

# Mobility Parameter Planning for 3GPP LTE: Basic Concepts and Intra-Layer Mobility

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This white paper discusses the design of intra-layer mobility parameters for 3GPP LTE radio networks. Firstly, basic UE measurements defined in 3GPP Release 9 are reviewed. A measurement example illustrates their basic differences. Both idle mode and connected mode measurements and cell change rules from 3GPP are summarized in a vendor-independent way. Secondly, design criteria for setting handover margin, time to trigger and measurement filtering coefficient are discussed in detail. A simple parameter design example is given. The scope of this paper is limited to a review basic of concepts and design of intra-layer (intra-frequency) mobility parameters.

## 1. INTRODUCTION

This technical white paper introduces idle and connected mode mobility parameter design for 3GPP LTE. The target audience are radio planning and optimization engineers with some experience in LTE. Principles of OFDMA and SC-FDMA, as described in 3GPP LTE specifications, will not be repeated in this paper. Instead the reader is referred to well-known literature references [1–3]. Both FDD and TDD variants of LTE radio interface are addressed and the difference between the two is highlighted, where necessary.

In Section 2 Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ) are defined and their properties discussed. The relation of RSRQ to signal-to-noise-plus-interference ratio (SINR) is shown, and complemented by a measurement example illustrating the properties and interdependencies of the different RF measurement quantities. To keep the paper self-contained, Section 3 summarizes the idle mode mobility rules for 3GPP Rel9, while Section 4 does the same for connected mode handovers; the treatment is kept as vendor-independent as possible. In the key section of this paper we outline criteria on how to design handover parameters for practical network deployment. The selection of handover

margin, time to trigger and L3 filtering coefficient is a trade-off between network interference, probability of unnecessary ("ping-pong") handovers and too late handover triggering. Finally, a design example summarizes the key points of the paper.

The primary goal of the paper is to introduce some ideas for planning intra-layer mobility parameters. Post-launch mobility parameter tuning based on network measurements are very case-specific topics and beyond the scope here.

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## Abbreviations

BCCH	Broadcast Channel
CPICH	Common Pilot Channel
FDD	Frequency Division Multiplexing
LTE	Long Term Evolution
NAS	Non-Access Stratum
OAM	Operation and Maintenance
PCH	Paging Channel
PCI	Physical Cell Identity
PDSCH	Physical Downlink Shared Channel
PRB	Physical Resource Block
PSS	Primary Synchronization Signal
RAT	Radio Access Technology
RE	Resource Element
RRC	Radio Resource Control
RS	Reference Signal
RSCP	Received Signal Code Power
RSRQ	Reference Signal Received Quality
RSRP	Reference Signal Received Signal
RSSI	Received Signal Strength Indicator
SIB	System Information Block
SINR	Signal-to-Interference-Noise-Ratio
SNR	Signal-to-Noise Ratio
SSS	Secondary Synchronization Signal
TDD	Time Division Multiplexing
TTI	Transmission Time Interval
UE	User Equipment
USIM	UMTS Subscriber Identity Module

## 2. DEFINITION OF RSRP AND RSRQ

In this section, RSRP and RSRQ are defined, including their relation to SINR. A measurement example is shown to illustrate the main points.

### 2.1. Reference Signal Received Power (RSRP)

RSRP is defined as

$$\text{RSRP} = \frac{1}{K} \sum_{k=1}^K P_{\text{rs},k}, \quad (1)$$

where  $P_{\text{rs},k}$  is the estimated received power (in Watts) of the  $k$ th Reference Signal Resource Element transmitted from the first BTS antenna port. In Figure 1 these REs are denoted with

$R_0$ . To improve the accuracy of the RSRP estimate, the UE may optionally also measure the RS transmitted from the second antenna port ( $R_1$ ), if present. In case of four BTS transmit antennas, Reference Signals of the third and fourth BTS antenna ports are not used in the RSRP measurement. Since all LTE UEs have at least two receive antennas, it is also mandated by [6] that the RSRP must be equal or higher than the stronger of the two receive antennas' individual measured RSRP.

The maximum number of PRBs over which RSRP should be measured<sup>1</sup> is sent to the UE over RRC signalling, and is denoted in this paper with  $N_{\text{prb}}$ . For example, in case of 10MHz measurement bandwidth ( $N_{\text{prb}} = 50$ ), the OFDM symbol carrying  $R_0$  (Figure 1) contains a total of 100 REs for  $R_0$ , hence in this case  $K = 100$  in Eq. (1) for this OFDM symbol<sup>2</sup> assuming UE implementation does not use  $R_1$  in RSRP estimation.

RSRP measures only the RS power and excludes all noise and interference power. Thus RSRP is a purely coverage-based handover trigger which is ideally independent of the network load, similar to CPICH RSCP in 3G. It should be noted that, since it is defined as the average power of RS resource elements, RSRP does not depend on the number of BTS transmit antennas.

The reporting range of RSRP is divided in 1dB bins over  $-140 \dots -44$  dBm, the lowest RSRP value having reported value of '0'.

The 3GPP specification does not specify how the RSRP measurement should be implemented in a UE. However, the RSRP measurement accuracy requirements are stated in some detail in [5], see Table 1 for a summary. Under normal operating conditions, absolute measurement ac-

<sup>1</sup>Measurement bandwidth can be less than the actual downlink system bandwidth. This is useful for keeping measurement parameter configuration simple in multi-bandwidth deployment scenarios.

<sup>2</sup>3GPP specification does not state any requirements on how many OFDM symbols UE should average. Only measurement accuracy requirement is stated.

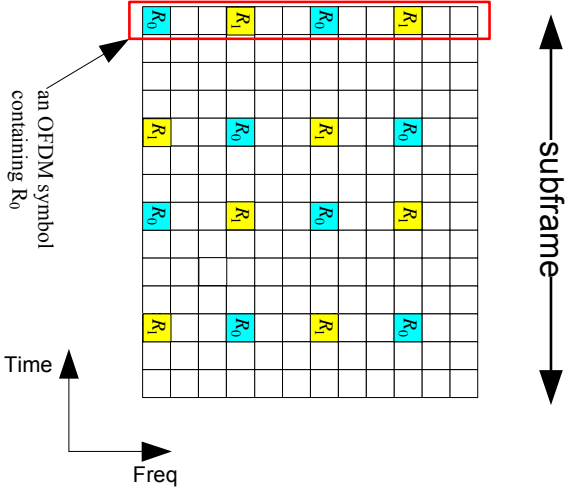


Figure 1. Reference Signals as seen by UE, shown for transmit antenna port 1 ( $R_0$ ) and transmit antenna port 2 ( $R_1$ ) for one 1ms subframe and 12 subcarriers.

accuracy is allowed to have up to 6dB error for intra-frequency RSRP measurement. Measured RSRP difference between serving and a neighbour cell on the same carrier frequency should have at most 3dB error. For inter-frequency RSRP measurement, the absolute and relative error under normal conditions should both be less than 6dB. It can be seen that inter-frequency RSRP measurement is considerably less accurate for "power budget" type handover triggering than intra-frequency RSRP measurement.

The above cited measurement accuracy requirements hold for  $\text{SNR} = -6\text{dB}$  and without any higher layer measurement filtering. Higher SNR and application of L3 filtering results in improved measurement accuracy. Therefore, in typical network conditions, measurement error can be expected to be smaller than shown in Table 1.

Table 1

UE RF measurement L1 accuracy requirements.

Parameter	Absolute Accuracy*	Relative Accuracy*
RSRP intra-freq	$\pm 6\text{dB}$	$\pm 3\text{dB}$
RSRP inter-freq	$\pm 6\text{dB}$	$\pm 6\text{dB}$
RSRQ intra-freq	$\pm 3.5\text{dB}$	n/a
RSRQ inter-freq	$\pm 3.5\text{dB}$	$\pm 4\text{dB}$

\* When  $\text{SNR} \geq -6\text{dB}$ ,  $\text{RSRP} \geq -127 \dots -124\text{dBm}$  depending on frequency band [5].

## 2.2. Reference Signal Received Quality (RSRQ)

Reference Signal Received Quality is the ratio of RSRP and total received signal and noise power normalized to 1PRB bandwidth. As a formula we have

$$\text{RSRQ} = N_{\text{prb}} \frac{\text{RSRP}}{\text{RSSI}} \quad (2)$$

$$= N_{\text{prb}} \frac{\frac{1}{K} \sum_{k=1}^K P_{\text{rs},k}}{\sum_{n=1}^{N_{\text{re}}} P_n}, \quad (3)$$

where  $N_{\text{re}} = 12N_{\text{prb}}$  is the total number of REs (including RS REs) in the measurement bandwidth  $N_{\text{prb}}$ , and  $P_n$  is the total received power on the  $n$ th RE. The RSSI term in the denominator of Eq. (3) is the sum power received over the OFDM symbol that contains  $R_0$ , including own cell power, thermal noise and interference from other cells. For example, for 10MHz (50PRBs) measurement bandwidth  $N_{\text{re}} = 600$  and, assuming that only  $R_0$  is measured,  $K = 100$ .

As with RSRP, implementation of the RSRQ measurement is not defined in detail by 3GPP. Measurement accuracy requirements are given in Table 1. It can be seen that no relative accuracy requirement has been defined for intra-frequency RSRQ. This is because in intra-frequency case the ratio of RSRQs depends only on the ratio of RSRPs of serving and neighbour cells. This can be seen by writing down the RSRQ ratio between two cells on the same car-

rier frequency, that is,

$$\frac{\text{RSRQ}_{\text{serv}}}{\text{RSRQ}_{\text{neigh}}} = \frac{N_{\text{prb}} \frac{\text{RSRP}_{\text{serv}}}{\text{RSSI}}}{N_{\text{prb}} \frac{\text{RSRP}_{\text{neigh}}}{\text{RSSI}}} = \frac{\text{RSRP}_{\text{serv}}}{\text{RSRP}_{\text{neigh}}}, \quad (4)$$

since RSSI does not depend on the measured cell as it is simply the total received signal power<sup>3</sup>. Therefore, the ratio of RSRQs only depends on the ratio of the RSRPs. This essentially makes relative RSRQ redundant as a trigger for intra-frequency handover. In contrast, ratio of RSRQs may be a useful trigger for inter-frequency handover where it can be used to direct UEs to a less loaded layer.

The reporting range of RSRQ is divided in 0.5dB bins over  $-19.5 \dots -3$  dB, the lowest RSRQ value having reporting value '0'. For unloaded cell having one transmit antenna port, we have  $\text{RSRQ} = -3\text{dB}$ , assuming no other-cell interference and negligible thermal noise. Similarly, a cell with two transmit antenna ports has  $\text{RSRQ} = -6\text{dB}$ . On the other hand a fully loaded 1Tx cell has  $\text{RSRQ} \approx -11\text{dB}$ , again neglecting any neighbour cell interference and thermal noise. Therefore, from mobility parameter planning viewpoint, setting any RSRQ-based handover trigger to a value higher than  $-11\text{dB}$  could result in "ping-ponging" if UE happens to measure RSRQ at a time instant when there is data download ongoing in the serving cell. Because of this dependency on the instantaneous traffic load, RSRQ measurements should be averaged over a longer period than RSRP. This is very similar to the fluctuation of CPICH  $E_c/N_0$  seen in HSDPA networks.

### 2.3. Relation of RSRQ and SINR

It is a common practice to use Signal-to-Interference Ratio (SINR) as an indicator for network quality. It should be however noted that 3GPP specifications do not define SINR and

<sup>3</sup>Since RSRQ is in general measured at different time instants for the serving and the neighbour cell, instantaneous RSSI could actually be different depending on fading variations and subcarrier activity during the measured subframes. Time-averaged RSSI could however be assumed approximately equal for serving and neighbour cell.

therefore UE does not report SINR to the network. SINR is still internally measured by most UEs and recorded by drive test tools. Unfortunately UE chipset and RF scanner manufacturers have implemented SINR measurement in various different ways which in the authors' field experience are not always easily comparable. While at first it may seem that defining SINR should be unambiguous, in case of LTE downlink this is not the case. This is because different REs within a radio frame carry different physical signals and channels each of which, in turn, see different interference power depending on inter-cell radio frame synchronization. For example, in a frame-synchronized network SINR estimation based on synchronization signals (PSS/SSS) results in different SINR than SINR estimation based on Reference Signals, since in the latter case the frequency shift of the RS depends on the PCI plan. This is illustrated in Figure 3, and will be discussed in more detail in the sequel.

In what follows we show one way of converting RSRQ to SINR. Towards this end, we first define average subcarrier SINR as

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

where  $I$  is the average interference power and  $N$  is the thermal noise power. All quantities are measured over the same bandwidth and normalized to one subcarrier bandwidth. In OFDM own cell interference is often assumed to be negligible and consequently  $I$  is due to other cell interference only. RSSI reads

$$\text{RSSI} = S_{\text{tot}} + I_{\text{tot}} + N_{\text{tot}}, \quad (6)$$

where the subscript 'tot' indicates that the power is measured over the  $12N_{\text{prb}}$  subcarriers of the measurement bandwidth. The total serving cell received power depends on the number of transmitted subcarriers in the OFDM symbol carrying  $R_0$ , and on the number of transmit an-

tennas<sup>4</sup>. We can model this impact using the per-antenna subcarrier activity factor  $\rho$  and set

$$S_{\text{tot}} = \rho 12N_{\text{prb}} \text{RSRP}. \quad (7)$$

The value of  $\rho = 1$  indicates full load such that all subcarriers of one transmit antenna are transmitted for the OFDM symbol carrying  $R_0$ . If only RS is transmitted (i.e., unloaded cell) the resulting subcarrier activity factors would be  $\rho = \frac{1}{6}$  and  $\rho = \frac{1}{3}$  for one and two transmit antennas, respectively; Figure 1 illustrates this. When calculating  $\rho$  for two transmit antennas, one should take into account that REs overlapping with adjacent antenna RS transmission are muted, and therefore, for example, in a fully loaded 2Tx cell the scaling factor is  $\rho = \frac{5}{3}$ , instead of two<sup>5</sup>.

Since subcarrier interference plus noise power is

$$I + N = \frac{I_{\text{tot}} + N_{\text{tot}}}{12N_{\text{prb}}}, \quad (8)$$

by combining the above equations we have the following relation of average subcarrier SINR and RSRQ

$$\text{SINR} = \frac{1}{\frac{1}{12\text{RSRQ}} - \rho} \quad (9)$$

These formulas are illustrated in Figure 2. An uncomfortable property of the RSRQ to SINR mapping is that it depends on the instantaneous serving cell subcarrier activity factor  $\rho$ , which is typically not known in live network measurements. Another problem is the sensitivity of the mapping on RSRQ values; a small change in RSRQ can result in a very large change in SINR which makes such mapping difficult to

<sup>4</sup>For the first OFDM symbol of the subframe this includes RS, PDCCH, PHICH, PCFICH subcarriers. For other OFDM symbols this may include PDSCH, PSS/SSS and PBCH subcarriers, depending on the subframe. Note that  $\rho$  may vary even between different OFDM symbols of the same subframe.

<sup>5</sup>It is assumed that all subcarriers have the same power, i.e., there is no power boosting for any channel.

use in fading radio conditions. Indeed, plotting a RSRQ versus SINR scatter graph from a drive test measurement one rarely obtains such a nice-looking curve as shown in Figure 2.

#### 2.4. Measurement Example

The RF quantities discussed in this section are illustrated by the scanner measurement shown in Figure 3. The scanner location is roughly between two sectors of the same BTS; note that the serving and neighbour cell RSRPs that are within two decibels of each other. In the beginning of the measurement, both cells are fully loaded (all subcarriers are transmitted). After 85 seconds, the neighbour cell PDSCH utilization drops to 0%. At 165 seconds, also the serving cell PDSCH load<sup>6</sup> drops to 0%. The following observations summarize the main points in this section:

- RSRP is independent of own cell load and neighbour cell interference. This illustrates how, from handover triggering point of view, it simply measures coverage similarly to CPICH RSCP in 3G.
- RSRQ reacts to load changes in both serving cell and neighbour cell.
- At the end of the measurement,  $\text{RSRQ} \approx -9\text{dB}$ . This agrees with the theoretical ( $\frac{1}{8}$ ) value when the UE is at cell border of two unloaded cells.
- The RSRQ difference between the two cells is about the same as the RSRP difference. Hence using relative RSRQ as intra-frequency handover trigger is redundant: using relative RSRP alone is sufficient with the added benefit that RSRP measurement is also more robust under bursty network traffic. The relative RSRP can be realized using the A3 measurement event, to be described later in the paper.

<sup>6</sup>BCCH and PCH also use PDSCH, so strictly speaking PDSCH utilization will always be slightly above 0%.

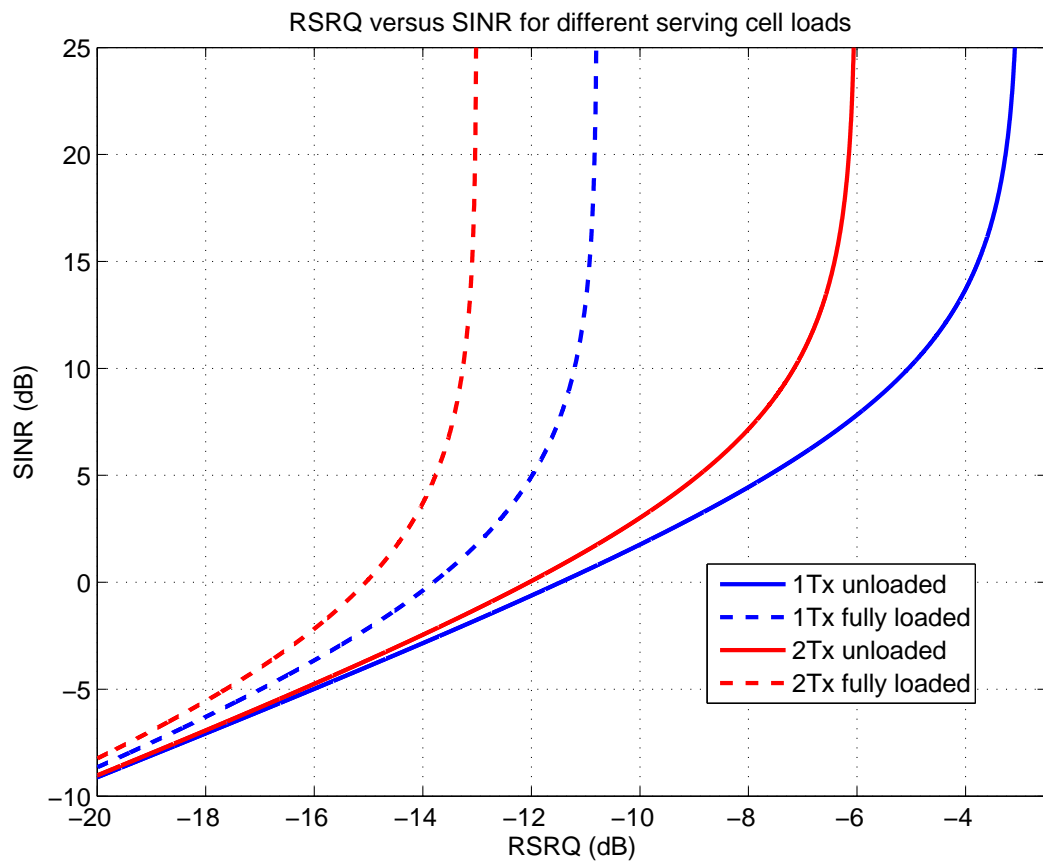


Figure 2. Theoretical comparison of RSRQ versus SINR.

- Since the radio frames are transmitted at the same frame timing in both cells, the Secondary Synchronization Signals (SSS) overlap fully in time. Therefore SINR measured from SSS is continuously close to 0dB, independently of cell loads. In TD-LTE all cells in the network are frame-synchronized, which makes SSS SINR a simple and useful indicator for measuring physical RF dominance.
- Serving cell load does not impact serving cell RS SINR since PDSCH of the serving cell does not overlap with serving cell RS. On the other hand, neighbour cell RS SINR is reduced by serving cell load since serving cell PDSCH overlaps with neighbour cell RS<sup>7</sup>.
- In the beginning of the measurement, where both cells are fully loaded RSRQ  $\approx -15$ dB and SINR  $\approx 0$ dB, which corresponds to Figure 2 for fully loaded 2Tx cell.
- At the end of the measurement, where both cells are idle, serving cell RS SINR  $\approx 15$ dB. Ideally, the RS SINR should be much higher since the reference signals of the two cells do not overlap and only thermal noise limits RS SINR. The exact reason for the RS SINR degradation is unclear, but might be caused by neighbour cell PDCCH colliding with own cell RS. The theoretical SINR in Eq. (9) is defined for the whole measurement bandwidth, while in the scanner measurement shown in Figure 2 SINR is apparently measured based on RS resource elements only (the SINR estimation method used was not documented by the scanner vendor).

<sup>7</sup>In the measurement, the serving and neighbour cell are frame-synchronized and the RSs of these two cells do not collide because of the PCI plan.

### 3. INTRA-FREQUENCY IDLE MODE MOBILITY

#### 3.1. Introduction

3GPP Release 8 specifies idle mode cell reselection rules, which allows defining an absolute priority for a cell; usually all macro cells of a frequency are assigned the same priority. Based on these so-called priority-based cell reselection rules, the UE always selects the network layer (cell) that has the highest absolute priority, provided that the RSRP and RSRQ from the cell are above a configured threshold value<sup>8</sup>. This mechanism is different from the conventional pre-Rel8 cell reselection where the UE reselects to a cell with the best signal level or signal quality, instead of priority. In case the layer priorities are equal the signal level and quality still determine the serving cell even in 3GPP Rel9. The lengthy topic of inter-layer mobility is beyond the scope of this white paper. In this section, we focus on the intra-layer case where all cells are assumed to have equal priority.

The term 'layer' in this paper means a set of cells having the same carrier frequency<sup>9</sup> and radio access technology. With this definition, LTE2600, LTE900, UMTS900, GSM900 are all different layers.

Research papers on the intra frequency handover design and performance include [7] and [8], and many others.

#### 3.2. Initial PLMN and Cell Selection

When powered on, the UE selects the PLMN and the initial serving cell. In the process UE uses pre-stored information saved at previous detach to speed up the initial cell selection. After loss of coverage and in certain NAS signalling failure cases the UE makes a fresh PLMN selection (without pre-stored information) in which different RATs are searched in a UE implementation specific order. Alternatively, the operator can influence the RAT search order by storing radio access priorities on the USIM;

<sup>8</sup>3GPP Rel8 defines only RSRP based threshold.

<sup>9</sup>In case of GERAN the same frequency band.

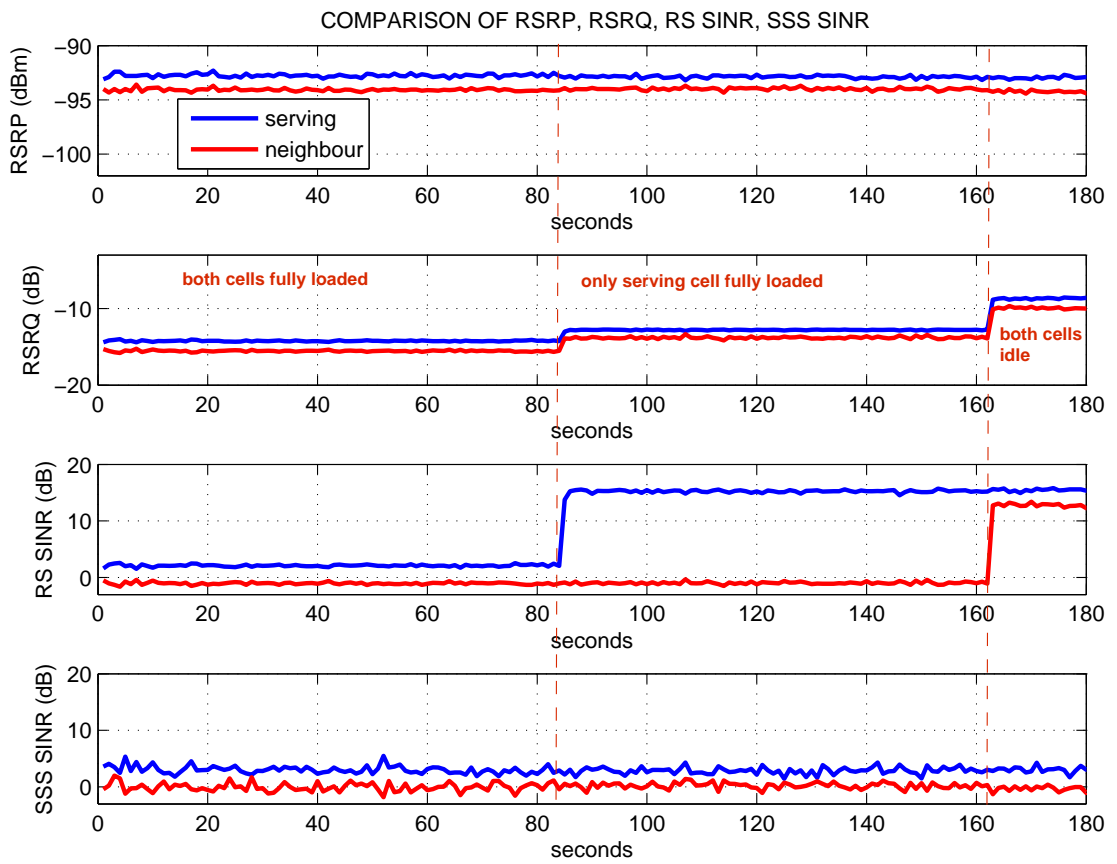


Figure 3. Comparison of RSRP, RSRQ, RS SINR, S-SCH SINR for two sectors of the same BTS in fading channel conditions. Serving cell PCImod3=0, neighbour cell PCImod3=2. Both cells have two transmit antennas.



for example LTE may be searched prior to 3G.

It should be noted that cell absolute priorities are not used in initial cell selection.

The full details of the initial PLMN and cell selection procedure are described in more detail in 3GPP TS 36.304 and TS 23.122. In the following we assume that the PLMN and cell selection has been completed, and the UE is in the reselection phase.

### 3.3. Intra-Frequency Cell Reselection Rules

A Rel8 UE may only camp on a cell that satisfies  $\text{RSRP} > \text{RSRP}_{\min}$ . In turn, a 3GPP Rel9 UE may only camp on a cell that satisfies both

$$\text{RSRP} > \text{RSRP}_{\min} \quad (10)$$

$$\text{RSRQ} > \text{RSRQ}_{\min}, \quad (11)$$

assuming that UE transmit power is not limited<sup>10</sup> by cell broadcast settings.

If  $\text{RSRQ}_{\min}$  is not broadcasted, UE assumes  $\text{RSRQ}_{\min} = -\infty$ , in other words the RSRQ criterion is always satisfied for all cells. While in Rel9 camping on a cell requires that both RSRP and RSRQ criteria are fulfilled, the actual cell ranking in intra-frequency cell reselection is only based on RSRP (among cells satisfying the above criteria).

For equal priority cells, the basic form of intra-frequency cell ranking criterion in 3GPP Rel9 is

$$R_s = \text{RSRP}_s - \text{RSRP}_{\min} + Q_{\text{hyst}} \quad (12)$$

$$R_n = \text{RSRP}_n - \text{RSRP}_{\min}, \quad (13)$$

where  $R_s$  and  $R_n$  are the R-criterion for serving cell and  $n$ th neighbour cell, respectively. The quantities are average values given in decibel scale and the parameter  $\text{RSRP}_{\min}$  (termed

<sup>10</sup>Otherwise an offset, equal to the difference of the maximum UE transmit power capability and maximum allowed UE transmit power in the cell, is applied to the measured RSRP value. As in 2G and 3G, the motivation of the offset is to prevent UE from attempting cell access when uplink link budget is limited.

$Q_{\text{rxlevmin}}$  in 3GPP specification) for both serving and neighbour cells is broadcast on BCCH<sup>11</sup>. Hysteresis value  $Q_{\text{hyst}}$  can be applied to serving cell RSRP measurement, in order to reduce ping-pong cell reselection. The cell ranking criterion is evaluated for all detected cells and the UE reselects to the cell that has the highest  $R$  value.

In LTE, it is not mandatory to broadcast any neighbour cell information for cell reselection purposes. However, sometimes special neighbour-specific reselection offsets are needed. For this purpose up to 16 cell individual offset values can be broadcasted in BCCH SIB4, and UE ranks the cell, identified by its PCI, according to

$$R_n = \text{RSRP}_n + Q_{\text{offset},n} - \text{RSRP}_{\min}. \quad (14)$$

Finally, a Rel8 UE is not required to perform intra-frequency idle mode measurements if the RSRP of the serving cell is stronger than a threshold defined by the parameter  $S_{\text{IntraSearch}}$ . In turn, for a Rel9 UE the rule requires that both RSRP and RSRQ are better than thresholds  $S_{\text{IntraSearchP}}$  and  $S_{\text{IntraSearchQ}}$ , respectively. The search thresholds are optionally transmitted on BCCH and in the absence of these parameters the UE default behaviour is to search and measure intra-frequency cells continuously regardless of serving cell RSRP and RSRQ.

### 3.4. Intra-Frequency Cell Reselection Measurement Processing

The UE continuously scans for new neighbour cells and evaluates the cell reselection R-criterion for the cells it detects. The measurement requirement has been engineered in such a way that the UE only needs to measure cells at every paging opportunity of the serving cell, therefore maximizing battery savings. Each neighbour cell is averaged over an integer multiple of the idle mode DRX cycle defined in the table below. A minimum of two RSRP/RSRQ

<sup>11</sup>One  $Q_{\text{rxlevmin}}$  value is broadcast for the serving cell in SIB1 and another one for all intra-frequency neighbour cells in SIB3. Typically the same value of  $Q_{\text{rxlevmin}}$  would be used for cells in a given macrocell layer.

measurement samples should be averaged for RSRP/RSRQ evaluation; hence the averaging time is at least as long as the sampling interval. It can be seen that the worst-case sampling interval in idle mode is 2.56 seconds, see Table 2.

Table 2  
RSRP/RSRQ measurement sampling interval for intra-frequency cells, based on 3GPP TS 36.133.

DRX cycle [sec]	sampling interval [sec] (number of DRX cycles)
0.32	1.28 (4)
0.64	1.28 (2)
1.28	1.28 (1)
2.56	2.56 (1)

The UE is required to evaluate the R criterion, and possibly reselect to a new cell, at least once every DRX cycle. From planning and optimization point of view the cell reselection delay is of some interest. There are two subcases to consider: i) a cell that has not been detected has better RSRP than the serving cell; ii) an already detected and measured cell has R criterion better than the serving cell. The former case can happen when UE comes out, for example, of an elevator or turns around a street corner. The difference here to the second case is that the UE can only scan a limited number of PCIs during a DRX cycle, and hence detecting a new cell may require several DRX cycles therefore increasing the cell reselection delay. The cell reselection time for the two subcases is given in Table 3. For example, when idle mode DRX cycle is 0.64 seconds selecting to an undetected cell may take up to about 18 seconds, while for an already detected cell the time is about 5 seconds. Here it has been assumed that  $T_{\text{reselection}} = 0$  seconds. If a positive value of  $T_{\text{reselection}}$  timer is used, then the neighbour cell has to fulfill the R criterion for at least  $T_{\text{reselection}}$  seconds before cell reselection can be made.

From Table 3 the difference between undetected and detected cell reselection time can be interpreted as the time it takes for UE to scan over the entire PCI range; the scanning interval over the range of 504 PCIs can be interpreted to be 20 DRX cycles, in other words at least 25 PCIs should be scanned during every DRX cycle.

Table 3  
Requirements for intra-frequency cell reselection time when  $T_{\text{reselection}} = 0$ , based on 3GPP TS 36.133.

DRX cycle length [s]	Reselection time to undetected cell [s]	Reselection time to detected cell [s]
0.32	11.52 (36)	5.12 (16)
0.64	17.92 (28)	5.12 (8)
1.28	32 (25)	6.4 (5)
2.56	58.88 (23)	7.68 (3)

#### 4. INTRA-FREQUENCY CONNECTED MODE MOBILITY

In this section measurement processing and basic handover triggers in connected mode are discussed. Again, the reader is reminded that the focus in this paper is on intra-frequency handovers.

##### 4.1. Measurement Processing

In connected mode, the UE continuously scans for new neighbour cells. Slightly simplifying the requirements in TS 36.133, a UE configured in connected mode DRX must be able to detect a neighbour cell in less than 800 ms. The measurement processing described in the following applies only to cells that have been detected by the UE. When long DRX cycle is in use, the time to detect a new cell is 20...40 DRX cycles. In the very worst case (2.56 second long cycle), the detection may take up to  $20 \cdot 2.56 = 51.2$  seconds. (In practice UE would probably move to idle mode before this, or would transmit some data and exit the DRX long cycle.) Hence

connected mode DRX is expected to degrade handover measurement performance in the network.

For each detected cell, the UE makes a physical layer RSRP/RSRQ measurement,  $M_n$ , and provides results to RRC layer for averaging once every 200 ms<sup>12</sup>. The physical layer measurement accuracy requirements were given in Table 1. The raw measurement result  $M_n$  at time instant  $n$  is filtered at RRC layer (also called L3) using the formula

$$F_n = (1 - \beta)F_{n-1} + \beta M_n, \quad (15)$$

where  $F_0 = M_0$  and the filter coefficient  $k$  in  $\beta = 2^{-k/4}$  is optionally signalled to UE in RRC measurement configuration message. The filtering is done in logarithmic domain. In case  $k$  is not explicitly signalled, the default value  $k = 4$ , i.e.,  $\beta = 0.5$ , is used. The filter coefficient  $\beta$  is defined separately for RSRP and RSRQ. The value  $\beta = 1$  corresponds to the case with no L3 filtering.

#### 4.2. Power Budget Handover Based on the A3 Criterion

Perhaps the most basic measurement event is the A3 event, or the "power budget" handover trigger event. In its basic form the UE sends an A3 measurement report when a non-serving cell RSRP becomes better than the serving cell RSRP by a margin defined by an A3 offset parameter. In other words, when

$$\Delta\text{RSRP} > \text{A3 offset}, \quad (16)$$

where  $\Delta\text{RSRP} = \text{RSRP}_{\text{neigh}} - \text{RSRP}_{\text{serv}}$ . The  $\Delta\text{RSRP}$  is calculated for the L3 filtered values obtained from Eq. (15). The condition must hold for a duration defined by a time-to-trigger parameter. As with the 2G power budget handover, the motivation here is to keep UE connected to the cell that has the least downlink

<sup>12</sup>The value of 200ms is the nominal measurement period from L3 point of view, UE may also perform measurements more frequently.

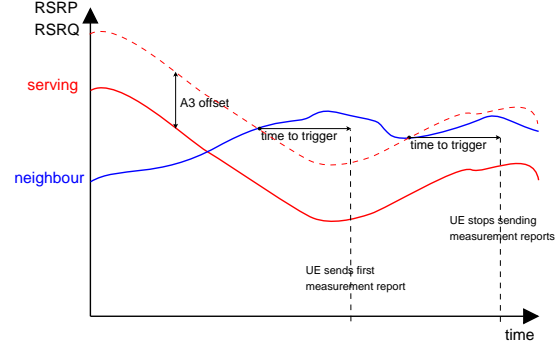


Figure 4. A3 measurement event criterion. RSRQ A3 measurement applies to inter-frequency HO only.

path loss<sup>13</sup>. Figure 4 shows an example of the A3 reporting event. During the time A3 condition applies, the UE sends measurement reports to BTS at reporting interval defined in the measurement configuration. Provided target cell selection and handover preparation to target cell succeeds, the BTS will send a handover command to the UE. The UE stops sending measurement reports when the A3 condition is no longer fulfilled or a configured amount of measurement reports have been sent – or if the connection is released, handed over, or dropped. If desired, a hysteresis can be applied to activation and deactivation of the reporting condition but is neglected here for simplicity.

#### 4.3. Coverage Handover Based on the A5 Criterion

The RSRP-based A5 measurement event is the second basic intra-frequency handover trigger<sup>14</sup>.

<sup>13</sup>Downlink path loss is defined as the difference between RS transmit power per subcarrier and RSRP, where RSRP, by definition, is equal or better than the RSRP of the stronger receive antenna. Uplink path loss, however, depends on transmit antenna and thus may be higher than downlink path loss if the power imbalance between UE antennas is large.

<sup>14</sup>Using RSRQ for intra-frequency HO triggering is not necessary since RSSI is the same for source and target cell and

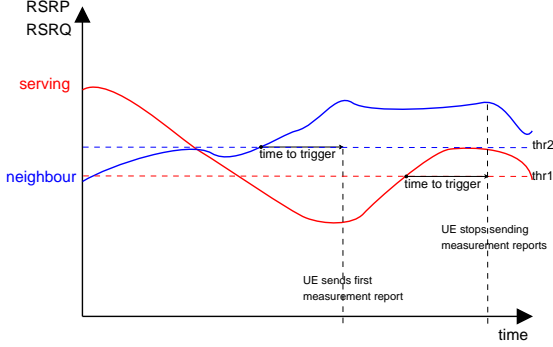


Figure 5. A5 measurement event criterion.

The UE sends a A5 measurement event when  $RSRP_{serv} < thr_1$  and  $RSRP_{neigh} > thr_2$  for a duration defined by a time-to-trigger parameter, see Figure 5. The A5 event can be only be triggered when the RSRP from the serving is below threshold 1. The A5 event may become handy for triggering a fast handover in case of rapid signal drop, with short time to trigger and small margin between the serving and neighbour cell. Using the A3 event to achieve a similar fast reaction time, would result in increased ping-ponging in good coverage, which is not desirable. Another use case for the A5 event is load balancing between cell layers.

## 5. MOBILITY PARAMETER DESIGN

### 5.1. Design Principles

Any mobility parameter design should satisfy some basic requirements, including:

- Handover margin should be small enough so that no excessive interference is generated by UEs connected to a cell with non-minimum path loss.
- The amount of unnecessary handovers

therefore the difference of RSRQs depends only on the difference of RSRPs.

and ping-pong handovers should be minimized

- There should not be excessive handover triggering delay which would increase call drops when signal level drops sharply.

In addition, idle mode and connected mode mobility parameters should be aligned so that there are no ping-pong cell changes in when UE changes from idle to connected mode, and vice versa.

Obviously, other design criteria may be applied, such as load balancing between cells. However, in this paper we focus on the simple intra-layer use case where the goal is to set handover margin, time to trigger and L3 filtering coefficient in such a way that the abovementioned criteria are satisfied.

In general, the handover parameters should be set differently depending on the service. For example, voice calls cause relatively low network load and hence a larger handover margin could be tolerated. On the other hand, voice call drops due to late handover triggering should be minimized, as these cause noticeable end user dissatisfaction.

### 5.2. Impact of A3 Offset on Uplink Interference

Figure 6 shows how increasing A3 offset results in increased uplink interference in the network. Since not all UEs are connected to the cell with minimum path loss, they tend to use unnecessarily high transmit power thus creating uplink interference. The simulation assumptions for the result are listed in Table 4. Optimization of uplink power control parameters can reduce the SINR degradation, as can certain vendor-specific radio features such as inter-cell interference coordination.

Downlink interference will not be impacted as much since there is no dynamic power control for the PDSCH channel. Therefore, the BTS uses a constant downlink transmit power per subcarrier; the transmit bandwidth in PRBs depends

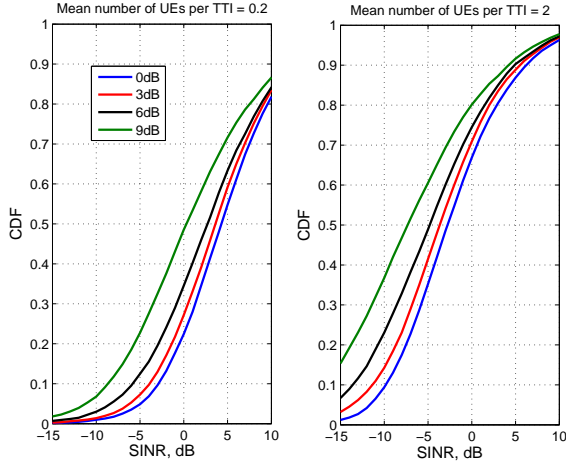


Figure 6. Network uplink SINR distribution for different A3 offset values. Simulation assumptions are given in Table 4.

however on vendor-specific link adaptation and scheduler implementation.

### 5.3. Impact of Time To Trigger and L3 Filtering Coefficient on Measurement Report Triggering Delay

Handover triggering delay is here defined as the time difference between the time instant where the UE would send the measurement report assuming it had perfect RSRP/RSRQ information available, and the actual time instant of sending the measurement report with non-ideal radio channel and measurement processing. The handover triggering delay is difficult to measure with real UEs, and hence to illustrate the impact of parameters some simulation results are shown in Figure 9. The simulation is based on fading channel model at 2.6GHz with UE speed of 20 m/s. The scenario is shown in Figure 7, where it can be seen that at about 20-25 seconds after the beginning of the trace, the serving cell level experiences a transient (emulating a UE driving into a tunnel or being sud-

Table 4  
Simulation assumptions for Fig. 6.

Parameter	Value
Path loss model	Cost-Hata Urban
Shadowing std	8 dB
Penetration loss	20 dB
BTS / UE antenna height	30 m / 1.5 m
BTS / UE antenna gain	18 dBi / 0 dBi
Antenna -3dB beamwidth	65 degrees
Antenna downtilt	2 degrees
Network layout	3GPP TS 25.914
Number of sites / cells	19 / 57
Inter-Site Distance	500 meters
Carrier frequency	2.6 GHz
System bandwidth	20 MHz
BTS noise figure	2 dB
UL power control $P_0 / \alpha$	-100 dBm / 1
Data model	full buffer

denly shadowed by a building). A neighbour cell average RSRP is 5 dB less than the serving cell RSRP in the beginning of the trace prior to the transition. The ideal "genie-aided" triggering point would be at 24.5 seconds time instant, but due to signal fading of serving and neighbour cells as well as UE L3 filtering, there is certain delay in triggering the handover; note that in some cases fading may actually trigger a measurement report before the genie-aided point. Simulating a large number of fading realizations with different values of A3 offset, time to trigger and  $\beta$  provides some insight into the impact of these parameters on the handover triggering delay.

Figure 8 illustrates how the L3 filtering influences the measurement report delay for A3 margin of 3dB and a few values of time to trigger. Firstly, if A3 margin and time to trigger are fixed, there is an optimum value of  $\beta$  that minimizes the delay. The second observation is that the delay is minimized for a fairly wide and consistent range of  $\beta = 0.25 \dots 0.5$ , almost independently of the time to trigger value. While this behaviour may seem illogical at first, the reason

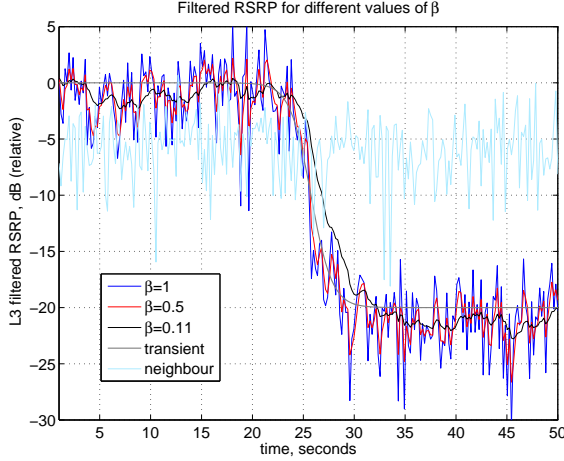


Figure 7. Example of RSRP L3 filtering, UE speed is 20 m/s, center frequency is 2.6GHz, and L3 sampling interval is 200ms.

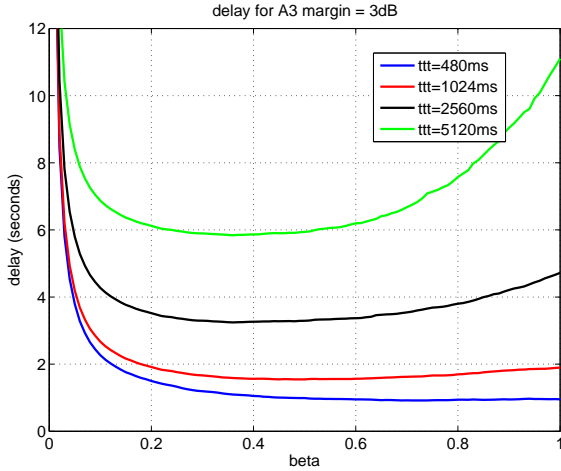


Figure 8. Impact of  $\beta$  on average handover measurement report delay for different values of time to trigger. A3 offset is 3dB. UE speed = 20 m/s, carrier frequency is 2.6GHz. Measurement bandwidth = 6PRB.

is that unfiltered fading ( $\beta = 1$ ) in serving and neighbour cell can result in fast varying  $\Delta\text{RSRP}$  values that frequently cross the A3 threshold, thus restarting the time to trigger timer. Moderate filtering  $\beta = 0.25 \dots 0.5$  averages away the high signal peaks without overly increasing delay. Decreasing  $\beta$  to values below  $\beta \approx 0.1$  increases the filtering delay rapidly<sup>15</sup>.

The targeted delay bound can be met by several combinations of feasible parameter triplets (A3 offset, ttr,  $\beta$ ). To ease design, another way of plotting the inter-dependence of the parameters of interest is depicted in Figure 9. The Figure 9 shows  $\beta$ -TTT parameter contours for A3 event triggering delays of 1, 2 and 4 seconds. The minimum delay occurs at  $\beta = 0.25 \dots 0.5$  for all evaluated A3 margin values. If  $\beta$  is either near unity or very small, the delay is increased compared to the minimum value. As an example, looking at the lower left subplot where A3 offset is 3dB, one can see that if time-to-trigger is 2.56 seconds, having either  $\beta \approx 0.11$  or  $\beta \approx 0.8$  both result in measurement report triggering delay of four seconds.

For design purposes, the radio planner first chooses some maximum allowed measurement report triggering delay, ideally, based on service type (real-time or non-real-time), carrier frequency and UE speed. A design curve such as the one in Figure 9 can then be used to define a range of allowed handover parameters. Measurement report triggering delay is usually not the only design criterion for handover parameters; examples of multi-criteria design are presented in other sections of this paper.

It should also be remembered that the total end to end intra-frequency handover delay includes:

- neighbour cell detection delay, 3GPP requirement is  $< 0.8\text{sec}$  when DRX is not in use
- measurement report transmission delay,

<sup>15</sup>Filter coefficients  $k = 13$  and  $k = 15$  correspond to  $\beta = 2^{-\frac{13}{4}} \approx 0.11$  and  $\beta = 2^{-\frac{15}{4}} \approx 0.07$ , respectively.

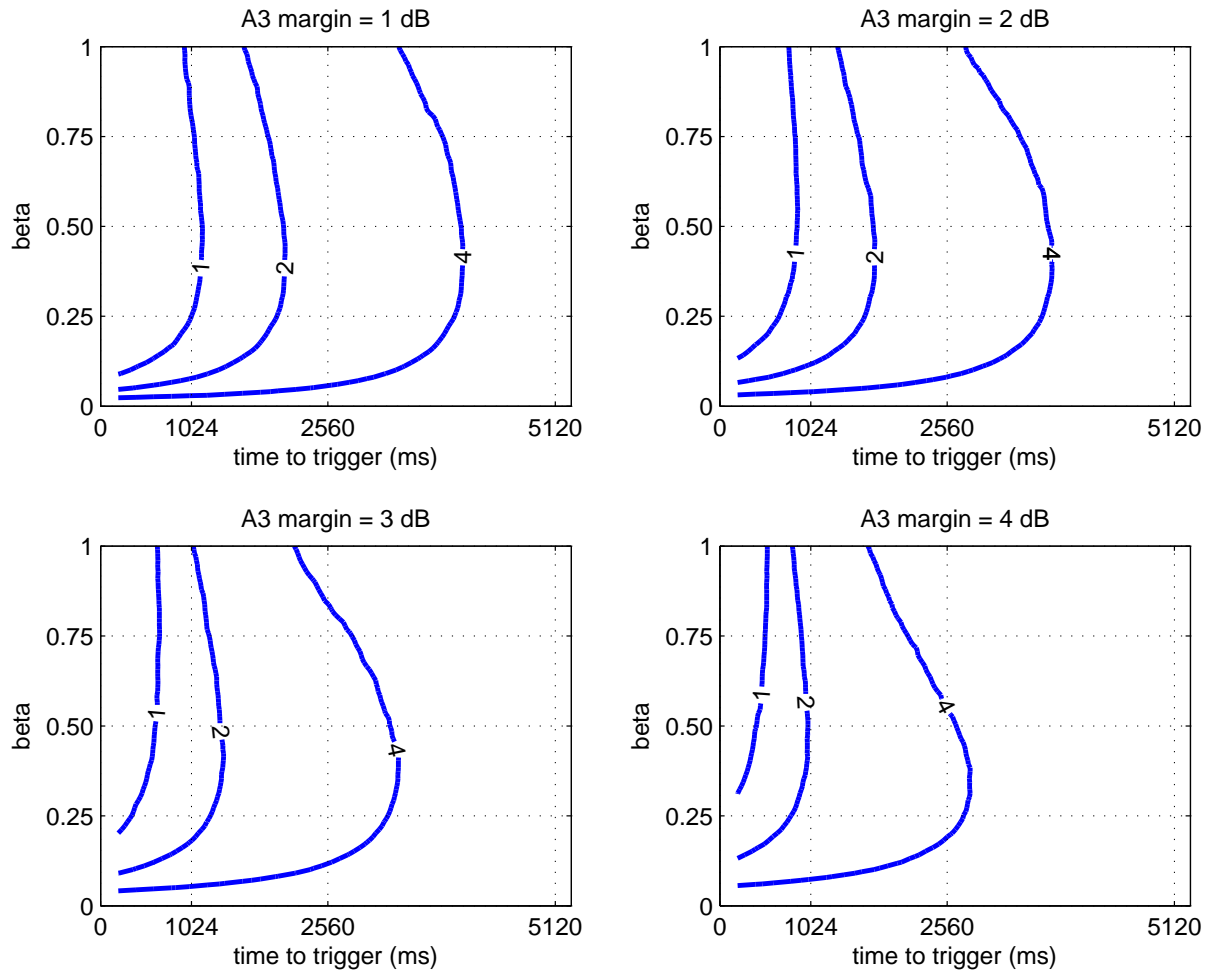


Figure 9. Impact of  $\beta$  and time-to-trigger on handover measurement report delay. Delay contours for 1, 2, 4 seconds shown for various values of A3 offset. UE speed = 20 m/s. Measurement bandwidth = 6PRB.

including delays due to uplink scheduling request and measurement report HARQ/RLC retransmissions

- BTS internal processing delay for measurement processing, handover triggering, target cell selection, S1AP/X2AP signalling processing etc. These can be assumed to be small, not more than a few milliseconds.
- handover preparation delay due to X2 or S1 interface signalling, typically less than 100ms, but depends on transport network topology
- handover preparation processing at target cell, for example radio and transport resource reservation and admission control
- handover execution delay, consisting of handover command in source cell, cell synchronization and random access delay in target cell, typically totalling about 20-30ms
- additional delays due to dedicated preamble retransmissions and RRC signalling retransmissions at HARQ/RLC layer, in bad radio conditions up to 500 ms

Therefore, for initial parameter design purposes, a margin of up to 2 seconds may be added to the measurement report triggering delay curves. If connected mode discontinuous reception (DRX) is in use, the UE may choose to wait until active time to send the measurement report. This adds a random delay of up to the DRX cycle length to measurement report triggering.

#### 5.4. Impact of Time to Trigger and A3 Offset on Measurement Report Triggering Delay

Figure 10 illustrates how time to trigger and A3 offset influence the measurement report triggering delay. Parameter contours corresponding to delays of 1, 2, 4 seconds are plotted for different values of L3 filtering coefficient,  $\beta$ . The same simulation setup as in Figure 9 was used.

The figure again confirms the intuition that increasing A3 margin increases also measurement report triggering delay. As in Figure 9, several pairs of A3 offset and time to trigger values result in the same triggering delay. The delay behaviour is quite insensitive to L3 filtering in value range  $\beta = 0.25 \dots 0.5$  whereas values  $\beta < 0.1$  increase the delay strongly unless A3 margin and time to trigger are also very small.

#### 5.5. Impact of Time to Trigger and A3 Margin on Ping-Pong Probability

Figure 11 shows the impact of A3 margin and time to trigger on the probability of UE being unnecessarily handed over to a neighbour cell. The figure has been created using simulation where serving and neighbour cells have equal average RSRP, but undergo independent small-scale fading. The results are again shown for four different values of  $\beta$ . The ping-pong probability is the fraction of L3 filtered measurement samples (200ms interval) that result in A3 event trigger.

It can be seen that as  $\beta$  becomes smaller the ping-pong behaviour becomes less sensitive on the value of time to trigger. It is interesting to notice that, to keep ping-pong probability small, increasing L3 filtering (decreasing  $\beta$ ) requires increasing the time to trigger window. The reason is that with unfiltered fading the A3 criterion (difference of serving and neighbour RSRPs) signal frequently criss-crosses the A3 threshold which is why a long time to trigger efficiently mitigates ping-pong, as it is unlikely that several consecutive A3 samples are above the threshold. On the other hand, L3 smoothing of serving and neighbour cell RSRPs results in fewer A3 level crossings but also lengthens the duration of time the smoothed A3 value stays above a certain threshold.

From handover parameter planning point of view, the L3 filter coefficient is the same for all measurement events, while a dedicated time to trigger value can be defined for each event. Because of this, one should choose the  $\beta$  value, so that it suits all handover purposes in the



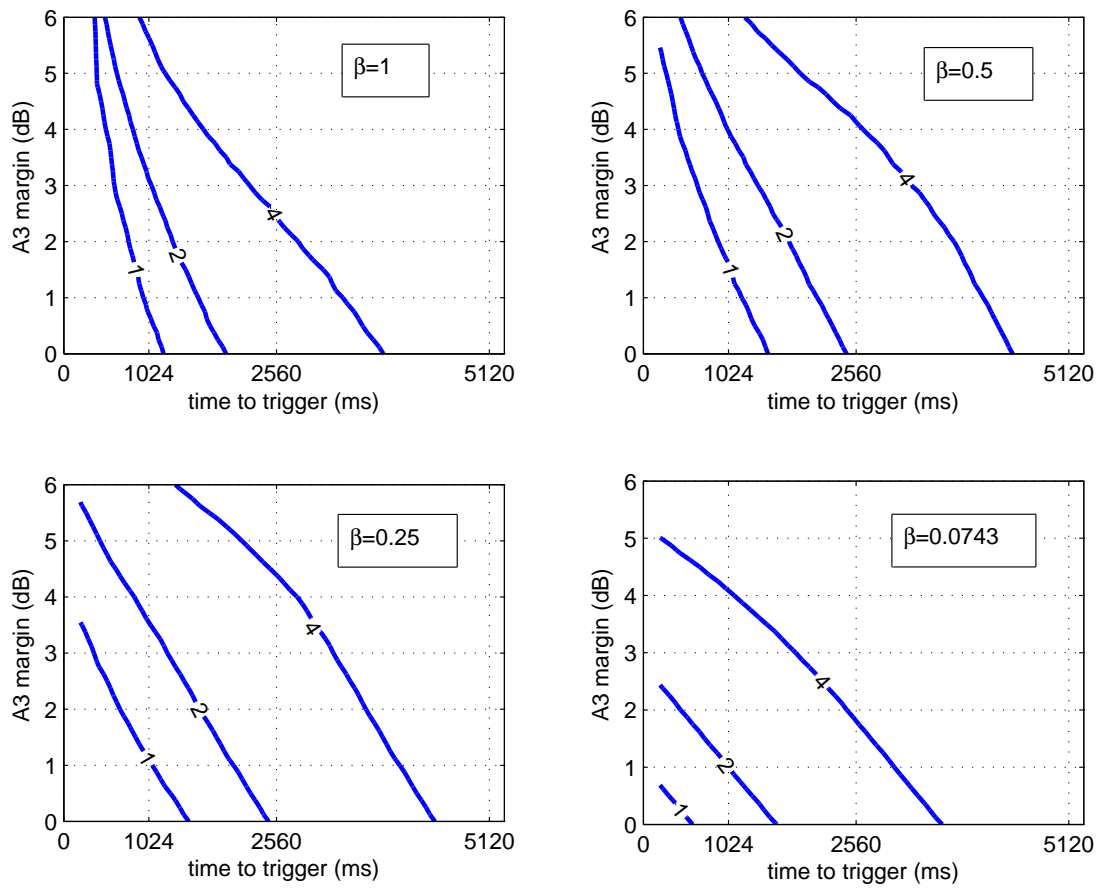


Figure 10. Impact of A3 offset and time-to-trigger on handover measurement report delay. Delay contours for 1, 2, 4 seconds shown for various values of  $\beta$ . UE speed = 20 m/s. Measurement bandwidth = 6PRB.

network, and then tune the performance using event-specific time to trigger and power thresholds.

### 5.6. Other Handover Parameters

In addition to time to trigger, A3 margin and L3 filtering coefficient, there are many other handover parameters that need to be configured. These are briefly summarized below.

- *Reporting Interval.* As long as the measurement event criterion is satisfied, the UE will keep sending periodic measurement report once every reporting interval. Reporting interval should be set jointly with the filter coefficient; small  $\beta$  requires using longer reporting interval since less new information is introduced every measurement period (200ms). Further, setting too short a reporting interval not only consumes more air interface capacity, but more disturbingly it leaves less time for handover preparation over the X2 or S1 interface as well as delivering the handover command in the source cell. Therefore setting reporting interval of non-urgent handovers (e.g. non-real time data) to less than 320ms is not recommended. Typical value for A3 event reporting interval is 320...1024ms.
- *Hysteresis.* Starting and stopping conditions for measurement reporting can be modified with hysteresis. For example, assuming A3 margin of 3dB and hysteresis of 1dB, the UE would start reporting when a neighbour cell is 4dB better than the serving cell, and stop reporting when neighbour cell is less than 2dB better than the serving cell. In the earlier subsections, it was assumed that hysteresis is zero dB, since usually there is no use case for adopting non-zero hysteresis. According to 3GPP TS 36.331 time to trigger applies to both entry and exit condition for the event reporting, therefore already including built-in hysteresis in time domain.

- *Maximum number of reported cells.* Maximum number of reported cells can be configured, up to eight cells.
- *Report Amount.* The UE can be configured to report a finite number of measurement reports (up to 64), or report indefinitely as long as the measurement event conditions are fulfilled. There is some benefit in configuring a finite amount of reports since otherwise, in case of missing or temporarily unavailable neighbour, a handover will not be triggered and a stationary UE will continue to send measurement reports until it is moved to RRC idle.
- *Report On Leave.* This is a boolean parameter that determines whether the UE should send one last measurement report at the instant when the event reporting condition stops applying.

UE can also be commanded to report RSRP/RSRQ measurements periodically, instead of event-based reporting. This can be useful for optimization if the system is able to collect RF performance statistics from such reports, or use the periodic reporting data to automatically guide RRM algorithms.

## 6. PARAMETER DESIGN EXAMPLES

The purpose of this section is to illustrate the presented concepts by means of simple parameter design examples.

### 6.1. Basic Example

Consider a typical early LTE macrocell network where majority of UEs are USB data modems and the dominant service type is best effort non-GBR data. The mobility in the network is low as UEs are mostly stationary. The carrier frequency is 2.6GHz. The following generic requirements have been determined for the initial mobility parameter design:

- SINR degradation (noise rise) should be minimized as much as possible

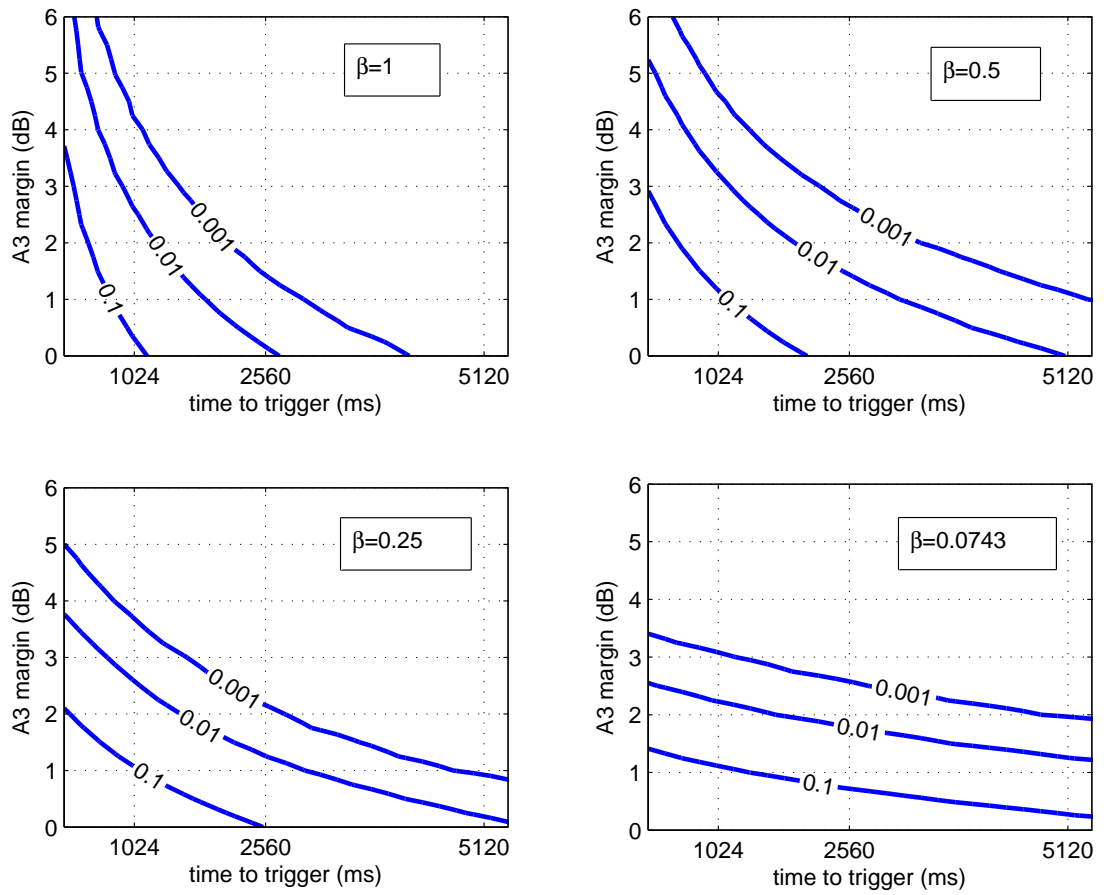


Figure 11. Ping-pong handover probability in the case of equally strong serving and neighbour cell, UE speed = 0.1 m/s, carrier frequency 2.6 GHz. A3 offset versus time to trigger for L3 filter values of  $\beta = \{1, 0.5, 0.25, 0.0743\}$ . Measurement bandwidth = 6PRB, SNR = 0dB.

- Total handover delay under quick power transient should be less than 4 seconds
- Ping-pong handover probability at cell border should be less than 1 percent, assuming quasi-stationary UE.

Obviously, the conditions stated above are somewhat contrived, for the sake of presenting the following design example.

Only the A3 event based power budget handover is used in the network; the A5 coverage handover will be added in the second part of the example. There are three main parameters to select: A3 margin, A3 time to trigger and the RSRP filtering coefficient  $\beta$ .

From Figure 6 it can be seen that A3 margin above three decibels results in SINR CDF shift of more than about 1 dB, hence it is preferred not to have A3 margin higher than 3dB.

It is assumed that neighbour detection, HO preparation and execution delay can be up to two seconds; therefore the allowed measurement report triggering delay should not be more than two seconds to keep the total handover delay less than four seconds. In Figures 9 and 10 we hence focus on the parameter contours denoting two seconds delay. From Figure 10 it is clear that at A3 margin values of at most 3dB and see that time to trigger values of 1024 ms or less result in triggering delay of less than two seconds, except when  $\beta = 0.0743$ . Selecting 3 dB / 1024 ms as initial point, from lower left subplot of Figure 9 or from Figure 8 it is evident that all values in the range  $\beta = 0.2 \dots 1$  result in triggering delay of at most 2 seconds, indicating that there is some freedom in selecting  $\beta$ . To make ping-pong handover probability as small as possible, we select  $\beta = 0.25$ . The final handover parameters are:

- A3 margin of 3dB
- A3 time to trigger of 1024ms
- L3 filtering coefficient  $\beta$  of 0.25 ( $k = 8$ )

The idle mode reselection hysteresis,  $Q_{hyst}$  is set to the same value as the A3 margin, to minimize unnecessary cell changes when UE moves from idle to connected mode, and vice versa.

Before moving forward, it should be noted that there are other parameter combinations that approximately satisfy the boundary conditions. For example, using  $\beta = 0.5$  instead would not substantially change the handover behaviour.

## 6.2. Basic Example Continued

The simple example from the previous subsection is continued. Assume that smartphones are introduced to the network, and hence UE mobility increases due to subscribers browsing in trains, buses etc. The A3 handover works fine in keeping the UE connected to the strongest cell, without excessive ping-ponging. However, in some cases UE received signal fades very quickly down to RSRP levels below  $-120\text{dBm}$ , resulting in bad service quality and increased probability of call drop due to slow triggering of the A3 event. If 2G/3G coverage is available, the UE can be directed to those safety layers (inter-layer HOs are not discussed further in this paper). Prior to triggering inter-layer handover, it is worth trying to keep the UE on the serving LTE layer if a suitable cell can be found. For this purpose, one can also utilize the A5 event with quick triggering. Assume that if serving cell  $\text{RSRP} < -120\text{dBm}$ , the UE would be directed to another layer. In this case, setting A5 threshold 1 (serving) and threshold 2 (neighbour) to, say,  $-118\text{dBm}$  and  $-117\text{dBm}$  with short time to trigger of 160ms will make the last desperate attempt to move the UE to another intra-frequency cell, that now needs to be only 1dB stronger with short time to trigger. Should no such cell be available, the UE would then as a last resort be directed to another layer.

## 7. CONCLUSION

In this paper intra-frequency mobility parameter design for LTE was discussed. Basic measurement quantities RSRP and RSRQ were re-

viewed and measurement example was shown to illustrate practical usage. The idle and connected mode mobility parameters were summarized. The intra-layer mobility parameter design problem was defined in terms of three primary handover parameters: handover margin, time to trigger and measurement filter coefficient. In order to find a set of feasible solutions for these parameters, the boundary conditions for uplink noise rise, handover delay and ping-pong handover probability were considered. To illustrate the framework a simplified parameter planning example was given.

Finally, as is well-known to practitioners in the field, radio network mobility parameters should not be left to initially planned values, such as those obtained based on the framework presented here. Rather, constant optimization process should be in place to ensure sufficient performance as network load increases and new services are introduced.

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