New First - Path Detector for LTE Positioning Reference Signals

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***Abstract*—In today's world, where positioning applications reached a huge popularity and became virtually ubiquitous, there is a strong need for determining a device location as accurately as possible. A particularly important role in positioning play cellular networks, such as Long Term Evolution (LTE). In the LTE Observed Time Difference of Arrival (OTDOA) positioning method, precision of device location estimation depends on accuracy of the Positioning Reference Signal (PRS) first-path detection, what is particularly challenging in multipath environment. There are a few algorithms, available in the literature, that are dedicated to detect the first-path of PRS signals, often basing on estimation of the strongest path or which do not adapt to continuously changing environmental conditions. The paper presents a new algorithm, called First-Path Estimator (FPE), which detects the first path of received PRS signal in the LTE system. Simulations showed that proposed algorithm reduces Received Signal Time Difference (RSTD) measurement error compared to the well-known Maximum Likelihood Estimator (MLE) in urban scenario.**

Keywords-RSTD; LTE; OTDOA; PRS.

I. INTRODUCTION

Long Term Evolution (LTE) system specification driven by the 3rd Generation Partnership Project (3GPP) consortium [1] defines several methods for positioning, i.e., locating of mobile terminals in the network coverage area. These methods may be particularly useful in harsh environments such as densely populated urban areas or indoor locations, where Global Navigation Satellite Systems (GNSS) [2][3] are not working with accuracy demanded for some applications. One of the specified method is Observed Time Difference of Arrival (OTDoA) [4][5], for which special reference signals, called Positioning Reference Signals (PRS) [6], were defined. The OTDoA bases on measurements of the reception time differences between PRS signals arriving from multiple base stations to the User Equipment (UE). These measurements, along with knowledge of the geographical coordinates of the measured base stations and their relative timing, allow for estimation of the UE location in the network. Despite the frequency reuse factor in LTE equals one, transmissions of the PRS signals take place with frequency reuse factor of six in order to avoid near-far effect. In time domain, PRS signals are located on so-called positioning occasions, which are periodically repeating. Every positioning occasion consists of the set of consecutive PRS subframes. Furthermore, it is possible to mute PRS transmission in chosen positioning occasion, what, with scalable bandwidth of PRS signals, gives a sophisticated tool for flexible management of radio resources. The PRS signal main parameters are shown in Table I [7].

TABLE I. PRS SIGNAL PARAMETERS

PRS Bandwidth	1.4, 3, 5, 10, 15, 20 MHz
PRS Periodicity	160, 320, 640, 1280 ms
Consecutive PRS Subframes	1, 2, 4, 6

Accuracy of UE positioning in OTDOA depends mainly on PRS signals time of arrival estimation accuracy, therefore it is crucial to detects PRS reception time as precisely as possible. In this paper, new Time Delay Estimation (TDE) algorithm, called First-Path Estimator (FPE), detecting the first path of PRS signal, is proposed. The aim of its elaboration is to fulfill the requirements imposed by 3GPP on the accuracy of UE location estimation [8].

There are several algorithms available in the literature that detect arriving signal, e.g., Maximum Likelihood Estimator (MLE) or Fitz estimator [7]. The MLE algorithm detects the strongest path in the received signal, what may causes large errors in multipath environments, where in majority of cases the first arriving signal path is not the strongest one. The Fitz estimator is a low complex algorithm that moves signal reception time estimation into frequency domain. Its performance is close to the MLE in terms of Root Mean Square Error (RMSE) of time of signal arrival estimation. Another worth to mention algorithm is an estimator that detects the first arriving signal by the first occurrence of signal level above a -30 dB detection threshold relative to the strongest peak in the Power Delay Profile (PDP). If the dynamic range of the PDP is less than 30 dB, the first occurrence of signal level above the noise floor in PDP is used [9]. This algorithm however, does not adjust threshold to the noise floor, what may results in errors of first path detection in different power of noise relative to the power of arriving signal scenarios. FPE algorithm adjusts dynamically threshold accordingly to the ratio of signal power to noise power, what makes it more precise in the estimation of the first path time of arrival.

The rest of this paper is organized as follows. Section II describes MLE and proposed FPE estimator. Section III gives an overview on simulation model and section IV presents results of the simulations. At the end of the paper conclusions were drawn.

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II. Time Delay Estimation Algorithms

Time delay estimation algorithms, with regard to positioning process in LTE, are in charge of reception time measurements of the PRS signals, performing in order to calculate the Received Signal Time Difference (RSTD) value. RSTD defined by 3GPP in [10] is a parameter specifying the relative timing difference between the neighbour cell *j* and the reference cell *i* and is defined as

$$RSTD = T_{SubframeRxj} - T_{SubframeRxi} \tag{1}$$

where $T_{SubframeRxj}$ is the time when the user equipment receives the start of one subframe containing PRS signal from cell *j* and $T_{SubframeRxi}$ is the time when the UE receives the corresponding start of one subframe (also containing PRS signal) from cell *i* that is the closest in time to subframe received from cell *j*.

Among other things, accuracy of the RSTD measurements depends on the size of search window, where the TDE algorithm searches for the desired signals. LTE system provides a tool for prior estimation of the expected RSTD and expected RSTD uncertainty values, both determining a search window for PRS signals. Properly evaluated search window is necessary for accurate estimation of the position in time of PRS signals receiving from neighbour base stations. Generally, the smaller the search window, the more accurate estimation could be performed. Referring to the Fig. 1, minimal and maximal values of RSTD can be evaluated as [11]:

$$RSTD_{\min} = \frac{\left|d_{nei1} - d_{ref1}\right|}{c} \tag{2}$$

$$RSTD_{\max} = \frac{\left|d_{nei2} - d_{ref2}\right|}{c} \tag{3}$$

where *c* is the radio waves propagation velocity. Values d_{ref1} and d_{ref2} could be estimated based on the cell size or Timing Advance (TA) measurements [10]. Then, it can be written:

$$RSTD_{\min} = \frac{\left|d_{ref-nei} - 2 \cdot d_{ref}\right|}{c} \tag{4}$$

$$RSTD_{\max} = \frac{\left|d_{ref-nei}\right|}{c} \tag{5}$$

where $d_{ref-nei}$ is the distance between eNodeB$_{\text{ref}}$ and eNodeB$_{\text{nei}}$ and $d_{ref} = d_{ref1} = d_{ref2}$. Expected RSTD value is computed as a mean value of (4) and (5):

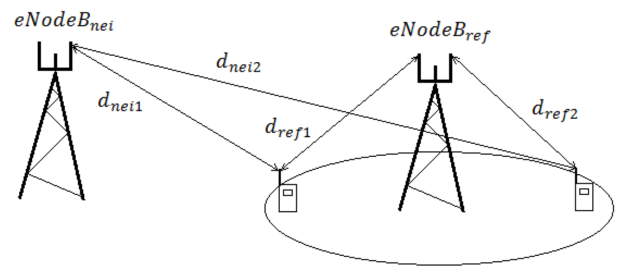

Figure 1. Illustration to expected RSTD and expected RSTD uncertainty values computation

$$RSTD_{\exp} = \frac{RSTD_{\min} + RSTD_{\max}}{2} \tag{6}$$

Finally, the search window, in which TDE algorithm searches for PRS signals arriving from a base station, is $\left\langle RSTD_{\min}, RSTD_{\max} \right\rangle$ centered at (6).

A. Maximum Likelihood Estimator

Maximum Likelihood Estimator finds the position of the strongest path in the received signal and can be defined as [7]:

$$T_{PRS} = \arg\max \left\{ \left| \sum_{i=0}^{P-1} r[i+m] \cdot s^{*}_{PRS}[i] \right|^{2} \right\} \tag{7}$$

where T_{PRS} is a position in time of PRS signal, *i* is a time index, *m* refer to delays of correlation function, *P* is a PRS signal length in time domain, $r[i]$ is a received signal, $s_{PRS}[i]$ is a PRS signal and $(\cdot)^{*}$ is a complex conjugation operation.

B. Proposed First - Path Estimator

Proposed First-Path Estimator searches for the first path in the receiving signal through analyzing the correlation between receiving PRS signal and signal pattern stored in the memory. Algorithm, using knowledge about parameters of the highest correlation peak and all correlation peaks that lies before the highest one, significantly reduces search window and chooses from the new window the first peak, assuming that it correspond to the first path of the received signal.

The problem of detecting the first path in the correlation function is to set the threshold above which it may be assumed that detected peaks corresponds to the paths of the useful signal. Setting too low threshold THR_{low} (Fig. 2) induces detection of peak *P1*, which does not represent path of the useful signal. On the other hand, setting too high

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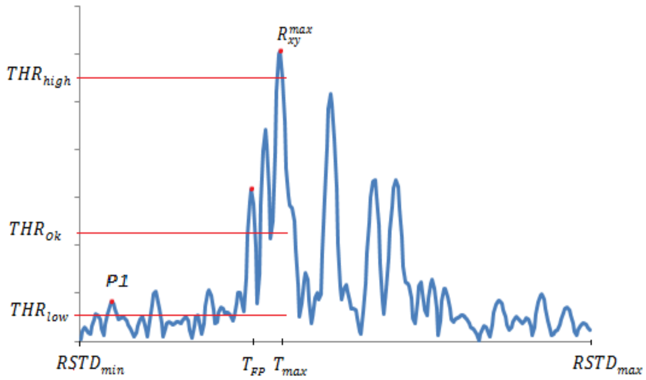

Figure 2. Correlation function of received PRS signal and PRS signal pattern stored in the receiver memory

threshold THR_{high} causes that peak detector misses the first path, in the worst case, becomes MLE estimator.

Therefore, it is necessary to find an appropriate value THR_{Ok}, which is done here through the estimation of the difference between maximum value of the correlation function and the mean value of all peaks that lies before this maximum value.

In order to find an estimate of the first path, algorithm firstly evaluate position $T_{\max}$ and value $R_{\max}$ of the highest peak in the correlation function $R_{xy}[m]$:

$$R_{xy}[m] = \sum_{i=0}^{P-1} r[i+m] \cdot s_{PRS}^{*}[i] \tag{8}$$

$$T_{\max} = \arg\max\left\{ \left| R_{xy}[m] \right|^2 \right\} \tag{9}$$

$$R_{\max} = \max\left\{ \left| R_{xy}[m] \right| \right\} \tag{10}$$

A position of the peak T_{FP} in function (8) that corresponds to the first path of received signal satisfies $T_{FP} \leq T_{\max}$, thus searching out the highest peak in the correlation function (8) allows to reduce the search window to $\langle RSTD_{\min}, T_{\max} \rangle$. Then, algorithm finds all the correlation peaks in a new interval, i.e., set R^p containing all pairs $\{m, R_{xy}[m]\}$ for which the conditions (11), (12) and (13) are satisfied.

$$R_{xy}[m-2] < R_{xy}[m-1] < R_{xy}[m] \tag{11}$$

$$R_{xy}[m] > R_{xy}[m+1] > R_{xy}[m+2] \tag{12}$$

$$m \leq T_{\max} \tag{13}$$

The mean value $\overline{R}_{xy}$ of all peaks within set R^p is given by

$$\overline{R}_{xy} = \frac{1}{\left| R^p \right|} \sum_{R_{xy}[m] \in R^p} R_{xy}[m] \tag{14}$$

where $\left| R^p \right|$ is a number of elements within set R^p.

The value of the threshold THR_{Ok} then is computed as

$$THR_{Ok} = \begin{cases} A \cdot R_{\max}, & if\ 0.8 \leq R_{xy}^{con} \leq 1 \\ B \cdot R_{\max}, & if\ 0.7 \leq R_{xy}^{con} < 0.8 \\ C \cdot R_{\max}, & if\ 0.5 \leq R_{xy}^{con} < 0.7 \\ D \cdot R_{\max}, & otherwise \end{cases} \tag{15}$$

where

$$R_{xy}^{con} = \left(R_{\max} - \overline{R}_{xy} \right) / R_{\max} \tag{16}$$

Position of the first peak in the correlation function (8) above THR_{Ok} is assumed as the first path position in the received signal. Algorithm changes THR_{Ok} threshold accordingly to the difference between the highest and the mean value of the remains peak components in the correlation function from $\langle RSTD_{\min}, T_{\max} \rangle$ adjusting threshold properly to the environmental conditions. When the difference $R_{\max} - \overline{R}_{xy}$ in (16) decreases, THR_{Ok} value has to be increased in order to avoid detection of the peak component that do not relate to the useful signal path. Values of the weights A = 0.33, B = 0.5, C = 0.9 and D = 1 in (15) were chosen empirically to minimize RSTD measurement error.

III. Simulation Model

In the implemented simulation model, UE performs RSTD measurements between subframes containing PRS signals transmitted from two base stations. In order to receive reference signals, UE firstly synchronizes with the reference cell using Primary Synchronization Signals (PSS) and then is informed about expected RSTD and expected RSTD uncertainty values, which determine position and size of the search window for PRS signals. In the prior RSTD value estimation process, the distance between $eNodeB_{ref}$ and UE is estimated through TA measurements. Due to an inaccuracy of timing advance measurements, measured distance $\underline{d_{TA}}$ is a random variable described by:

$$\underline{d_{TA}} = d + \underline{d_{TA}^{'}} \tag{17}$$

where d is the real distance between base station and UE and $\underline{d_{TA}^{'}}$ is a random variable generated from the normal distribution with mean value of 0m and standard deviation

48.83m corresponding to UE Rx-Tx time difference [10] measurements accuracy requirements given by 3GPP [5] and equals to $\pm 10 \cdot T_s$, where $T_s = 1/(15000 \cdot 2048)$ is the LTE basic timing unit [6]. Therefore, it can be written:

$$d_{ref} = d + \underline{d'_{TA}} \quad (18)$$

Distance $d_{ref-nei}$ between eNodeB$_{ref}$ and eNodeB$_{nei}$ is given in Table III, among other simulation parameters.

A. Base station model

For the purposes of the present simulations, physical layer of the implemented base station model consists of blocks creating PRS and PSS signals. Extract of transmitted signal resource grid is presented on Fig. 3. In the first subframe, PSS signal is transmitted in order obtain coarse synchronization between transmitter and receiver. In the second one PRS signals are placed.

B. Channel model

Channel model was realized as a Finite Impulse Response (FIR) filter, which scheme is shown on Fig. 4. Signal $s(t)$ from the base station antenna passes through the set of delay units and multipliers. Individual taps $\{\tau_i, a_i, b_i(t)\}$ represent consecutive paths of receiving signal, where τ_i is delay of *i-th* path, a_i is attenuation of *i-th* path and $b_i(t)$ is Rayleigh coefficient modeling motion of the receiver relative to the transmitter for *i-th* path. To the sum of signals from all taps complex Additive White Gaussian Noise (AWGN) is added forming signal $r(t)$ as an input of the receiver.

Values of the delays $\{\tau_o, \tau_1, \ldots, \tau_{L-1}\}$ are generated through random process defined as [12]:

$$\tau_i = -\gamma \cdot \log(1 - \underline{P_\tau}) \quad (19)$$

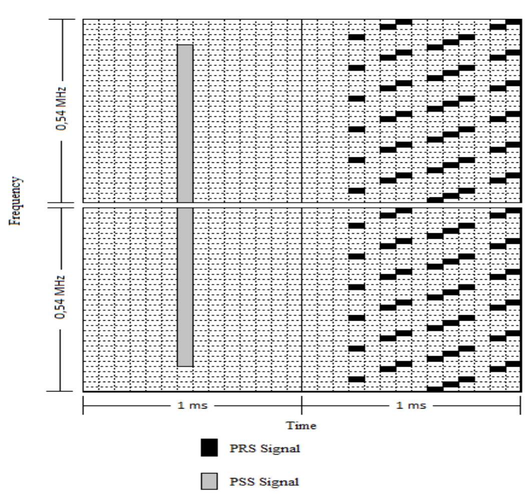

Figure 3. Extract of the resource grid of transmitted signal

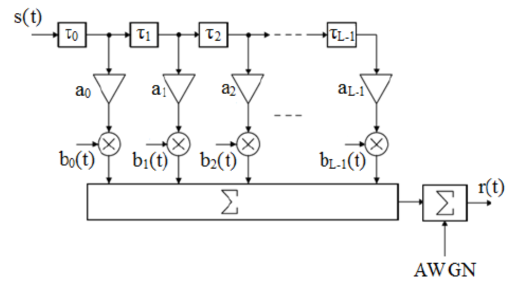

Figure 4. Channel model as a FIR filter

where $\underline{P_\tau}$ is a random variable uniformly distributed within $\langle 0,1 \rangle$ and $\gamma = 0.83$. Process (19) is normalized to the value of rms delay spread τ_{rms}, which limits values of random delays. The value of rms delay spread τ_{rms} is computed in accordance with [13][14]:

$$\tau_{rms} = T_1 d^{\varepsilon} y \quad (20)$$

where T_1 is a median value of τ_{rms} at $d = 1km$, ε is an exponent depended on environment, $\underline{Y} = 10\log(y)$ is a Gaussian random variable having zero mean and standard deviation σ_y. Values of parameters T_1, σ_y and ε can be found in Table II.

Overall attenuation of the channel g is a sum of attenuations of individual paths and is defined as [13]:

$$g = \frac{G_1}{d^{\alpha}} x = a_0 + a_1 + \ldots + a_{L-1} \quad (21)$$

where d is the distance between receiving and transmitting antenna, G_1 is the median value of g at distance $d = 1km$ determined by Hata model [15], α is an exponent which lies between 3 - 4 dB, $\underline{X} = 10\log(x)$ is a Gaussian random variable having zero mean and standard deviation σ_x of value 6 - 12 dB. Basing on (21) and function:

$$\begin{aligned} f(\tau_i) = & 8.5 \cdot 10^{-1} + 1.3 \cdot 10^{-3} \tau_i - 2.1 \cdot 10^{-6} \tau_i^2 \\ & + 10^{-9} \tau_i^3 - 2.1 \cdot 10^{-13} \tau_i^4 + 1.5 \cdot 10^{-17} \tau_i^5 \end{aligned} \quad (22)$$

which is polynomial interpolation of 3GPP Extended Typical Urban (ETU) delay profile model [16] for LTE system, values of individual paths attenuations $\{a_1, a_2, \ldots, a_{L-1}\}$ could be computed.

TABLE II. PARAMETERS VALUES OF FUNCTION (20)

T_1	0,4μs (urban microcells) 0,4–1.0μs (urban macrocells) 0,3μs (suburban areas) 0,1μs (rural areas)
σ_y	2 – 6 dB
ε	0,5 (urban, suburban, rural areas) 1,0 (mountainous areas)

Relationship (22) defines relative powers of individual, accordingly delayed paths of received signal. Plot of the function (22) is presented on Fig. 4. The dots on Fig. 4 are the interpolation nodes.

Rayleigh coefficients $\{b_0(t), b_1(t), \ldots, b_{L-1}(t)\}$ are generated with the use of sum-of-sinusoids method [17]:

$$b_i(t) = b_r(t) + jb_u(t) \tag{23}$$

$$b_r(t) = \sqrt{\frac{2}{N}} \sum_{n=1}^{N} \cos[\omega_d t \cos(\alpha_n) + \varphi_n] \tag{24}$$

$$b_u(t) = \sqrt{\frac{2}{N}} \sum_{n=1}^{N} \sin[\omega_d t \cos(\alpha_n) + \varphi_n] \tag{25}$$

$$\alpha_n = \frac{2\pi n + \Theta_n}{N} \tag{26}$$

where Θ_n and φ_n are independent random variables uniformly distributed within $<-\pi, \pi)$, N is a number of summations. For $N \geq 8$ model is highly convergent with desired channel characteristics [17].

C. User equipment model

Determining the position of PRS signals in time is preceded by cell synchronization process. It is assumed that UE and base stations are fully synchronized in frequency domain. The first action undertaken by the UE is to search for PSS signal in samples of the received signal. Finding of PSS signal allows to determine the position of time-frequency signal structure and ensure coarse synchronization. Cell synchronization is performed by maximum likelihood estimator which finds PSS position m_0 in time [18]:

$$m_0 = \arg\max\left\{\left|\sum_{i=0}^{M-1} r[i+m] \cdot s_{PSS}^*[i]\right|^2\right\} \tag{27}$$

where i is a time index, m refers to delays of correlation function, M is a PSS signal length in time domain, $r[i]$ is received signal, $s_{PSS}[i]$ is a PSS signal.

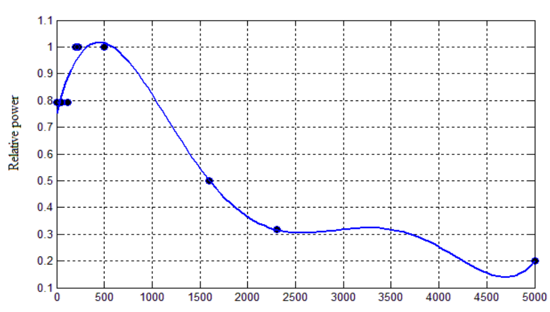

Figure 4. Plot of the function (22)

After successful cell synchronization process, receiver removes Cyclic Prefix (CP) from the received symbols minimizing Inter-Symbol Interferences (ISI) impact. Through consecutive Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) operations and appropriate signal processing, all unnecessary Orthogonal Frequency Division Multiplexing (OFDM) symbols are removed, keeping only PRS symbols. Received PRS symbols are correlated with the known pattern in the receiver and time position of PRS signal is determined on the basis of a given algorithm.

IV. SIMULATION RESULTS

Simulations were carried out in compliance with the conditions specified by 3GPP for RSTD measurements accuracy requirements [8]. The main parameters of the simulation is presented in Table III, where (PRS Es/Iot)$_{ref}$ and (PRS Es/Iot)$_{nei}$ are ratios of received energy per Resource Element (RE) during the useful part of the symbol to received power spectral density of the total noise and interference for a certain RE, respectively for PRS signals transmitted from reference and neighbour base station. During the simulations, mean RSTD measurement error and number of trials that satisfy requirements given by 3GPP was evaluated. Mean RSTD measurement error is given by

$$\overline{RSTD}^{err} = \frac{1}{N_{err}} \sum_i \left|RSTD_i^{err}\right| \tag{28}$$

where $RSTD_i^{err}$ is an RSTD measurement error on *i-th* trial and $N_{err} = 5000$ is the number of trials. Comparison of the results obtained with MLE and FPE algorithms is shown in Table IV. LOC$_{\%}$ is a percentage of trials number which falls into the requirements of RSTD measurements accuracy imposed by 3GPP [8]. For 5 and 10 MHz bandwidth and 1 ms duration of PRS signal the required accuracy is $\pm 5 \cdot T_s$ and $\pm 6 \cdot T_s$ respectively. The use of the FPE estimator significantly reduces mean RSTD error compared to the MLE estimator.

TABLE III. SIMULATION PARAMETERS

PRS bandwidth	5 MHz, 10 MHz
PRS duration	1 ms
(PRS Es/Iot)$_{ref}$	≥ -6 dB
(PRS Es/Iot)$_{nei}$	≥ -13 dB
$d_{ref\text{-}nei}$	3 km
Expected RSTD uncertainty	< 5 µs
Max. Doppler frequency shift	50 Hz
Receiver sampling frequency	50 MHz
Environment	Urban macrocells
α	3 dB
σ_x	8 dB
T_1	1.0µs
σ_y	4 dB
ε	0.5
N_{err}	5000

TABLE IV. SIMULATION RESULTS

	$\overline{RSTD}^{err}$ $[T_s]$		LOC% [%]	
	5 MHz	10 MHz	5 MHz	10 MHz
MLE	9.01	8.85	42	44.5
FPE	5.2	3.41	76.4	80.5

This improvement may be even higher at longer distances between base stations and mobile terminal due to larger rms time delay spread of receiving signals. It should be noticed that gain from using FPE estimator is obtained only when it is possible to separate more than one path of the received signal in the correlation function of received signal and pattern stored in the receiver. This could be done only if bandwidth of PRS signal is sufficiently large relating to the delays of consecutive signal paths arriving to the receiver. The larger the PRS signal bandwidth is, the narrower autocorrelation function of PRS signal becomes and the greater possibilities in extracting distinct received signal paths from correlation function. Further assessments showed that for 1.4 MHz bandwidth of PRS signals, it is not possible to distinguish any two paths of receiving PRS signals in the correlation function due to small mutual delay between consecutive signal paths. It means that for 1.4 MHz PRS bandwidth, use of FPE algorithm does not improve accuracy of RSTD measurements. Therefore, for such small bandwidth it is justified to use MLE algorithm due to its smaller processing consumption.

V. CONCLUSIONS

A new First-Path Estimator FPE was proposed for detecting the first path in receiving PRS signal. Simulations have shown that it significantly reduces RSTD measurement error in urban environment, comparing to the well-known Maximum Likelihood Estimator. Moreover, it ensures that about 80% of RSTD measurement falls into accuracy range defined by 3GPP for 5 and 10 MHz PRS bandwidth, becoming a reliable tool for positioning purposes.

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