad (11)$$

Here SINR depends on the cell edge throughput target and  $SIR_{min}$  on the network geometry. One can see that noise rise is very steep near the pole  $SINR = \frac{SIR_{min}}{\gamma}$ . Therefore, it is increasingly difficult to reach the upper limit cell edge throughput.

### 3.3. Trade-off between cell range, network load and cell edge throughput

In this section we illustrate the relationship between the three basic network planning variables: cell range, average network load and cell edge throughput. Towards this end, we write

$$SNR = \frac{S}{N} \quad (12)$$

$$= \frac{EIRP}{LN}, \quad (13)$$

where EIRP is the effective isotropic radiated power, and  $L$  is the path loss, given in linear scale as

$$L = MA d^B. \quad (14)$$

Here  $A$  is the median path loss at one kilometer distance (depends on carrier frequency and propagation environment),  $B$  is the path loss exponent,  $d$  is the distance in kilometers and  $M$  is the shadow-fading margin.

In linear scale, SINR as a function of cell range  $d$  and network load  $\gamma$  is

$$SINR = \frac{1}{\frac{\gamma}{SIR_{min}} + \frac{MA d^B N}{EIRP}} \quad (15)$$

There is a one-to-one mapping between SINR and average throughput. Therefore, (15) describes the tradeoff between  $\gamma$ ,  $d$  and throughput. In the sequel, the three two-dimensional special cases are considered.

In the sequel, path loss model is based on 3GPP system LTE system simulation specification according to  $L[\text{dB}] = 128 + 37 \log_{10}(d)$  [4]. Shadowing standard deviation is 8dB with shadowing margin of  $M = 8.7\text{dB}$  (95% single-cell area probability) and building penetration loss of 20 dB. Other parameters are as given in Table 2, except that system bandwidth is 10 MHz. The SINR-throughput mapping was simulated for a  $2 \times 2$  transmit diversity system.

#### 3.3.1. Cell range vs network load, fixed cell edge throughput

In Fig. 4, the relation of network load and cell range is shown for various values of cell edge throughput. As network load increases, the cell range decreases for fixed cell edge throughput.

#### 3.3.2. Network load vs cell edge throughput, fixed cell range

In Fig. 5, the relation of network load and cell edge throughput is shown for various values of cell range. For our later discussion concerning inter-cell interference coordination, it is instructive to note that when cell range is small, cell edge throughput is sensitive to network load. For cell range of 0.5km, if one was able to reduce effective network load from 0.4 to 0.1 cell edge throughput would double from 6 Mbps to 12 Mbps. Such a reduction could be possible

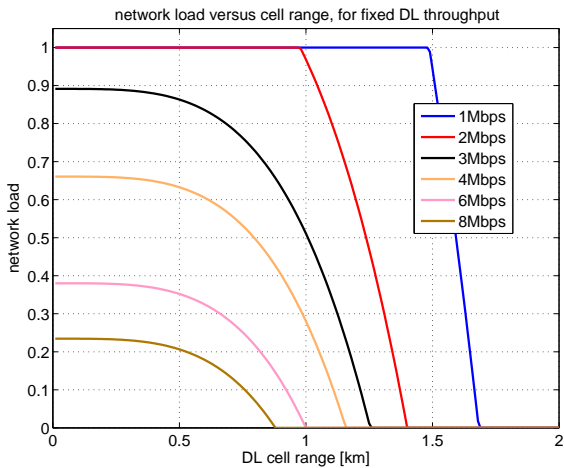


Figure 4. Network load versus cell range for fixed downlink cell edge throughput.

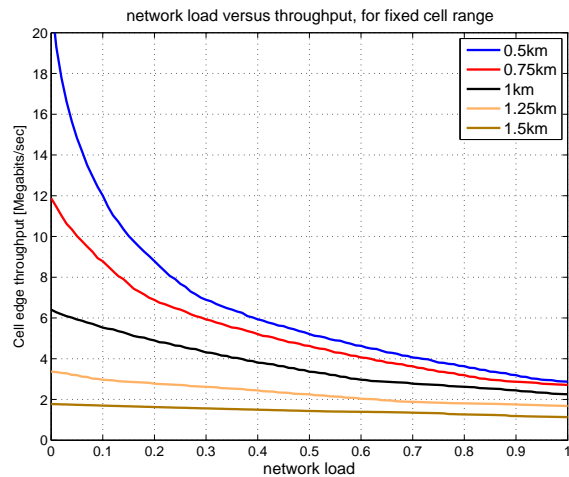


Figure 5. Network load versus cell edge throughput for fixed cell range.

by applying interference coordination between neighboring cells, hence directing interference to other part of the frequency spectrum. This will be discussed further later in this paper.

### 3.3.3. Cell range versus cell edge throughput, fixed network load

In Fig. 6, the relation of cell range and cell edge throughput is shown for various values of network load. As the cell range increases, the cell edge throughput approaches the same limit regardless of cell load. Even the low network load of 10% limits throughput to less than 14Mbps by creating a noise floor from other-cell interference. It should be noted that downlink common channels, SCH and BCCH, alone cause at least > 10% network load over the  $\approx 1$  MHz bandwidth over which they are transmitted. On top of this, reference signals are transmitted over the entire system bandwidth. Early network implementations are expected to be non-frame-synchronized, so that it is not possible to avoid interference by cleverly coordinating transmission in time and frequency.

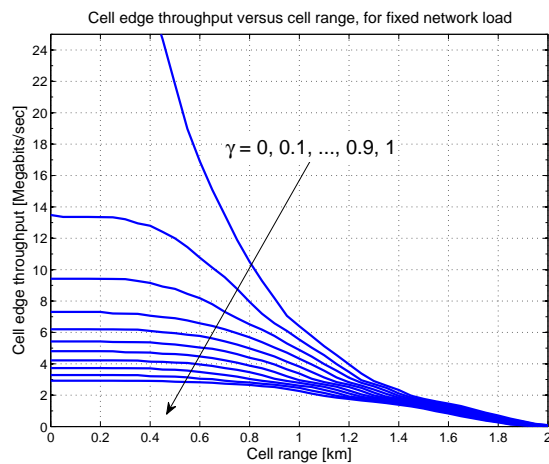


Figure 6. Cell range versus cell edge throughput for fixed network load.

## 4. MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) CONFIGURATIONS

### 4.1. MIMO Transmission Schemes in LTE

While in common engineer talk there are appears to be several interpretations for the term, in this paper MIMO is taken to mean any radio interface that has at least two antennas at both ends, i.e., with this definition smallest MIMO antenna configuration would then be  $2\text{Tx} \times 2\text{Rx}$ . Note that in LTE all UEs are required to have two receive antennas, while the number of base station antennas can be<sup>2</sup> 1, 2, or 4. In principle, there are three ways to utilize MIMO antennas:

- *Combined transmit/receive diversity*: Normal two-branch diversity reception or transmission has the benefit of producing two copies of the same signal for reception, which with a suitable signal combining technique reduces fading variation. Similarly, a  $2\text{Tx} \times 2\text{Rx}$  antenna transmission results in reception of four signal replicas, with the corresponding additional reduction in fading. This version of MIMO is hence simply an enhanced diversity scheme, and as such is not by many considered "true" MIMO, since it does not actually increase transmission data rate. In LTE, space-frequency block coding based diversity scheme is used; this is an open-loop scheme where UE feedback (CQI) is not required at the base station.
- *Beamforming*: This is very similar to the diversity transmission, the main nomenclatural difference being that in beamforming one typically considers a physical antenna beam being constructed towards the UE.

<sup>2</sup>With precoding using UE-specific reference signals ("beamforming") arbitrary number of antennas can be used. However, this transmission scheme is not expected to be supported in first vendor releases, due to hesitance from operators to deploy antenna arrays. The coverage gains from such configuration in rural/road environments would be substantial however, e.g., 9 dB from an 8-antenna panel array.

This requires closely spaced antennas, unlike the diversity schemes which require at least a few wavelength antenna spacing. Beamforming using 3GPP codebook also requires CQI feedback from UE. Mathematically, both beamforming and transmit diversity are both special cases of so-called rank-1 precoding<sup>3</sup>. LTE Rel 8 supports rank-1 precoding (or, "beamforming") using pre-defined 3GPP codebook (for 2 and 4 antennas), and any vendor-specific beamforming when using UE-specific reference signals (arbitrary number of base station antennas).

- *Spatial Multiplexing*: This is what many consider to be a true MIMO transmission scheme. With beamforming and diversity, base station transmits a single stream of information but uses the multiple antennas to either reduce fading (diversity) or increase signal power (beamforming). On the other hand, with  $2\text{Tx} \times 2\text{Rx}$  spatial multiplexing the idea is to transmit two parallel information streams over the same bandwidth, hence theoretically doubling the data rate and spectral efficiency. Looking back, from the WCDMA multiuser detection schemes, where receiver simultaneously detects signals from two or more sources<sup>4</sup>, it is but a minor step of thought to move to MIMO spatial multiplexing by considering that now the two received information signals originate from two different antennas of the same subscriber (instead of two different subscribers with one antenna each); the mathematical signal model is in both cases the same. From this point of view, the spatial multiplexing is very similar to multiuser detection, originally devised for CDMA systems in the 80s. With single-user dual-stream spa-

<sup>3</sup>In this paper, rank-1 precoding and beamforming are considered synonymous.

<sup>4</sup>A conventional non-multiuser detection receiver would simply consider the signal from other source as noise.

tial multiplexing the data rate is doubled, under ideal conditions. Both open-loop (only channel rank and CQI reported by UE) and closed-loop spatial multiplexing are supported (also precoding matrix information reported by UE). In uplink, spatial multiplexing is not supported for a single UE, but two different UEs are allowed to transmit at the same time; this is called multiuser-MIMO. Delving slightly in implementation details, in LTE both open-loop and closed loop spatial multiplexing have been engineered in such a way that symbols in information streams are interleaved between the MIMO subchannels. Thus, the average SINR experienced by the transmitted symbols is the average of the two MIMO subchannels' SINRs.

In practice, the choice of transmission scheme depends on instantaneous radio channel conditions and is adapted continuously. The main difference to non-MIMO transmission that, in addition to SINR, now also the channel rank has to be considered, since spatial multiplexing is feasible only if the instantaneous radio channel (during 1ms TTI) supports transmission of more than one information stream, or in terms of matrices, the  $2\text{Tx} \times 2\text{Rx}$  matrix channel's condition number and SINR are good enough. As a rule of thumb, in a spatially uncorrelated channel spatial multiplexing becomes useful when  $\text{SINR} > 10$  dB. Looking at Fig. 3 one can see that this requires very low network load for spatial multiplexing to work at cell edge, assuming that other-cell interference is uncoordinated.

#### 4.2. Benefit of MIMO

The benefits of different MIMO schemes in downlink are roughly as follows:

*Transmit/receive diversity:* Compared to  $1\text{Tx} \times 2\text{Rx}$  the gain of  $2\text{Tx} \times 2\text{Rx}$  is about 6 – 7 dB due to following factors: i) transmit power is doubled by adding another amplifier (3dB); ii) average received signal power is doubled because of two-antenna reception (3dB); iii) di-

versity from four signal paths brings additional gain which however strongly depends on the propagation environment (here pessimistically assumed 0 – 1dB, higher gains are possible).

*Beamforming (rank-1 precoding):* For slow-moving UEs the gain is 1 – 2 dB higher than with the transmit/receive diversity. For fast-moving mobiles this improvement over diversity diminishes, or goes negative, since the CQI feedback cannot track the channel fast enough.

*Spatial multiplexing:* This scheme does not improve link budget, but increases data rate. With two antennas and an ideal MIMO radio channel, the data rate would be doubled. In practice, gains are considerably smaller due to the fact that for ideal operation the SINR of the two parallel subchannels should be high enough to support the same modulation and coding scheme. This is very rarely the case, and the second stream must be transmitted at lower information bit rate. This point is further illustrated in the following subsection.

#### 4.3. Example of Measured MIMO Radio Channel

Spatial multiplexing transmission is feasible only at those time instants when the radio channel conditions are favorable. There exist a wealth of literature on the theory of MIMO communication systems, and the interested reader is referred to the references. From radio planning point of view, the  $2\text{Tx} \times 2\text{Rx}$  MIMO channel power response  $\lambda$  at any given time instant can be written, on a point frequency, as<sup>5</sup>  $\lambda = \lambda_1 + \lambda_2$ , where  $\lambda_1$  and  $\lambda_2$  are the power responses of the first and second MIMO subchannels, respectively. Each of the subchannels carries one information stream. As with a normal non-MIMO channel, the powers of the subchannels experience signal fading. If the power of the weaker subchannel, say  $\lambda_2$ , is very weak, the second information stream should not be transmitted at that time instant, since it will either be

<sup>5</sup>The symbol  $\lambda$  is used here for historical reasons, since the MIMO subchannel power is related to the eigenvalues of the MIMO radio channel.

buried in noise, or alternatively, from link adaptation point of view, it is more spectrally efficient to transmit one stream with higher-order modulation and/or less channel coding. In either case, usage of spatial multiplexing depends on the instantaneous channel conditions which are reported to, and tracked, by the base station. When the second subchannel is weak, the channel is said to have "rank one", and spatial multiplexing is not used<sup>6</sup>.

Fig. 7 presents an example of a narrow-band measurement of a  $2\text{Tx} \times 2\text{Rx}$  channel in an urban environment at 2.1 GHz carrier frequency. Two base station antenna configurations are shown: i) two vertically polarized transmit antennas at 3 wavelength separation ( $||$ ); ii) two cross-polarized transmit antennas at 0 deg and 90 deg angles ( $+$ ). The dual-branch UE antenna is a realistic terminal microstrip antenna integrated in the terminal chassis, whose branch polarizations are not well-defined, as is typically the case for small integrated antennas. The figure shows the powers of the two MIMO subchannels as a function of travelled distance. Roughly in the midpoint of the measurement route the UE enters line-of-sight and the signal power of the stronger stream ( $\lambda_1$ ) increases. The second stream power behaves differently for the two antenna setups. With the cross-polarized antenna base station setup the second stream ( $\lambda_2$ ) is about 15 dB weaker than the stronger one. In contrast with the vertically polarized antennas the second stream is about 30 dB weaker. Thus, if the channel SINR is 20 dB, with the cross-polarized configuration the first stream SINR would be almost 20dB while the second stream would experience about  $\text{SINR} \approx 5$  dB which would still allow fairly high bit rate transmission over the second MIMO subchannel. However, with the vertically polarized antennas the second stream would be  $\text{SINR} \approx -10$  dB, which would not support high-rate trans-

mission of the second stream.

Fig. 8 illustrates the same measurement routes using two different figures of merit, namely the total MIMO channel power response and ratio of MIMO subchannel powers,  $\frac{\lambda_1}{\lambda_2}$ . From the upper subplot it can be seen that the total power responses of the two antenna setups are slightly different. Vertically polarized configuration has almost negligibly higher received power in the line-of-sight, while the cross-polarized configuration, in turn, has slightly better power response in non-line-of-sight. From the lower subplot we note that the cross-polarized antenna setup has advantage in terms of the second subchannel power in line-of-sight conditions; the second subchannel is about 10 dB weaker than the first, compared to the 30 or so dBs for the vertically polarized case.

Summarizing the main radio planning message from the two figures:

- Dual-stream transmission is only feasible when the SINR of the second subchannel is high enough. This depends on the total channel SINR and the ratio of the subchannel powers.
- Base station antenna configuration has impact on the spatial multiplexing performance in two respects: total received signal and spatial multiplexing gain.
- In terms of total received signal power, the two compared antenna configurations are roughly equal with slight advantage for v-pol in line-of-sight, and vice versa in non-line-of-sight.
- In terms of spatial multiplexing gain, x-pol has large advantage in line-of-sight. There is no noticeable difference in non-line-of-sight.

The results indicate that cross-polarized base station antenna configuration should be favored when usage of spatial multiplexing is desired, as it offers more robust performance in all channel

<sup>6</sup>Mathematically, the rank of the  $2\text{Tx} \times 2\text{Rx}$  channel is practically always two, so this terminology is strictly speaking a misnomer.

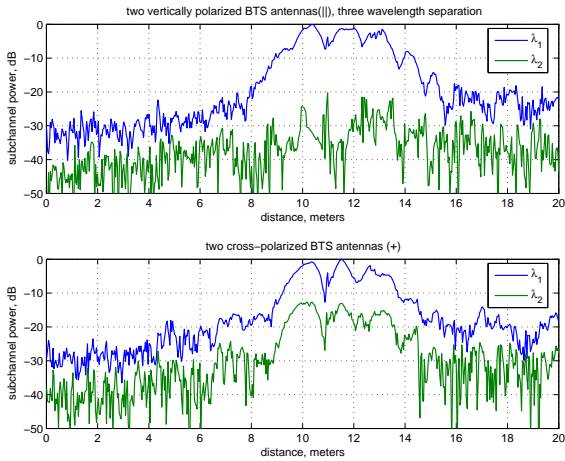


Figure 7. Example of measured MIMO radio channel, power response of the MIMO subchannels for two base station antenna configurations.

conditions. While these conclusions are in this paper illustrated by means of a single measurement example, similar conclusions have been drawn from large channel measurement campaigns reported in literature [5].

## 5. RADIO RESOURCE MANAGEMENT FEATURES

So far, we have discussed a simple "baseline" LTE radio configuration, assuming fully random (uncoordinated) interference and no special radio resource management features. The LTE radio interface specification Release 8 includes several air interface functionalities that potentially improve network performance in certain environments. These are explained in the following.

### 5.1. Frequency-Aware UL/DL Scheduling

Baseline scheduler assumes no knowledge of the instantaneous frequency response of the radio channel. For slow-moving UEs such knowledge is available at the BTS in the form of sub-

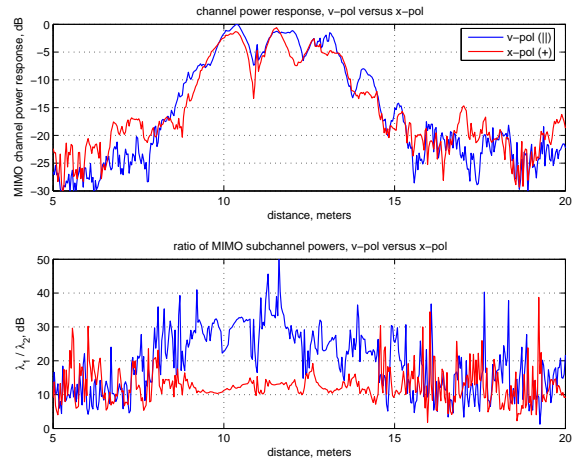


Figure 8. Example of measured MIMO radio channel, total channel power response and subchannel power ratio for two base station antenna configurations.

band CQI feedback from UE. In case there is only a single user to be scheduled in downlink, it is optimal to allocate whole bandwidth, since this offers highest coding gain. In UL, the optimal bandwidth for a single simultaneous user may be less than the system bandwidth, see Fig. 2 for an example. Focusing on the downlink, in the case there are multiple simultaneous UEs to be scheduled during a TTI, the base station can schedule each UE in the frequency subband with the strongest channel power response, hence avoiding fading dips in frequency domain. This results in frequency-domain multiuser scheduling gain, which can be quantified in terms of network-level throughput gain and cell edge throughput gain.

Practical (including system imperfections) achievable downlink multiuser scheduling network-level throughput gains have been simulated to be about  $< 30 - 40\%$  at network level, for 3 – 7 users [6]. For the cell edge, throughput can be almost doubled with a suitable schedul-

ing algorithm (always vendor-dependent). Here the gain should be interpreted relative to the throughput of a frequency-unaware scheduler with the same instantaneous number of users per TTI. Of course, even if the network-level throughput increases, actual per-user throughput will decrease when the number of simultaneous users increases.

Another benefit of the frequency-aware scheduling emerges in case the time correlation of other-cell interference power is long enough so that the scheduler has time to learn the interference spectrum and divert transmission to a cleaner part of the system bandwidth. This is only possible if UE is moving slowly and the interference is persistent in time over, say, a few dozens of TTIs. This interference rejection gain can be seen similar to what is obtained from inter-cell interference coordination, to be discussed next.

## 5.2. Inter-Cell Interference Coordination

There are two basic methods to coordinate frequency usage between cells in a network: static and dynamic. Static coordination means fixed allocation of frequency resources per cell over extended periods of time while dynamic frequency allocation means fast coordination within a time frame of seconds or even less, without need for manual operator intervention. In LTE, dynamic inter-cell interference coordination is inherently supported by 3GPP-specified signalling between base stations.

The network-level throughput gain from frequency use coordination is most visible with low-to-medium network load; when the network load is high no coordination will help since all frequency resources of all cells tend to be used most of the time. Hence, interference coordination is most useful for non-congested networks. Looking at Fig. 5, considerable cell edge throughput gains are possible if one can reduce the effective network load seen by the UE by allocating neighbor cell frequency resource on a different part of the system bandwidth. From Fig. 5, if the cell ra-

dius is small the throughput gain can be considerable. At network-level, throughput gains similar to channel-aware scheduling have been reported in literature for low-to-medium network loads ( $\gamma < 50\%$ ). Summarizing, inter-cell interference coordination is mostly useful in small-range cells during off-peak hours or during early phases of network life cycle.

## 5.3. Uplink Fractional Power Control

LTE supports both cell-specific and UE-specific uplink power control. In LTE downlink, there is no power control in the conventional sense. With LTE power control scheme it is possible to compensate only a fraction of the path loss, reducing transmit power of cell edge UEs that generate most of the interference to other cells. This is in contrast to conventional power control schemes that attempt to compensate path loss to the full extent allowed by the UE transmit power. The benefit of the fractional scheme is that, due to reduction in UE transmit power, network-level interference is reduced and overall UL throughput is increased. This improvement is at the expense of reduction in cell edge UL throughput. For each optimization goal - maximizing cell edge throughput or network throughput - there exist an optimum optimum power control parameter set. For early system simulation examples, see [7].

## 6. CONCLUSION

In this paper topics related to radio planning in LTE were discussed. Besides the link budget for coverage and interference-limited cases, the tradeoff between cell range, cell edge throughput and network load was discussed under uncoordinated interference. Impact of MIMO and antenna configurations was illustrated using a measurement example. Finally, some advanced radio resource management features were briefly reviewed.

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