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Ph.D. Dissertation

Evaluation of the LTE Positioning Capabilities in Realistic Navigation Channels

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Outline

Introduction

Fundamentals of LTE positioning

Performance limits of LTE positioning signals

Positioning techniques for LTE signals in multipath scenarios

Implementation and test of an experimental LTE positioning receiver

Conclusions and future work

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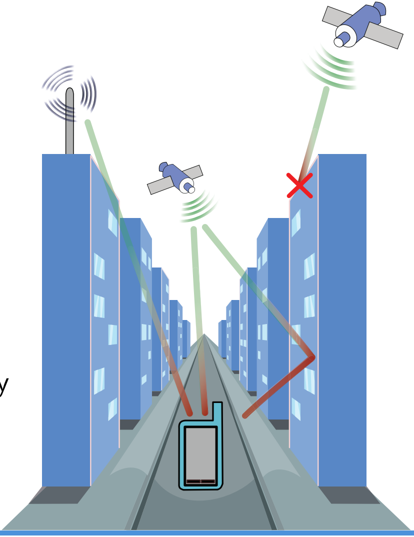
Ubiquitous positioning for mobile applications

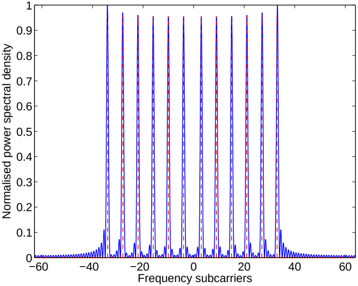
- Location-based services (LBS) are actively used by millions of mobile devices every day in many applications, e.g. geotagging, social networks, marketing...
- Need of **ubiquitous** positioning.
- Traditional GNSS fails in urban areas, due to signal blockage.
- Thus, mobile communications systems, such as LTE, that already offer data services in these scenarios can also be considered natural enablers of positioning.



Navigation with multicarrier signals

The practical case of LTE

- LTE adopts multicarrier signals due to their good properties for communications.
- But, LTE also specifies a dedicated multicarrier signal for positioning, in order to enhance the support of mobile location applications.
- Attractive features of LTE OFDM signals to achieve accurate positioning:
  - tight synchronisation between base stations,
  - wideband and low-interference signals, e.g. **positioning reference signal (PRS).**



Motivation and objectives

- In general, signal processing techniques proposed for ranging with multicarrier signals over multipath channels are variations of synchronization techniques proposed for communication systems, hence it is timely to investigate on time-delay estimation techniques for OFDM that properly tackle the needs of positioning applications.
- Objectives of this dissertation:
  - Explore capabilities of multicarrier signals to combat multipath from a positioning perspective, i.e. in order to achieve a very accurate time-delay estimation (TDE).
  - Assessment in realistic conditions with the practical case of LTE.
  - Design a new joint time-delay and channel estimation technique to counteract multipath.
  - Validate positioning performance of the novel technique in realistic navigation channels.

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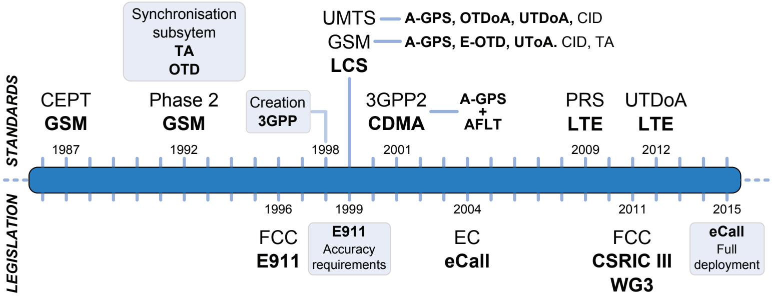
LTE and its predecessors

- The Long Term Evolution (LTE) is a standard for wireless communications, based on a cellular network of base stations that provides higher data rates to mobile devices wrt previous systems.
- A main new feature is the use of wideband multicarrier signals.
- Rapid commercial deployment of LTE around the world, as well as more potential demand of accurate positioning services.



STANDARDS

1987: CEPT **GSM**

1992: Phase 2 **GSM** — Synchronisation subsytem **TA** **OTD**

1998: Creation **3GPP**

1999: **LCS** — GSM — **A-GPS, E-OTD, UToA.** CID, TA; UMTS — **A-GPS, OTDoA, UTDoA,** CID

2001: 3GPP2 **CDMA** — **A-GPS + AFLT**

2009: PRS **LTE**

2012: UTDoA **LTE**

LEGISLATION

1996: FCC **E911**

1999: **E911** Accuracy requirements

2004: EC **eCall**

2011: FCC **CSRIC III WG3**

2015: **eCall** Full deployment

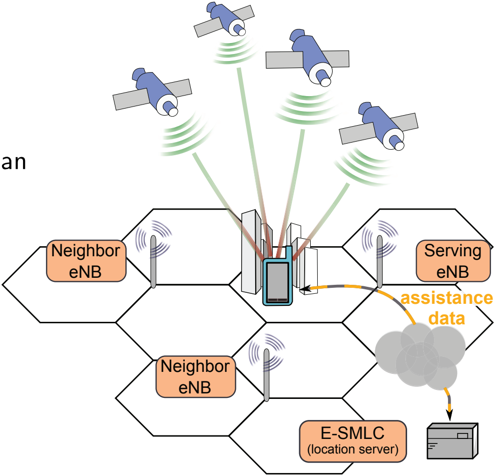
LTE solutions to challenges in cellular positioning

- Main sources of positioning errors using TDE in wireless systems:
    - Synchronisation among reference or base stations (BSs).
    - Inter-cell interference between transmitters that use the same frequency for spectral efficiency.
    - Attenuation of the LoS due to obstacles.
    - Dense multipath contribution in indoor and urban scenarios.
- Main features of LTE to combat these positioning errors:
    - Tight network synchronisation.
    - PRS muting in OTDoA.
    - Use of wideband signals.
    - Provides three (Rel. 9) / four ($\geq$ Rel. 11) positioning methods.

LTE positioning methods

A-GNSS

failures in indoor/urban scenarios.



LTE positioning methods

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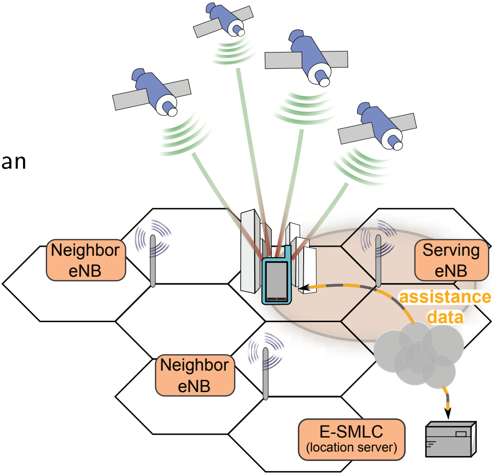
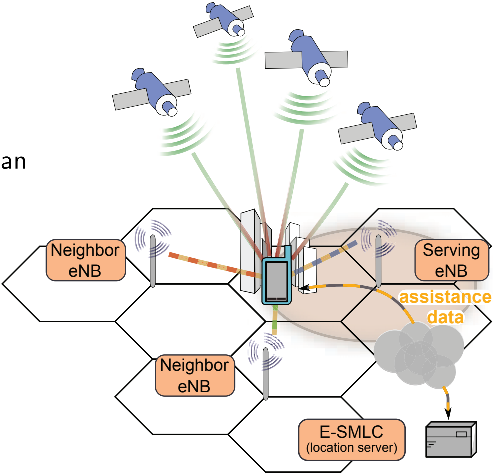


E-CID

coarse positioning accuracy.

LTE positioning methods



A-GNSS

failures in indoor/urban scenarios.

OTDoA

improved accuracy with PRS.

E-CID

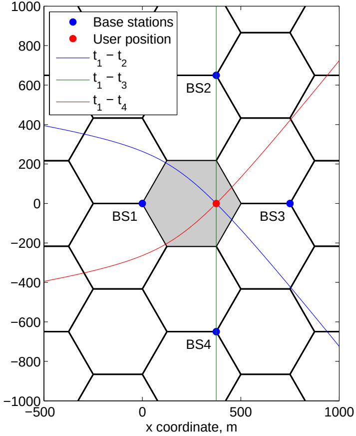
coarse positioning accuracy.

LTE and OTDoA principles

- The OTDoA method is based on the time delay differences between the reference BS (i.e. BS 1) and the neighbour BSs:

$$t_1 - t_i = \frac{\sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_i - x)^2 + (y_i - y)^2}}{c}$$

- The time-difference measurements follow different hyperbolas that intersect in the user equipment (UE) location, which is then calculated with a trilateration technique.



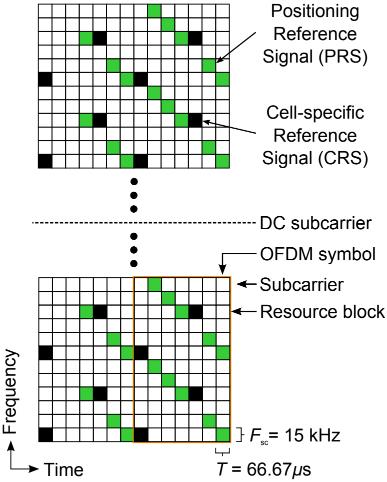
LTE multicarrier signals

- Downlink OFDM transmission:

$$x(m) \doteq \sqrt{\frac{2C}{N}} \sum_{n=0}^{N-1} d(n)\cdot p(n) \exp\left(j\frac{2\pi nm}{N}\right)$$

- Uplink SC-OFDM transmission.
- Scalable system bandwidths from 1.4 MHz to 20 MHz.
- Several signals can be used for positioning, such as PSS, SSS, **CRS**, **PRS** or SRS.
- CRS and PRS with a frequency reuse factor of six, $N_{\mathrm{ID}}^{\mathrm{cell}} \bmod 6$.
- Positioning occasions every 160, 320, 640 or 1280 ms.

Downlink allocation



Positioning Reference Signal (PRS)

Cell-specific Reference Signal (CRS)

DC subcarrier

OFDM symbol

Subcarrier

Resource block

Frequency

Time

F_{sc} = 15 kHz

T = 66.67μs

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Achievable OTDoA accuracy

- In an LTE network perfectly synchronised, i.e. no clock offsets,

noise+interference

Estimated range differences: $\hat{\mathbf{d}} = \mathbf{d} + \mathbf{n}, \quad \mathbf{n} \sim \mathcal{N}\left(0, \mathbf{R}\right)$

True range differences: $\mathbf{d} = |\mathbf{x} - \mathbf{x}_1| - |\mathbf{x} - \mathbf{x}_j|, \quad j = 2, \ldots, K$

- Accuracy from Cramér-Rao bound (CRB) for OTDoA positioning, i.e.

$$\mathrm{CRB}(\mathbf{x}) = \left(\mathbf{D}^{\mathrm{T}} \mathbf{R}^{-1} \mathbf{D}\right)^{-1},$$

$$\mathbf{D} = \begin{pmatrix} \frac{x-x_1}{d_1} - \frac{x-x_2}{d_2} & \frac{y-y_1}{d_1} - \frac{y-y_2}{d_2} \\ \frac{x-x_1}{d_1} - \frac{x-x_3}{d_3} & \frac{y-y_1}{d_1} - \frac{y-y_3}{d_3} \\ \vdots & \vdots \\ \frac{x-x_1}{d_1} - \frac{x-x_K}{d_K} & \frac{y-y_1}{d_1} - \frac{x-x_K}{d_K} \end{pmatrix}, \quad \mathbf{R} = \begin{pmatrix} \sigma_1^2 + \sigma_2^2 & \sigma_1^2 & \cdots & \sigma_1^2 \\ \sigma_1^2 & \sigma_1^2 + \sigma_3^2 & \cdots & \sigma_1^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_1^2 & \sigma_1^2 & \cdots & \sigma_1^2 + \sigma_K^2 \end{pmatrix}.$$

- The position error in meters wrt the true position **x** is computed as,

$$\varepsilon_{\mathbf{x}} = \sqrt{\mathrm{tr}\left(\mathrm{CRB}(\mathbf{x})\right)}.$$

CRB for TDE over AWGN channel and matched filter

The covariance matrix **R** of the range estimation is modelled with:

- TDE performance of a certain estimator over AWGN channel:
  - Synchronization techniques based on blind estimation, e.g. van de Beek, have an accuracy of T_s (i.e. 277.78 m for 1.08 MHz).
  - Use of pilot signals with matched filter, inherited in LTE from CDMA systems (e.g. UMTS or CDMA2000), hereby called conventional TDE.

Received LTE signal: $y(m) = x(m) \circledast h(m) + v(m) \hookleftarrow$

ML time-delay estimation: $\hat{\tau} = \arg\max_{\tau} \left\{ \left| R_{\mathrm{yx}}(\tau) \right|^2 \right\}$

Noise plus interference

Correlation function: $R_{\mathrm{yx}}(\tau) \doteq \sum_{m=0}^{N-1} y(m) \cdot x_{\mathrm{s}}^{*}(m-\tau)$

- CRB for TDE over AWGN channel,

$$\boxed{\mathrm{CRB}(\tau) = \frac{T^2}{8\pi^2 \cdot \mathrm{SINR} \cdot \sum_{n\in\mathcal{N}_{\mathrm{a}}} p(n)^2 \cdot n^2}}$$

Impact of inter-cell interferences

Using an urban macro-cell layout, three main interference scenarios are identified:

- Non-coordinated network

$$\mathrm{SINR} = \frac{P_{rx,i}}{\sum_{j\neq i} P_{rx,j} + N_{rx}}$$

- Interference cancellation

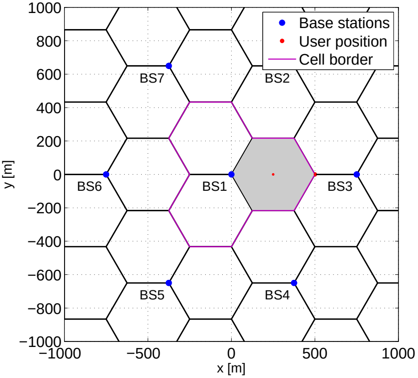
$$\mathrm{SINR} = \frac{P_{rx,i}}{\sum_{\substack{j\neq i\\ j\neq m}} P_{rx,j} + N_{rx}}$$

- Coordinated network

$$\mathrm{SINR} \approx \mathrm{SNR}$$

3GPP TR 36.942

BS ant. model	3-sectorial, $P_{\mathrm{tx,max}} = \{43, 46\}$ dBm
BS ant. pattern	$\bar{G}_{\mathrm{tx}} - \min\left\{12\left(\theta/\theta_{\mathrm{3dB}}\right)^2, A_{\mathrm{min}}\right\}$
UE ant. model	Omnidirectional, $G_{\mathrm{rx}} = 0$ dBi
Path loss model	$128.1 + 37.6\log_{10}(R)$ dB



Impact of inter-cell interferences

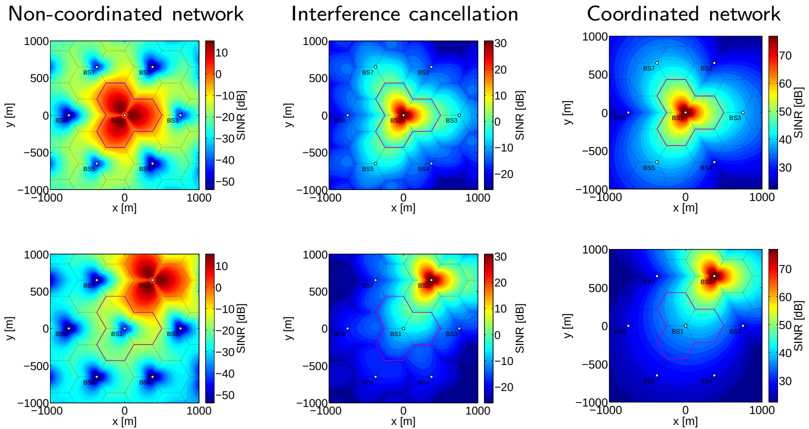
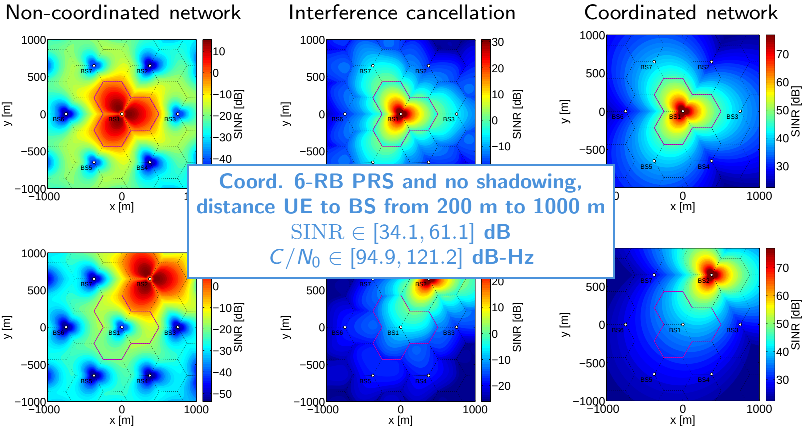


Figure: SINR maps computed for BS 1 and BS 2 transmitting 6-RB PRS (i.e. 1.02 MHz bandwidth) in the three interference scenarios identified.

Impact of inter-cell interferences


Non-coordinated network

Interference cancellation

Coordinated network

Coord. 6-RB PRS and no shadowing, distance UE to BS from 200 m to 1000 m

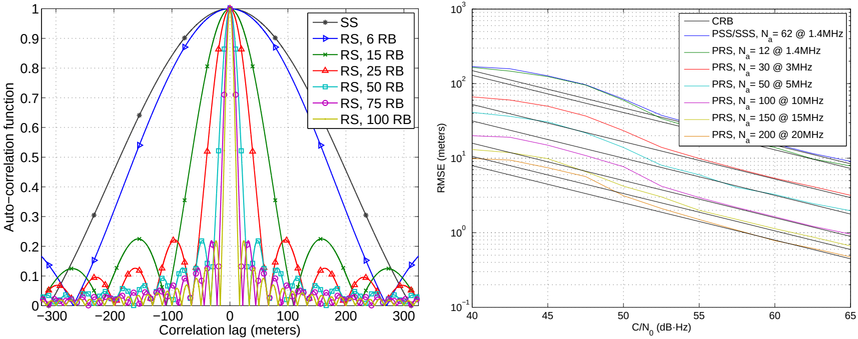
$\mathrm{SINR} \in [34.1, 61.1]$ **dB**

$C/N_0 \in [94.9, 121.2]$ **dB-Hz**

Figure: SINR maps computed for BS 1 and BS 2 transmitting 6-RB PRS (i.e. 1.02 MHz bandwidth) in the three interference scenarios identified.

Conventional TDE for AWGN Channel

Ranging performance and CRB for TDE



- Main lobe of the ACF is narrower as BW increases $\Longrightarrow$ better accuracy.
- RMSE of the matched filter attains the CRB for moderate to high C/N_0.
- Matched filter is saturated (producing outlier estimations) below C/N_0 threshold of 55 dB-Hz, i.e. SINR = -5 dB for 6-RB PRS.

Impact of multipath on time-delay estimation

LTE standard channel models and first-peak estimation

- Realistic navigation scenarios, such as urban environments, are characterized by the presence of multipath.
- The LTE standard specifies tapped-delay line (TDL) models, i.e. EPA, EVA and ETU channel models that can represent (in general terms) these realistic navigation scenarios:

$$h(m) = \sum_{k=0}^{L_{\mathrm{c}}-1} \underset{\uparrow\ \text{Rayleigh-distributed}}{h_k} \cdot \mathrm{sinc}\left(m - \overset{\substack{\text{fixed taps delays}\\ \downarrow}}{\tau_{\mathrm{c},k}} - \overset{\substack{\text{time delay of 1st path}\\ \downarrow}}{\tau}\right).$$

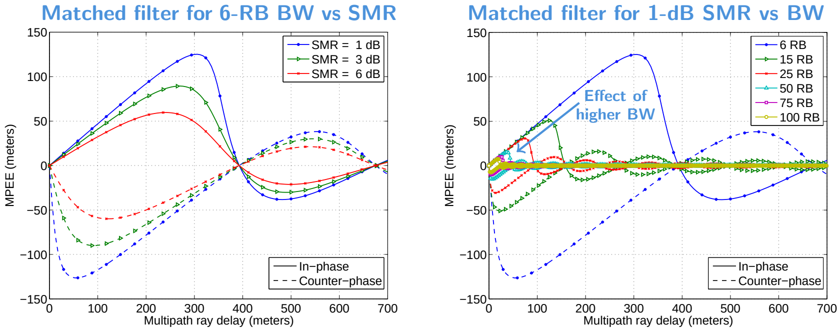
- Poor TDE performance of the matched filter in these scenarios.
- Many authors use the first-peak estimator (or threshold-based estimator), as an extension of the matched filter, to improve TDE.
- The first-peak estimator is based on finding the first peak (above the noise level) of the correlation function to obtain the TDE.

Impact of multipath on time-delay estimation

Ranging performance metrics (I): MPEE

- **Multipath error envelope (MPEE)** shows the time-delay error produced by a single multipath ray added to the LoS signal:

$$y(m) = x(m-\tau) + a_1 \cdot e^{j\phi_1} \cdot x(m-\tau-\tau_1).$$



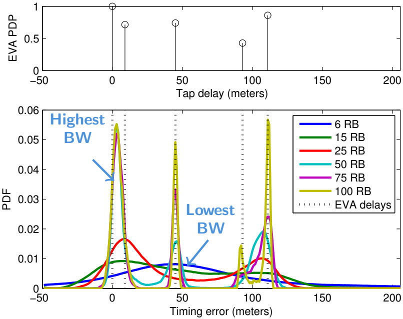
Impact of multipath on time-delay estimation

Ranging performance metrics (II): Mean delay and timing error histogram

- **Mean delay** $\bar{\tau}$ of PDP approximates the delay error for low BW.
- **Timing error histogram** shows impact of the multipath channel on the ranging accuracy of the TDE, e.g. using matched filter.

Example: EVA channel model

$$\bar{\tau} = \frac{\sum_{k=1}^{K} \tau_{\mathrm{c},k}|a_k|^2}{\sum_{k=1}^{K}|a_k|^2} \xrightarrow{\text{EVA}} \bar{\tau} = 47 \text{ m}$$

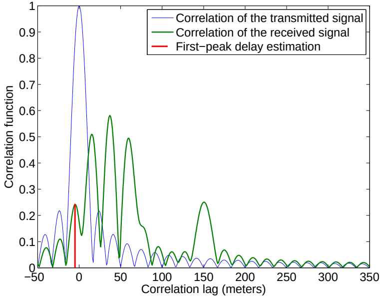


Timing error histogram for EVA channel using matched filter

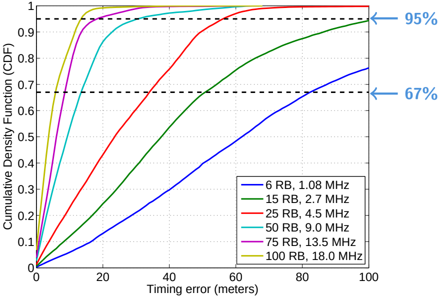
Impact of multipath on time-delay estimation

Ranging performance metrics (III): Cumulative density function (CDF)

Example: ETU channel model, $\mathrm{SNR} = 50$ dB (i.e. PRS-enabled at cell edge)



Cross-correlation function for 100-RB PRS



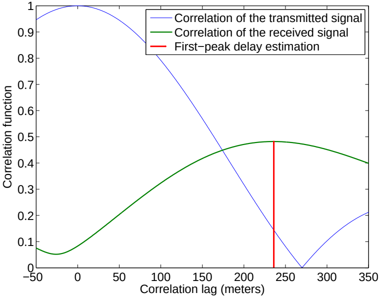
CDF using first-peak estimation

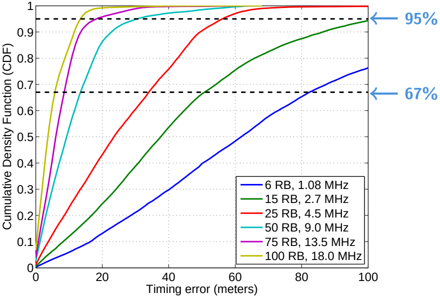
- First-peak estimator improves TDE wrt matched filter for high BW.
- 67% and 95% CDF can be used for accuracy requirements, e.g. E911.
- Poor TDE performance for low BW ($\bar{\tau} = 59$ m for ETU model).

Impact of multipath on time-delay estimation

Ranging performance metrics (III): Cumulative density function (CDF)

Example: ETU channel model, $\mathrm{SNR} = 50$ dB (i.e. PRS-enabled at cell edge)





Cross-correlation function for 6-RB PRS

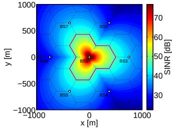
CDF using first-peak estimation

- First-peak estimator improves TDE wrt matched filter for high BW.
- 67% and 95% CDF can be used for accuracy requirements, e.g. E911.
- Poor TDE performance for low BW ($\bar{\tau} = 59$ m for ETU model).

Impact of both interference and multipath

- Considering an LTE coordinated network, the achievable position accuracy of a first-peak estimator is assessed in pedestrian and urban scenarios, characterized by EPA and ETU models:
  1. SINR computed with 5 most powerful BSs wrt user location **x**
  2. Applying multipath, 67% and 95% CDF of TDE errors are considered typical values of the std. dev. of pseudoranges for every SINR.
  3. Compute CRB for OTDoA at **x** using these std. dev. values in **R**.

①



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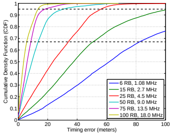


③

$$\mathrm{CRB}(\mathbf{x}) = \left(\mathbf{D}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{D}\right)^{-1}$$

$$\varepsilon_{\mathbf{x}} = \sqrt{\mathrm{tr}\left(\mathrm{CRB}(\mathbf{x})\right)}$$

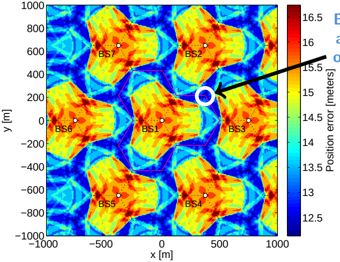
$\Longrightarrow$ **Assessment of the achievable positioning accuracy**

Conventional localization accuracy in LTE

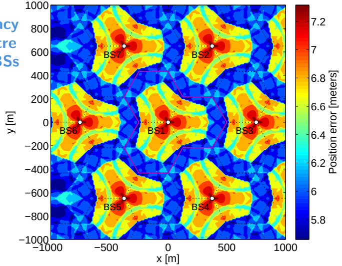
Some conclusions...

- Inter-cell interference is removed by synchronized and coord. PRS.
  - Lowest position error using 6-RB PRS in EPA channel ($\bar{\tau} = 13$ m) at any $\mathbf{x} \Longrightarrow \sim 12$ m for 67% and ~ 30 m for 95%
  - High BW required to achieve ≤ 12 m in ETU channels ($\bar{\tau} = 59$ m).
- Poor performance in urban channels (i.e. ETU) due to multipath

$\Longrightarrow$ **need to be counteracted**



Best accuracy at barycentre of 3 close BSs



67% CDF of EPA channel, 6-RB PRS

67% CDF of ETU channel, 100-RB PRS

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Countermeasures against multipath channel

- As a solution to counteract multipath, we can resort to the joint estimation of the time-delay and channel response.
- Thus, the definition of the channel estimation model is fundamental to later reduce the impact of multipath on TDE.
- But, the complexity of the estimation has to be also considered.

Freq. domain received signal: $\boxed{\mathbf{r} = \mathbf{B}\boldsymbol{\Gamma}_{\tau}\mathbf{F}_{L}\mathbf{h} + \mathbf{w}}$

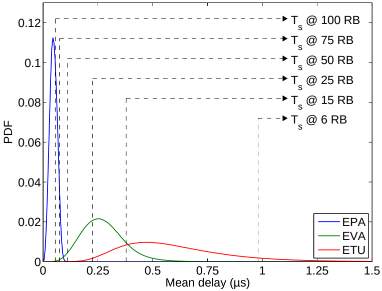
Channel estimation model

Channel frequency response

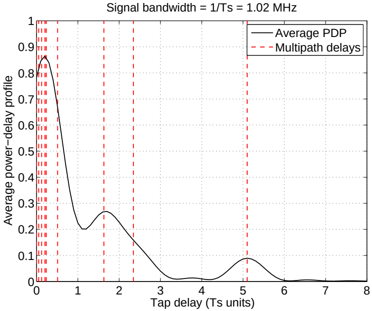
$$H(n) = \sum_{k=0}^{L-1} h_k \cdot e^{-j\frac{2\pi}{N}\cdot n\cdot(\tau+\tau_k)}$$

Characterization of propagation channel models

- Close-in multipath has most of its channel contribution within a sampling period T_s wrt the LoS ray.
  - *Examples*: EPA model or ETU model with a 6-RB bandwidth
  - Average PDP of the channel can be used to set the model order L.



PDF of the mean delay for LTE models



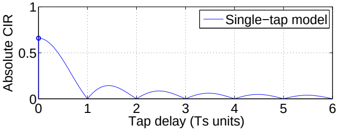
Average PDP for ETU with 6-RB PRS

Channel estimation models and their CRB

Single-tap estimation model:

$$\tau_k = 0 \quad , \qquad k = 0$$

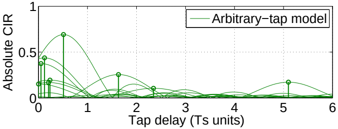
$$\mathrm{CRB}_{\tau,\mathrm{ST}} = \left[\mathbf{J}^{-1}\left(\tau, h_0\right)\right]_{1,1}$$



Arbitrary-tap estimation model:

$$\tau_k = \tau_{\mathrm{c},k} \quad , \quad 0 \leq k < L_{\mathrm{c}}$$

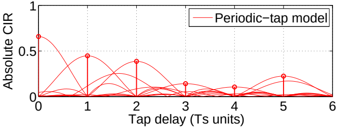
$$\mathrm{CRB}_{\tau,\mathrm{AT}} = \left[\mathbf{J}^{-1}\left(\tau, \mathbf{h}, \boldsymbol{\tau}_c\right)\right]_{1,1}$$



Periodic-tap estimation model:

$$\{\tau_k\} = \{0, 1, \cdots, L-1\} \quad , \quad 0 \leq k < L$$

$$\mathrm{CRB}_{\tau,\mathrm{PT}} = \left[\mathbf{J}^{-1}\left(\tau, \mathbf{h}\right)\right]_{1,1}$$

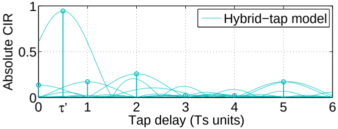


Hybrid-tap estimation model:

$$\{\tau_k\} = \{0, \tau', 1, \cdots, L-2\} \quad , \quad 0 \leq k < L$$

$$0 < \tau' < 1$$

$$\mathrm{CRB}_{\tau,\mathrm{HT}} = \left[\mathbf{J}^{-1}\left(\tau, \mathbf{h}, \tau'\right)\right]_{1,1}$$



One-dimensional joint ML (1D-JML) estimator

Periodic-tap estimation model, $L > 1$

- Joint maximum likelihood estimation of the time delay τ and the channel coefficients $\mathbf{h} = [h_0, \cdots, h_{L-1}]^{\mathrm{T}}$:

$$\begin{bmatrix} \hat{\tau} \\ \hat{\mathbf{h}} \end{bmatrix} = \arg\min_{\tau,\mathbf{h}} \left\{ \left\| \mathbf{r} - \mathbf{B}\Gamma_{\tau}\mathbf{F}_{L}\mathbf{h} \right\|^2 \right\}$$

$$\mathbf{A}_{\tau} = \mathbf{B}\Gamma_{\tau}\mathbf{F}_{L} \quad \longrightarrow \quad \hat{\mathbf{h}} = \mathbf{A}_{\tau}^{\dagger}\mathbf{r} = \left(\mathbf{A}_{\tau}^{\mathrm{H}}\mathbf{A}_{\tau}\right)^{-1}\mathbf{A}_{\tau}^{\mathrm{H}}\mathbf{r}$$

$$\hat{\tau} = \arg\min_{\tau} \left\{ \min_{\mathbf{h}} \left\| \mathbf{r} - \mathbf{A}_{\tau}\mathbf{h} \right\|^2 \right\} = \arg\min_{\tau} \left\{ \left\| \left(\mathbf{I} - \mathbf{A}_{\tau}\mathbf{A}_{\tau}^{\dagger} \right) \mathbf{r} \right\|^2 \right\}$$

- Severe degradation of the TDE performance due to close-in multipath, because it is not properly modelled between the first two samples, i.e. model mismatch.
- Particular case for $L = 1$ results in single-tap estimation model, i.e. conventional matched filter.

Two-dimensional joint ML (2D-JML) estimator

Novel hybrid-tap estimation model, $L > 1$

Joint maximum likelihood estimation of the time delay τ, the arbitrary tap delay τ' and the channel coefficients $\mathbf{h} = [h_0, \cdots, h_{L-1}]^{\mathrm{T}}$:

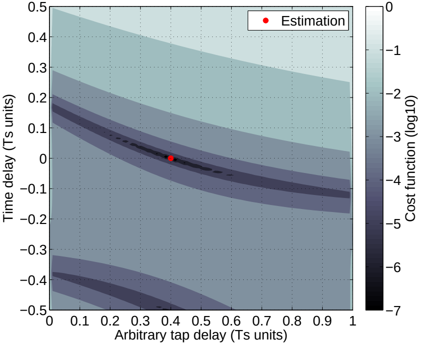
$$\begin{bmatrix} \hat{\tau} \\ \hat{\tau}' \end{bmatrix} = \arg\min_{\tau,\tau'} \left\{ \left\| \mathbf{P}^{\perp}_{\mathbf{A},\tau,\tau'} \mathbf{r} \right\|^2 \right\}$$

$$\text{s.t. } 0 < \tau' < 1$$

$$\mathbf{P}^{\perp}_{\mathbf{A},\tau,\tau'} = \mathbf{I} - \mathbf{A}_{\tau,\tau'} \left(\mathbf{A}^{\mathrm{H}}_{\tau,\tau'} \mathbf{A}_{\tau,\tau'} \right)^{-1} \mathbf{A}^{\mathrm{H}}_{\tau,\tau'}$$

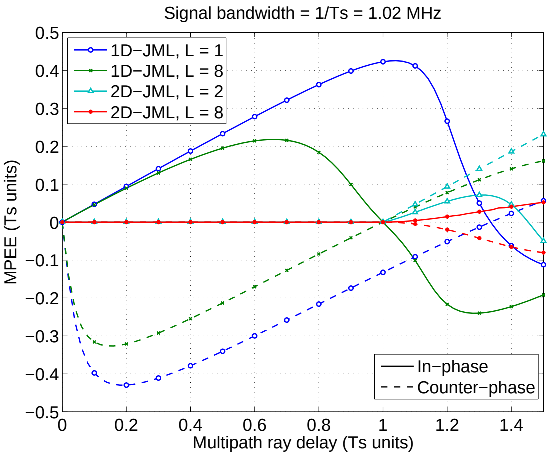
$$\mathbf{A}_{\tau,\tau'} = \mathbf{B}\mathbf{\Gamma}_{\tau}\mathbf{F}_{L,\tau'}$$

$\Longrightarrow$ **Improves characterization of the channel, while only adding the complexity of one more estimation parameter.**



Two-ray multipath, $\tau_1 = 0.4, \phi_1 = \pi$

MPEE of the 1D- and 2D-JML estimators



Simulation parameters:

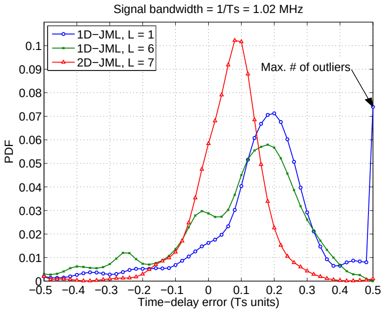
- 1-dB SMR, no noise.
- 6-RB PRS, $N = 68$ sc.
- $T_{\mathrm{s}} = T/N = 980.39$ ns.
- TDE in $[-T_s/2, T_s/2]$.

Conclusions:

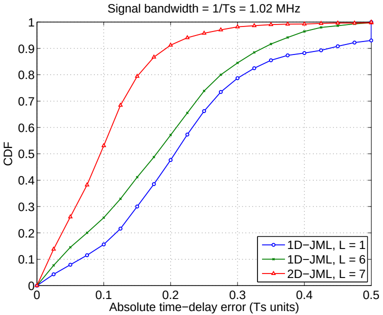
- 1D-JML for $L > 1$ outperforms 1D-JML for $L = 1$, but still significant bias.
- 2D-JML TDE is completely unbiased for τ_1 within 0 and 1.
- Same 2D-JML performance even when decreasing L.

Bias induced by LTE channel models

Example: Low signal bandwidth of 1.4 MHz in ETU channel



PDF of the time-delay errors



CDF of the absolute time-delay errors

- Particular case of ETU channel with 6-RB PRS (absence of noise):
  - Poor performance of the 1D-JML estimators, e.g. 67% CDF errors $\Longrightarrow 0.25\cdot T_s$ ($= 73.5$ m) with $L = 1$, $0.23\cdot T_s$ ($= 67.7$ m) with $L = 6$
  - Notable improvement provided by 2D-JML estimator for $L = 7$ $\Longrightarrow 0.12\cdot T_s$ ($= 35.3$ m) for 67% CDF

Bias induced by LTE channel models

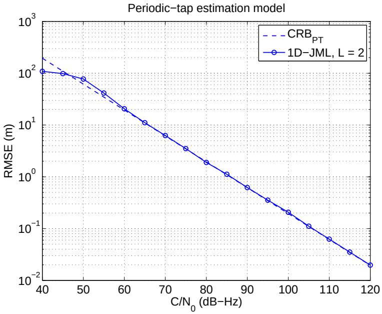
General assessment of the channel estimation models

- In order to find the ultimate positioning accuracy in LTE, we need to study the performance limits of the 1D- and 2D-JML TDE for a wide variety of scenarios (first, in absence of noise):
  - LTE signal bandwidths from 6 RB to 100 RB,
  - LTE channel models, i.e. EPA, EVA and ETU,
  - L estimation taps, i.e. from 1 to a maximum of 90.
- CDF of the time-delay errors of these estimators is computed.
- Concluding remarks:
  - At low signal bandwidths (e.g. 6-RB PRS), propagation rays jointly contribute to the multipath effect, thus L_{opt} is equivalent to the delay spread of the channel.
  - When the signal bandwidth is increased, more independent multipath contribution lead to the adaptive selection of the model order L.
  - Using the optimum number of taps L_{opt}, the 2D-JML estimator achieves the minimum bias in most of the cases.

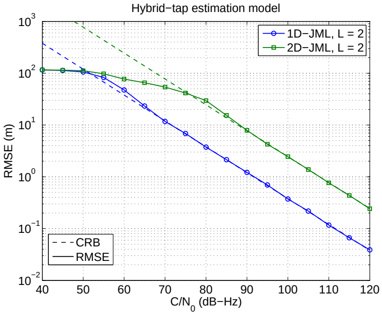
RMSE and bias of the JML estimators

Attainability of the CRB for TDE

- Considering a two-ray multipath with $\phi_1 = \pi$ and $\mathrm{SMR} = 1$ dB:
  - Both 1D- and 2D-JML estimators attain their corresponding CRB.
  - One more estimation variable increases RMSE and C/N_0 threshold.
  - Trade-off $\Longrightarrow$ counteract multipath vs robustness against noise.



Case 1: $\tau_{c,k} = \{0, 1\}$

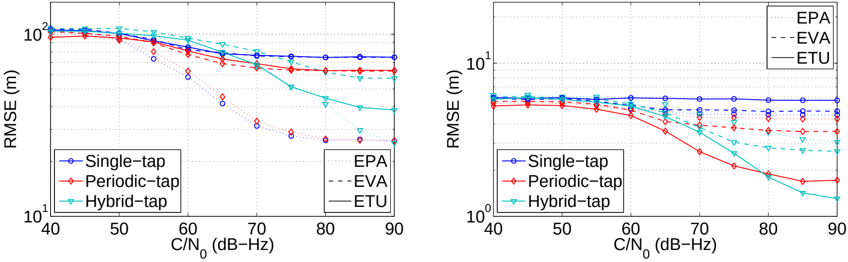


Case 2: $\tau_{c,k} = \{0, 0.5\}$

RMSE and bias of the JML estimators

Achievable ranging accuracy in realistic navigation channels

- Using EPA, EVA and ETU models $\Longrightarrow$ appropriate L is chosen.
  - Conventional matched filter has the worst performance.
  - For $L > 1$, and in most of the cases, 2D-JML has lower RMSE than 1D-JML at moderate to high C/N_0, i.e. $> C/N_0 = \{70, 80\}$ dB-Hz.
  - At $C/N_0 = 85$ dB-Hz (cell edge of macro-cell), 2D-JML TDE achieves an accuracy from 30 to 60 m for 1.4 MHz and < 5 m for 20 MHz.



1.4 MHz, $L_p = \{2, 2, 6\}$, $L_h = \{2, 4, 7\}$

20 MHz, $L_p = \{4, 2, 10\}$, $L_h = \{5, 6, 11\}$

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Implementation and test of an experimental LTE positioning receiver

Conclusions and future work

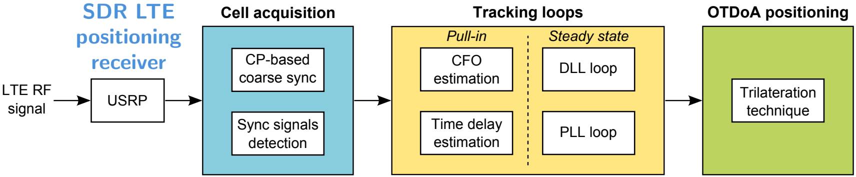
Experimental validation of LTE positioning performance

- The results obtained with the novel 2D-JML technique can be validated with real LTE signals, generated at the European Navigation Laboratory (ENL) of ESA (ESTEC, The Netherlands).
- Thus, a software-defined radio (SDR) LTE positioning receiver is implemented in MATLAB to acquire, track and position with LTE radio signals.
- This experimental LTE positioning receiver is then tested for the scenarios under study.

Testbench and SDR LTE receiver

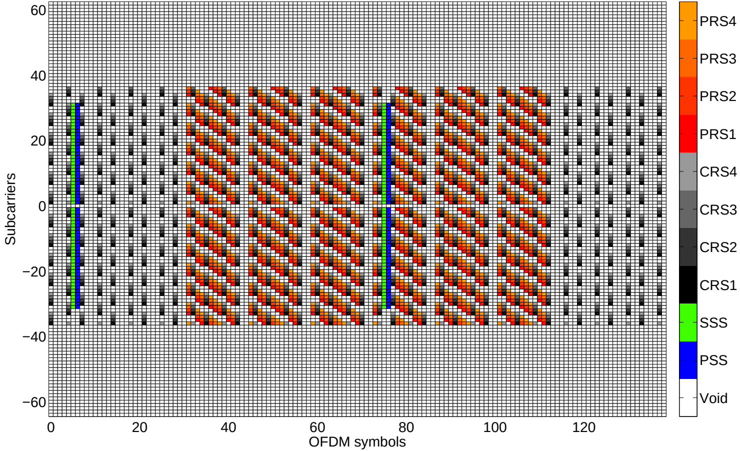
Testbench:

- Spirent E2010 and VR5,
- USRP N210 with DBSRX2,
- 4 sync. BSs at 1.86 GHz,
- 1.4-MHz system bandwidth,
- PRS-enabled, but CRS symbols without data are used (more frequent).



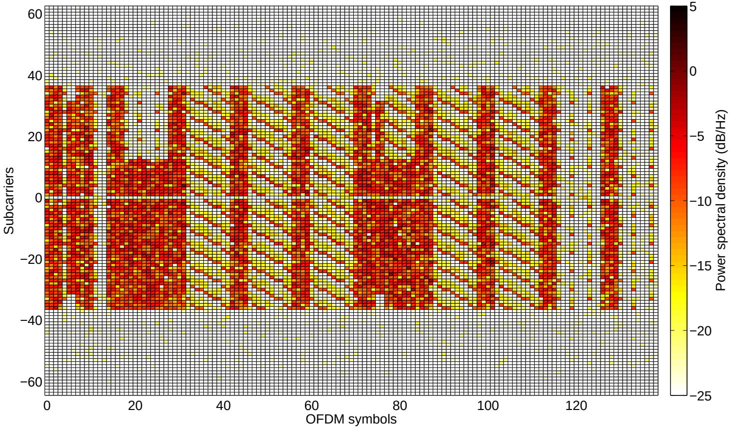
Validation of the SDR LTE positioning receiver

LTE pilot signals



Validation of the SDR LTE positioning receiver

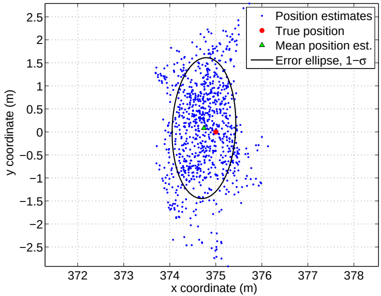
Time and frequency representation of the PSD for the received signal



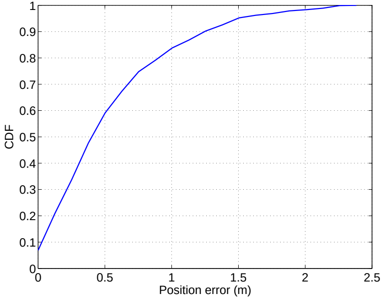
Validation of the SDR LTE positioning receiver

OTDoA positioning results

- Once in signal tracking, timing offset among BSs is calibrated.
- Positioning engine **validated** $\Longrightarrow$ Position errors lower than 3 m, in a static AWGN scenario for 6-RB CRS with $C/N_0 \in [70, 80]$ dB-Hz.



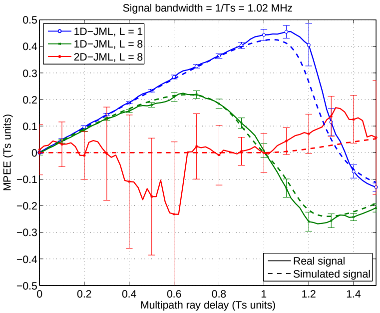
Position estimations and true position



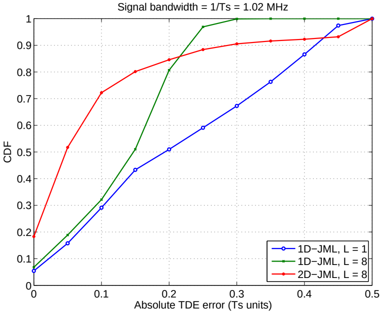
CDF of position errors

Multipath error envelope using real LTE signal

- First, acquisition and tracking in LoS, then TDE with multipath.
- Main results of the MPEE using real and simulated signal:
  - 1D-JML estimators obtain very similar performance in both cases.
  - Impact of noise is more severe for 2D-JML than for 1D-JML.



MPEE of 1D- and 2D-JML estimators

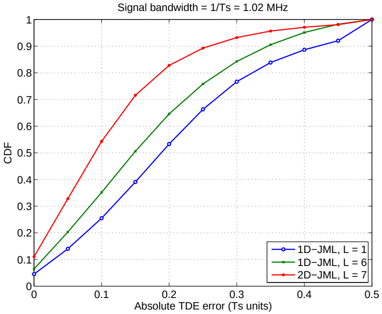


CDF of JML ranging errors

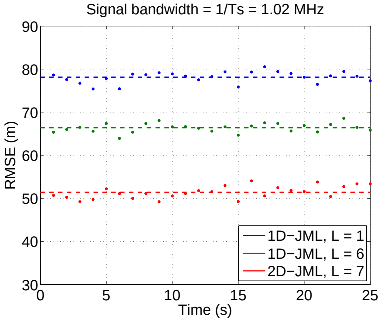
Achievable ranging performance in urban channels

Accuracy of 1D- and 2D-JML estimators

- Realistic navigation channel is emulated with ETU model.
- Using 1.4-MHz system bandwidth $\Longrightarrow$ close-in multipath scenario.
- 2D-JML TDE outperforms 1D-JML TDE for $C/N_0 \simeq 85$ dB-Hz.



CDF of ranging errors



RMSE over 1 s (dots) and 25 s (dashes)

Achievable ranging performance in urban channels

Comparison between using real and simulated signals

- The experiment **validates** simulation results for close-in multipath:
  - JML ranging errors are in accordance with simulations (in black).
  - Achievable ranging accuracy of 2D-JML with real signal (**in blue**) is $\sim$ 50 m for a 1.4-MHz bandwidth and $C/N_0 \simeq 85$ dB-Hz.

Time-delay estimator	$\epsilon_{67\%}$ (m)	$\epsilon_{95\%}$ (m)	RMSE (m)	Bias (m)
1D-JML $L = 1$	73.5 / **74.4**	147.1 / **137.4**	75.3 / **78.1**	52.5 / **54.2**
1D-JML $L = 6$	67.7 / **62.1**	113.2 / **117.4**	63.4 / **66.4**	28.2 / **25.1**
2D-JML $L = 7$	35.3 / **40.3**	69.1 / **99.1**	39.6 / $\boxed{\textbf{51.4}}$	19.8 / **19.1**

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Conclusions

- Achievable positioning of LTE with conventional estimators:
  - Necessary coordination of PRS transmission for accurate positioning.
  - Achievable accuracy between 12 m and 30 m in pedestrian channels (with almost LoS) for 6-RB PRS.
  - In urban channels, lower than 12 m only for high signal bandwidths.
- New 2D joint ML (2D-JML) time-delay and channel estimator:
  - Novel hybrid-tap channel estimation model to counteract critical impact of close-in multipath over TDE.
  - CRB derived for the channel estimation models.
  - 2D-JML TDE outperforms 1D-JML TDE in most of the cases studied.
- Practical validation with real LTE signal emulated at ESA:
  - Implementation of an experimental software LTE positioning receiver.
  - Satisfactory results of 2D-JML wrt 1D-JML in urban channel for 6 RB.
- Use 2D-JML in close-in multipath, 1D-JML is sufficient for high signal bandwidths.

Future work

- Adaptive joint time-delay and channel estimation:
  - To estimate adaptively the model order of the JML estimators.
  - To improve the robustness of the 2D-JML estimator against noise.
- Assessment of positioning capabilities in real LTE deployments.
  - Adapt JML estimators to dynamic propagation conditions.
  - Hybridisation of GNSS and LTE in a common SDR positioning receiver.

Contributions of the thesis

Performance limits of LTE positioning signals

- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "**Preliminary Analysis of the Positioning Capabilities of the Positioning Reference Signals of 3GPP LTE**", *5th European Workshop on GNSS Signals and Signal Processing*, Toulouse, France, 8-9 December 2011.
- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "**Achievable Localization Performance Accuracy of the Positioning Reference Signal of 3GPP LTE**", *Proc. International Conference on Localization and GNSS (ICL-GNSS)*, Starnberg, Germany, 25-27 June 2012.
- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "**Evaluation of the LTE Positioning Capabilities Under Typical Multipath Channels**", *Proc. 6th Advanced Satellite Multimedia Systems Conference and 12th Workshop on Signal Processing for Space Communications (ASMS/SPSC)*, Baiona, Spain, 5-7 September 2012.
- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "**Analysis of Positioning Capabilities of 3GPP LTE**", *Proc. 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS)*, Nashville, Tennessee, USA, 17-21 September 2012.

Contributions of the thesis

Positioning techniques for LTE signals in multipath scenarios

- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "Joint Channel and Time Delay Estimation for LTE Positioning Reference Signals", *6th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC)*, Noordwijk, The Netherlands, 5-7 December 2012.
- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, M. Crisci, "Joint Maximum Likelihood Time-Delay Estimation for LTE Positioning in Multipath Channels", *EURASIP Journal on Advances in Signal Processing, special issue on Signal Processing Techniques for Anywhere, Anytime Positioning*, Vol. 2014, nº 33, pags. 1–13, 2014.

Implementation and test of an experimental LTE positioning receiver

- J. A. del Peral-Rosado, J. A. López-Salcedo, G. Seco-Granados, F. Zanier, P. Crosta, R. Ioannides, M. Crisci, "Software-Defined Radio LTE Positioning Receiver Towards Future Hybrid Localization Systems", *Proc. AIAA International Communication Satellite Systems Conference (ICSSC)*, Florence, Italy, 14-17 October 2013.