Observed Time Difference Of Arrival (OTDOA) Positioning in 3GPP LTE

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1 Scope

This document describes the functionalities for the support of OTDOA location in LTE as currently defined in 3GPP (and OMA). It is intended as a one stop guide to provide an overview of the OTDOA feature for operators and manufacturers interested in the deployment of OTDOA location capabilities including references to where the standard details on each subject can be found.

The contents of the document include the following:

- Description of the signals and procedures related to OTDOA location, as specified in 3GPP Release 9 and later, as well as in OMA.
- Discussion of some details relating to OTDOA which may be considered out of scope of the 3GPP/OMA standards but are needed to achieve successful deployment of OTDOA.

This document is organized as follows:

Section 4 describes the OTDOA location principle, and the measurement defined for OTDOA location in 3GPP LTE.

Section 5 provides a summary of the Position Reference Signal (PRS) details as introduced in 3GPP Release 9 specifically for OTDOA location.

Section 6 briefly describes the LCS architecture, together with the signaling and procedures required for OTDOA location. Detailed message sequence diagrams for individual use cases (e.g., emergency calls) are beyond the scope of this paper.

Section 7 summarizes the assistance data required for OTDOA location, as defined in 3GPP and OMA.

Section 8 describes several factors which influence OTDOA location performance. Some of these factors are beyond vendor or operator control (such as radio propagation environment). Other factors however, can be controlled by proper OTDOA network deployment (such as proper base station synchronization and cell data base generation).

2 References

[1] 3GPP TS 23.271: "Functional stage 2 description of Location Services (LCS)".

[2] 3GPP TS 36.305: "Stage 2 functional specification of User Equipment (UE) positioning in E-UTRAN".

[3] 3GPP TS 36.211: "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation".

[4] 3GPP TS 36.213: "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures".

[5] 3GPP TS 36.214: "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer – Measurements".

[6] 3GPP TS 36.331: "Evolved Universal Terrestrial Radio Access (E-UTRA); "Radio Resource Control (RRC); Protocol specification".

[7] 3GPP TS 36.355: "Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP)".

[8] 3GPP TS 36.455: "Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol A (LPPa)".

[9] 3GPP TS 36.133: "Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management".

[10] 3GPP TS 24.171: Control Plane Location Services (LCS) procedures in the Evolved Packet System (EPS).

[11] 3GPP TS 29.171: "Location Services (LCS); LCS Application Protocol (LCS-AP) between the Mobile Management Entity (MME) and Evolved Serving Mobile Location Centre (E-SMLC); SLs interface".

[12] 3GPP TS 24.301: "Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3".

[13] OMA-AD-SUPL-V2_0: "Secure User Plane Location Architecture Draft Version 2.0".

[14] OMA-TS-ULP-V2_0: "User Plane Location Protocol Draft Version 2.0".

[15] OMA-TS-LPPe-V1_1: "LPP Extensions Specification Version 1.1".

3 Definitions and Abbreviations

3.1 Definitions

Location Server: a physical or logical entity (e.g., E-SMLC or SUPL SLP) that manages positioning for a UE by obtaining measurements and other location information and providing assistance data to the UE to help determine this. A Location Server may also compute (UE-assisted) or verify (UE-based) the final location estimate.

UE assisted positioning: the UE provides position measurements to the location server (RSTD measurements in case of OTDOA) for computation of a location estimate by the location server.

UE based positioning: the UE performs both, position measurements and computation of a location estimate.

Observed Time Difference Of Arrival (OTDOA): The time interval that is observed by a UE between the reception of downlink signals from two different cells. If a signal from cell 1 is received at the moment t_1, and a signal from cell 2 is received at the moment t_2, the OTDOA is $t_2 - t_1$.

Real Time Difference (RTD): The relative synchronization difference between two cells. If cell 1 transmits a signal at the moment t_3, and cell 2 at the moment t_4, the RTD is $t_4 - t_3$. If the cells transmit exactly at the same time that means that the network is perfectly synchronized and hence RTDs = 0.

Geometric Time Difference (GTD): The time difference between the reception (by a UE) of signals from two different cells due to geometry. If the length of the propagation path between cell 1 and the UE is d_1, and the length of the path between cell 2 and the UE is d_2, then GTD = $(d_2 - d_1) / c$, where c is the speed of radio waves. The relationship between OTDOA, RTD and GTD is: OTDOA = RTD + GTD.

Primary Cell: The cell, operating on the primary frequency, in which the UE either performs the initial connection establishment procedure or initiates the connection re-establishment procedure.

Secondary Cell: A cell, operating on a secondary frequency, which may be configured once an RRC connection is established and which may be used to provide additional radio resources.

Serving Cell: For a UE in RRC_CONNECTED not configured with CA there is only one serving cell comprising of the primary cell. For a UE in RRC_CONNECTED configured with CA the term 'serving cells' is used to denote the set of one or more cells comprising of the primary cell and all secondary cells.

3.2 Abbreviations

3GPP	3rd Generation Partnership Project
ARFCN	Absolute Radio Frequency Channel Number
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BS	Base Station (synonymously for eNodeB)
BW	Bandwidth
CA	Carrier Aggregation
CGI	Cell Global Identity
CMAS	Commercial Mobile Alert System
CoMP	Coordinated Multipoint Transmission
CP	Control Plane
CP	Cyclic Prefix
CRS	Cell-specific Reference Signal
DAS	Distributed Antenna System
DL	Down-Link
EARFCN	EUTRA Absolute Radio Frequency Channel Number
ECGI	Evolved Cell Global identity
eICIC	Enhanced Inter-Cell Interference Coordination
EPDU	External Protocol Data Unit
EPRE	Energy per Resource Element
E-SMLC	Evolved Serving Mobile Location Center
ETWS	Earthquake and Tsunami Warning System
EUTRA	Evolved Universal Terrestrial Radio Access
FDD	Frequency Division Duplex
GDOP	Geometric Dilution of Precision
GMLC	Gateway Mobile Location Center
GPRS	General Packet Radio Service
GPS	Global Positioning System
GTP	GPRS Tunneling Protocol
GW	Gateway
HARQ	Hybrid ARQ
IP	Internet Protocol
L1	Layer 1
L2	Layer 2
LCS	Location Services
LCS-AP	LCS Application Protocol
LIS	Low Interference Subframe
LPP	LTE Positioning Protocol
LPPa	LPP Annex
LPPe	LPP Extensions
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Media Access Control
MBMS	Multimedia Broadcast Multicast Service
MBSFN	Multicast/Broadcast over a Single Frequency Network
MME	Mobility Management Entity
NAS	Non Access Stratum
OFDM	Orthogonal Frequency Division Multiplexing
OMA	Open Mobile Alliance
OTDOA	Observed Time Difference Of Arrival

PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCI	Physical Cell Identity
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PHICH	Physical HARQ ACK/NACK Indicator Channel
PPS	Pulse Per Second
PRS	Positioning Reference Signal
PSS	Primary Synchronization Signal
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head
RSTD	Reference Signal Time Difference
RTD	Real Time Difference
S1-AP	S1 Application Protocol
SCTP	Stream Control Transmission Protocol
SET	SUPL Enabled Terminal
SFN	System Frame Number
SIB	System Information Block
SINR	Signal to Interference and Noise Ratio
SLP	SUPL Location Platform
SSS	Secondary Synchronization Signal
SUPL	Secure User Plane Location
TAC	Tracking Area Code
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDOA	Time Difference Of Arrival
TLS	Transport Layer Security
TOA	Time Of Arrival
TS	Technical Specification
UDP	User Datagram Protocol
UE	User Equipment
UL	Up-Link
ULP	User Plane Location Protocol
UP	User Plane
WGS-84	World Geodetic System 1984

4 Multilateration in OTDOA Positioning

4.1 Introduction

Observed Time Difference Of Arrival (OTDOA) is a downlink positioning method in LTE Rel-9. It is a multilateration method in which the User Equipment (UE) measures the time of arrival (TOA) of signals received from multiple base stations (eNodeB's).

The TOAs from several neighbour eNodeB's are subtracted from a TOA of a reference eNodeB to form Observed Time Difference Of Arrival's.

Geometrically, each time (or range) difference determines a hyperbola, and the point at which these hyperbolas intersect is the desired UE location.

At least three timing measurements from geographically dispersed eNodeB's with good geometry are needed to solve for two coordinates (x,y or latitude/longitude) of the UE.

The OTDOA positioning method is illustrated in Figure 4-1, where the UE measures three TOA's relative to the UE internal time base, τ_1, τ_2, and τ_3. The measurement from eNodeB$_1$ is selected as reference base station, and two OTDOA's are formed: $t_{2,1} = \tau_2 - \tau_1$ and $t_{3,1} = \tau_3 - \tau_1$.

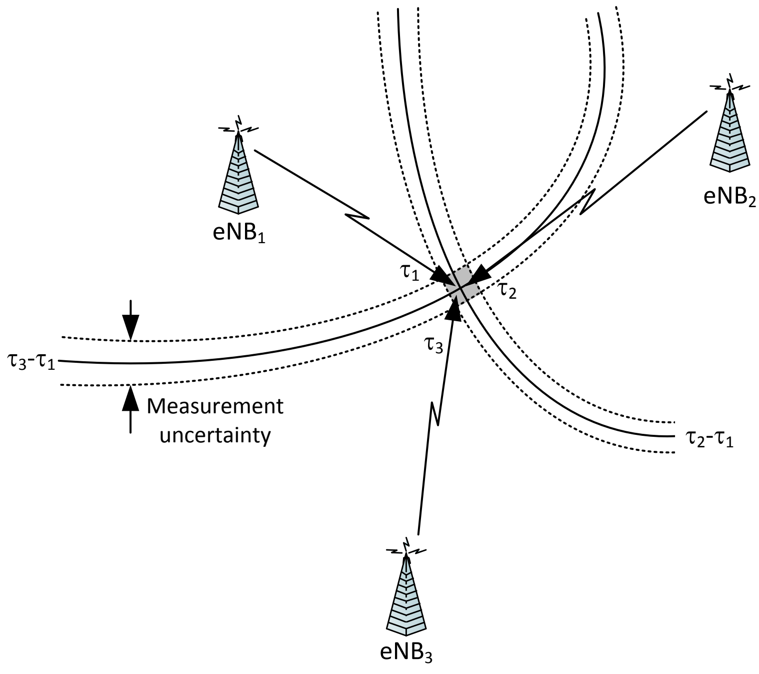

Figure 4-1: Multilateration in OTDOA Positioning.

Since each TOA measurement τ_i has a certain accuracy/uncertainty, the hyperbolas in Figure 4-1 are shown with a certain width, illustrating the measurement uncertainty. The estimated UE location is the intersection area of the two hyperbolas (gray shaded area).

4.2 Reference Signal Time Difference Measurement (RSTD)

4.2.1 Definition

The UE measurement for OTDOA positioning is the Reference Signal Time Difference Measurement (RSTD), specified in 3GPP TS 36.214 [5]. The RSTD is defined as the relative timing difference between two cells – the reference cell and a measured cell – calculated as the smallest time difference between two subframe boundaries received from the two different cells:

> RSTD is the relative timing difference between the neighbour cell *j* and the reference cell *i*, defined as $T_{SubframeRxj} - T_{SubframeRxi}$
> where:
> $T_{SubframeRxj}$ is the time when the UE receives the start of one subframe from cell *j*
> $T_{SubframeRxi}$ is the time when the UE receives the corresponding start of one subframe from cell *i* that is closest in time to the subframe received from cell *j*.

The RSTD measurement is applicable in RRC_CONNECTED state (a UE is in RRC_CONNECTED state when an RRC connection has been established).

The reference cell *i* is selected by the UE (3GPP TS 36.355 [7], section 6.5.1.5).

The RSTD measurement is possible on an intra-frequency cell and on an inter-frequency cell.

An intra-frequency RSTD measurement is performed when both, the reference cell *i* and the neighbour cell *j* are on the same carrier frequency as the UE serving cell.

An inter-frequency RSTD measurement is performed when at least one of the reference cell *i* and the neighbour cell *j* is on a different carrier frequency as the UE serving cell.

4.2.2 RSTD Measurement Report Mapping

The reporting range of the RSTD measurement is defined from -15391×Ts to 15391×Ts with 1Ts resolution for absolute value of RSTD less or equal to 4096Ts and 5Ts for absolute value of RSTD greater than 4096Ts (3GPP TS 36.133 [9]).

Ts is the basic time unit in LTE, and is defined as Ts = 1/(15000 × 2048) seconds, which is a little more than 32 ns, which corresponds to about 9.8 meters.

Therefore, the full reporting range of the RSTD measurement is about ± 0.5 ms (i.e., one LTE subframe), with a 1Ts reporting resolution if the measurement is between ± 133 μs.

4.3 Basic OTDOA Navigation Equations

The TOA measurements performed by the UE are related to the geometric distance between the UE and the eNodeB. In a 2-D Cartesian coordinate system, we denote the (known) coordinates of an eNodeB as $\mathrm{x}_i = [x_i, y_i]^T$ and the (unknown) coordinates of the UE as $\mathrm{x}_t = [x_t, y_t]^T$. The RSTD measurements are defined as the time difference between two eNodeB's (modulo 1-subframe (1-ms)), and therefore, correspond the following range differences between a neighbour eNodeB *i* and the reference eNodeB 1:

$$RSTD_{i,1} = \sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}/c - \sqrt{(x_t - x_1)^2 + (y_t - y_1)^2}/c + (T_i - T_1) + (n_i - n_1)$$

where

- $RSTD_{i,1}$ is the time difference between an eNodeB i and the reference cell 1 measured at the UE;
- $(T_i - T_1)$ is the transmit time offset between the two eNodeB's, referred to as "Real Time Differences" (RTDs);
- n_i, n_1 are the UE TOA measurement errors, and
- c is the speed of light.

At least two neighbour cell measurements i are needed, which gives two equations with two unknowns (x_t, y_t) if the coordinates of the eNodeB antennas (x_i,y_i) as well as the transmit time offsets (RTDs) ($T_j - T_i$) are known. Usually, more than two neighbour cell measurements are desired, and the system of equations is solved in the least-squares, or weighted-least-squares sense.

The transmit time offsets ($T_i - T_1$) should (ideally) be zero in a synchronized network, and the equation above defines the time-difference-of-arrival (TDOA).

Geometrically, each TDOA defines a hyperbola, where the width of the hyperbola is determined by the TDOA errors ($n_i - n_1$) as shown in Figure 4-1.

Only if the eNodeB coordinates $\mathrm{x}_i = [x_i, y_i]^T$ and the transmit time offsets ($T_i - T_1$) are known at the location server, the UE coordinates $\mathrm{x}_t = [x_t, y_t]^T$ can be determined. Any uncertainty in the eNodeB coordinates and transmit time offsets have a direct impact on the accuracy of the UE location estimate (see sections 8.3 and 8.4).

5 Positioning Reference Signals (PRS)

5.1 Overview

RSTD measurements can in principle be performed on any DL signals (e.g., CRS or synchronization signals). However, these DL signals suffer from poor hearability, which is crucial for OTDOA positioning when multiple neighbour cell signals have to be detected by the UE.

A neighbour cell with its synchronization signals (Primary-/Secondary Synchronization Signals) and reference signals is seen as detectable, when the Signal-to-Interference-and-Noise Ratio (SINR) is at least –6 dB [9]. However, this is not enough to detect a sufficient number of (geographically dispersed) eNodeB’s.

Therefore, Positioning Reference Signals (PRS) have been introduced in the 3GPP LTE Release-9 standard to allow proper timing (ranging) measurements of a UE from eNodeB signals to improve OTDOA positioning performance.

PRS have still some similarities with cell-specific reference signals as defined in LTE Rel-8. It is a pseudo-random QPSK sequence that is being mapped in diagonal patterns with shifts in frequency and time to avoid collision with cell-specific reference signals and an overlap with the control channels (PDCCH).

Positioning reference signals are transmitted on antenna port 6[1].

The positioning reference signals cannot be mapped to resource elements allocated to PBCH, PSS or SSS regardless of their antenna port.

Positioning reference signals are defined for $\Delta f = 15\,\mathrm{kHz}$ only.

5.2 Sequence Generation

The positioning reference-signal sequence $r_{l,n_s}(m)$ is defined by (3GPP TS 36.211 [3], section 6.10.4.1):

$$r_{l,n_s}(m) = \frac{1}{\sqrt{2}}\left(1 - 2\cdot c(2m)\right) + j\frac{1}{\sqrt{2}}\left(1 - 2\cdot c(2m+1)\right), \quad m = 0,1,\ldots,2N_{\mathrm{RB}}^{\mathrm{max,DL}} - 1$$

where

[1] An antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed. The way the "logical" antenna ports are mapped to the "physical" TX antennas lies completely in the responsibility of the base station.

n_s	is the slot number within a radio frame (slot = 0.5 ms; frame = 10 ms), n_s = 0..19;
l	is the OFDM symbol number within the slot; l = 0..6 for normal cyclic prefix; l = 0..5 for extended cyclic prefix.
$c(i)$	is a length-31 Gold sequence as defined in [3GPP TS 36.211 [3], section 7.2];
$N_{\mathrm{RB}}^{\mathrm{max,DL}}$	is the largest downlink bandwidth configuration, expressed in multiples of $N_{\mathrm{sc}}^{\mathrm{RB}}$;
$N_{\mathrm{sc}}^{\mathrm{RB}}$	is the resource block size in the frequency domain, expressed as a number of subcarriers . $N_{\mathrm{sc}}^{\mathrm{RB}} = 12$ subcarriers for PRS, with $\Delta f = 15\,\mathrm{kHz}$ spacing (180 kHz total).

The pseudo-random sequence generator for $c(i)$ is initialized with $c_{\mathrm{init}} = 2^{10} \cdot (7 \cdot (n_s + 1) + l + 1) \cdot (2 \cdot N_{\mathrm{ID}}^{\mathrm{cell}} + 1) + 2 \cdot N_{\mathrm{ID}}^{\mathrm{cell}} + N_{\mathrm{CP}}$ at the start of each OFDM symbol where

$$N_{\mathrm{CP}} = \begin{cases} 1 & \text{for normal Cyclic Prefix} \\ 0 & \text{for extended Cyclic Prefix} \end{cases}$$

$N_{\mathrm{ID}}^{\mathrm{cell}}$ Physical layer cell identity.

Therefore, the PRS sequence depends on the frame/slot timing (n_s, l) and the physical cell ID (PCI, $N_{\mathrm{ID}}^{\mathrm{cell}}$).

5.3 Mapping to Resource Elements

The reference signal sequence $r_{l,n_s}(m)$ is generated for a specific slot in a radio frame. The reference signal sequence $r_{l,n_s}(m)$ is mapped to complex-valued QPSK modulation symbols $a_{k,l}^{(p)}$ used as reference signal for antenna port $p = 6$ in slot n_s according to 3GPP TS 36.211 [3], section 6.10.4.2:

$$a_{k,l}^{(p)} = r_{l,n_s}(m')$$

where

Normal cyclic prefix:

$$k = 6\left(m + N_{\mathrm{RB}}^{\mathrm{DL}} - N_{\mathrm{RB}}^{\mathrm{PRS}}\right) + \left(6 - l + v_{\mathrm{shift}}\right) \bmod 6$$

$$l = \begin{cases} 3,5,6 & \text{if } n_s \bmod 2 = 0 \\ 1,2,3,5,6 & \text{if } n_s \bmod 2 = 1 \text{ and } (1 \text{ or } 2 \text{ PBCH antenna ports}) \\ 2,3,5,6 & \text{if } n_s \bmod 2 = 1 \text{ and } (4 \text{ PBCH antenna ports}) \end{cases}$$

$$m = 0,1,\ldots,2 \cdot N_{\mathrm{RB}}^{\mathrm{PRS}} - 1$$

$$m' = m + N_{\mathrm{RB}}^{\mathrm{max,DL}} - N_{\mathrm{RB}}^{\mathrm{PRS}}$$

Extended cyclic prefix:

$$k = 6\left(m + N_{\mathrm{RB}}^{\mathrm{DL}} - N_{\mathrm{RB}}^{\mathrm{PRS}}\right) + \left(5 - l + v_{\mathrm{shift}}\right) \bmod 6$$

$$l = \begin{cases} 4,5 & \text{if } n_s \bmod 2 = 0 \\ 1,2,4,5 & \text{if } n_s \bmod 2 = 1 \text{ and } (1 \text{ or } 2 \text{ PBCH antenna ports}) \\ 2,4,5 & \text{if } n_s \bmod 2 = 1 \text{ and } (4 \text{ PBCH antenna ports}) \end{cases}$$

$$m = 0,1,\ldots,2 \cdot N_{\mathrm{RB}}^{\mathrm{PRS}} - 1$$

$$m' = m + N_{\mathrm{RB}}^{\mathrm{max,DL}} - N_{\mathrm{RB}}^{\mathrm{PRS}}$$

The bandwidth for positioning reference signals is $N_{\mathrm{RB}}^{\mathrm{PRS}}$ and the cell-specific frequency shift is given by $v_{\mathrm{shift}} = N_{\mathrm{ID}}^{\mathrm{cell}} \bmod 6$. Therefore, PRS have an effective reuse of six (i.e., six possible frequency shifts, or six possible diagonal pattern).

The PRS bandwidth $N_{\mathrm{RB}}^{\mathrm{PRS}}$ may be smaller than the LTE system bandwidth $N_{\mathrm{RB}}^{\mathrm{max,\,DL}}$. In that case, the PRS resource blocks occupy the central resource blocks.

The mapping of positioning reference signals to resource elements is shown in Figure 5-1 for normal cyclic prefix and one-or-two transmit antenna ports (left), and four transmit antenna ports (right). Figure 5-2 shows the corresponding mapping for the extended cyclic prefix case.

Each square in Figure 5-1 and Figure 5-2 indicates a resource element with frequency-domain index k and time-domain index l. The squares labelled R_6 indicate PRS resource elements within a block of 12 subcarriers over 14 or 12 OFDM symbols, respectively.

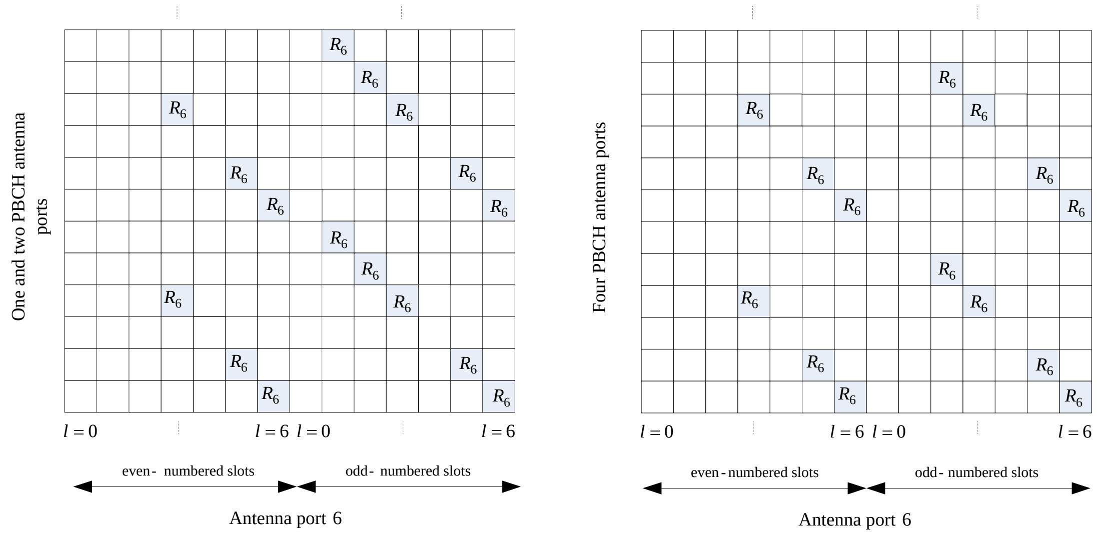

Figure 5-1: Mapping of positioning reference signals (normal cyclic prefix)

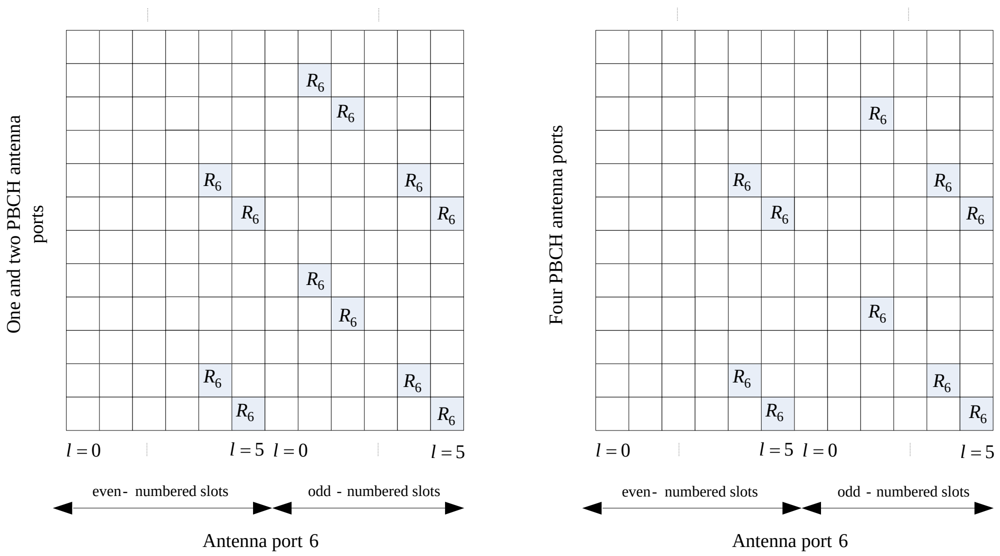

Figure 5-2: Mapping of positioning reference signals (extended cyclic prefix).

5.4 PRS Transmission Schedule

PRS are transmitted in pre-defined positioning subframes grouped by several consecutive subframes N_{PRS}, which are termed "positioning occasions". Positioning occasions occur periodically with a certain periodicity T_{PRS}. The period T_{PRS} is defined in 3GPP TS 36.211 [3] and can be 160, 320, 640, or 1280 subframes (or milli-seconds), and the number of consecutive subframes N_{PRS} can be 1, 2, 4, or 6 subframes. Figure 5-3 shows an example of positioning occasions with N_{PRS} = 4 subframes, separated by T_{PRS} subframes.

The 3rd parameter which characterizes the PRS transmission schedule is the cell specific subframe offset Δ_{PRS} which defines the starting subframe of PRS transmission, relative to SFN=0 (which can be inferred relative to the beginning of each PRS period T_{PRS}), as shown in Figure 5-4. The parameters T_{PRS} and Δ_{PRS} are derived from the PRS Configuration Index I_{PRS}, as shown in Table 5-1 (3GPP TS 36.211 [3], section 6.10.4.3).

Table 5-1: PRS Configuration Index.

PRS configuration Index I_{PRS}	PRS periodicity T_{PRS} (subframes)	PRS subframe offset Δ_{PRS} (subframes)
0 – 159	160	I_{PRS}
160 – 479	320	$I_{PRS} - 160$
480 – 1119	640	$I_{PRS} - 480$
1120 – 2399	1280	$I_{PRS} - 1120$
2400-4095	Reserved	

In general, the positioning reference signal instances, for the first subframe of the N_{PRS} downlink subframes, satisfies $(10 \times n_f + \lfloor n_s/2 \rfloor - \Delta_{PRS}) \bmod T_{PRS} = 0$, where n_f is the system frame number (SFN), and n_s is the slot number within a radio frame.

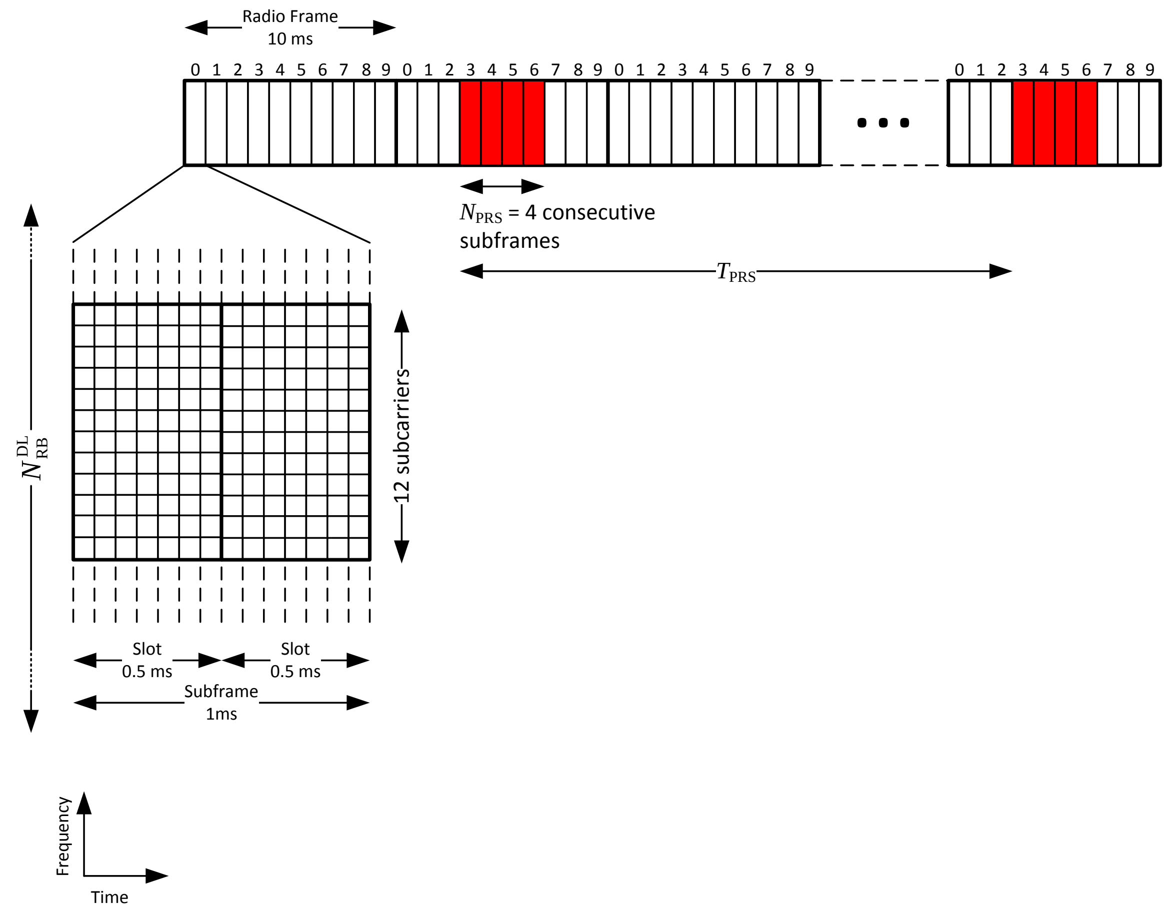

Figure 5-3: PRS Transmission Schedule.

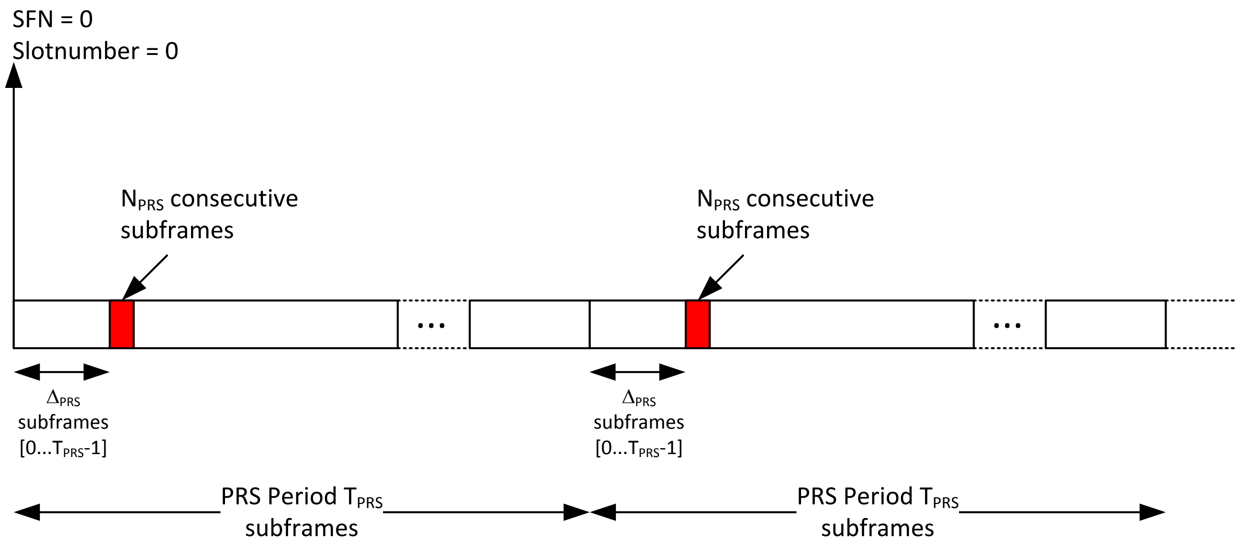

Figure 5-4: PRS subframe configuration.

5.5 Low Interference Subframes (LIS)

Positioning subframes have been designed as Low Interference Subframes, that is, without transmission on data channels (PDSCH). As a result, in perfectly synchronized networks, PRS are interfered by other cell PRSs with the same pattern index (i.e., with the same frequency shift $v_{\text{shift}} = N_{\text{ID}}^{\text{cell}} \bmod 6$), but not by data transmission (see also section 5.7).

Figure 5-5 shows an example of a PRS resource block in positioning subframes. The white area does not contain any data.

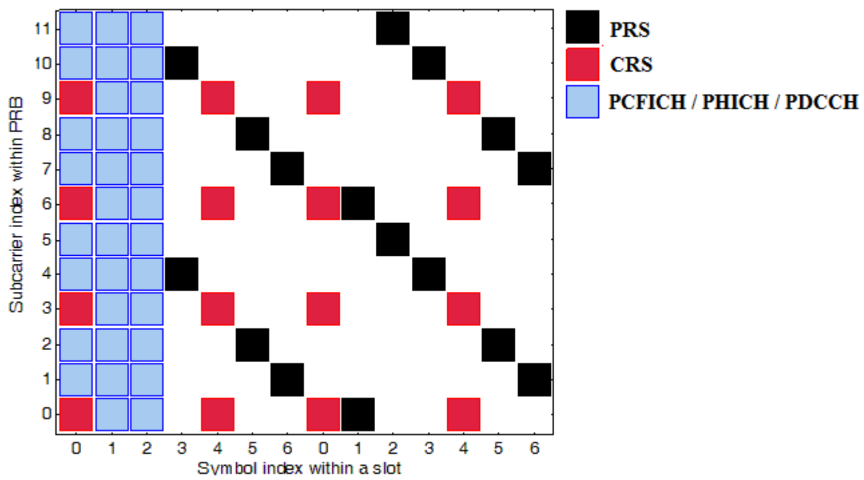

Figure 5-5: PRS pattern for vshift=1 and 1 PBCH antenna port.

5.6 PRS Muting

The PRS in the individual positioning occasions are transmitted with constant power (see also section 5.11). PRSs in certain positioning occasions can also be transmitted with zero power, which is referred to "PRS muting" . When the (strong) PRS signal the UE receives from its e.g., serving base station is muted, the (weak) PRS signals from the neighbour base stations (with same frequency shift) can be more easily detected by the UE.

The PRS muting configuration of a cell is defined by a periodic muting sequence with periodicity T_{REP}, where T_{REP} counted in number of PRS positioning occasions can be 2, 4 , 8, or 16 (3GPP TS 36.355 [7]). The PRS muting info is represented by a bit string of length 2, 4, 8, or 16 bits (corresponding to the selected T_{REP}), and each bit in this bit string can have the value "0" or "1". If a bit in the PRS muting info is set to "0", then the PRS is muted in the corresponding PRS positioning occasion. The first bit of the PRS muting sequence corresponds to the first PRS positioning occasion that starts after the beginning of the assistance data reference cell SFN=0 (see also section 7).

A 16-bit muting pattern cannot be used together with T_{PRS} = 1280 ms, because the range of T_{REP} would then extend over 16 × 1.28 seconds = 20.48 seconds, which is twice as big as the roll-over value of the SFN (10.24 seconds).

Figure 5-6 shows an example of PRS muting pattern with T_{REP} of four positioning occasions. The yellow marked positioning occasions are muted in this example. Therefore, the corresponding PRS muting bit string would be '1100'.

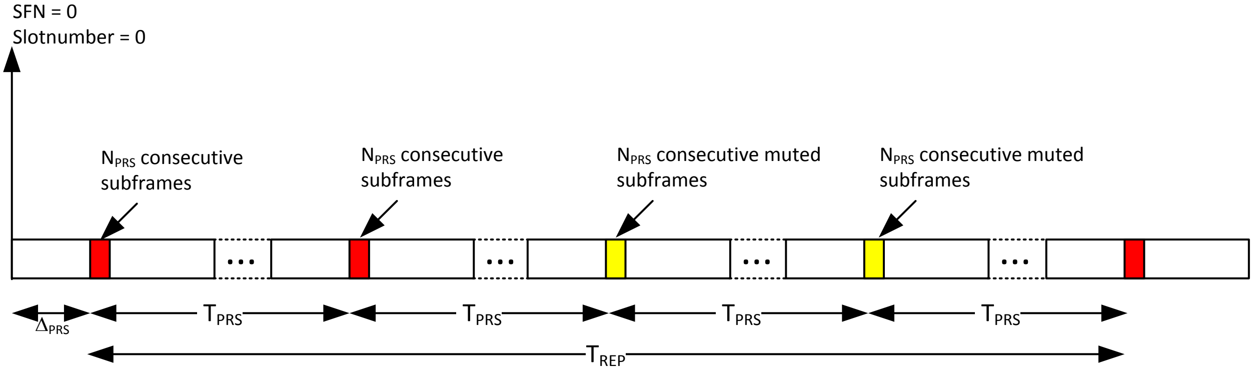

Figure 5-6: Example of PRS Muting pattern.

A PRS configuration with four cells is illustrated in Figure 5-7. The PRS occasions in each cell are synchronized. Since the PRS of cell PCI=0 and cell PCI=6 in the example would have the same pattern index, the PRS symbols overlap in frequency (and therefore, would interfere each other). To reduce interference (and therefore, increase hearability), PRS occasions can be muted. Muting means that a scheduled PRS occasion is transmitted at zero power. In the example of Figure 5-7 when PRS of cells PCI=0 and PCI=1 are transmitting PRS occasions, the PRS occasions with the same pattern index PCI=6 and PCI=7 would be muted.

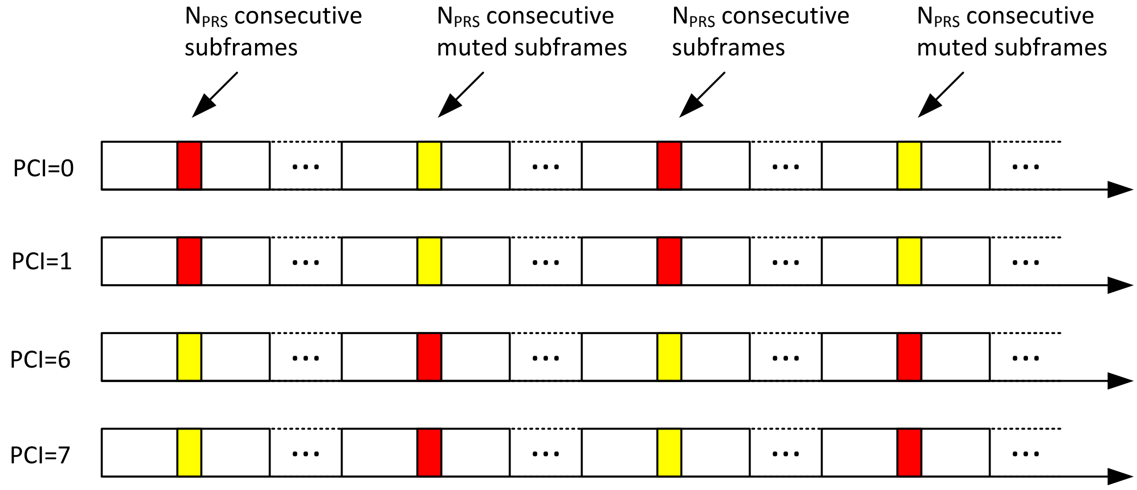

Figure 5-7: PRS configuration example with several cells and alternating muting pattern.

5.7 Network Synchronization for PRS

In order to exploit the high detection capability of the PRS, the network need to be synchronized to LTE frame boundaries and the PRS occasions for all eNodeB's on one frequency layer need to be aligned in time. (Note, network synchronization is anyhow a requirement for OTDOA positioning (see section 4)). This is illustrated in Figure 5-7 for 4 cells. The PRS occasions in all cells shown in Figure 5-7 are aligned in time. Specifically, this means the same number of PRS subframes N_{PRS} in each positioning occasion for each cell on the same frequency layer, and the same PRS periodicity T_{PRS} for each cell on the same frequency layer. Otherwise a strong cell (e.g., primary cell) can potentially overpower PRS of a neighbour cell with other channels; e.g., PDSCH.

The available value ranges for the specified OTDOA assistance data elements (see section 7; in particular the RSTD search window in section 7.1.4) support (at least partially) synchronized PRS occasions on each frequency layer. The maximum offset between the transmitted PRS positioning occasions cannot exceed half a subframe. Schematic examples of the full and partial alignment of PRS are shown in Figure 5-8. Partial alignment means that there is an overlap of at most 0.5 ms between subframes of any two cells. Partial alignment increases the interference from neighbour cells and complicates the network data base, since the transmit time offsets $((T_j - T_i)$ in section 4.3) would be non-zero and must be accurately known in the network. Therefore, for maximum performance, the offset between the transmitted PRS occasions on each frequency layer should be zero.

If the cells on a frequency layer are SFN-synchronized, the above requirement means that the I_{PRS} (see Table 5-1) for each cell is the same. If the cells on a frequency layer are synchronized on frame boundaries, but not on SFN, this means the I_{PRS} is different between the cells.

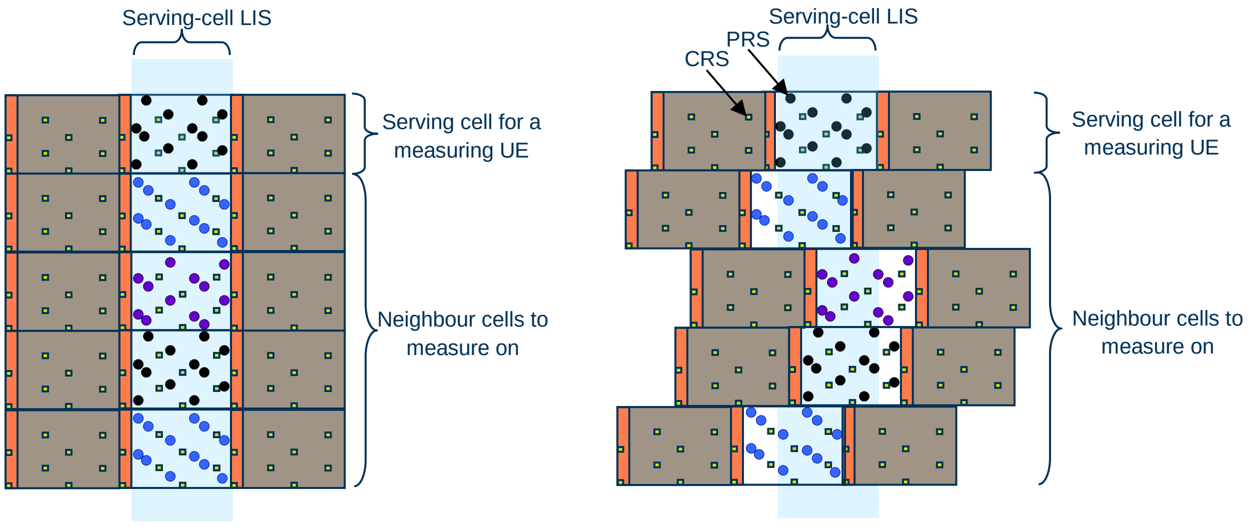

Figure 5-8: Full and partial alignment of positioning subframes (example with one positioning subframe).

5.7.1 PRS Synchronization Offset between Frequency Layer

The inter-frequency measurements, including RSTD, are usually conducted during inter-frequency measurement gaps which are configured by E-UTRAN (see also section 6.4). Since a measurement gap for RSTD measurements is 6 ms, about up to 4 PRS subframes only are available for inter-frequency RSTD measurements, because the first and last subframe in the gap are needed for the UE radio to switch frequencies.

The measurement gaps colliding with positioning subframes on more than one frequency can only be used for measuring on one of the frequencies. Therefore, PRS occasions on different frequency layers should not be aligned, as illustrated in Figure 5-9. If the positioning subframes on f1 and f2 would align, the UE would not be able to measure the PRS occasion on f1 when a measurement gap occurs.

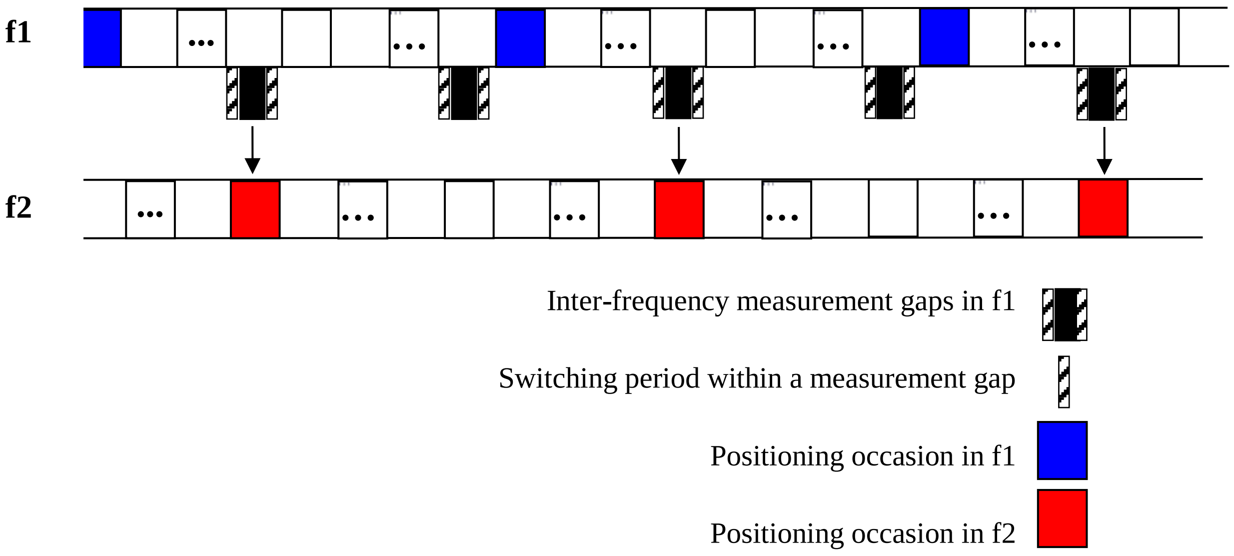

Figure 5-9: Example of Positioning Subframes in Frequency Layer f2 shifted with respect to Frequency Layer f1.

5.8 Isolation of PRS Tones

As discussed in the previous sections, the 3GPP standard for PRS signals provide three layers of isolation for PRS tones to improve hearability (i.e., the ability to detect weak neighbour cells):

1. **Code domain:** The PCI is used to initialize the seed of the PRS sequence, as described in section 5.2. Cells with a different PCI will have a different PRS sequence. 504 different PCI's are defined for LTE.

2. **Frequency domain**: PRS has a frequency re-use of six, and the value of mod(PCI,6) determines one of the six possible frequency arrangements, as described in section 5.3. If two cells have the same mod(PCI,6) values, the PRS tones collide and will no longer be orthogonal. In such cases, the isolation from the PRS sequence distinguishes one cell from the other. However, e.g., for a UE close to the serving cell, the received power difference from neighbouring cells can easily be more than the isolation that the PRS sequence provides.

3. **Time domain:** If PRS collide in frequency domain, muting can make the PRS occasions again orthogonal to each other, as described in section 5.6.

5.9 PRS Overhead

The overhead of OTDOA is not only from new reference signals, i.e. PRS, but also from low interference subframes (see section 5.5). The PRS overhead can be defined as:

$$PRS_{OVH} = \frac{N_{PRS}}{T_{PRS}} \cdot \frac{BW_{PRS}}{BW_{Sys}} \qquad (5\text{-}1)$$

and is summarized in Table 5-2 for 20 MHz LTE system bandwidth for a T_{PRS}=160 ms. The overhead is expressed as percentage of the LTE system bandwidth.

PRS overhead percentage (LTE System BW 20 MHz)				
PRS BW [MHz]	N_{PRS}			
	1	2	4	6
1.4	0.0438	0.0875	0.1750	0.2625
3	0.0938	0.1875	0.3750	0.5625
5	0.1563	0.3125	0.6250	0.9375
10	0.3125	0.6250	1.2500	1.8750
15	0.4688	0.9375	1.8750	2.8125
20	0.6250	1.2500	2.5000	3.7500

Table 5-2: PRS Overhead in Percentage of LTE System Bandwidth.

The selection of the PRS bandwidth and N_{PRS} is a tradeoff between performance and overhead. The UE intra-frequency RSTD measurement performance requirements are specified in 3GPP TS 36.133 [9] based on the green cells in Table 5-2 which give the best tradeoff between performance and overhead (see also section 8.1). I.e., for 1.4 and 3 MHz PRS bandwidth $N_{PRS} = 6$ is needed to obtain the specified minimum performance; for 5 MHz PRS bandwidth $N_{PRS} = 2$ is needed, and for 10, 15, 20 MHz PRS bandwidth $N_{PRS}=1$ is sufficient.

Increasing the T_{PRS} would reduce the overhead. For example, increasing T_{PRS} from 160 ms to 320 ms while retaining the same N_{PRS} value reduces the overhead shown in Table 5-2 by half. However, this would then also increase the UE response time. In addition, user motion over the measurement period adds additional uncertainty to the user location.

5.10 Restrictions for PRS subframes

Positioning reference signals are transmitted in configured DL subframes (3GPP TS 36.211 [3]).

Positioning reference signals cannot be transmitted in special subframes (3GPP TS 36.211 [3]).

The positioning reference signals cannot be mapped to resource elements allocated to PBCH, PSS or SSS (3GPP TS 36.211 [3]).

Positioning reference signals should not be present in resource blocks in which the UE shall decode PDSCH according to a detected PDCCH. E.g., when the UE is receiving SIB1 (in the serving cell only), it may assume PDSCH REs instead of PRS REs (3GPP TS 36.213 [4]).

Therefore, to avoid blanking of PRS symbols, I_{PRS}, N_{PRS} should be selected such that no positioning subframes overlap with PBCH, PSS, SSS, or SIB1.

In addition, I_{PRS}, N_{PRS} should be selected such that no (or minimal) collision of PRS occasions occur with measurement gaps and paging occasions[2].

5.10.1 FDD Configuration

Subframes which should not be configured with PRS are illustrated in Figure 5-10.

Subframe 0 contains the PBCH, as well as PSS and SSS, and should therefore, not be configured with PRS.

[2] In RRC_CONNECTED state, the UE can be paged for ETWS/CMAS, however this is not really about reaching a specific UE but to inform about the fact the ETWS/CMAS notifications are being broadcast. UE can also be paged for system info modification.

Subframe 5 contains the PSS and SSS, and occasionally SIB1, and should therefore, not be configured with PRS.

Subframes 0, 4, 5, and 9 can be used for paging, dependent on the defined paging cycle.

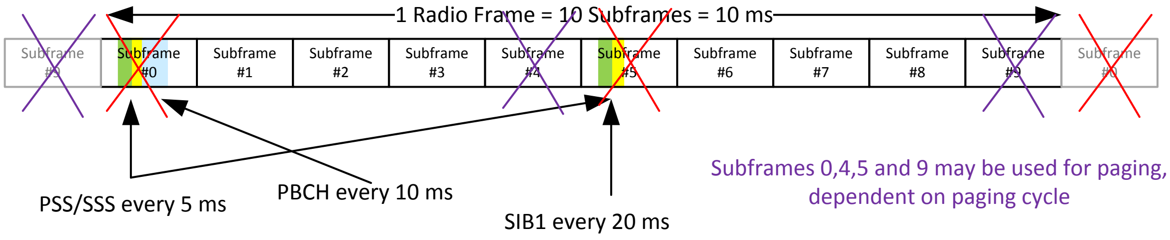

Figure 5-10: LTE subframe structure for FDD operation, indicating subframes which should not be used for PRS.

5.10.2 TDD Configuration

Subframes which should not be configured with PRS are illustrated in Figure 5-11.

Special subframes are not configured with PRS.

Subframe 0 contains the PBCH, and should therefore, not be configured with PRS.

The PSS is broadcast using the third symbol of time slot 2 (subframe 1) and the third symbol of time slot 12 (subframe 6).

Subframe 1 is always a special subframe so the PSS is sent as part of the Downlink Pilot Time Slot (DwPTS).

Subframe 6, may or may not be a special subframe, depending upon the uplink-downlink subframe configuration. It is a special subframe for configurations 0, 1, 2 and 6. Otherwise it is a normal downlink subframe. However, the 3rd symbol of even numbered slots contains no PRS REs (see Figure 5-1 and Figure 5-2).

The SSS is broadcast using the last symbol of time slot 1 (subframe 0) and the last symbol of time slot 11 (subframe 5). Both time slots 1 and 11 are always within normal downlink subframes, but slot 1 (subframe 0) should anyhow not be used for PRS (since allocated for PBCH). If PRS are configured in subframe 5, the last symbol would then not be available for PRS. However, subframe 5 also contains occasionally SIB1 (every 20 ms), and may contain a paging occasion, and should therefore, not be configured with PRS.

Subframes 0, 1, 5 and 6 can be used for paging, dependent on the paging cycle.

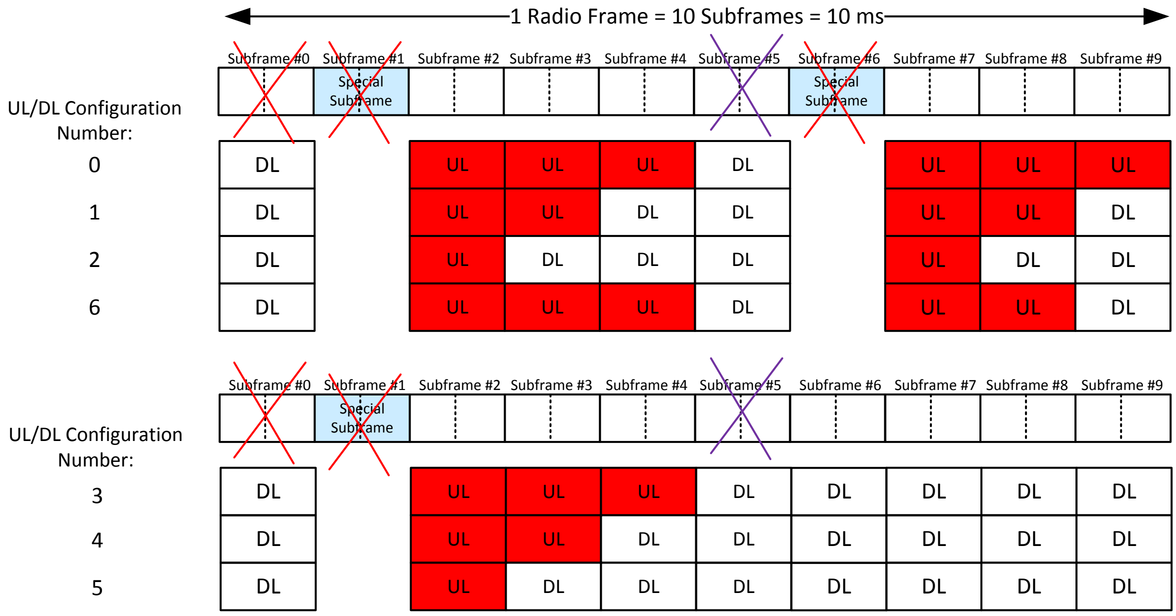

Figure 5-11: LTE subframe structure for TDD operation, indicating subframes which should not be used for PRS.

5.11 PRS Power Offset

The downlink positioning reference signal Energy Per Resource Element (EPRE) is assumed to be constant across the positioning reference signal bandwidth and across all OFDM symbols that contain positioning reference signals in a given positioning reference signal occasion (3GPP TS 36.213 [4]).

A power offset can be used to change the power of PRS REs. This power offset is typically expressed with respect to the power of CRS REs.

Increasing the PRS transmit power increases hearability of neighbour cells, but at the same time influences the PRS inter-cell interference experienced to neighbour cells.

In particular, as the number of measured eNodeB's grows, it is more likely that PRS of other cells interfere with the PRS of a desired cell (i.e., overlapping PRS pattern in frequency domain). Increasing the PRS power essentially raises the noise floor and may not yield performance improvements.

If muting is supported to make PRS orthogonal in time domain, the interference from neighbour cell PRS is reduced and the main source of noise in such cases should be primarily thermal noise. An increase of PRS power with respect to CRS (e.g., by 3 dB) may then improve the detection probability of neighbour cells.

In 3GPP specifications (e.g., 36.133 [9]), the Energy Per Resource Element (EPRE) is distinguished between OFDM symbols that do contain RE carrying CRS symbols and OFDM symbols that do not. The following nomenclature is used in 3GPP:

- xCH_RA: xCH-to-RS EPRE ratio for the channel xCH in all transmitted OFDM symbols not containing CRS.

- xCH_RB: xCH-to-RS EPRE ratio for the channel xCH in all transmitted OFDM symbols containing CRS.

Since PRS REs are always transmitted in OFDM symbols not containing CRS only a PRS_RA is defined:

- PRS_RA: PRS-to-RS EPRE ratio for the PRS in all transmitted OFDM symbols not containing CRS.

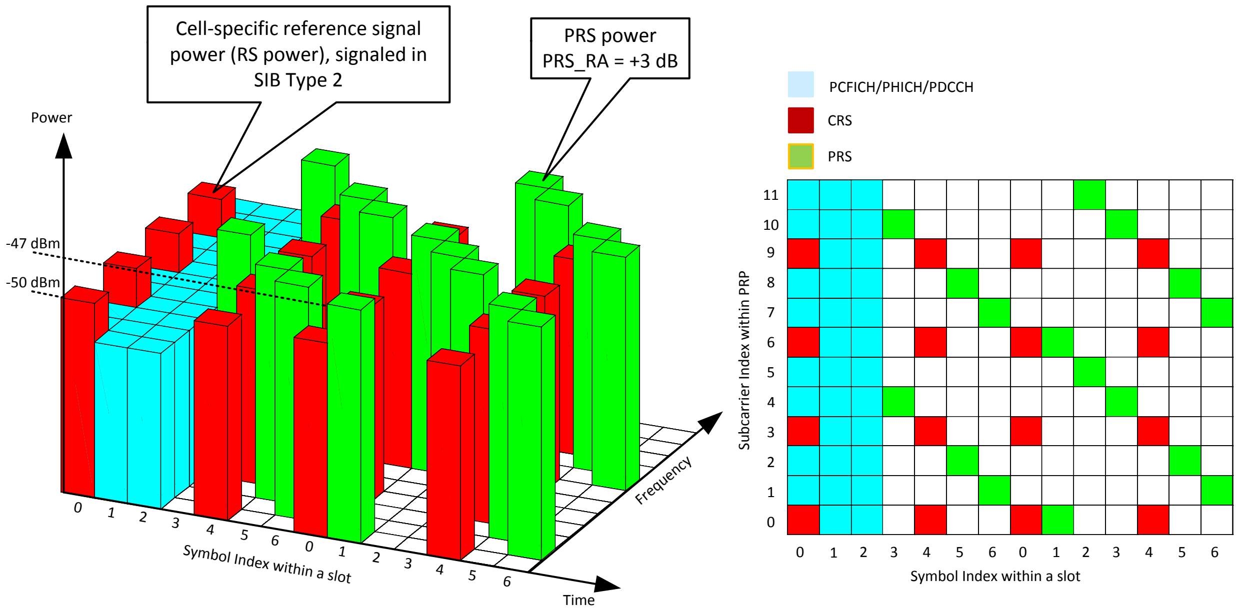

Figure 5-12: Example of PRS Power Boosting.

6 General OTDOA Positioning Procedures

There are two principle architecture variants to support location services standardized: Control Plane (CP) and User Plane (UP).

Control Plane solutions are standardized in e.g., 3GPP for each individual air interface technology (e.g., [2] for LTE). In Control Plane, all the signaling used to initiate a positioning event and the signaling related to the positioning event itself occur over the control channels of the cellular network.

In the user plane architecture, all the signaling used to initiate a positioning event and signaling related to the positioning event itself occur over user bearer channels and appear simply as user data to the wireless network. It allows the bypass of many of the traditional telecommunication elements by allowing the handset to make a TCP/IP connection directly with the location server. The user plane location architecture is independent of a particular air interface technology (e.g., common to GSM, UMTS, or LTE, etc.) and is standardized in OMA as Secure User Plane Location (SUPL) [13].

6.1 Architecture Overview

A simplified positioning architecture is shown in Figure 6-1.

The key network element for supporting OTDOA (or LCS in general) is the Location Server. In control plane (CP) positioning, the location server is an E-SMLC; in user plane (UP) positioning, the location server is a SUPL SLP.

The GMLC is the first node in control plane positioning an external LCS client accesses. After performing registration and authorization, it sends positioning requests to the MME and receives final location estimates from the MME (3GPP TS 23.271 [1]).

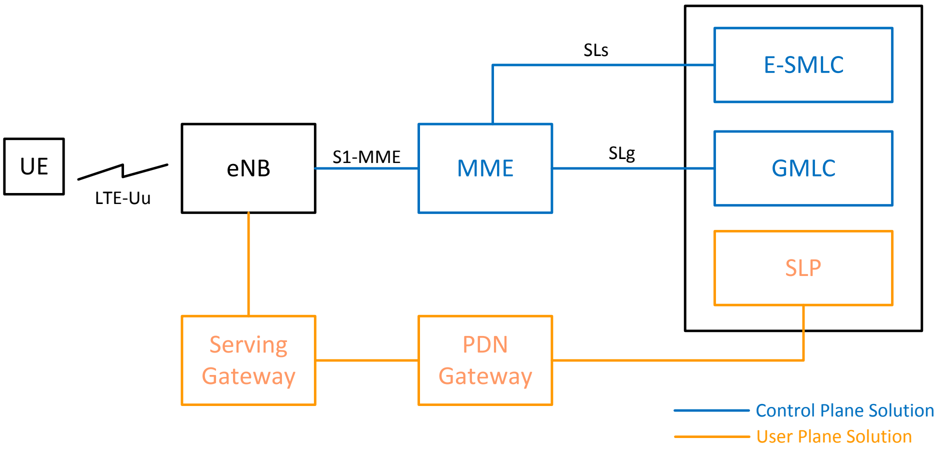

Figure 6-1: LTE LCS Architecture Overview.

The location server (E-SMLC or SUPL SLP) manages OTDOA positioning for a target device by obtaining RSTD measurements from the UE and providing assistance data to the UE to help determine this. The Location Server may also compute (UE-assisted) or verify (UE-based) the final location estimate.

In control plane solution, the MME receives a request for some location service associated with a particular target UE from another entity (e.g., GMLC or UE) or the MME itself decides to initiate some location service on behalf of a particular target UE (e.g., for an IMS emergency call from the UE) as described in 3GPP TS 23.271 [1]. The MME then sends a location services request to an E-SMLC. The E-SMLC processes the location services request which include transferring OTDOA assistance data to the target UE. The E-SMLC then returns the result of the location service back to the MME. In the case of a location service requested by an entity other than the MME (e.g., UE or GMLC), the MME returns the location service result to this entity.

The SLP is the SUPL entity responsible for positioning over the user plane [13]. The SLP communicates directly with the UE over the user plane (data bearer). The SLP OTDOA functionality is the same as that of the E-SMLC.

6.2 Signalling between Location Server and UE

For OTDOA positioning, the LTE Positioning Protocol (LPP) is used between the location server and the UE (see section 6.3). LPP is used in both, control plane solution and SUPL user plane solution. Only the transport channels of the LPP messages are different between CP and UP.

In CP, LPP messages are carried as transparent PDUs across intermediate network interfaces using the appropriate protocols (e.g., S1-AP over the S1-MME interface, NAS/RRC over the Uu interface).

6.2.1 Protocol Layering for Control Plane Solution

Figure 6-2 shows the protocol layering used to support transfer of LPP/LPPe messages between an E-SMLC and UE. The LPP(e) PDU is carried in NAS PDU between the MME and the UE (see section 6.6 for LPPe details).

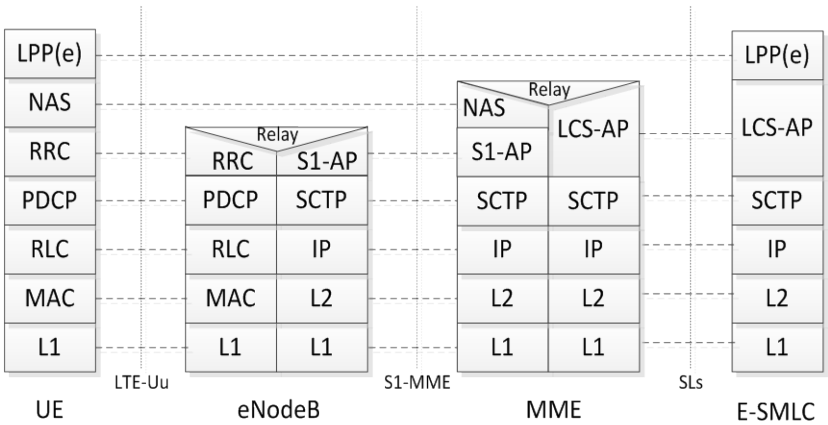

Figure 6-2: Protocol Layering for E-SMLC to UE Signaling.

- **LTE-Uu interface:** The LTE-Uu interface, connecting the UE to the eNodeB over the air, is used as transport link for the LTE Positioning Protocol. The LPP payload is transported in RRC UL/DL Information Transfer messages (3GPP TS 36.331 [6]). The Dedicated NAS Info in these RRC messages is the UL/DL Generic NAS Transport container, specified in 3GPP TS 24.301 [12].
- **S1-MME interface:** The S1-MME interface between the eNode B and the MME is transparent to all UE-positioning related procedures. It is involved in these procedures only as a transport link for the LTE Positioning Protocol.
- **SLs interface:** The SLs interface, between the E-SMLC and the MME, is transparent to all UE related and eNodeB related positioning procedures. It is then used only as a transport link for the LTE Positioning Protocols LPP and LPPa.
  The SLs interface supports location sessions instigated by the MME. The LCS-AP protocol is specified in 3GPP TS 29.171 [11]. LPP and LPPa transport are then supported as part of any location session.

6.2.2 Protocol Layering for User Plane Solution

SUPL, including the use of LPP over SUPL ULP, takes place as part of the general user-plane protocol stack shown in Figure 6-3. SUPL ULP occupies the application layer in the stack, with LPP/LPPe (or another positioning protocol) transported as another layer above SUPL ULP.

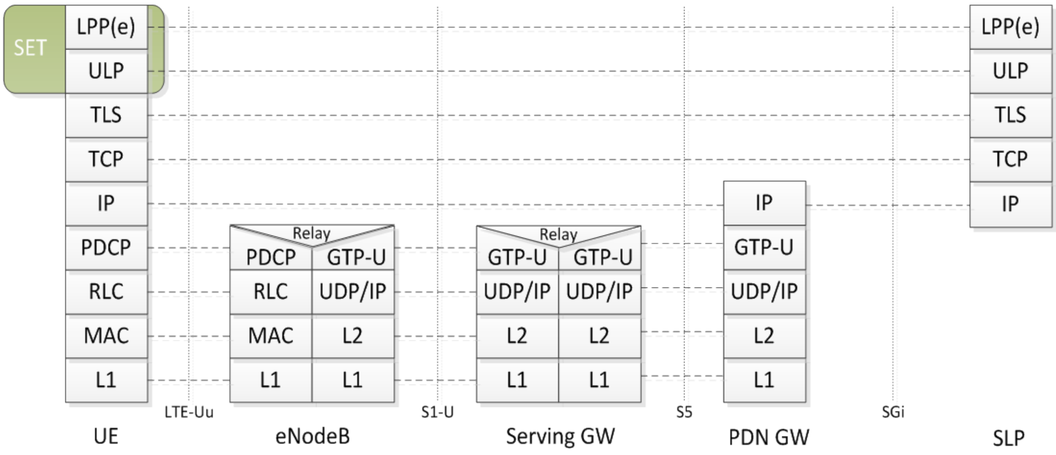

Figure 6-3: User-plane protocol stack (for SLP to UE/SET Signaling).

6.3 LPP Procedures

The LPP procedures between location server (E-SMLC or SUPL SLP) usually consist of

(a) Capability Transfer,

(b) Assistance Data Transfer,

(c) Location Information Transfer,

and is shown in Figure 6-4 (3GPP TS 36.355 [7]).

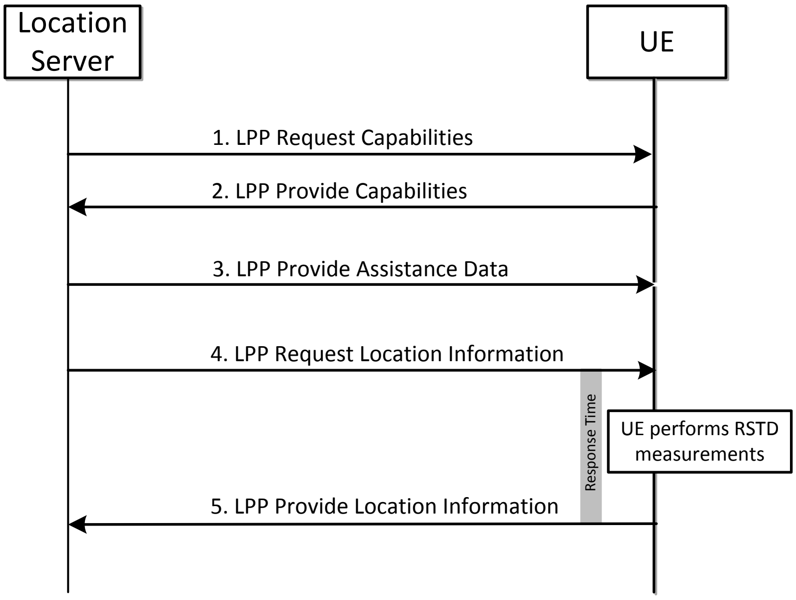

Figure 6-4: LPP Positioning Procedure.

1. The location server sends a Request Capabilities message to the UE, which indicates the type of capabilities needed. For OTDOA, this includes the *OTDOA-RequestCapabilities* IE, indicating that the UE's OTDOA capabilities are requested.
2. The UE responds with a *ProvideCapabilities* message to the server. If OTDOA capabilities were requested in step 1, this message includes:
   a. OTDOA Mode supported: LPP supports only UE-assisted mode. UE-based mode is supported via LPPe (see section 6.6).
   b. Supported frequency bands: This field specifies the frequency bands for which the UE supports RSTD measurements.
   c. Support for inter-frequency RSTD measurements: This field specifies whether the UE supports inter-frequency RSTD measurements or not.
3. The location server sends a *ProvideAssistanceData* message to the UE containing OTDOA assistance data. The OTDOA assistance data are described in section 7.

   The OTDOA assistance data include an assistance data reference cell, and assistance for up to 72 neighbour cells. If the UE indicates support for inter-frequency RSTD measurements (step 2c), the neighbour cell assistance data may be provided for up to 3 frequency layers.
4. The location server sends a *RequestLocationInformation* message to the UE to request RSTD measurements. This message usually includes:
   a. Location Information Type: For OTDOA over LPP, this can only be location measurements (i.e., UE-assisted mode).
   b. Desired accuracy (of the location estimate that could be obtained by the server from the RSTD measurements provided by the UE).
   c. Response Time: Specifies the maximum response time as measured between receipt of the *RequestLocationInformation* and transmission of a

ProvideLocationInformation. This is given as an integer number of seconds between 1 and 128.

i Optionally, periodic measurement reporting may be requested, with a specified reporting period and duration.

d. Environment Characterization: Provides the UE with information about expected multipath and non line of sight (NLOS) in the current area.

5. The UE then performs the RSTD measurements, using the provided assistance data received at step 3. The assistance data include candidate cells for measurements together with their PRS configuration (see section 7). At the latest, when the response time received at step 4 expired, the UE provides the RSTD measurements in a *ProvideLocationInformation* message to the location server. This message includes:

   a. Time stamp of the measurement set in form of the SFN.

   b. Identity of the reference cell used for calculating the RSTD (PCI, ARFCN and/or ECGI).

   c. Quality of the TOA measurement from the reference cell.

   d. Neighbour cell measurement list for up to 24 cells:

      i Identity of the measured neighbour cell (PCI, ARFCN and/or ECGI).

      ii RSTD measurement (as described in section 4.2).

      iii Quality of the RSTD measurement.

A LPP location session as shown in Figure 6-4 comprises one or more LPP transactions, with each LPP transaction performing a single operation (capability exchange, assistance data transfer, or location information transfer). LPP transactions within a session usually occur serially. Messages within a transaction are linked by a common transaction identifier. A Transaction End Flag is used to indicate when a transaction has ended. For example, a LPP assistance data transfer procedure (step 3 in Figure 6-4) may comprise one or more LPP Provide Assistance Data messages. This may be the case if the assistance data to be provided do not fit into a single message. Similarly, multiple LPP Provide Location Information messages (step 5 in Figure 6-4) may be used in case the UE has to report more measurements that would fit into a single message (e.g., more than 24 RSTD measurements), or if the UE provides periodic measurements.

The quality indicator for the TOA measurement of the reference cell (step 5c) and for the RSTD measurements (step 5d-iii) can be any metric which indicates a relative quality of each measurement; e.g., a standard deviation, a signal-to-noise-ratio, etc. This information may be used at the position calculation function for weighting the individual measurements. E.g., a good quality measurement may get a higher weight in the position calculation function than a low quality measurement.

6.4 RRC Procedures for Inter-Frequency RSTD Measurements

RSTD measurements are applicable to intra-frequency and inter-frequency cells (see section 4.2). Inter-frequency measurements usually require measurement gaps available at the UE.

The idea of the measurement gap is to create a small gap during which no transmission and reception happens. Since there is no signal transmission and reception during the gap, UE can switch to the target cell frequency and perform the RSTD measurement and come back to the current cell frequency.

Two possible gap pattern can be configured by the network, each with a gap length of 6 ms (3GPP TS 36.133 [9]):

- gap pattern #0: the gap occurs every 40 ms;
- gap pattern #1: the gap occurs every 80 ms.

For RSTD measurements, only gap pattern #0 is applicable (3GPP TS 36.133 [9]).

Measurement gaps are always configured at the eNodeB. However, in OTDOA positioning, the eNodeB is not aware of an OTDOA measurement request, since the measurement request via LPP is transparent to the eNodeB.

In order to configure the pre-defined measurement gap pattern #0 for a given UE when performing the inter-frequency RSTD measurements, the eNodeB has to be aware of whether an inter-frequency positioning measurement is requested by the E-SMLC for this UE.

For that reason, a new UE-triggered measurement gap request message was introduced in 3GPP Rel-10: RRC Inter-Frequency RSTD Measurement Indication procedure, defined in 3GPP TS 36.331 [6], and shown in Figure 6-5.

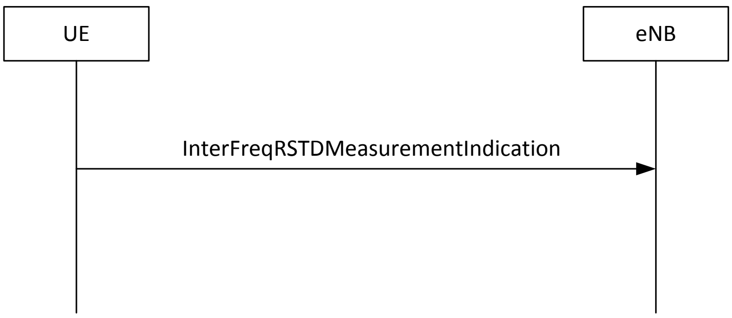

Figure 6-5: RRC *InterFreqRSTDMeasurementIndication* procedure.

The purpose of this procedure is to indicate to the eNodeB that the UE is going to start/stop inter-frequency RSTD measurements.

The UE sends a *RRC InterFrequRSTDMeasurementIndication* message “start” to the eNodeB, if

- LPP layer indicates to start performing inter-frequency RSTD measurements, and
- the UE requires measurement gaps for these measurements while measurement gaps are either not configured or not sufficient.

The message for “start” includes:

- EARFCN the UE needs to perform inter-frequency measurements on.
- *measPRS-Offset*:
    - Indicates the requested gap offset for performing inter-frequency RSTD measurements. The *measPRS-Offset* is illustrated in Figure 6-6.
      It is the smallest subframe offset from the beginning of subframe 0 of SFN=0 of the serving cell of the requested gap for measuring PRS positioning occasions in the carrier frequency for which the UE needs to perform the inter-frequency RSTD measurements. The value of *measPRS-Offset* is obtained by mapping the starting

subframe of the PRS positioning occasion in the measured cell onto the corresponding subframe in the serving cell and is calculated as the serving cell's number of subframes from SFN=0 mod 40.

The UE also takes into account any additional time required to start PRS measurements on the other carrier when it does this mapping for determining the *measPRS-Offset* (e.g., may place the positioning occasions in the middle of the gap as illustrated in Figure 6-6).

The message for "stop" is an empty message (does not include any parameter).

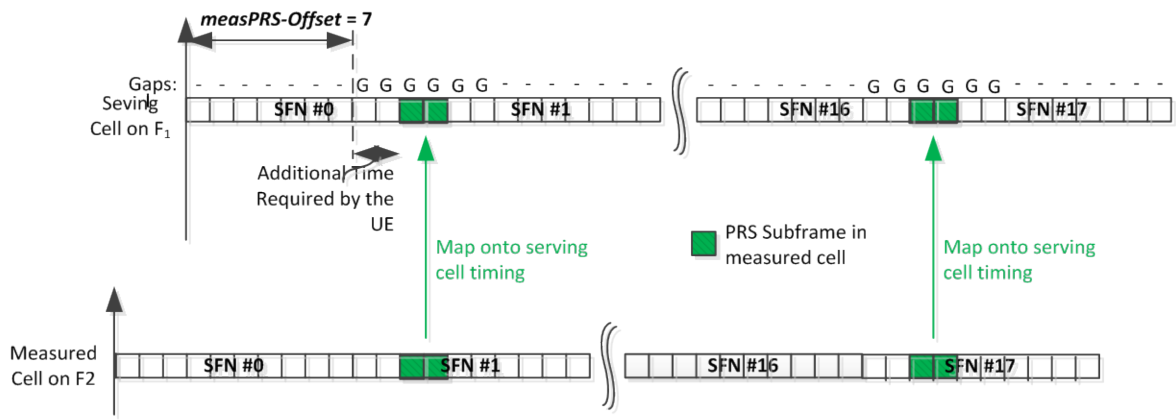

Figure 6-6: Calculation of *measPRS-Offset* field.

The overall procedure for inter-frequency RSTD measurements, including the LPP and RRC measurement gap request, is summarized in Figure 6-7.

At step (c) in Figure 6-7, the UE requests appropriate measurement gaps (RRC *InterFreqRSTDMeasurementIndication*), which are usually appropriate for RSTD measurements on one PRS inter-frequency layer (since PRS occasions on different frequency layer should not align (see section 5.7.1)). If the assistance data received at step (a) include neighbour cells on more than one inter-frequency layer, the UE would usually send a new measurement gap request message once the first frequency layer measurements are completed, as illustrated in Figure 6-8. Therefore, multiple different inter-frequency layer measurements create additional overhead and require additional allowed response time at the UE.

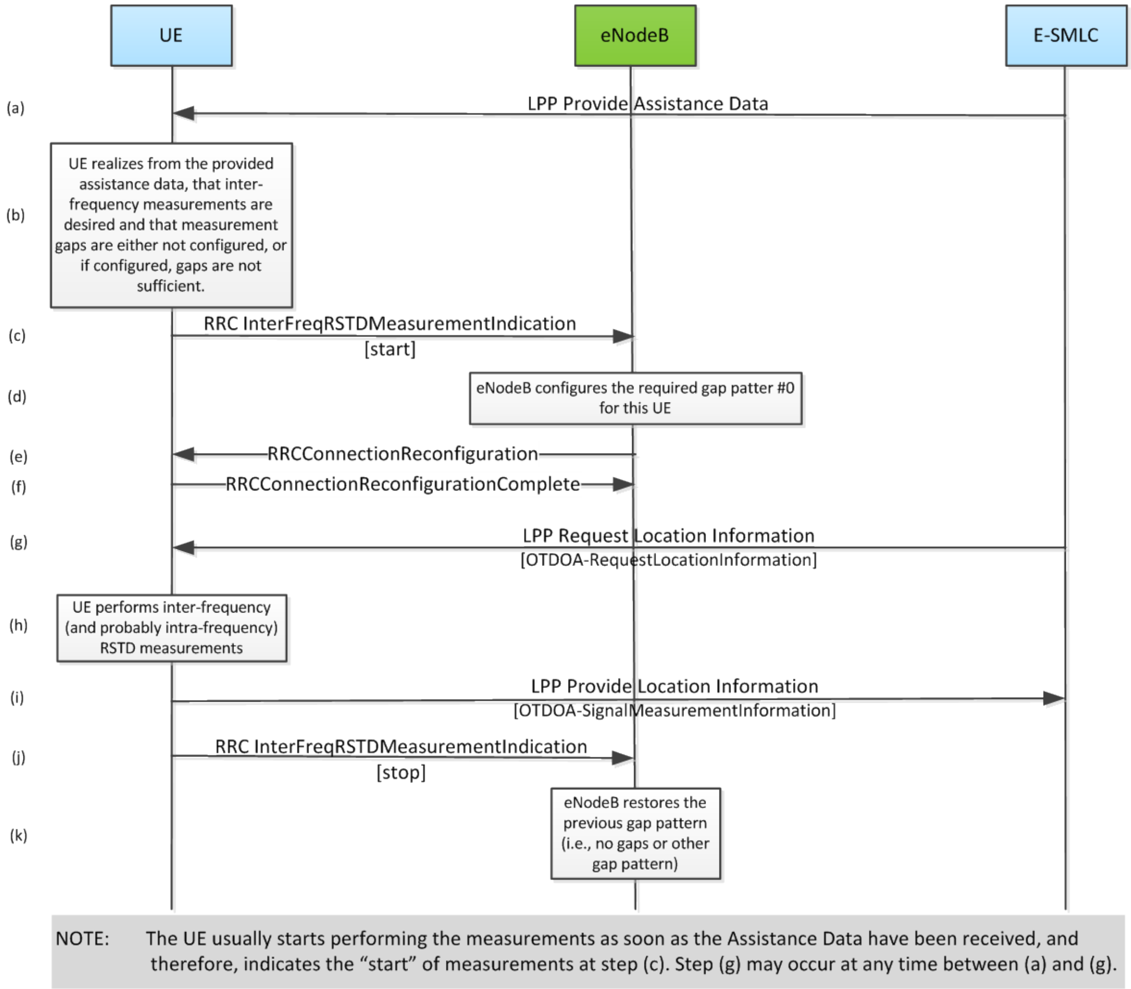

Figure 6-7: Example OTDOA measurement procedure including inter-frequency RSTD measurements.

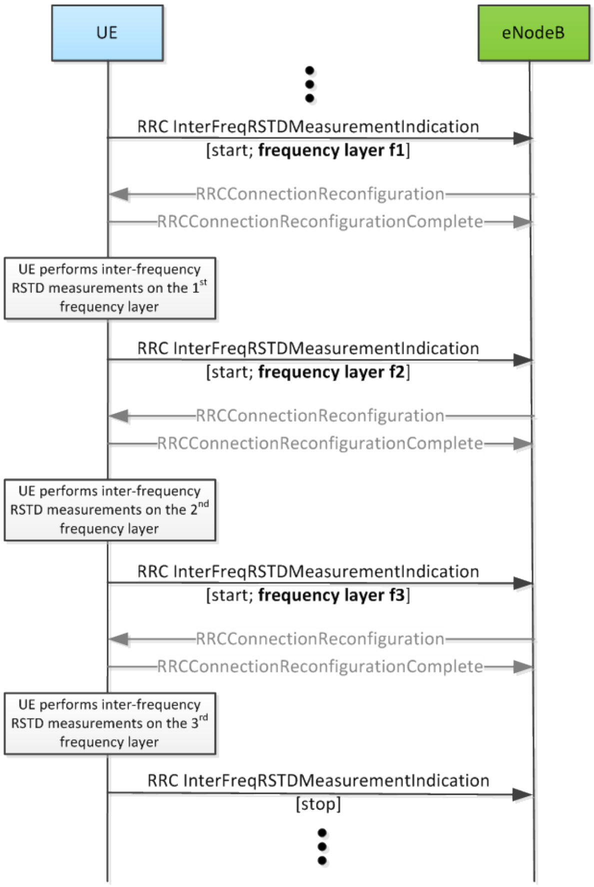

Figure 6-8: RRC *InterFreqRSTDMeasurementIndication* procedure for RSTD measurements on multiple inter-frequency layer.

6.5 LPPa Procedure

The LTE Positioning Protocol Annex (LPPa) carries information between the eNodeB and the E-SMLC and is specified in 3GPP TS 36.455 [8]. It may be used for OTDOA to support data collection from eNodeBs for support of OTDOA positioning.

The LPPa protocol is transparent to the MME. The protocol layering for E-SMLC to eNode B signaling is shown in Figure 6-9.

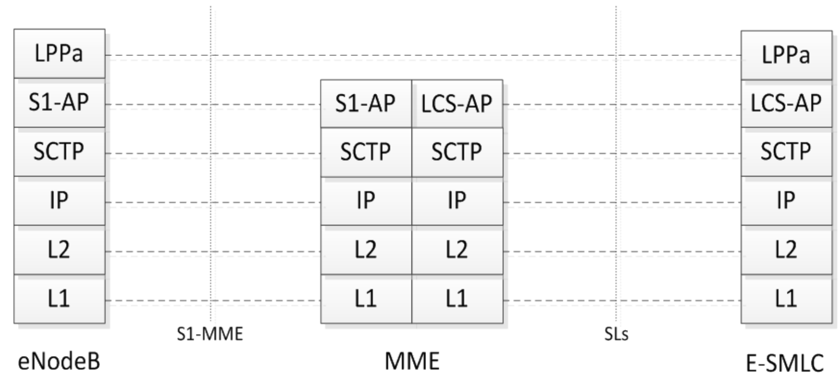

Figure 6-9: Protocol Layering for E-SMLC to eNode B Signaling.

The LPPa Assistance Data that may be transferred from the eNodeB to E-SMLC include:

- PCI and CGI of the cells under the eNodeB;
- Timing information on the eNodeB;
- Geographical coordinates of the eNodeB.

The LPPa procedure used for this purpose is the OTDOA Information Exchange procedure (3GPP TS 36.455 [8]) shown in Figure 6-10.

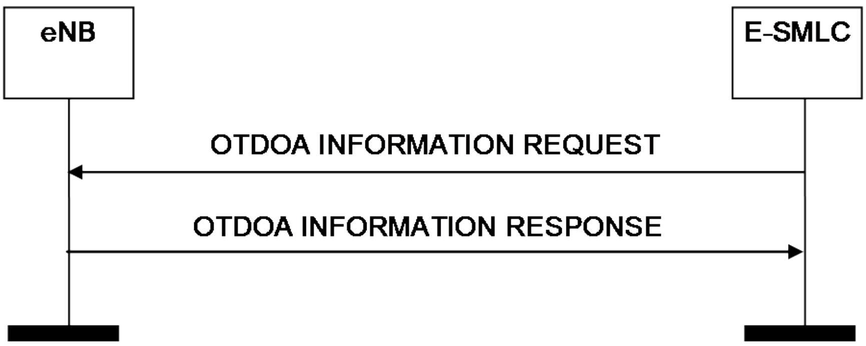

Figure 6-10: LPPa OTDOA Information Exchange procedure.

The OTDOA Information Request message includes a request for the eNode B to provide:

- PCI, ECGI, TAC, EARFCN;
- PRS Bandwidth, PRS Configuration Index I_{PRS}, CP length, Number of consecutive PRS DL subframes N_{PRS}, Number of antenna ports;
- SFN Initialization time;
- Antenna coordinates;
- PRS muting configuration.

The OTDOA Information Response message includes the requested information.

The SFN Initialization time is defined as a 64-bit string and provides the time in seconds relative to 00:00:00 on 1 January 1900 (calculated as continuous time without leap seconds and traceable to a common time reference) where binary encoding of the integer part is in the first 32 bits and binary encoding of the fraction part in the last 32 bits. The fraction part is expressed with a granularity of 1 /2^{32} second.

6.6 LPPe OTDOA Support

The 3GPP LTE Positioning Protocol (LPP) has been designed in such a way that it can also be utilized outside the control plane domain such as in the user plane in the context of OMA SUPL.

LPP elementary messages (Request and Provision of Capabilities and Location Information and Assistance Data) each include a container, an EPDU, which can be used by standardization fora outside 3GPP to define their own extensions to LPP messages. OMA LPP Extensions (LPPe) take advantage of this feature [15].

LPP EPDU containers are identified by a unique EPDU-ID, specified in 3GPP TS 36.355 [7].

Although, LPPe is defined in OMA primarily for User Plane location within SUPL, LPPe EPDU's can also be used in control plane solution.

The 3GPP LPP protocol supports only UE-assisted mode of OTDOA (i.e., the UE performs RSTD measurements and the location estimate is calculated at the location server). OMA LPPe provides extensions for OTDOA UE-based mode (i.e., where the location estimate is calculated in the UE).

The location procedure is the same as described in section 6.3, but each of the three LPP elementary messages include an EPDU with additional data:

- LPP Request Capabilities:
  - The LPPe EPDU is used to request LPPe defined capabilities.
- LPP Provide Capabilities:
  - For OTDOA, the LPPe EPDU provides information on whether or not the target device supports UE-based OTDOA related assistance data. The UE can indicate this support separately for eNodeB's and Home eNodeB's.
- LPP Provide Assistance Data
  - For OTDOA, the LPPe EPDU provides additional assistance data information for UE-based OTDOA, as described in section 7.3.
- LPP Request Location Information:
  - The LPPe EPDU is used to request UE-based OTDOA.
- LPP Provide Location Information
  - The LPPe EPDU provides time information when the UE calculated location estimate is valid (LTE SFN). The actual location estimate (latitude/longitude/altitude) is provided using LPP information elements.

7 OTDOA Assistance Data

Without the knowledge of when the to-be-measured PRS signals are expected to arrive at the UE in time, and without the knowledge of the specific PRS configuration, the UE would not be able to perform the RSTD measurements.

To enable the RSTD measurements, a location server in the network transmits OTDOA assistance data to the UE (3GPP TS 36.355 [7]; see also section 6.3).

The OTDOA assistance data contain two elements:

1. **OTDOA Reference Cell Info:** This element contains parameters for the reference cell. Elements in the OTDOA Neighbour Cell Info element are provided relative to this reference cell.
2. **OTDOA Neighbour Cell Info:** This element contains parameters for each of the neighbour cells. The OTDOA Neighbour Cell Info list is sorted in decreasing order of priority for measurements. The sorting of this list is left to server implementation. The UE should provide the available RSTD measurements in the same order as provided by the location server.

7.1 OTDOA Assistance Data Elements

7.1.1 OTDOA Reference Cell Info

The OTDOA Reference Cell Info element includes information about the identity of the reference cell, and the PRS configuration of the reference cell, as summarized in Table 7-1.

- 'M' indicates the element is mandatory present in the message.
- 'O' indicates the element is optional present in the message.
- 'C' indicates the element is conditional present in the message, where the condition is described in the definition of the element.

Table 7-1: OTDOA Reference Cell Assistance Information.

Element	Definition	Presence
Physical Cell ID	Specifies the PCI of the reference cell. Identifies the cell and is used for determining the PRS sequence (see section 5.2).	M
Cell Global ID	Specifies the ECGI of the reference cell, which is the global unique identity of the cell in the E-UTRA. May be used to solve any PCI ambiguity problems.	O
EARFCN	Specifies the EARFCN of the reference cell, in case it is different compared to the UE's primary cell.	C
Antenna Port Configuration	Specifies whether 1 (or 2) or 4 antenna ports are used for the cell specific reference signals of the reference cell, in case it is different compared to the UE's primary cell. Determines the CRS mapping to resource elements (3GPP TS 36.211 [3]).	C

Element	Definition	Presence
CP Length	Specifies the Cyclic Prefix length of the reference cell PRS and CRS, in case it is different compared to the UE's primary cell. Determines the sequence generation and mapping to resource elements (see sections 5.2 and 5.3).	C
PRS Info	Defines the PRS configuration of the cell (see section 7.1.3), if PRS are configured on the reference cell.	C

7.1.2 OTDOA Neighbour Cell Info

The OTDOA Neighbour Cell Info element includes information about the identity of each neighbour cell, the PRS configuration of each neighbour cell, and an RSTD search window for each neighbour cell, as summarized in Table 7-2. The OTDOA neighbour cell info list can include information for up to 72 neighbour cells.

Table 7-2: OTDOA Neighbour Cell Assistance Information.

Element	Definition	Presence
Physical Cell ID	Specifies the PCI of the particular neighbour cell. Identifies the cell and is used for determining the PRS sequence (see section 5.2).	M
Cell Global ID	Specifies the ECGI of the particular neighbour cell, which is the global unique identity of the cell in the E-UTRA. May be used to solve any PCI ambiguity problems.	O
EARFCN	Specifies the EARFCN of the particular neighbour cell, in case it is different compared to the OTDOA reference cell.	C
CP Length	Specifies the Cyclic Prefix length of the particular neighbour cell PRS and CRS, in case it is different compared to the OTDOA reference cell. Determines the sequence generation and mapping to resource elements (see sections 5.2 and 5.3).	C
PRS Info	Determines the PRS configuration of the cell (see section 7.1.3), in case it is different compared to the OTDOA reference cell.	C
Antenna Port Configuration	Specifies whether 1 (or 2) or 4 antenna ports are used for the cell specific reference signals of the particular neighbour cell, in case it is different compared to the OTDOA reference cell. Determines the CRS mapping to resource elements (3GPP TS 36.211 [3]).	C
Slot Number offset	Specifies the slot number offset at the transmitter between this particular cell and the assistance data reference cell in case the slot timing is different compared to the OTDOA reference cell. The Slot Number Offset together with the current slot number of the assistance data reference cell is used to calculate the current slot number of this particular cell which may further be used to generate the CRS sequence by the target device. PRS/CRS sequence depends on the frame/slot timing (see section 5.2).	C
PRS Subframe Offset	Specifies the offset between the first PRS subframe in the assistance data reference cell on the reference carrier frequency and the first PRS subframe in the closest subsequent PRS positioning occasion of this cell on the other carrier frequency (see section 7.1.4) (in case of inter-frequency cells are included in the assistance data).	C
Expected RSTD	Specifies the RSTD value that the UE is expected to measure between this cell and the assistance data reference cell (see section 7.1.4).	M
Expected RSTD Uncertainty	Specifies the uncertainty in Expected RSTD value (see section 7.1.4).	M

7.1.3 PRS Configuration Info

Both, the OTDOA Reference Cell Info and OTDOA Neighbour Cell Info element contain the PRS Information (see Table 7-1 and Table 7-2). The PRS Info allows the UE to determine the PRS configuration and schedule, and is summarized in Table 7-3.

Table 7-3: PRS Information Element.

Element	Definition	Presence
PRS Bandwidth	Specifies the bandwidth used for PRS in number of resource blocks. 1.4, 3, 5, 10, 15, and 20 MHz are possible	M
PRS Configuration Index	Specifies the I_{PRS}, defined in Table 5-1.	M
Number of PRS DL frames	Specifies the number of consecutive DL subframes N_{PRS}. 1, 2, 4, or 6 consecutive DL subframes are possible (see section 5.4).	M
Muting Info	Specifies the PRS muting configuration of the cell, if muting is used. The PRS muting configuration is defined by a periodic PRS muting sequence with periodicity T_{REP} where T_{REP}, counted in the number of PRS positioning occasions, can be 2, 4, 8, or 16. The Muting Info is provided as a bit string of length 2, 4, 8, or 16 (i.e., T_{REP}). If a bit in the PRS muting sequence is set to "0", then the PRS is muted in the corresponding PRS positioning occasion. A PRS positioning occasion comprises of N_{PRS} downlink positioning subframes (see also section 5.6). The first bit of the PRS muting sequence corresponds to the first PRS positioning occasion that starts after the beginning of the assistance data reference cell SFN=0.	C

7.1.4 RSTD Search Window

The location server predicts the RSTD value the UE is expected to measure, and provides a search window to the UE in the assistance data (see Table 7-2). The location server needs to know a (rough) a-priori location of the UE, e.g., from Cell-ID or Enhanced Cell-ID positioning. Based on this location, neighbour cell candidates for RSTD measurements are selected (e.g., neighbour cells around the a-priori UE location so that good measurement geometry can be obtained (see also section 8.2)).

With the a-priori UE location and the location of each neighbour eNodeB, the location server can calculate the distance between the a-priori UE location and each candidate neighbour eNodeB, and therefore, can calculate the RSTD value the UE is expected to measure.

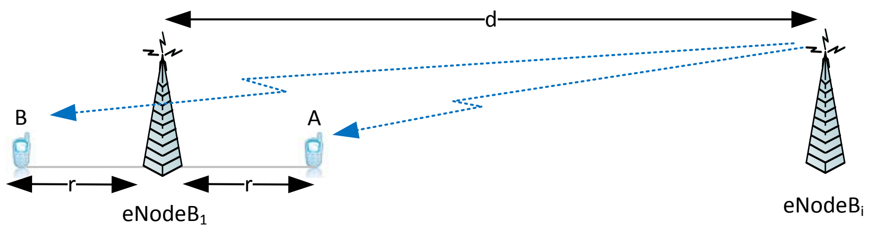

Figure 7-1: Illustration of RSTD Search Window Size calculation.

Figure 7-1 illustrates a scenario with two eNodeB's, reference eNodeB$_1$ and neighbour eNodeB$_i$, and two possible UE locations, A and B, the closest and furthest with respect to the neighbour $eNodeB_i$, respectively. Assume the signal transmitted at $eNodeB_1$ at time *t* arrives at locations A and B at $t+r/c$, where *c* is the speed of the radio waves. The signal transmitted by the neighbour $eNodeB_i$ at time $t+\Delta$, where Δ is the transmit time difference (RTD), is received at $(t+\Delta)+(d-r)/c$ and $(t+\Delta)+(d+r)/c$ in locations A and B, respectively (if the eNodeB transmissions are perfectly synchronized, the RTD Δ=0). Therefore, the RSTD of $eNodeB_i$ transmission with respect to $eNodeB_1$ transmission at the locations A and B are $[(\Delta+d/c)-2r/c]$ and $[\Delta+d/c]$, respectively. If the reference $eNodeB_1$ is the UE serving cell, r/c may be known via the timing advance, or may generally be based on the maximum cell radius of $eNodeB_1$. Therefore, the search window is in the range $[-r/c; +r/c]$ centered at $(\Delta+d/c-r/c)$. In other words, the search window size depends on the distance (radius) of the reference eNodeB to the UE, and therefore, the search window size is generally the same for all neighbour eNodeB's in the assistance data neighbour list. The distance (radius *r*) is usually the maximum cell radius.

The search window center is the expected RSTD parameter, and the search window size is the expected RSTD Uncertainty parameter. Both values together define a search window for the UE where the RSTD can be found.

- **Expected RSTD** (3GPP TS 36.355 [7]):
  Indicates the RSTD value that the UE is expected to measure between a neighbour cell and the assistance data reference cell. It takes into account the expected propagation time difference as well as any transmit time difference of PRS positioning occasions between the two cells. The resolution is $3\times T_s$, with $T_s=1/(15000\times2048)$ seconds.
- **Expected RSTD Uncertainty** (3GPP TS 36.355 [7]):
  Indicates the uncertainty in Expected RSTD value. The uncertainty is related to the location server's a-priori estimation of the UE location. The resolution is $3\times T_s$, with $T_s=1/(15000\times2048)$ seconds.

Figure 7-2 illustrates the Expected RSTD and Uncertainty for two cells on the same frequency layer. The Figure shows the signal timing as seen at the UE.

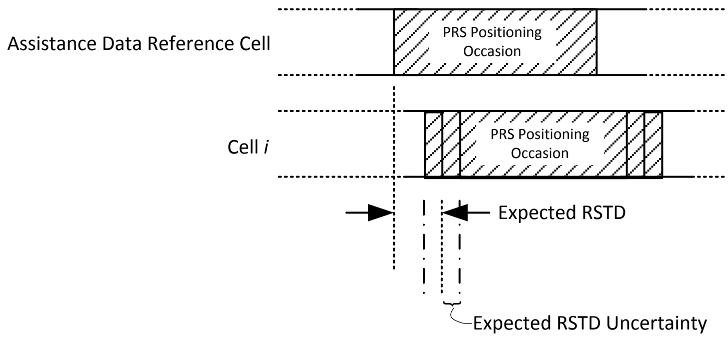

Figure 7-2: Expected RSTD and Uncertainty for cells on the same frequency layer.

In case the network consists of multiple frequency layers with PRS, the PRS occasions on the two frequency layer should have an offset from each other (see section 5.7.1). In that case, the PRS Subframe Offset (see Table 7-2) specifies the offset between the first PRS subframe in the assistance data reference cell on the reference carrier frequency layer and the first PRS subframe in the closest subsequent PRS positioning occasion of the neighbour cell on the other carrier frequency layer, as illustrated in Figure 7-3.

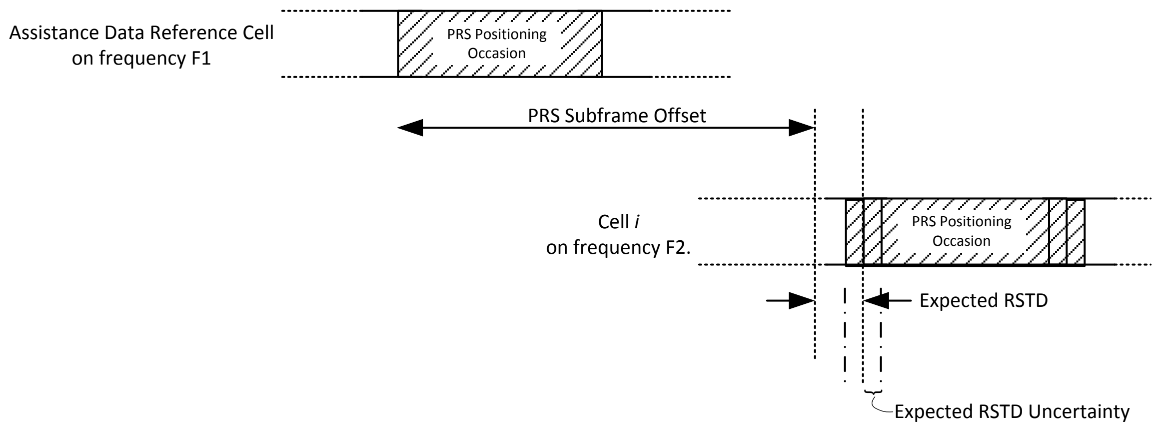

Figure 7-3: Expected RSTD and Uncertainty for cells on different frequency layer.

The UE determines the beginning of the PRS positioning occasion of the neighbour cell within the search window of size [-Expected RSTD Uncertainty×3×T_s *;* +Expected RSTD Uncertainty×3×T_s] centered at T_{REF} + (1 millisecond×N) + (Expected RSTD × 3×T_s), where T_{REF} is the reception time of the beginning of the PRS positioning occasion of the assistance data reference cell at the UE antenna connector; N = 0 when the EARCFN of the neighbour cell is equal to that of the assistance data reference cell, and N = PRS Subframe Offset otherwise.

The Expected RSTD is encoded in LPP as an Integer between -8192 and +8191 (14-bits). Therefore, the search window range is [-8192×3×Ts ; 8191×3×Ts] ≈ [-0.8 ms ; + 0.8 ms]. This value range also supports "partial synchronized" PRS occasions (where the maximum offset between the transmitted PRS positioning occasions Δ cannot exceed half a subframe (0.5 ms) (see also section 5.7).

7.2 Requirements for Selection of OTDOA Assistance Data

The PRS configuration parameter depends on the cell timing (e.g., SFN). The PRS instances, for the first subframe of the N_{PRS} downlink subframes, satisfies $(10 \times n_f + \lfloor n_s/2 \rfloor - \Delta_{PRS}) \bmod T_{PRS} = 0$, where n_f is the system frame number (SFN), and n_s is the slot number within a radio frame (see section 5.4). When the UE receives a PRS configuration index I_{PRS} in the OTDOA assistance data, the UE determines the PRS periodicity and the PRS subframe offset using Table 5-1. In order to determine the frame and slot when a PRS is scheduled in the specific cell, the UE needs to know the frame and slot timing (SFN) of this cell (n_f, n_s).

In addition, the muting pattern is defined relative to SFN=0 of the assistance data reference cell (see section 5.6 and 7.1.3).

Since the PRS occasions from all cells on the same frequency layer are aligned in time (see section 5.7), the assistance data cells need to include at least one cell for which the UE can obtain the SFN. The SFN for the other cells can be derived based on the fact that the PRS occasions overlap in time.

If muting is used, the cell with the known SFN must be the assistance data reference cell, since the first bit in the PRS muting sequence corresponds to the first PRS occasion that starts after the beginning of the assistance data reference cell SFN=0 (see sections 5.6 and 7.1.3).

The UE conventionally has only the SFN of the serving cell available. Therefore, the assistance data reference cell should be the UE's serving cell.

7.3 Additional OTDOA Assistance Data Elements in LPPe

The LPPe OTDOA assistance data elements include extensions to the assistance data described in section 7.1; i.e., extensions to the OTDOA Reference Cell Info and OTDOA Neighbour Cell Info to support UE-based OTDOA.

7.3.1 LPPe OTDOA Reference Cell Info

The LPPe OTDOA Reference Cell Info element includes additional information about the timing and location of the reference cell, as summarized in Table 7-4.

Table 7-4: LPPe OTDOA Reference Cell Assistance Information.

Element	Definition	Presence
System Frame Number	Provides a time stamp (SFN) for the RTD information, which may be used to calculate the RTD at a later time using the RTD drift rate (see Table 7-5).	C
RTD reference standard deviation	Provides the standard deviation of the timing of the reference cell, used to determine the RTD values (see also section 4.3) provided in the LPPe OTDOA Neighbour Cell Info List (Table 7-5).	O
Cell Location	Provides the antenna location of the reference cell.	M

7.3.2 LPPe OTDOA Neighbour Cell Info

The LPPe OTDOA Neighbour Cell Info element includes additional information about the timing and location of each neighbour cell, as summarized in Table 7-5.

Table 7-5: LPPe OTDOA Neighbour Cell Assistance Information.

Element	Definition	Presence
Cell Location	Provides the location and optional uncertainty in location of the antenna of the neighbour cell relative to a reference point.	M
RTD Info	Provides the RTD between the particular neighbour cell and the reference cell (see also section 4.3), together with its standard deviation and drift rate, in units of 10 ns.	M

8 Factors Influencing OTDOA Accuracy

8.1 RSTD Measurement Performance

RSTD measurement accuracy requirements are specified in 3GPP TS 36.133 [9]. The UE physical layer shall be capable of reporting RSTD measurements for the reference cell and all neighbour cells *i*, provided that the PRS SINR of the reference cell is greater than –6 dB and the PRS SINR of the neighbour cells is greater –13 dB:

$$\left(PRS\,\frac{\hat{E}_s}{I_{ot}}\right)_{ref} \geq -6\;dB \qquad (8\text{-}1)$$

$$\left(PRS\,\frac{\hat{E}_s}{I_{ot}}\right)_{i} \geq -13\;dB \qquad (8\text{-}2)$$

The accuracy requirements when the above conditions are fulfilled depend on the PRS bandwidth, and are different for intra-frequency and inter-frequency measurements. The requirements assume that no measurement gaps overlap with PRS subframes of the measured serving cell and the expected RSTD Uncertainty (see section 7.1.4) is less than 5 µs (about 154 Ts).

8.1.1 Intra-Frequency Accuracy Requirement

Accuracy	**Minimum PRS bandwidth, which is minimum of serving cell channel bandwidth and the PRS bandwidths of the reference cell and the measured neighbour cell *i***	**Minimum number of available measurement subframes among the reference cell and the measured neighbour cell *i***
Ts	**RB**	**N_{PRS}**
±15	≥ 6	6
±6	≥ 25	≥ 2
±5	≥ 50	≥ 1

- Ts is the basic time unit defined in 3GPP TS 36.211 [3]. Ts = 1/(15000 × 2048) seconds, which is a little more than 32 ns, which corresponds to about 9.8 meters.
- Resource Blocks RB:
  - 6 RB's correspond to 1.4 MHz bandwidth
  - 25 RB's correspond to 5 MHz bandwidth
  - 50 RB's correspond to 10 MHz bandwidth
- N_{PRS} is the number of PRS subframes in each positioning occasion (see section 5.4)

- Therefore, the accuracy requirement is a function of PRS bandwidth (BW):
  - +/- 15 Ts with BW < 5 MHz
  - +/- 6 Ts with 5 MHz ≤ BW < 10 MHz
  - +/- 5 Ts with 10 MHz ≤ BW

I.e., the accuracy requirements vary between +/- ~150 m for low bandwidth to +/- ~50 m for 10 MHz bandwidth (and greater) under AWGN conditions.

8.1.2 Inter-Frequency Accuracy Requirement

Accuracy	Minimum PRS bandwidth, which is minimum of serving cell channel bandwidth and the PRS bandwidths of the reference cell and the measured neighbour cell *i*	Minimum number of available measurement subframes among the reference cell and the measured neighbour cell *i*
Ts	RB	N_{PRS}
±21	≥ 6	4
±10	≥ 25	≥ 2
±9	≥ 50	≥ 1

- Accuracy requirements are worse compared to intra-frequency (i.e., between +/- 210 m and +/- 90 m). This is because processing delay of various front-end components, such as Analog/Digital converter, mixers, amplifier and filter will change as the frequency changes, which cause extra measurement error to PRS arrival time.
- For low PRS bandwidth, 4 PRS subframes only can be used (compared to 6 in case of intra-frequency). This is because a measurement gap is 6 ms long, and the first and last subframe in the gap are needed to switch frequencies (see also section 6.4, and Figure 6-6).
- Therefore, the accuracy requirement is a function of PRS bandwidth (BW):
  - +/- 21 Ts with BW < 5 MHz
  - +/-10 Ts with 5 MHz ≤ BW < 10 MHz
  - +/- 9 Ts with 10 MHz ≤ BW

I.e., the accuracy requirements vary between +/- ~210 m for low bandwidth to +/- ~90 m for 10 MHz bandwidth (and greater) under AWGN conditions.

8.1.2.1 Inter-Frequency Scenarios

For RSTD measurements, there are three cells relevant: The UE serving cell, the RSTD reference cell, and the RSTD neighbour cell. 3GPP TS 36.133 [9] defines two inter-frequency scenarios:

Scenario #1:

- Serving Cell frequency layer is F1
- Reference Cell frequency layer is F2

- Neighbour Cell frequency layer is F2

Scenario #2:

- Serving Cell frequency layer is F1
- Reference Cell frequency layer is F1
- Neighbour Cell frequency layer is F2

In scenario #1, the RSTD measurements are made between two cells on the same frequency layer F2, which is different from the UE serving cell frequency F1.

In scenario #2, the RSTD measurements are made between two cells on different frequency layers.

For both scenarios, the inter-frequency accuracy requirements apply (section 8.1.2).

The requirements are the same for any two different frequencies, independent on their absolute and relative location in the spectrum; i.e., are common for inter-frequency intra-band and inter-band.

In addition to the accuracy requirements, there are also reporting delay (response time) requirements specified in 3GPP TS 36.133 [9]. For scenario #1 above, the intra-frequency reporting delay requirements apply; for scenario #2, the inter-frequency reporting delay requirement apply, which are twice as big as the reporting delay for intra-frequency measurements (see 3GPP TS 36.133 [9] for further details). I.e., inter-frequency measurements require more response time.

Note, for scenario #1 the UE need to be able to obtain the SFN of a cell on frequency layer F2 (different from the UE serving cell frequency – see section 7.2), which may not always be possible (since SFN is conventionally available on serving cell only).

8.1.2.2 Carrier Aggregation Scenarios

Carrier aggregation allows the UE to simultaneously receive and transmit data over more than one carrier frequency. Each carrier frequency is referred to as a component carrier (CC). These channels or carriers may be in contiguous elements of the spectrum, or they may be in different bands.

If the UE has been configured with one or more secondary cells, it means the UE is able to receive signals on two different frequencies (primary cell frequency and secondary cell frequency) simultaneously. Therefore, the UE can perform the inter-frequency RSTD measurements without measurement gaps (i.e., the UE would not need to request measurement gaps from the eNodeB as described in section 6.4.).

- Reference cell and neighbouring cells belong to the primary component carrier:

  the intra-frequency RSTD accuracy requirements apply;
- Reference cell and neighbouring cells belong to the secondary component carrier:

  the intra-frequency RSTD accuracy requirements apply;
- Reference cell and neighbouring cell do not belong to the same carrier:

  the inter-frequency RSTD accuracy requirements apply.

All requirements apply regardless of whether the configured secondary cells are activated or not. If the RSTD measurement is required for cells on frequencies different from both, primary and secondary cell frequencies (i.e., non-configured frequencies), then the UE would still require measurement gaps in order to perform the measurements.

Note, the location server (E-SMLC or SUPL SLP) is not aware of whether or not the UE has secondary cells configured and must therefore, select e.g., the desired response time assuming normal inter-frequency measurements (i.e., which require measurement gaps).

8.2 Measurement Geometry

The measurement geometry has an impact on accuracy. The most general parameter used to assess the impact of the geometry on the final accuracy is the Geometrical Dilution of Precision (GDOP). The GDOP is a measure of how much the position error that results from RSTD measurement errors depends on the mobile/eNodeB relative geometry. If all the TOA measurements made by the MS to calculate the RSTD's have the same error variance σ^2, the positioning error can be approximated as

$$\sigma_{pos} \approx GDOP \times \sigma \qquad (8\text{-}3)$$

Figure 8-1 shows the GDOP for 3 base stations as a function of the UE location. The GDOP is smallest, when the UE is located in the middle of triangle formed by the three eNodeB's (<1.4), and increases quickly if the UE moves out of the centre of the triangle. The GDOP decreases when more eNodeB's are measured by the UE. Figure 8-2 shows an GDOP example with 5 eNodeB's. If the UE is in the middle of area formed by the five eNodeB's, the GDOP can become less than 0.

For example, if we assume the UE RSTD measurement error is ±5Ts (±50 m), and the GDOP is 1.8, we can approximate the positioning error (excluding other error sources) with about 90m.

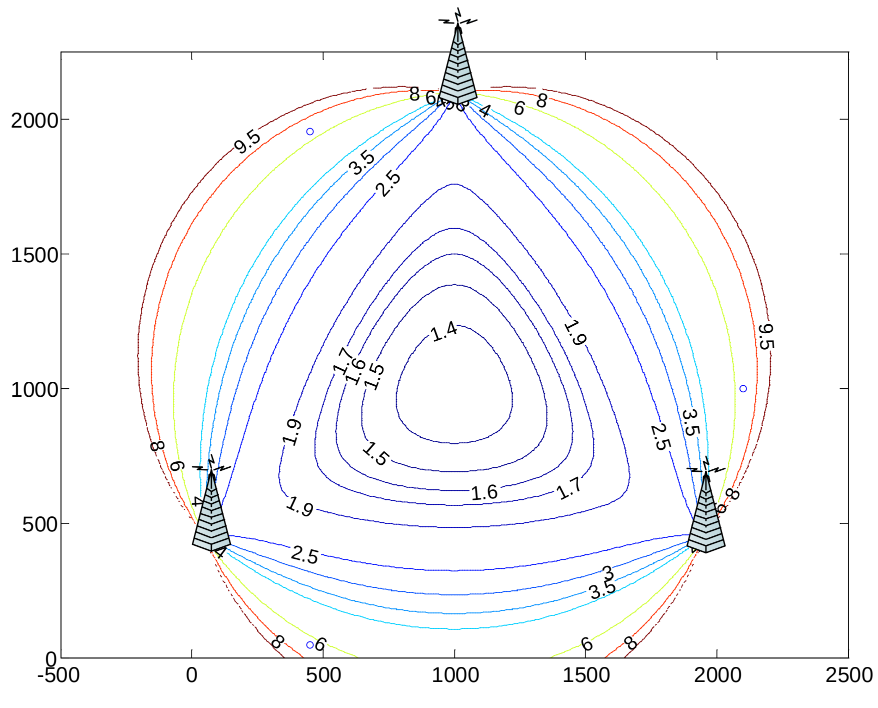

Figure 8-1 : GDOP with 3 eNodeB's.

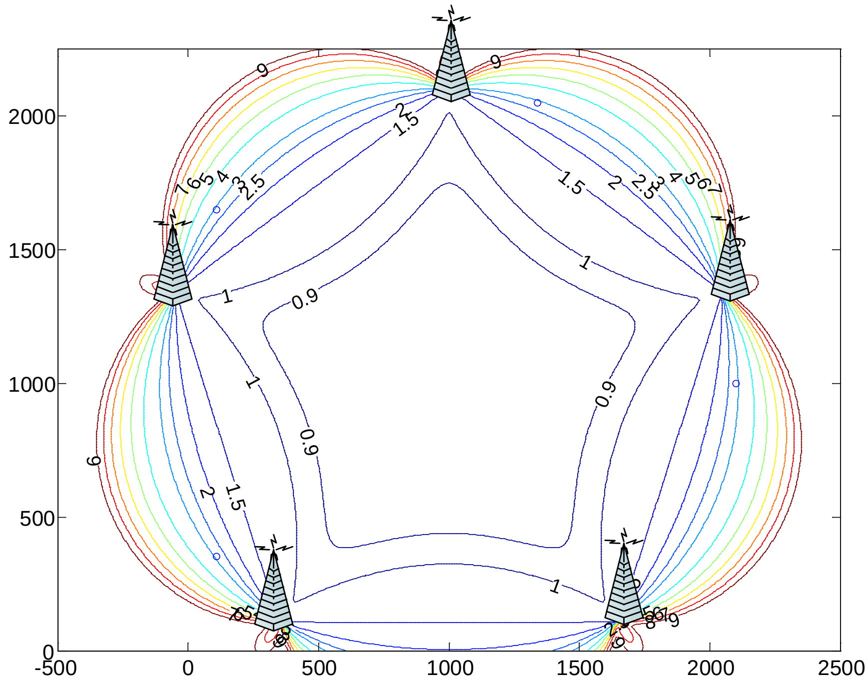

Figure 8-2 : GDOP with 5 eNodeB's.

The geometric effect can be illustrated by plotting the hyperbolic lines of position. As described in section 4.1, the UE location is geometrically determined by the intersection of hyperbolas, where each hyperbola is given by the time (range) difference measurement. Since each time (range) difference measurement has an uncertainty, each hyperbola has a certain width, corresponding to the measurement uncertainty. The intersection area is the desired UE location estimate. Figure 8-3 illustrates the hyperbolic lines of position in case of a low GDOP; Figure 8-4 illustrates the same example with a high GDOP. As can be seen by comparing Figure 8-3 and Figure 8-4, the intersection area (i.e., UE location uncertainty area) is much smaller in case of measurement geometry with low GDOP.

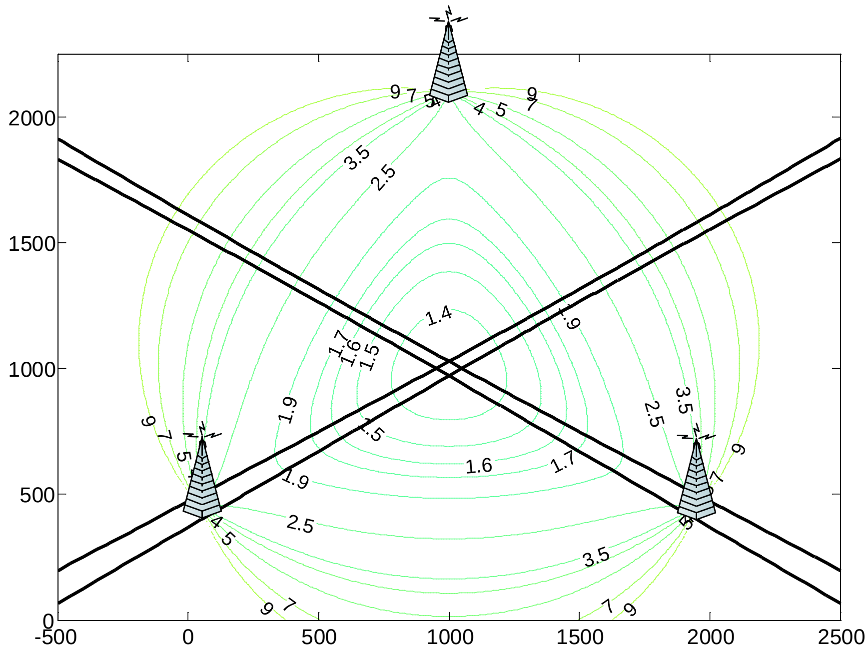

Figure 8-3: Illustration of GDOP Phenomenon: Low GDOP.

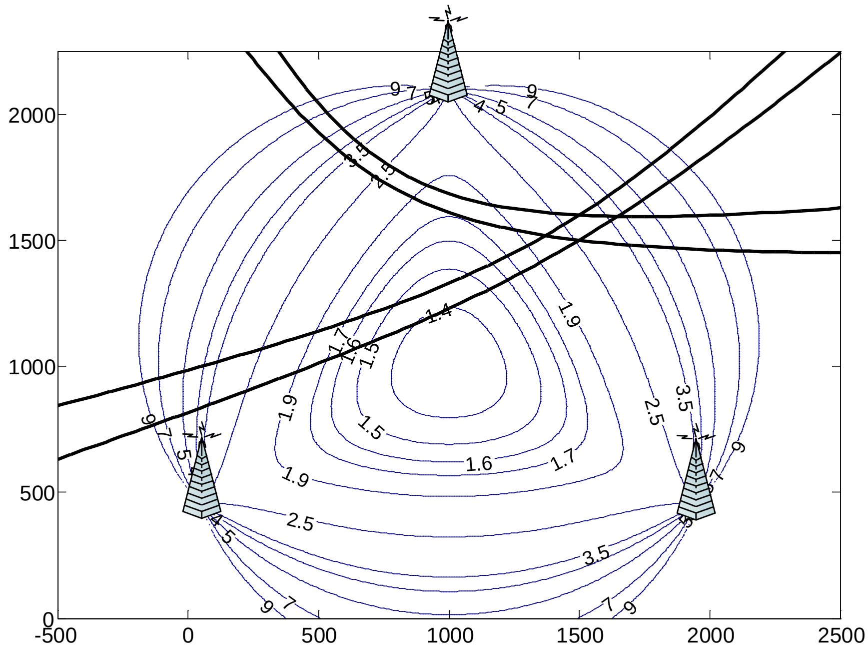

Figure 8-4: Illustration of GDOP Phenomenon: High GDOP.

8.3 eNodeB Synchronization

As described in section 4.1, the eNodeB's participating in OTDOA positioning must be time-synchronized very accurately and reliably for OTDOA to work. At the speed of light, each nsec of error in timing translates into about a foot (~0.3 m) of error in position. As inter-eNodeB synchronization degrades, the OTDOA measurements become less accurate, the hyperbolas become "fuzzy", and the position error increases proportionally. The synchronization requirements for OTDOA are much more stringent compared to the synchronization requirements for communication purposes. Table 1 summarizes some requirements for LTE eNodeB's.

<table>
<tr><th></th><th>Requirement for Clock Frequency Precision</th><th>Requirement for Clock Phase Synchronization</th></tr>
<tr><td>LTE FDD</td><td rowspan="5">50 ppb (wide area BS)
100 ppb (local area BS)
250 ppb (home BS)</td><td>NA</td></tr>
<tr><td>LTE TDD</td><td>±1.5 μs small cell; ±5 μs large cell</td></tr>
<tr><td>LTE MBSFN</td><td>±1-30 μs, implementation dependent</td></tr>
<tr><td>LTE-A CoMP, eICIC, etc.</td><td>±1.5-5 μs (TBD, implementation dependent)</td></tr>
<tr><td>OTDOA</td><td><<0.1 μs, implementation dependent</td></tr>
</table>

Table 8-1: Requirements for clock synchronization.

Figure 8-5 illustrates the phase synchronization between two cells. The term phase synchronization implies that all associated nodes have access to a reference timing signal whose rising edges occur at the same instant. This term might also include the notion of frame timing (i.e., the point in time when the time slot of an outgoing frame is to be generated).

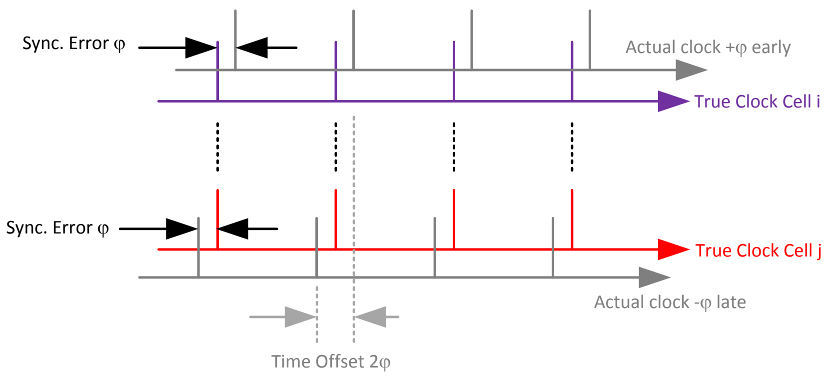

Figure 8-5: Phase Synchronization between two cells.

For OTDOA location, the phase (or time) difference between two eNodeB's impact the location accuracy. As described in section 4.3, the RSTD measurement performed by the UE is related to the range difference only if the time difference between the two eNodeB's (T_i-T_1) is essentially zero (or known at the location server, so that the RSTD measurements can be compensated for the time offset (RTD)):

$$RSTD_{i,1} = \sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}/c - \sqrt{(x_t - x_1)^2 + (y_t - y_1)^2}/c + (T_i - T_1) + (n_i - n_1)$$

Assuming the eNodeB's have a clock phase accuracy of ±φ seconds, the maximum offset between two eNodeB's would then be 2×φ seconds, as illustrated in Figure 8-5.

To illustrate the impact of base station synchronization on location accuracy, the configuration shown in Figure 8-3 is considered: The UE is located in the middle of the triangle formed by the three surrounding eNodeBs, and the UE location is calculated assuming a certain base station clock phase accuracy φ. Since only the impact of base station synchronization accuracy is of interest, the RSTD measurement error is assumed to be zero (i.e., $n_i = 0$ and $n_1 = 0$) and the base station coordinates are known exactly. The resulting location error as function of base station synchronization error is shown in Figure 8-6. The x-axis shows the maximum clock phase accuracy φ in micro-seconds. For example, if the base station synchronization accuracy is ±0.1 µs, the maximum location error due to base station synchronization error alone could be up to 40 meters. In practice, the actual base station synchronization error may be randomly distributed between ±φ and part of the synchronization error may cancel when calculating the RSTD difference. The figure shows the worst case (maximum) location error in this three eNodeB example.

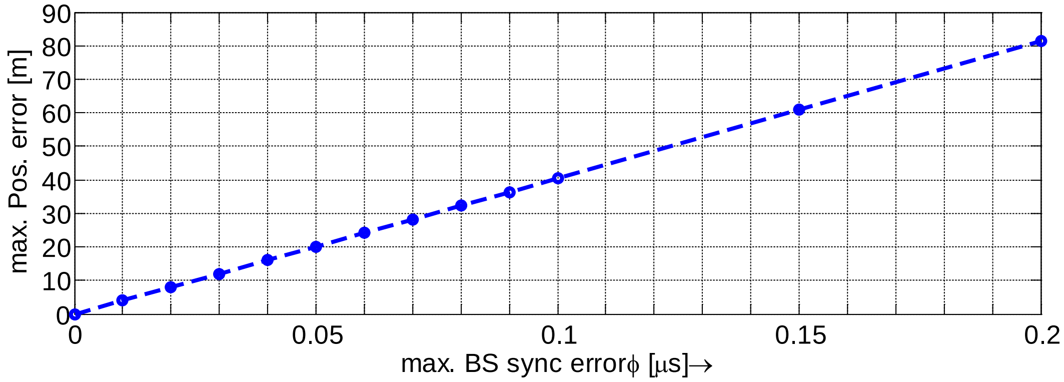

Figure 8-6: Impact of Base Station Synchronization Error on Location Accuracy.

For obtaining reasonable position location accuracies, the eNodeB's participating in OTDOA should be synchronized to within at least 100 ns (0.1 µs).

Achieving such synchronization accuracies usually requires a GPS Clock at each eNodeB, which easily synchronizes the cells to within 100 nsec or better.

The synchronization accuracy is required at the air interface; i.e., at the eNodeB antenna, as illustrated in Figure 8-7. Any additional errors due to antenna cables etc. should be compensated for as far as possible.

The total timing delay (e.g., RF amplifiers, antenna cables, etc.) should be compensated for at each eNodeB, such that the signal transmission of LTE frames is as accurate as possible aligned to the common (e.g., GPS) time. Only in that case, the time differences between eNodeB transmissions at the eNodeB antenna (as seen by the UE) can be as small as possible.

If time alignment at multiple eNodeB's cannot be achieved, then the transmit time offsets should be regularly measured and stored at the location server for each eNodeB.

High-accuracy OTDOA requires nano-seconds level synchronization between eNodeB's.

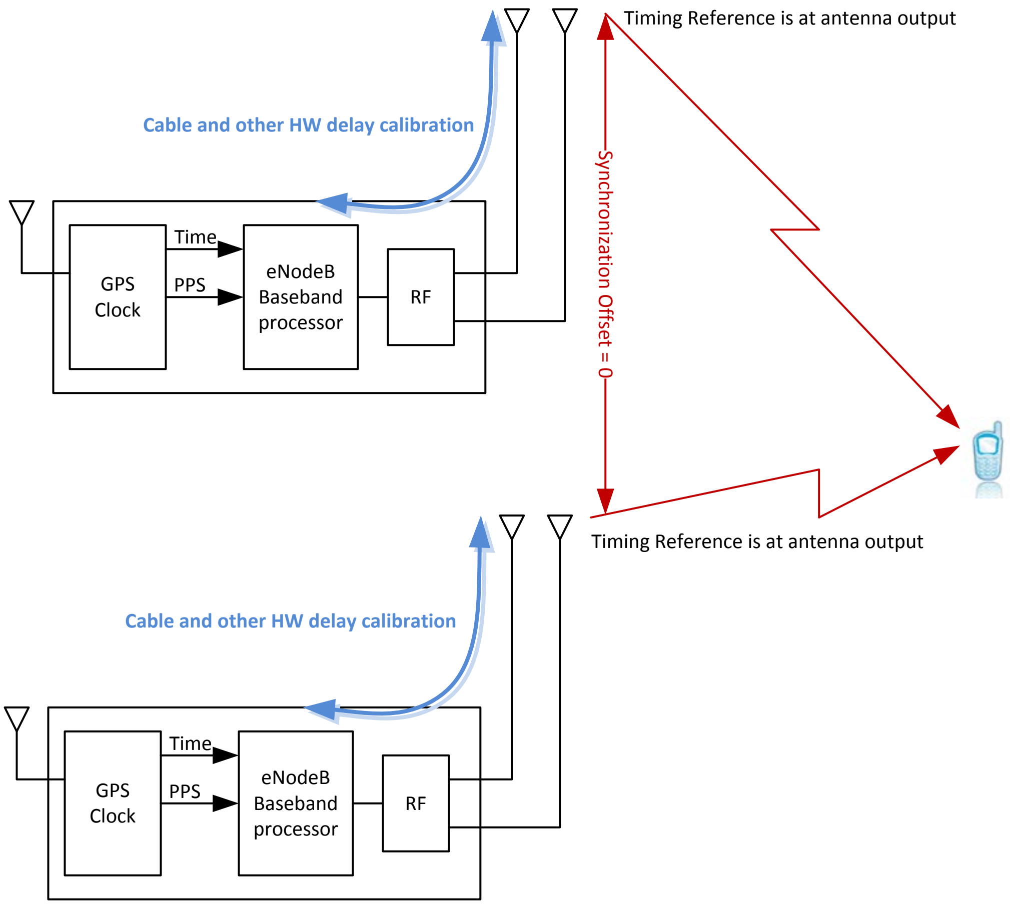

Figure 8-7: GPS Synchronized Base Stations.

8.4 Cell Data Base Accuracy

The location server includes a data base of static or semi-static information. For example, the location server needs to know the PRS configuration of each cell in the network in order to provide appropriate assistance data (see section 7) and the coordinates of the eNodeB transmit antennas.

It should be noted that not the coordinates of the eNodeB's are needed, but the coordinates of the antenna transmitting the PRS signal. These coordinates are needed (preferably in three dimensions) to determine the hyperbolic lines of position and calculate the UE location.

All the cell coordinates should be based on the same geodetic datum (e.g., WGS-84). The UE location is then determined within the same datum. If individual cells participating in a UE location calculation process use a different datum for the antenna coordinates, the effect is similar to an inaccurate cell data base. The datum shift between two different datums can vary from one place to another within one country or region, and can be anything from zero to hundreds of meters.

Similar as for the eNodeB synchronization described in section 8.3, errors in the PRS transmit antenna coordinates results in "fuzzy" hyperbolas, and the position error increases proportionally.

To illustrate the impact of base station antenna coordinates accuracy on location accuracy, we consider again the configuration shown in Figure 8-3: The UE is located in the middle of the triangle formed by the three surrounding eNodeBs, and the UE location is calculated assuming a certain radial base station antenna coordinates accuracy. In the Figure 8-8 we show the worst case impact of the base station antenna coordinate errors on location accuracy, excluding any other error sources, using the configuration shown in Figure 8-3. Similar as mentioned in section 8.3, part of the cell data base error may cancel when calculating the RSTD difference. The figure shows the worst case (maximum) location error in this three eNodeB example.

For high-accuracy OTDOA, the knowledge of the PRS transmit antenna coordinates should be known at the location server with an accuracy of better than about 3-5 meter.

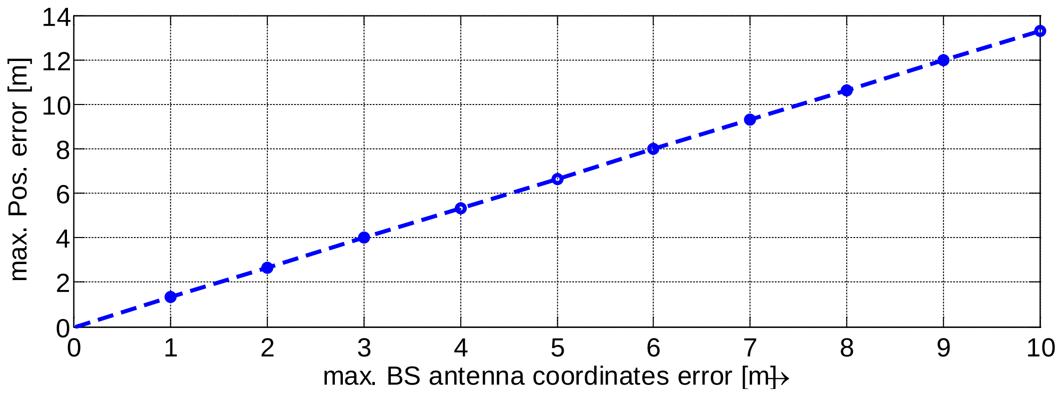

Figure 8-8: Impact of Base Station Antenna Coordinates Error on Location Accuracy.

In OTDOA location, the UE position is usually determined in two dimensions only (i.e., x,y or latitude,longitude), because the relative measurement geometry does usually not allow to derive UE altitude information (i.e., the eNodeB's involved in OTDOA positioning have not sufficient variation in altitude as compared to e.g., GPS, where the satellites are distributed in three dimensions) . Nevertheless, the altitude information of the eNodeB transmit antennas have an impact on OTDOA location accuracy, as illustrated in Figure 8-9. The distance to the two eNodeB's measured by the UE (in the ideal case) would be d_1 and d_2, respectively. If the position calculation algorithm would assume the eNodeB antennas have zero altitude, it would expect a distance measurement of $\tilde{d}_1$and $\tilde{d}_2$, respectively, resulting in an error in the position calculation. This error is usually bigger in small cells and for the UE serving eNodeB. Therefore, the cell data base of eNodeB antenna coordinates should include information about the antenna height.

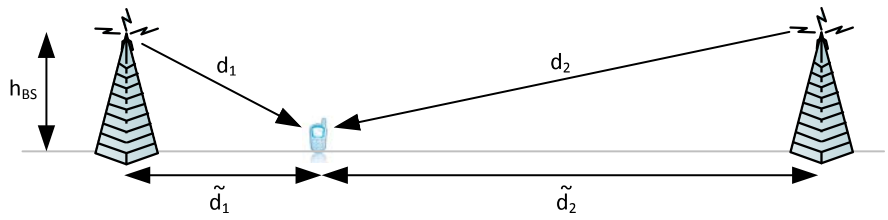

Figure 8-9: Impact of eNodeB Antenna Altitude on Location Estimation.

To illustrate the impact of base station antenna altitude on location accuracy, we consider again the configuration shown in Figure 8-3: The UE is located in the middle of the triangle formed by the three surrounding eNodeBs, and the UE location is calculated neglecting the antenna altitude information (i.e., assuming $h_{BS} = 0$). In Figure 8-10 we show the worst case impact of the base station antenna altitude on location accuracy, excluding any other error sources, using the configuration shown in Figure 8-3. As illustrated in Figure 8-9, the impact on location accuracy depends on the relative distance between eNodeB and UE. In the scenario of Figure 8-3, the true distance would be 1100 m. If the antenna altitude is 110 m (i.e., 10% of the distance), and if this altitude information is not considered in the position calculation, the resulting position error starts becoming significant (e.g., about 15 m in this example as can be seen in Figure 8-10).

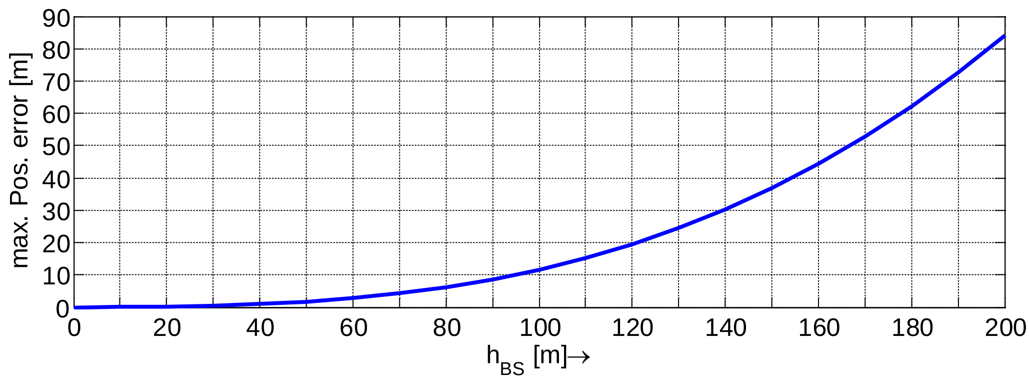

Figure 8-10: Impact of Base Station Antenna Altitude if not Considered in the Position Calculation.

8.5 PRS Network Planning

As described in section 5 there are six possible frequency shifts of PRS. The frequency shift is given by $v_{shift} = N_{ID}^{cell} \bmod 6$, where N_{ID}^{cell} is the physical cell ID (PCI) of the cell. If two cells have the same mod(PCI,6) values, the PRS tones collide and will no longer be orthogonal. Therefore, different v_{shift} should be used in adjacent cells.

The PCI is constructed of 3 different sequences called the Physical-Layer-Identities (0…2) defined by the PSS signal, and 168 different sequences called Physical-Layer-Cell-Identity-Groups (0…167) defined by the SSS signal [3]. Therefore, 168 Physical-Layer-Cell-Identity-Groups with 3 Physical-Layer-Identities per group gives 168 × 3 = 504 possible PCIs. For each cell, the PCI is given by:

$$PCI_i = 3S_j + P_k \tag{8-4}$$

with
i = 0 … 503
j = 0 … 167 (group)
k = 0 … 2 (ID).

The PCIs are usually split into 3 different "colour groups" and 168 "code groups". Two examples are shown in Table 8-2.

Example 1										
	0	**1**	**2**	**…**	**162**	**163**	**164**	**165**	**166**	**167**
0	0	3	6	…	486	489	492	495	498	501
1	4	7	10	…	490	493	496	499	502	1
2	8	11	14	…	494	497	500	503	2	5
Example 2										
	0	**1**	**2**	**…**	**162**	**163**	**164**	**165**	**166**	**167**
0	0	3	6	…	486	489	492	495	498	501
1	8	11	14	…	494	497	500	503	2	5
2	16	19	22	…	502	1	4	7	10	13

Table 8-2: PCI Colour and Code Groups.

If a colour group is assigned per sector and a code group is assigned per site, this will eliminate the risk of having the same frequency shift in the same site, in adjacent cells, or pointing at each other.

The Figure 8-11 shows a cluster of hexagonal cells. The sites are indicated by black circles, and each site serves three cells. A colour group is assigned to each sector (0…2) and a code group to each site (0…18 in this example). The PCI is indicated in each cell and each cell with the same mod(PCI,6) value is shown in the same colour.

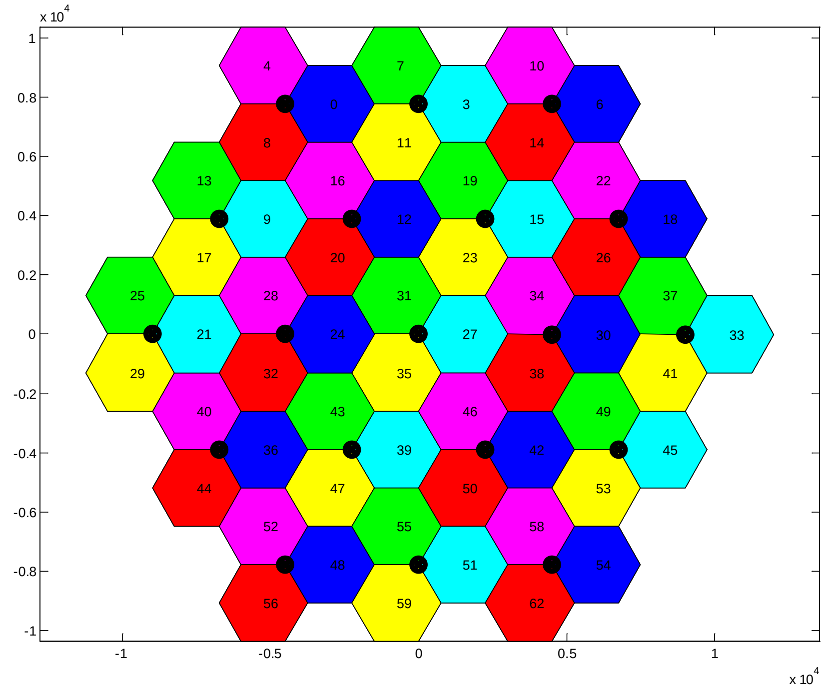

Figure 8-11: Example of PCI Planning for PRS.

As can be seen in Figure 8-11, PCI planning like this eliminates the risk of having the same frequency shift

- in the same site,
- in adjacent cells, or
- pointing at each other.

It also avoids the risk of having conflicting SSS sequences in adjacent cells.

For example, a mobile located in cell 35 (yellow cell in the middle of Figure 8-11), is not surrounded by any other yellow cell (i.e., the same mod(PCI,6) value). The mobile in cell 35 when measuring cell 35 will receive PRS interference from the yellow cells only; if the mobile in cell 35 is measuring neighbour cell 24, it will receive interference from the blue cells only, etc.

When the mobile in cell 35 is measuring cell 35, it may see for example cell 23 and cell 47 as interference. However, it is unlikely that the mobile in cell 35 will hear cell 47, since cell 47 points into the opposite direction. Cell 23 on the other hand, is more likely to be received by the mobile in cell 35, and therefore, will create interference. This could be avoided if appropriate muting pattern are assigned, such that for example cell 23 is muted when cell 35 is active. This would then make the PRS orthogonal again (in time domain).

In practice, with irregular pattern for site-to-site distances and sector angles it may not always be possible to follow a strict planning pattern.

In addition, PCI planning (if any) is constrained by other air-interface/communications reasons, and OTDOA related planning must usually play a secondary role.

8.6 Radio Environment

The radio propagation channel usually suffers from multipath propagation and shadow-fading conditions so that RSTD measurements may be far from accurate in many instances.

Multipath is a phenomenon that happens in the channel of mobile systems when the transmitted signal arrives at the receiver via different paths due to reflection, diffraction and scattering resulting in fading, as illustrated in Figure 8-12. There is only one transmitted signal, but obstacles like buildings, hills, trees, and so on, in the signal paths cause different signals to arrive at the receiver from various directions with different delays.

A multipath is a major source of error in TOA estimation. Figure 8-13 shows an example of a channel impulse response. In this example, there is no line of sight path, so even if the receiver is able to detect the first arriving path (which arrives at about 0.1 µs in this example), there would be a ranging error of 0.1 µs or about 30 m.

The signal/receiver bandwidth affects the resolution capability of the individual multipath components. As shown in Figure 8-13, with a 5 MHz bandwidth the first paths are not resolvable (red line), and the TOA estimator would pick a “smeared TOA” at about 0.25 µs (resulting in about 75 m ranging error).

With 20 MHz bandwidth (green line in Figure 8-13) the individual multipath components can be resolved in this example, but the first path has lower amplitude as the second path. So a receiver which simply picks the maximum in the channel impulse response would pick the second path at about 0.2 µs (resulting in about 60 m ranging error).

Therefore, TOA estimates (and therefore, the RSTDs) are usually biased in a multipath environment. The capability of detecting the first arriving path depends on the signal/receiver bandwidth, and even if the receiver is able to detect the first path correctly, it may be a non-line-of-sight path.

The effect of such biased RSTD measurements is usually reduced during position calculation if there are many RSTD measurements available (i.e., much more than the required minimum of 3 eNodeB measurements). In that case, it may be possible to detect large bias errors in the individual measurements and exclude them (or reduce its weight) in the position calculation (as long as there are enough measurements with less multipath and non-line-of sight propagation errors available).

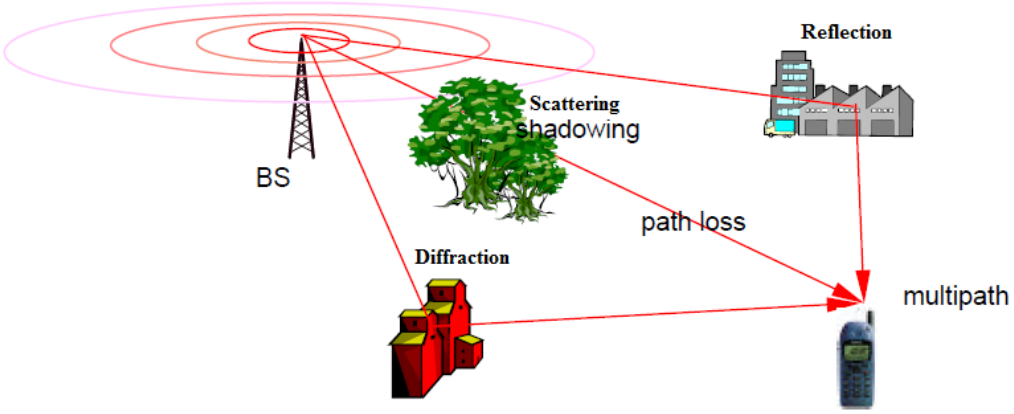

Figure 8-12: Propagation Components between Base Station and Mobile.

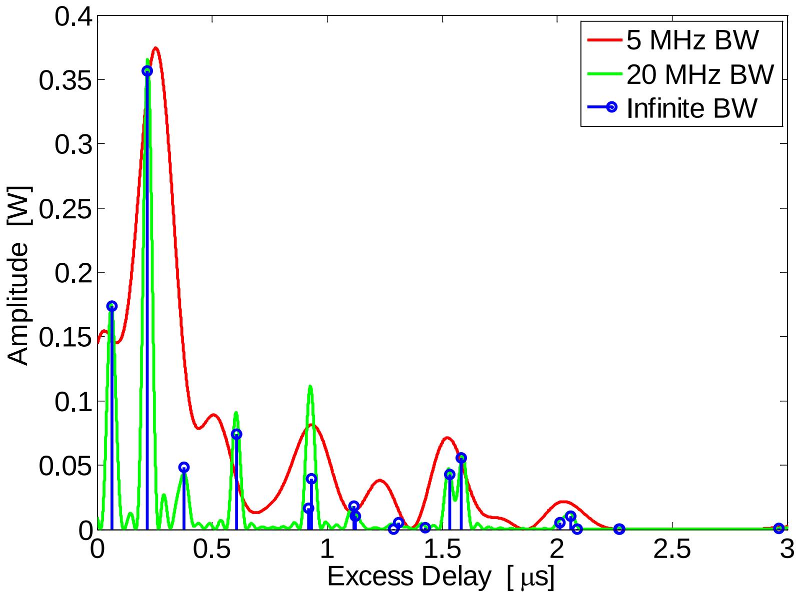

Figure 8-13: Example of Channel Impulse Response for Different Signal Bandwidths.

8.7 Exemplary Error Budget

A simplified OTDOA error budget can be summarized under certain assumptions as follows:

1. The UE can hear at least 5 eNodeB's with PRS SINR > -13 dB. With 10 MHz PRS bandwidth, the minimum accuracy of the RSTD measurements (in AWGN) is better than 5 Ts (~50 m) (section 8.1.1). In practice, the performance (in AWGN) is usually better than that. Assume:

   σ_{UE} = 40 m

2. The RSTD measurements are made from eNodeB's with good measurement geometry, so that the GDOP is < 1 (Figure 8-2):

   GDOP = 0.9

3. All eNodeB's are synchronized on the air interface with an accuracy of better than 50 ns:

   σ_{BS} = 15 m

4. The eNodeB antenna coordinates are known to be better than 3 m:

   σ_{ant} = 3 m

5. The multipath excess delay on average is assumed to be 0.1 µs ("suburban"):

   σ_{MP} = 30 m

6. Therefore, we can approximate the total link error in this example:

$$\sigma = \sqrt{\sigma_{UE}^2 + \sigma_{BS}^2 + \sigma_{ant}^2 + \sigma_{MP}^2} = \sqrt{40^2 + 15^2 + 3^2 + 30^2} \approx 52\text{m} \qquad (8\text{-}5)$$

7. with a GDOP of 0.9, we can estimate:

$$\sigma_{pos} = GDOP \times \sigma \approx 47 \text{ m} \qquad (8\text{-}6)$$

This figure approximates the standard deviation of the location estimate. Assuming a Gaussian distribution, this can be converted into 67 and 95 percentile levels as follows:

67-percentile error: 47 m × 0.97 ≈ 46 m

95-percentile error: 47 m × 1.96 ≈ 92 m

8.8 Repeaters, Remote Radio Heads, Distributed Antennas

Repeaters, Remote Radio Heads (RRH), and Distributed Antennas (DAS) can create problems for any network based location method, since the shortest propagation path from the eNodeB to the UE is altered.

8.8.1 Repeaters

Figure 8-14 is an illustration of a network using repeaters. In this case the signal path from BS4 to the UE can be either the direct path, with a time delay of $\tau 4$, or the path through the repeater, with a time delay of $\tau_{RB}+\tau_d+\tau_R$, where τ_d is introduced by the repeater. This extra time delay introduces an ambiguity when performing the location estimation.

If the UE can detect both paths, the direct path from BS 4 (τ_4) and the path through the repeater (τ_R), the effect is similar to multipath, where a strong second path is present in addition to a weak early path.

The measurement made from a repeater signal has usually a large delay ($\tau_{RB}+\tau_d+\tau_R$), relative to the measured delays from other neighbour cells, and may be detected and eliminated in the position calculation function, if the UE reports sufficient measurements from cells without associated repeaters.

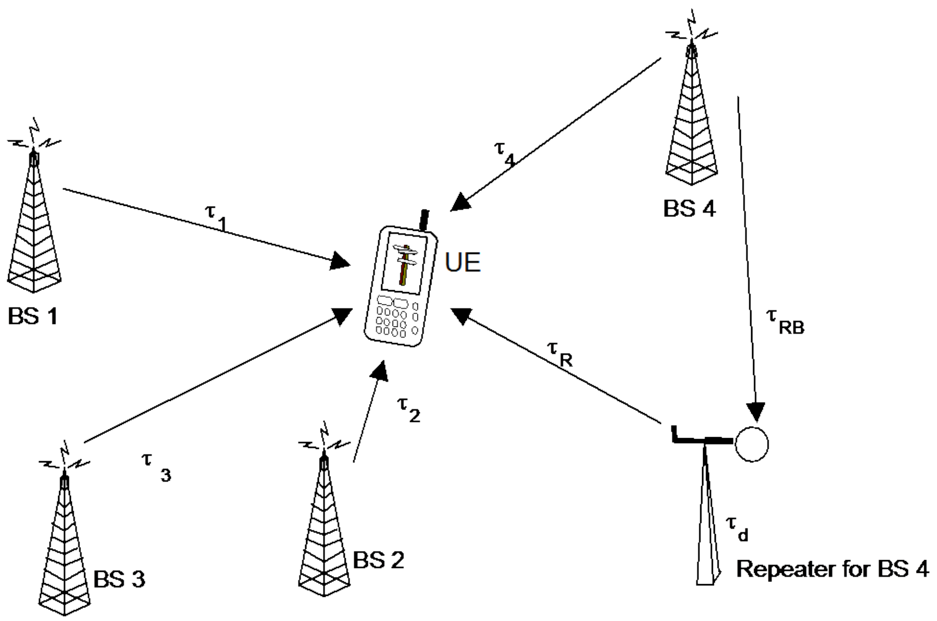

Figure 8-14: Illustration of the Effect of a Repeater Installation in a Network Using OTDOA.

8.8.2 Remote Radio Heads (RRH)

A Remote Radio Head (RRH) is a unit in which only the RF front-end functionalities are implemented. It is connected to the remaining baseband processing part of the base station through a bidirectional link. The transmission points created by the RRH may have a different or the same cell ID as the macro cell. If the transmission points have the same cell ID as the macro eNodeB, an ambiguity in the UE RSTD measurements will occur. Since all RRHs with the same cell ID as the macro eNodeB will transmit the same PRS signal, there is no unique mapping of the signal to a transmission point location. The UE may measure and report RSTD measurements as usual, but the location server is not able to determine the transmit antenna location for this measurement for position calculation (since multiple transmission points for the same signal exists in such a scenario).

Therefore, in deployment scenarios with RRHs within the macrocell coverage where the transmission points created by the RRHs have the same cell ID as the macro cell, the PRS signal should not be transmitted from the RRHs (e.g., muted). PRS should only be transmitted by the macro eNodeB in such scenarios.

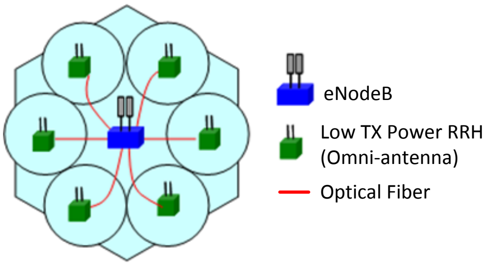

Figure 8-15: Network with low power RRHs within the macrocell coverage.

8.8.3 Distributed Antennas (DAS)

A DAS system has one or more antennas attached to a single LTE eNodeB. The concept is very similar to the RRH one. A DAS system distributes the radio signal more evenly from several point sources rather than a single one. For OTDOA location, the problem is similar to the RRH scenario; the location server cannot identify the transmission point location of the UE measured PRS signal. Therefore, the same PRS signal should not be transmitted from multiple antennas, or if possible, an “average transmission point” of a DAS system may be defined and used at the location server (e.g., a center-of-gravity location of all antennas forming a DAS system), if the DAS elements are not spaced too far apart.

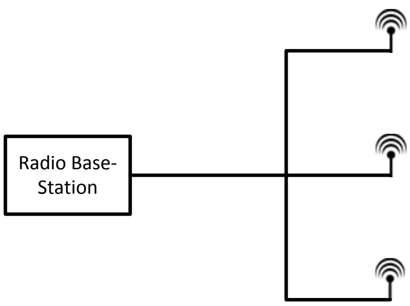

Figure 8-16: Multiple Antennas used by a Base Station.