Introduction to OTDOA on LTE Networks

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References

Reference documents are listed in Table 1-1.

Table 1-1 Reference Documents and Standards

Ref.	Document	
[1]	**Observed Time Difference Of Arrival (OTDOA) Positioning in 3GPP LTE (also known as the full-version of this paper)**[1]	**http://www.qualcomm.com/media/documents/otdoa-positioning-3gpp-lte**
[2]	Functional stage 2 description of Location Services (LCS)	3GPP TS 23.271
[3]	Stage 2 functional specification of User Equipment (UE) positioning in E-UTRAN	3GPP TS 36.305
[4]	Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP)	3GPP TS 36.355
[5]	Secure User Plane Location Protocol 2.0	OMA-TS-ULP-V2_0
[6]	Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation	3GPP TS 36.211
[7]	Evolved Universal Terrestrial Radio Access (E-UTRA); "Radio Resource Control (RRC); Protocol specification	3GPP TS 36.331
[8]	Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol A	3GPP TS 36.455
[9]	LPP Extensions Specification Version 1.1	OMA-TS-LPPe-V1_1
[10]	Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management	3GPP TS 36.133

[1] This whitepaper provides OTDOA highlights based on details in Reference [1].

Acronyms

3GPP	3rd Generation Partnership Project
AWGN	Additive White Gaussian Noise
BS	Base Station (synonymously for eNodeB)
BW	Bandwidth
CP	Control Plane
DL	Down-Link
eNB	eNodeB (synonymously for base station)
EPDU	External Protocol Data Unit
E-SMLC	Evolved Serving Mobile Location Center
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
LCS	Location Services
LPP	LTE Positioning Protocol
LPPa	LPP Annex
LPPe	LPP Extensions
LS	Location Server
LTE	Long Term Evolution
MME	Mobility Management Entity
OMA	Open Mobile Alliance
OTDOA	Observed Time Difference Of Arrival
PCI	Physical Cell Identity
PRS	Positioning Reference Signal
RRC	Radio Resource Control
RSTD	Reference Signal Time Difference
SFN	System Frame Number
SINR	Signal to Interference and Noise Ratio
SLP	SUPL Location Platform
SUPL	Secure User Plane Location
TDD	Time Division Duplex
TOA	Time Of Arrival
TS	Technical Specification
UE	User Equipment (synonymously for mobile station)
UP	User Plane
UTRAN	Universal Terrestrial Radio Access Network

1 How does OTDOA work

1.1 Overview

Observed Time Difference Of Arrival (OTDOA) is a mobile service downlink (DL) positioning method defined in 3GPP standards[2] . (See Reference [2], [3], and [4]). OTDOA uses multilateration in which the User Equipment (UE) measures the time of arrival (TOA) of signals received from multiple eNodeBs.[3]

The TOAs from several neighboring eNodeBs are subtracted from the TOA of a reference eNodeB to form the Observed Time Difference Of Arrival. Geometrically, each TOA determines a hyperbola, and the point at which the hyperbolas intersect is the desired UE location. At least three timing measurements from geographically dispersed eNodeBs with good geometry are needed to solve for two coordinates (latitude and longitude) of the UE. Performance is improved via incorporation of additional eNodeBs.

The OTDOA positioning method is illustrated in Figure 1-1, 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, and two OTDOA's are formed: $t_{2,1} = \tau_2 - \tau_1$ and $t_{3,1} = \tau_3 - \tau_1$.

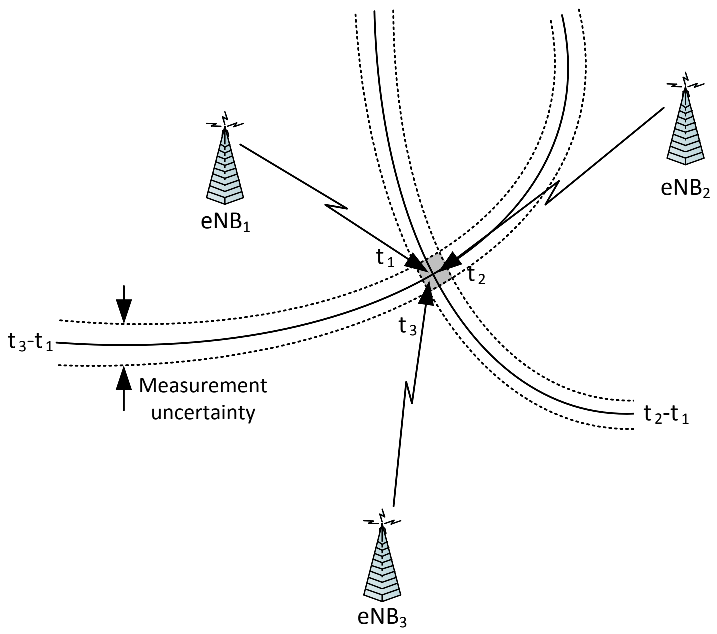

Figure 1-1: Multilateration in OTDOA Positioning

[2] OTDOA is the positioning method for UTRAN and for E-UTRAN, as specified in Reference [2]. Only OTDOA for E-UTRAN (i.e. on LTE networks) is introduced in this whitepaper.
[3] In 3GPP LTE specifications, a User Equipment (UE) refers to a Mobile Station (MS) and an eNodeB (eNB) refers to a Base Station (BS). In this whitepaper, UE and eNodeB/eNB are used synonymously for MS and BS.

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

The measurement made by the UE for OTDOA positioning is the Reference Signal Time Difference (RSTD) measurement. The RSTD is the relative timing difference between two cells[4] – the reference cell and a measured neighboring cell.

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 and the neighboring cell 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 and the neighboring cell is on a different carrier frequency as the UE serving cell.

1.2 Positioning Reference Signals (PRS)

In principle, RSTD measurements can be performed on any downlink signals (e.g., cell specific reference signals). Because these downlink signals may suffer from poor hearability, Positioning Reference Signals (PRS) have been introduced to allow the UE to perform proper timing (ranging) measurements of signals from multiple cells to improve OTDOA positioning performance.

The PRS[5] signal can be visualized as shown in Figure 1-2 and is delivered with pre-defined bandwidth and a set of configuration parameters such as subframe offset (Δ_{PRS}), periodicity (T_{PRS}), duration (N_{PRS}), muting pattern, and muting sequence periodicity (T_{REP}). PRS is 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} can be 160, 320, 640, or 1280 subframes, and the number of consecutive subframes N_{PRS} can be 1, 2, 4, or 6 subframes.

The positioning reference signal sequence is defined in Reference [6].

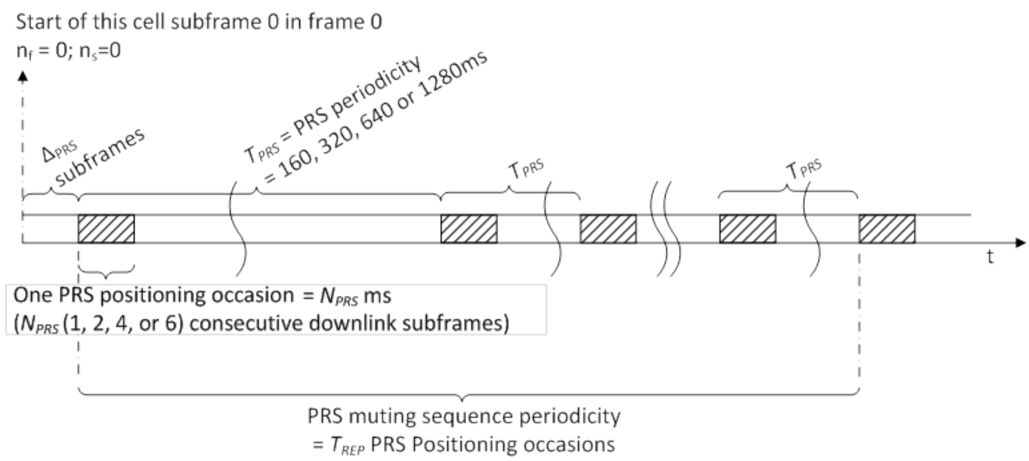

Figure 1-2: Example of PRS Transmission Schedule and PRS Muting

[4] A cell is a network area served through a base station (e.g. an eNodeB in LTE network) at a fixed location/site. Multiple cells, sometime called "sectors" can co-locate at a single eNodeB. Cells are typically assigned a Physical Cell Identity (PCI) at network planning.

[5] The PRS for OTDOA is designed for hearability, which is partially achieved by reserving LTE resources just for PRS occasions. So as such there is a tradeoff to be made between performance and overhead. For example, the selection of the PRS bandwidth and N_{PRS} is a tradeoff between performance and overhead. Some specific examples are included in Reference [1].

The eNodeBs can be configured for time based blanking, called "PRS muting." When the (strong) PRS signal is muted, the (weak) PRS signals from the neighbour cells are more easily detected by the UE. The PRS muting configuration of a cell is defined by a periodic muting sequence with periodicity T_{REP} as shown in Figure 1-2. The T_{REP} is counted in number of PRS positioning occasions, and can be 2, 4, 8, or 16.

In summary, isolation of PRS is key to the improvement OTDOA performance. The 3GPP standards for PRS signals provide three layers of isolation to improve hearability (*i.e.*, the ability to detect weak neighbour cells):

1. **Code domain:** Each cell transmits a different PRS sequence (orthogonal to other PRS sequences in the code domain).
2. **Frequency domain**: PRS has a frequency re-use of six, *i.e.*, six possible frequency arrangements (called frequency offset) is defined within the PRS bandwidth. If two cells have the same frequency offset, the PRSs collide in frequency domain. In such cases, the isolation from the orthogonal PRS sequences distinguishes one cell from the other.
3. **Time domain:** If PRSs collide in the frequency domain, muting (time based blanking) can make the PRS occasions again appear orthogonal to each other.

NOTE: From a conceptual point of view, there should be no difference between OTDOA/TDD and OTDOA/FDD.

1.3 OTDOA support on LTE Networks

A simplified 3GPP location services positioning architecture for LTE networks is shown in Figure 1-3.

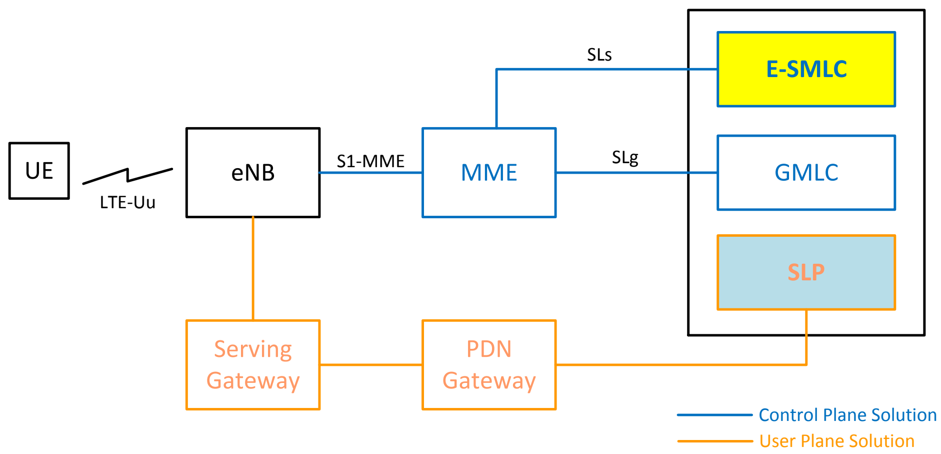

Figure 1-3: LTE Location Services Architecture Overview

The key network element for supporting OTDOA (or location services in general) is the Location Server (LS). In Control Plane (CP) positioning, the location server is an E-SMLC; in User Plane (UP) positioning, the location server is a SUPL SLP. See Reference [5].

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 User Plane, such signaling occurs over user bearer channels and appear simply as user data to the wireless network.

1.3.1 OTDOA Assistance Data

As PRS is configurable for each cell, the UE needs to be informed about the PRS configuration and when the to-be-measured PRS signals are expected to arrive at the UE.

To enable the RSTD measurements, the location server in the network provides OTDOA assistance data to the UE using LTE Positioning Protocol (LPP) messaging as defined in Reference [4].

The LPP OTDOA assistance data for the UE contains two sets of cell information:

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 UE should provide the available RSTD measurements in the same order as provided by the location server.

Reference [1] provides a summary of LPP OTDOA Assistance Data definitions.

NOTE: To provide OTDOA assistance Data for the UE, the location server needs PRS information from the eNodeBs that transmit the PRSs, for example, the cell identifications, the timing information, and the antenna coordinates of the eNodeBs. This information can be provisioned into a location server through the OA&M system, or through LPPa[6] messaging between the MME and the eNodeB. Reference [1] introduces the LPPa support of OTDOA (mainly, the Information Exchange procedure).

1.3.2 OTDOA Positioning Procedures

For OTDOA positioning on LTE networks, the LTE Positioning Protocol (LPP) is used between the location server and the UE. See Reference [4]. LPP is used in both the control plane solution and SUPL user plane solution. Only the transport channels of the LPP messages are different between CP and UP. Reference [1] introduces the protocol layering for CP and UP solutions.

The LPP procedures between location server (E-SMLC or SUPL SLP), shown in Figure 1-4, usually consist of

- Capability Transfer,
- Assistance Data Transfer,
- Location Information Transfer.

[6] The LTE Positioning Protocol Annex (LPPa) is a protocol that carries information between the eNodeB and the E-SMLC and is specified in Reference [8]. It may be used by the location server for data collection from eNodeBs for support of OTDOA positioning. The LPPa protocol is transparent to the MME.

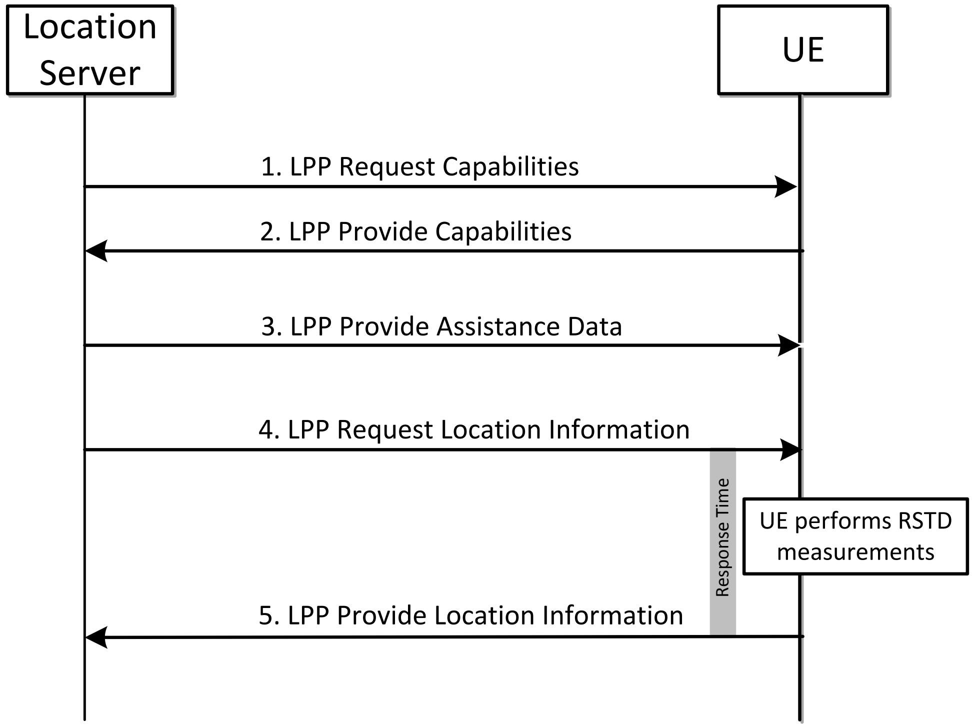

Figure 1-4: Example of LPP Positioning Procedure

1. The location server sends a *RequestCapabilities* message to the UE to indicate the type of capabilities needed.
2. The UE responds with a *ProvideCapabilities* message to the server. If OTDOA capabilities were requested in step 1, this message includes information elements such as OTDOA mode supported (note: LPP supports only UE-assisted mode[7]), supported frequency bands, and support for inter-frequency RSTD measurements.
3. The location server sends a *ProvideAssistanceData* message to the UE containing OTDOA assistance data. The OTDOA assistance data include an assistance for reference cell, and assistance for up to 72 neighbour cells[8]. If the UE indicates support for inter-frequency RSTD measurements, 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 information elements such as location information type, desired accuracy of the location estimate, and response time.

[7] 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 LPP Extensions (LPPe) [9] provides extensions for OTDOA UE-based mode (*i.e*., where the location estimate is calculated in the UE). LPP elementary messages (Request and Provision of Capabilities and Location Information and Assistance Data) each include a container, an External Protocol Data Unit (EPDU), which can be used by standardization outside 3GPP to define their own extensions to LPP messages. OMA LPPe uses the EPDU for exchanging additional data between the UE and the location server. See Reference [1].

[8] Prior to 3GPP Release 10, only OTDOA assistance data for up to 24 neighbour cells can be provided in *ProvideAssistanceData* message.

5. The UE then performs the RSTD measurements, using the provided assistance data received at step 3. The UE, based on the response time, provides the RSTD measurements in a *ProvideLocationInformation* message to the location server. This message includes information elements such as:
   - Time stamp of the measurement set in form of the System Frame Number (SFN).
   - Identity of the reference cell used for calculating the RSTD.
   - Quality of the TOA measurement from the reference cell.
   - Neighboring cell measurement list for up to 24 cells:
     - Identity of the measured neighbour cell.
     - RSTD measurement.
     - Quality of the RSTD measurement.

NOTE: A LPP location session, as shown in Figure 1-4 above, comprises one or more LPP transactions, with each LPP transaction performing a single operation (capability exchange, assistance data transfer, or location information transfer).

2 OTDOA Deployment

2.1 PRS Configuration

PRS have been designed so there is no data transmission when an eNodeB transmits PRS signals. As a result, PRS only suffers interference from other PRSs transmitted on the same frequency. Reference [1] provides examples of PRS transmission patterns in positioning subframes.

To exploit the high detection capability of the PRS, the network needs to be synchronized to LTE frame boundaries, and the PRS occasions for all eNodeBs on one frequency layer need to be 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.

2.2 Factors Influencing OTDOA Accuracy

For all the factors discussed in section 2.2wireless carriers/operators play an important role in the striving for OTDOA accuracy improvement.

2.2.1 PRS Bandwidth and Accuracy Requirements

PRS signals can be deployed in a defined LTE bandwidth.

RSTD measurement accuracy requirements are specified in Reference [10]. The UE physical layer shall be capable of reporting RSTD measurements for the reference cell and all neighbour cells, provided that the PRS SINR of the reference cell is greater than −6 dB and the PRS SINR of the neighbour cells is greater than −13 dB. The accuracy requirement for RSTD measurement is a function of PRS bandwidth (BW), as shown in Table 2-1 in Ts.[9]

PRS Bandwidth (BW)	Accuracy requirement for Intra-frequency RSTD[10]	Accuracy requirement for Inter-frequency RSTD[10]
BW < 5MHz	+/- 15 Ts	+/- 21 Ts
5 MHz ≤ BW < 10 MHz	+/- 6 Ts	+/-10 Ts
10 MHz ≤ BW	+/- 5 Ts	+/- 9 Ts

Table 2-1: Accuracy Requirements for RSTD Measurement

2.2.2 Radio Environment

The radio channel usually suffers from multipath and fading conditions. As a result, TOA estimates (and therefore, the RSTDs) can be biased in a multipath environment.

The PRS signal bandwidth affects the resolution capability of the individual multipath components at the UE. PRS with wider bandwidth can resolve multipath more accurately.

[9] Ts is the basic time unit. Ts = 1/(15000 × 2048) seconds, which is a little more than 32 ns, and corresponds to about 9.8 meters.
[10] See Reference [1] for details.

For example, for PRS transmitted on a 20MHz bandwidth, the UE can differentiate two clean multipaths that are ~10m apart in a majority of scenarios.

The effect of such biased RSTD measurements is usually reduced during the 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 their weight) in the position calculation.

2.2.3 Measurement Geometry

Measurement geometry has an impact on location 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 relative geometry between the UE and the eNodeBs.

Figure 2-1 below shows the GDOP for 5 eNodeBs as a function of the UE location. The GDOP is smallest when the UE is located in the middle of area formed by the 5 eNodeBs, and increases quickly if the UE moves out of the center of the area.

For example, assuming that the UE RSTD measurement error is ±50 m, and the GDOP is 1.8, the estimate of the positioning error (excluding other error sources) is about 90 m, which is 50 meters multiplied by 1.8.

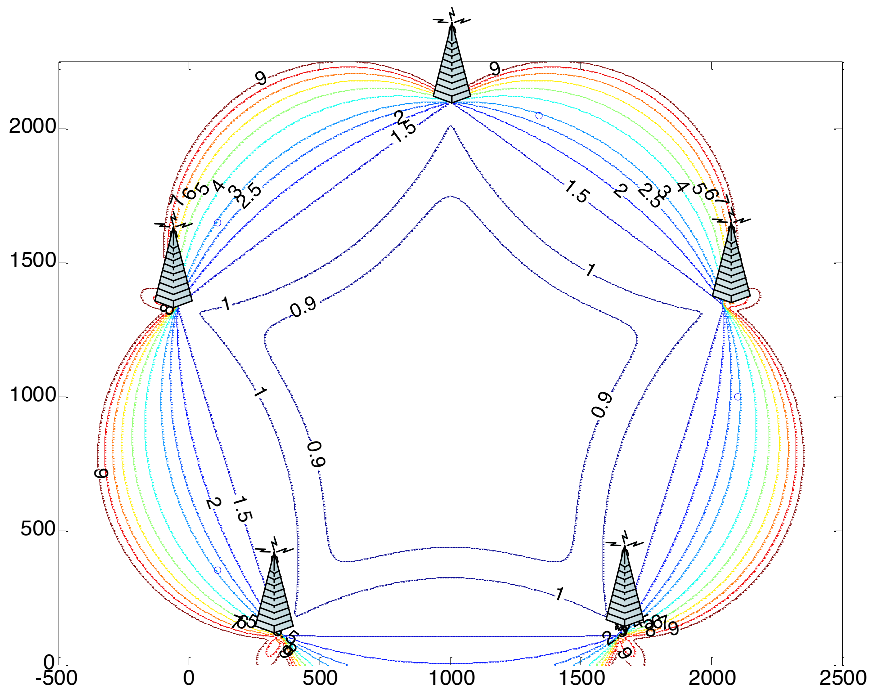

Figure 2-1: Example of GDOP with 5 eNodeB's

Reference [1] provides more details on estimating OTDOA positioning error based on GDOP.

2.2.4 eNodeB Synchronization

For OTDOA to perform properly, the eNodeBs used for OTDOA positioning must be time-synchronized accurately and reliably. 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 in Figure 1-1 become "fuzzy", and the position error increases proportionally.

The synchronization requirements for OTDOA are much more stringent compared to the synchronization requirements necessary for communication purposes. Table 2-2 below 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="3">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>OTDOA</td><td><<0.1 μs, implementation dependent</td></tr>
</table>

Table 2-2: Requirements for Clock Synchronization

To obtain acceptable positioning information, the eNodeBs 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 can synchronize the cells to within 100 nsec or better.

High-accuracy OTDOA requires nano-second-level synchronization between eNodeBs.

The synchronization accuracy is required at the air interface; *i.e*., at the eNodeB antenna. 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 and aligned to the common (e.g., GPS) time. Only in that case, can the time differences between eNodeB transmissions at the eNodeB antenna (as seen by the UE) be as small as possible.

An example of location error as a function of base station synchronization error is shown in Figure 2-2 below. The x-axis shows the maximum clock phase accuracy φ in microseconds. 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 as high as 40 meters.[11]

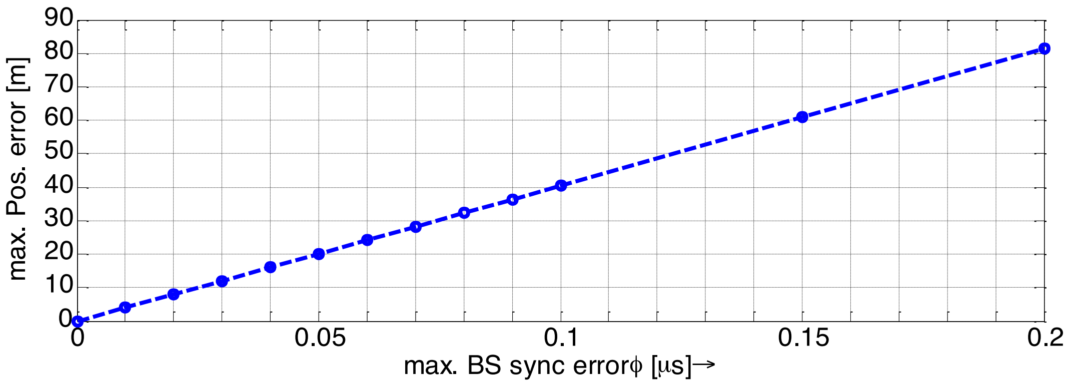

Figure 2-2: Example of Impact of eNodeB Synchronization Error on Location Accuracy

[11] 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. Figure 2-2 shows the worst case (maximum) location error in this three eNodeB example.

2.2.5 Cell Data Base Accuracy

For high-accuracy OTDOA, the antenna coordinates should be known at the location server with an accuracy of better than about 3 to 5 meters. The coordinates of the antenna transmitting the PRS signal are needed (preferably in three dimensions) to determine the hyperbolic lines of position and calculate the UE location. Error in the PRS transmit antenna coordinates results in "fuzzy" hyperbolas, like those shown in Figure 1-1, and the position error increases proportionally.

Figure 2-3 below shows an example of the worst case impact of the antenna coordinate errors (in longitude and latitude) on location accuracy, excluding any other error sources.

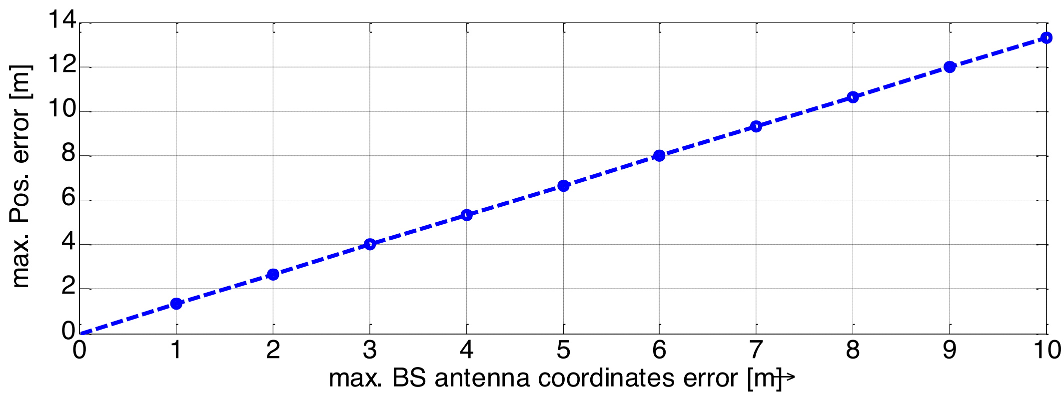

Figure 2-3: Example of Impact of Antenna Coordinates Error on Location Accuracy.

NOTE: Repeaters, Remote Radio Heads, and Distributed Antennas can create problems for OTDOA, since the use of these devices propagation path from the eNodeB to the UE is altered. Reference [1] discusses the impact to OTDOA accuracy.

2.2.6 PRS Network Planning

Each LTE cell is assigned a PCI of value 0 to 503. LTE standards for OTDOA positioning allow for six possible frequency shifts within the PRS bandwidth. If two cells have the same $mod(PCI, 6)$ values, the PRSs are transmitted with the same frequency shift (*i.e.*, they collide in the frequency domain). Therefore, different frequency shifts should be used in adjacent cells.

Figure 2-4 below shows a cluster of hexagonal cells. The sites are indicated by black circles, and each site serves three cells. The PCI is indicated in each cell and each cell with the same $mod(PCI, 6)$ value is shown in the same color. 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.

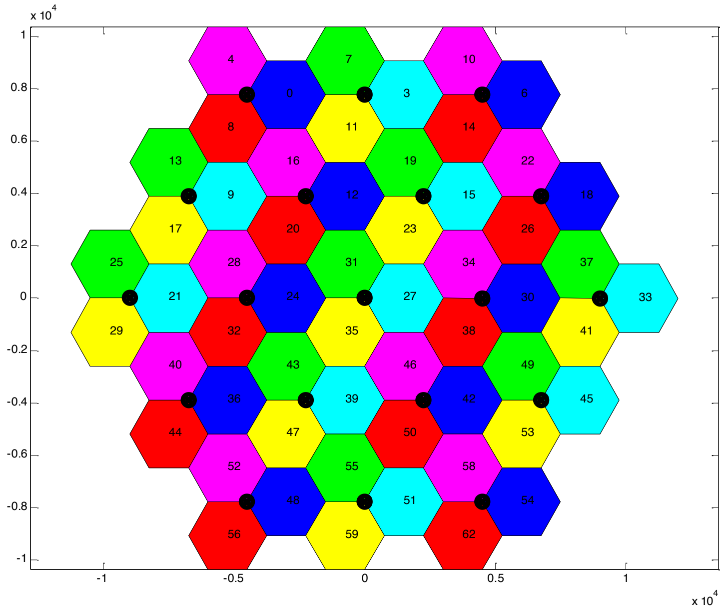

Figure 2-4: Example of PCI Planning for PRS

For example, if the mobile is in cell 35, when measuring PRS from cell 35, the mobile will receive PRS interference from the yellow cells only (e.g. cell 23 and cell 47). The demonstrated PCI planning ensures that cell 23 and cell 47 are not adjacent to cell 35 therefore less interference is expected.

2.3 Inter-frequency OTDOA Configuration

As noted earlier, the RSTD measurements are applicable to intra-frequency and inter-frequency cells.

2.3.1 Measurement Gaps

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 at the UE. Since there is no signal transmission and reception during the gap, the UE can switch to the target cell frequency and perform the RSTD measurement and come back to the current cell frequency. Therefore, PRS occasions on different frequency layers should not be aligned in time.

Reference [1] provides more details on measurement gaps.

2.3.2 RRC Procedure

In order to configure the measurement gap for a given UE when performing the inter-frequency RSTD measurements, the eNodeB[12] has to be aware of whether an inter-frequency positioning measurement is requested by the location server for this UE. A UE-triggered measurement gap request is specified in 3GPP standard, namely, the RRC Inter-Frequency RSTD Measurement Indication procedure. See Reference [7]. The overall procedure for inter-frequency RSTD measurements, including the LPP and RRC measurement gap request, is summarized in Figure 2-5 below.

[12] In OTDOA positioning, the eNodeB is not aware of an OTDOA measurement request, since the measurement request via LPP is transparent to the eNodeB.

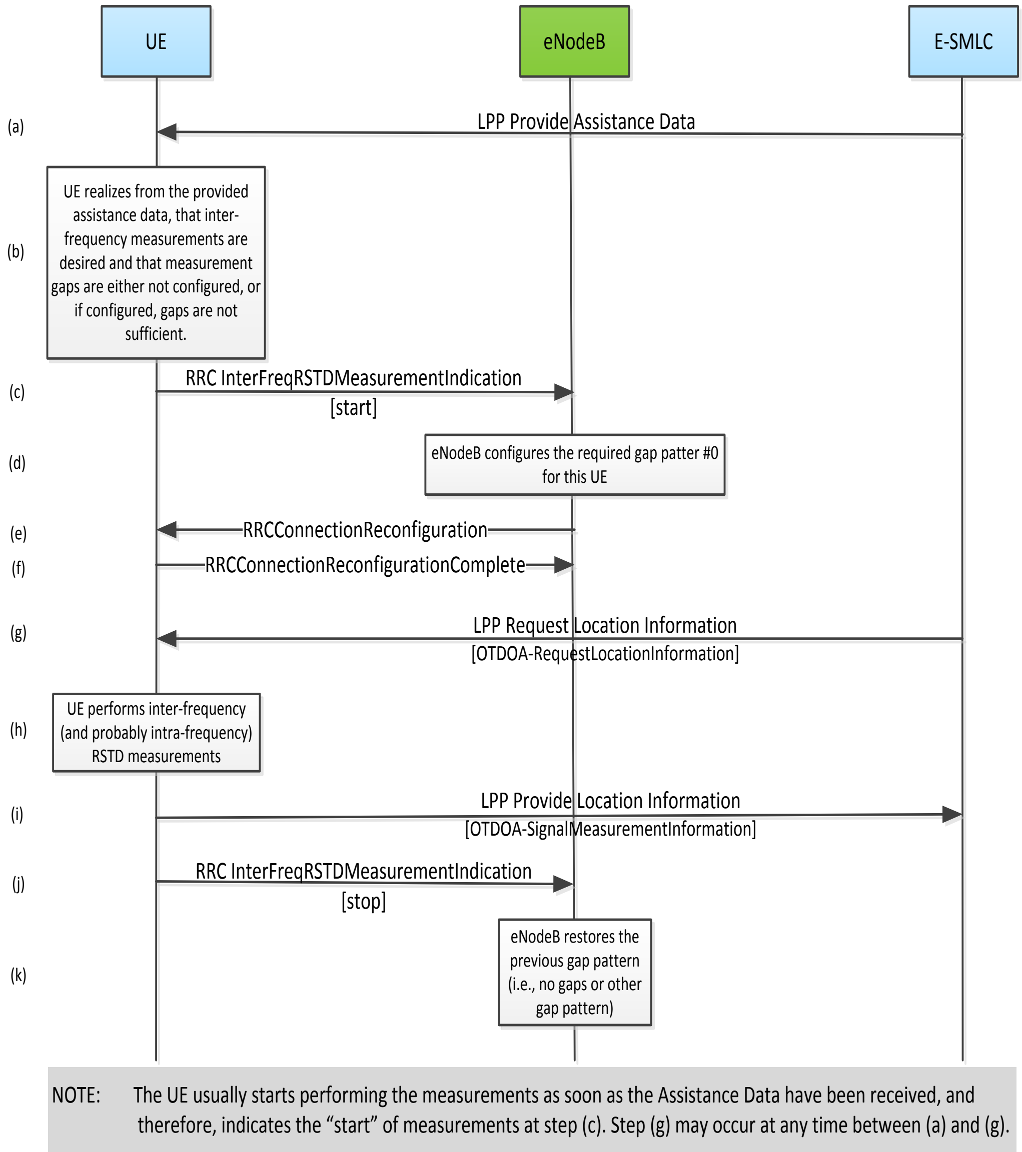

Figure 2-5: Example of Procedure with Inter-frequency RSTD Measurements

At step (c) in Figure 2-5, 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). At Step (j), the eNodeB stops the measurement gap pattern requested in step (c).

3 Conclusion

OTDOA is a terrestrial downlink positioning method specifically designed to provide improved positioning information. It has been standardized by 3GPP for use in LTE networks and employs a dedicated Positioning Reference Signal (PRS). OTDOA may be used with both the 3GPP control plane positioning solution and the OMA SUPL user plane solution for both commercial positioning applications and for emergency location services. OTDOA is already being deployed by several operators and enables accurate location both indoors and outdoors when networks are suitably configured and tuned (e.g., the factors defined in Section 2.2). Further improvement of OTDOA for use as indoor location method is expected in the future.