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Improving Positioning in LTE through Collaboration

Reza Monir Vaghefi and R. Michael Buehrer
Wireless @ Virginia Tech, Virginia Tech, Blacksburg, VA 24061
E-mail: {vaghefi, buehrer}@vt.edu

***Abstract*—This paper represents a preliminary study of cooperative positioning in Long Term Evolution (LTE) systems. Many applications, such as location-based services and Enhanced 911 (E911), require that the locations of users in a cellular system are available. The global navigation satellite system (GNSS) is the most accessible positioning systems which are widely used in cellphones. However, poor operation in indoor and dense environments leads us to use cellular localization as a backup solution. In cellular localization, the locations of users are determined via measurements obtained within the network without aid of any external sources (e.g., GNSS). Observed time difference of arrival (OTDOA) is a positioning technique introduced in Release 9 of the 3GPP LTE specification. In OTDOA technique, the User Equipment (UE) measures the time difference of signals between several eNodeBs (base stations in LTE) and uses a trilateration algorithm to find its location. In the current 3GPP LTE specification, the UE can only collect measurements from eNodeBs. Therefore, in many situations, the UE is not able to communicate to a sufficient number of eNodeBs and cannot find its location without ambiguity. In this paper, we propose a cooperative localization technique for LTE systems in which the UE communicates not only with eNodeBs but also with other UEs. It will be shown that cooperative localization can significantly improve the localizability in the network, meaning that more UEs can be localized. Cooperative localization also enhances the accuracy which is highly beneficial for some applications, especially E911. A series of computer simulations are conducted to show the benefits of cooperative localization where the 3GPP simulation parameters are assumed.**

***Index Terms*—Cooperative localization, observed time difference of arrival (OTDOA), long term evolution (LTE).**

I. INTRODUCTION

Determining the location of the User Equipment (UE) in a Long Term Evolution (LTE) network provides a wide range of applications such as location-based services, children and elderly tracking, and law enforcement aids. Moreover, the U.S. Federal Communications Commission (FCC) mandates cellular carriers to provide the locations of E911 users [1].

Modern mobile devices may be capable of network-independent, standalone positioning through the use of internal global navigation satellite system (GNSS) receivers. GNSS refers to any satellite-based positioning systems with global coverage such as the US NAVSTAR Global Positioning System (GPS) and the Russian Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS). In order to estimate a unique location, a GNSS receiver must initially perform a search of satellites in order to acquire at least four satellite signals. In dense environments without clear sky visibility (such as indoor or forest areas), GNSS positioning may not be available and any localization techniques based on GNSS would not be reliable. Therefore, the 3rd Generation Partnership Project (3GPP) includes several cellular-based localization techniques for LTE networks [2].

The aim of cellular localization is to determine the locations of UEs via noisy measurements obtained within the network without aid of any external sources. In cellular localization, there are typically a small number of eNodeBs (whose locations are fixed and known) and many UE whose locations are unknown and to be determined. The measurements typically collected for network localization are either range-based, such as time-of-arrival (TOA), time-difference-of-arrival (TDOA), and received-signal-strength (RSS), or angle-based, such as angle-of-arrival (AOA). Currently LTE supports three positioning techniques (E-CID, A-GNSS, and OTDOA) with a fourth (UTDOA) scheduled for inclusion in Release 11.

The cell ID (CID) positioning method allows for fast, low-complexity network-based positioning of a UE. Essentially, the UE location is simply estimated using the location of the eNodeBs with which it is associated. Unfortunately, this method can result in a very poor position estimate, worse than FCC E911 requirements, as the UE serving cell can span multiple kilometers. In order to improve CID positioning, the LTE specification supports enhanced cell ID (E-CID) positioning. In E-CID, the UE location is estimated using its CID as well as additional network attributes, such as round-trip time (RTT) and AOA measurements. Timing advance (TA) measurements provide an estimate of the RTT which, in turn, provides an estimate of the UE distance from its serving eNodeB, while the carrier phase shifts at multiple eNodeB antenna elements allow for the estimation of the UE signals AOA. Together, these measurements enable the network to quickly, yet still coarsely, localize the UE. Due to multipath reflections and uncertainties in the TA measurements, E-CID positioning errors of greater than 150 m are typical. For this reason, E-CID estimates are most often used as the initial inputs to more accurate positioning methods or as fallbacks when these other positioning methods are unavailable.

In order to assist the UE in the acquisition of available satellite signals, the LTE specification supports Assisted GNSS (A-GNSS) positioning. In A-GNSS, the cellular network provides the UE with assistance data which may be used to reduce the time required for satellite signal acquisition as well as improve positioning accuracy.

3GPP are supporting two stand-alone TDOA positioning methods (downlink and uplink) in the LTE specification. The downlink TDOA positioning method in LTE, known as observed time-difference-of-arrival (OTDOA), measures the differences in arrival times of downlink signals from multiple

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eNodeBs at the UE in order to calculate the UE location using hyperbolic trilateration. In this technique, either the eNodeBs should be synchronized or transmit times relative to the reference eNodeB must be known. Typically, reference signals such as the cell-specific reference signal (CRS) and positioning reference signal (PRS) are used for TDOA measurements. The uplink TDOA positioning method in LTE, known as uplink time-difference-of-arrival (UTDOA), is conceptually identical to OTDOA with the difference that the timing measurements are made from signals originating from the UE and received at neighboring eNodeBs [3].

Localization approaches (particularly in the research literature) can be divided into two categories: noncooperative and cooperative [4]–[6]. In noncooperative localization, the UE only communicates with eNodeBs. Current cellular communication networks employ only noncooperative positioning methods. As a result, a high density of eNodeBs and longer communication ranges are required to ensure that each UE is connected to a sufficient number of eNodeBs to enable positioning. It is the limited number of accessible eNodeBs and short communication ranges which have led to the emergence of cooperative localization. In collaborative localization, the UEs communicate not only with eNodeBs, but also with each other. Cooperation among UEs provides additional measurements which alleviate the need for dense eNodeB deployments and longer communication ranges.

Cooperative localization algorithms can be divided into two groups: centralized and distributed [4], [7]. In centralized localization, all measurements are collected at a central processor where they are analyzed and the locations of all the UEs in the network are simultaneously estimated. The estimated locations are then reported back to the requesting entities. Centralized algorithms are less practical in large networks, since their complexity intensifies as the number of UEs increases. On the other hand, in distributed localization, the location of each UE is estimated within the device and then reported to the network (if needed). Distributed algorithms are more popular for very large networks. However, centralized algorithms typically provide more accurate estimation than distributed algorithms.

In this paper, cooperative localization in LTE system is studied. eNodeBs are assumed to be synchronized and OTDOA measurements are obtained by UEs. UEs are also able to communicate with each other and collect measurements. Note that the Device-to-Device (D2D) communication is being discussed in 3GPP which allow UEs to transmit data signals to each other over a direct link using the cellular resources instead of through an eNodeB. Since UEs are not synchronized, round-trip time (RTT) measurement is considered for UE-UE connections. The measurement model for cooperative localization is introduced and the corresponding maximum-likelihood (ML) estimator is derived in the next sections. The benefits of cooperative localization in terms of localizability and accuracy will be shown through computer simulations where the 3GPP simulation assumptions are considered.

II. SYSTEM MODEL

The following notation is used throughout the paper. Lowercase and uppercase letters denote scalar values. Bold lowercase and bold uppercase letters denote vectors and matrices, respectively. $\|\cdot\|_2$ denotes the ℓ_2-norm. $\mathrm{diag}\{\mathbf{a}\}$ represents a square diagonal matrix which contains the elements of $\mathbf{a}$ on the main diagonal and zeros elsewhere. $[\mathbf{A};\mathbf{B}]$ means that matrices $\mathbf{A}$ and $\mathbf{B}$ are concatenated vertically.

Consider a LTE network with M eNodeBs and N UEs. Denote by $\mathcal{A}=\{N+1,\ldots,N+M\}$ the set of indices of the eNodeBs and by $\mathcal{B}=\{1,\ldots,N\}$ the set of indices of the UEs. Let $\mathbf{y}_i=[x_i,y_i]^T\in\mathbb{R}^2$, $i\in\mathcal{A}$ be the known coordinates of the ith eNodeB and $\mathbf{x}_k=[x_k,y_k]^T\in\mathbb{R}^2$, $k\in\mathcal{B}$ be the unknown coordinates of the kth UE. In cooperative cellular localization, two sets of the measurements are available to each UE: UE-eNodeB and UE-UE measurements. Let us define two sets for the kth UE as follows:

$$\begin{aligned}\mathcal{A}_k &= \{\ i\in\mathcal{A}\mid \text{eNodeB } i \text{ is connected to UE } k\ \}\\ \mathcal{B}_k &= \{\ i\in\mathcal{B}\mid \text{UE } i \text{ is connected to UE } k\ \}\end{aligned}\tag{1}$$

where the former and latter define UE-eNodeB and UE-UE connections, respectively. The UE measures the time difference between multiple eNodeBs and a reference eNodeB which is known as OTDOA. The serving eNodeB (the closest eNodeB to the UE) is typically used as a reference eNodeB. Note that in this technique, eNodeBs are assumed to be synchronized [1]. The time-difference measurements are then can be used to obtain the range-difference measurements

$$r_{ki}^{\mathcal{A}}=h_{ki}^{\mathcal{A}}+n_{ki}^{\mathcal{A}},\quad i\in\mathcal{A}_k\tag{2}$$

where $h_{ki}^{\mathcal{A}}=\|\mathbf{x}_k-\mathbf{y}_i\|-\|\mathbf{x}_k-\mathbf{y}_l\|$ and l is the index of the reference eNodeB. Each UE might have a different reference eNodeB which is usually selected as the closet eNodeB connected to the UE. $n_{ki}^{\mathcal{A}}$ represents the measurement errors which is typically modeled as Gaussian random variables with variance $\sigma^2_{\mathcal{A},ki}$. UEs in a LTE network are not synchronized and hence OTDOA measurements cannot be collected for UE-UE connections. For asynchronous networks, round-trip time (RTT) measurements can be used. In the RTT method, the first UE transmit a signal to the second UE which immediately sends it back to the first UE. Therefore, the first UE can determine its distance to the second UE by measuring elapse time between its transmission and reception, and dividing it by two. The RTT measurements are modeled as

$$r_{ki}^{\mathcal{B}}=h_{ki}^{\mathcal{B}}+n_{ki}^{\mathcal{B}},\quad i\in\mathcal{B}_k\tag{3}$$

where $h_{ki}^{\mathcal{B}}=2\|\mathbf{x}_k-\mathbf{x}_i\|$ and $n_{ki}^{\mathcal{B}}$ represents the measurement errors modeled as Gaussian random variables with variance $\sigma^2_{\mathcal{B},ki}$. The variance of TDOA and RT-TOA measurements depends on several parameters such as SINR, bandwidth, carrier and carrier frequency [8], [9]. In our simulations, the variances are determined from 3GPP contributions where the performance of TOA estimation is evaluated by simulating the LTE OFDM waveform [10]. The variance of TOA estimation varies from 0.02 to 0.12 µs depending on SINR [10].

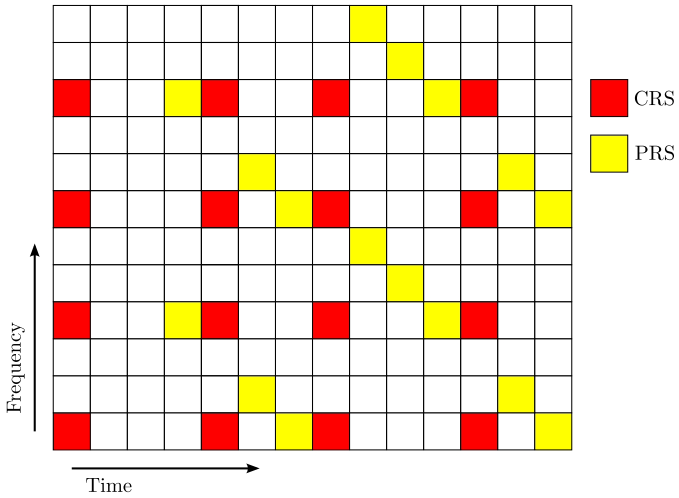


Fig. 1. The patterns of CRS and PRS in the OFDM subframe. Normal subframe with normal cyclic prefix.

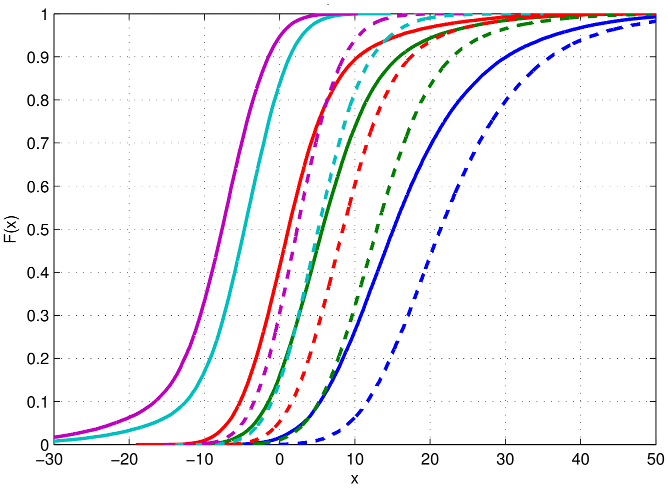


Fig. 2. SINR of the CRS (solid lines) and PRS (dashed lines) for the 5 best cells. The inter-site distance is 500 m.

III. Reference Signals

Typically, reference signals in OFDM frames are used to measure TOA, since they typically have lower levels of interference and are known in advance. Reference signals exist only at the physical layer and do not deliver any information. The main purpose of these reference signals is to provide a reference point for the downlink transmissions. The cell-specific reference signal (CRS) is used by UE to determine the phase reference for demodulating the downlink control channels and data [1]. The CRS is considered for OTDOA measurements, since its subframe does not carry any data and all power can be distributed over its resource block. LTE Release 8 enables eNodeBs to have CRS patterns with a reuse factor of 3 for 2 antenna ports [11]. Fig. 1 shows the CRS pattern with 2 antenna ports. Fig. 2 shows the cumulative distribution function (CDF) of SINR of CRS for the 5 best cells represented by solid lines.

Positioning reference signal (PRS) is included in LTE Release 9 to provide more power and less inter-site interference for positioning purposes by using a reuse factor of 6 [11]. The PRS pattern with 2 antenna ports is depicted in Fig. 1. The dashed lines in Fig. 2 represent the CDF of SINR of PRS for the 5 best cells. Comparing with CRS with a reuse factor of 3, PRS has less interference which increases the SINR and hearability in the network.

IV. Maximum Likelihood Estimator

In this section, a ML estimator for the cooperative localization models in (2) and (3) is derived. 3GPP considers a server in the network known as Evolved Serving Mobile Location Centre (E-SMLC) which provides services for positioning related tasks in LTE. In the OTDOA technique, all data and measurements are sent to E-SMLC for localization. Since complexity is not an issue in E-SMLC, a centralized algorithm is proposed here.

Because of several attractive properties, the ML estimator is a popular estimator. The main property of the ML estimator is that it can achieve the Cramér-Rao lower bound (CRLB) asymptotically [12, Ch. 7]. The CRLB expresses a lower bound on the variance of any unbiased estimator [12, Ch. 3]. Therefore, as the number of measurements tends to infinity (asymptotic behavior), no unbiased estimator has lower mean squared error than the ML estimator [13]. Let $\boldsymbol{\xi} = [\mathbf{x}_1^{\mathrm{T}}, \ldots, \mathbf{x}_N^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^{2N}$ be the vector of unknown parameters. Since the distribution of both measurement models in (2) and (3) is Gaussian, the ML estimator is simply obtained by the following minimization problem [12, Ch. 7]

$$\begin{aligned}\hat{\boldsymbol{\xi}} = \arg\min_{\boldsymbol{\xi}\in\mathbb{R}^{2N}} \; & \sum_{k\in\mathcal{B}} (\mathbf{r}_k^{\mathcal{A}} - \mathbf{h}_k^{\mathcal{A}})^{\mathrm{T}} \mathbf{Q}_{\mathcal{A},k}^{-1} (\mathbf{r}_k^{\mathcal{A}} - \mathbf{h}_k^{\mathcal{A}}) \\ & + (\mathbf{r}_k^{\mathcal{B}} - \mathbf{h}_k^{\mathcal{B}})^{\mathrm{T}} \mathbf{Q}_{\mathcal{B},k}^{-1} (\mathbf{r}_k^{\mathcal{B}} - \mathbf{h}_k^{\mathcal{B}}) \qquad (4)\end{aligned}$$

where $\mathbf{r}_k$ are the measurement vectors:

$$\begin{aligned}\mathbf{r}_k^{\mathcal{A}} &= [\ldots, r_{ki}^{\mathcal{A}}, \ldots]^{\mathrm{T}}, \quad i \in \mathcal{A}_k \\ \mathbf{r}_k^{\mathcal{B}} &= [\ldots, r_{ki}^{\mathcal{B}}, \ldots]^{\mathrm{T}}, \quad i \in \mathcal{B}_k\end{aligned}$$

and $\mathbf{h}_k$ are the model vectors:

$$\begin{aligned}\mathbf{h}_k^{\mathcal{A}} &= [\ldots, h_{ki}^{\mathcal{A}}, \ldots]^{\mathrm{T}}, \quad i \in \mathcal{A}_k \\ \mathbf{h}_k^{\mathcal{B}} &= [\ldots, h_{ki}^{\mathcal{B}}, \ldots]^{\mathrm{T}}, \quad i \in \mathcal{B}_k.\end{aligned}$$

$\mathbf{Q}_k$ are the covariance matrices of the measurements

$$\begin{aligned}\mathbf{Q}_{\mathcal{A},k} &= \mathrm{diag}\{\ldots, \sigma_{\mathcal{A},ki}^2, \ldots\}, \quad i \in \mathcal{A}_k \\ \mathbf{Q}_{\mathcal{B},k} &= \mathrm{diag}\{\ldots, \sigma_{\mathcal{B},ki}^2, \ldots\}, \quad i \in \mathcal{B}_k.\end{aligned}$$

The problem in (4) is nonlinear and its closed-form solution is not available. However, it can be approximately solved by iterative numerical techniques such as the Gauss-Newton (GN) algorithm [12], [14]. In the GN algorithm, the nonlinear cost function is linearized by using a first order Taylor series around the global minimum of the cost function. Since the global minimum is unknown, starting with an initial point, the

TABLE I
SUMMARY OF SIMULATION PARAMETERS.

Parameter	Assumption
Cell	Hexagonal grid, 19 cell site
Inter-Site distance	500 m
Pathloss model	$L = 128.1 + 37.6 \log_{10} R$
Penetration loss	20 dB (Case 1 & 3)
Shadowing std	8 dB
Shadowing correlation	0.5 (Between sites), 1 (Between sectors)
Antenna gain	15 dBi (3 sectors per site)
Antenna pattern	$A(\theta) = -\min[12(\theta/65^{o})^2, 20]$ dB
eNodeB power	46 dBm
UE power	21 dBm
UE noise figure	9 dB

algorithm iteratively tries to find the minimum [12, Ch. 8]. The minimization problem in (4) can be approximately solved with the following GN algorithm

$$\hat{\boldsymbol{\xi}}_{j+1} = \hat{\boldsymbol{\xi}}_j + \left(\mathbf{H}^{\mathrm{T}}(\hat{\boldsymbol{\xi}}_j)\mathbf{Q}^{-1}\mathbf{H}(\hat{\boldsymbol{\xi}}_j)\right)^{-1}\mathbf{H}^{\mathrm{T}}(\hat{\boldsymbol{\xi}}_j)\,\mathbf{Q}^{-1}(\mathbf{r}-\mathbf{h}(\hat{\boldsymbol{\xi}}_j))$$

where $\boldsymbol{\xi}$ is the vector of UEs locations and

$$\begin{aligned} \mathbf{r} &= [\mathbf{r}_1^{\mathcal{A}};\ldots;\mathbf{r}_N^{\mathcal{A}};\mathbf{r}_1^{\mathcal{B}};\ldots;\mathbf{r}_N^{\mathcal{B}}] \\ \mathbf{h} &= [\mathbf{h}_1^{\mathcal{A}};\ldots;\mathbf{h}_N^{\mathcal{A}};\mathbf{h}_1^{\mathcal{B}};\ldots;\mathbf{h}_N^{\mathcal{B}}] \\ \mathbf{Q} &= \mathrm{blkdiag}\{\mathbf{Q}_{\mathcal{A},1},\ldots,\mathbf{Q}_{\mathcal{A},N},\mathbf{Q}_{\mathcal{B},1},\ldots,\mathbf{Q}_{\mathcal{B},N}\}. \end{aligned}$$

$\hat{\boldsymbol{\xi}}_j$ is the estimate of UEs locations at the jth iteration which is obtained by updating the previous iteration. $\mathbf{H}$ is a Jacobian matrix obtained by taking derivative of the model vector, $\mathbf{h}$ with respect to unknown parameter [12], [15]:

$$\mathbf{H}(\hat{\boldsymbol{\xi}}_j) = \frac{\partial \mathbf{h}(\boldsymbol{\xi})}{\partial \boldsymbol{\xi}}\Big|_{\boldsymbol{\xi}=\hat{\boldsymbol{\xi}}_j}.$$

Iterations will stop if the change in the estimate is sufficiently small or the Jacobian matrix goes to zero. The Jacobian matrix goes to zero when the estimate reaches to a local minimum where the derivatives are zero.

V. SIMULATION RESULTS

This section discusses a series of computer simulations used to evaluate the performance of the proposed cooperative localization in LTE networks. Simulation parameters are selected based on the 3GPP assumptions in contributions [10], [16]. Table I summarizes the parameters used in our simulations.

Fig. 3 shows the configuration of the simulated LTE network. There are 19 eNodeBs depicted with solid triangles. Each eNodeB has a 3-sector antenna with the pattern defined in Table I. The UEs are randomly placed in the network. Once the UEs are placed, we need to determine the SINR for each link based on the used reference signal (CRS or PRS). For each UE, the SINR from eNodeBs and other UEs are calculated. If the SINR at the UE terminal is higher than a specific threshold, the corresponding link is assumed to be present.

Fig. 4 shows the received SINR from the eNodeB located at the center for CRS and PRS. When CRS is used, the SINR decreases significantly, as the UE goes away from the serving eNodeB due to interference from other eNodeBs operating in

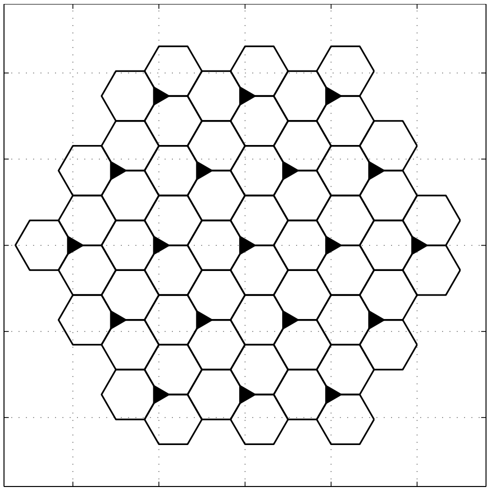
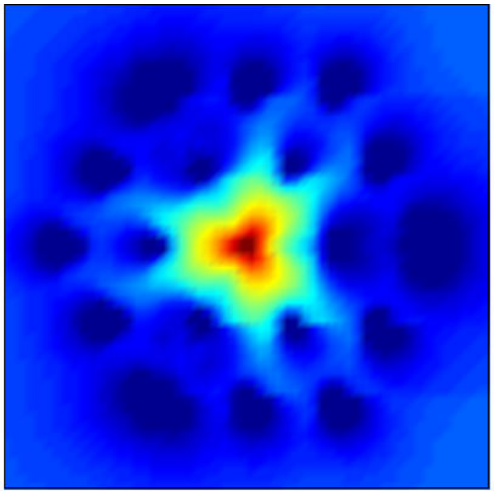
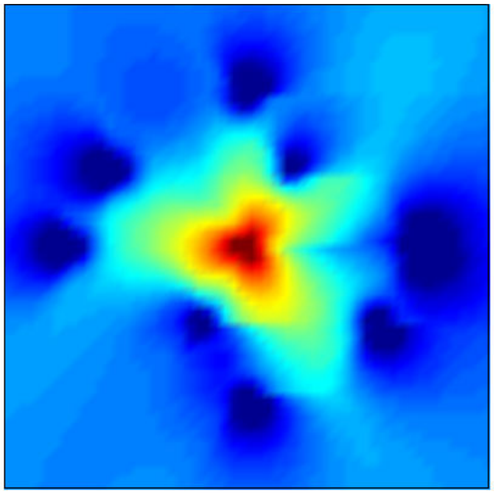


Fig. 3. Configuration of the simulated LTE network. The locations of eNodeBs are represented by solid triangles. The UEs are randomly placed in the network. The inter-site distance is 500 m.



(a) CRS



(b) PRS

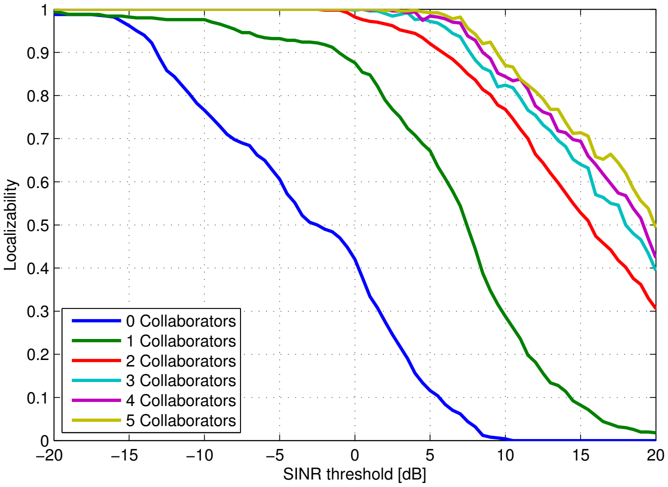
Fig. 4. The SINR of the eNodeB placed at the center for CRS (reuse of 3) and PRS (reuse of 6). Significantly higher SINR can be achieved by using PRS.

the same pattern. The UE receives significantly higher SINR by using PRS, as fewer eNodeBs operating in the same pattern and interfere with the serving eNodeB.

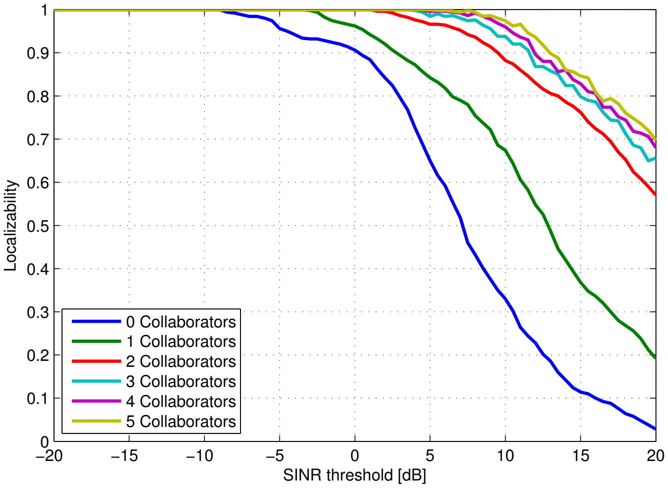
A. *Localizability*

One of the most important advantages of collaborative localization is *localizability*. Localizability refers to the ability of a UE to be uniquely localized without ambiguity (the conditions of which depend primarily on the connectivity of the UE). It is also referred to as *availability* in the literature as it characterizes the availability of a position fix. Cellular networks are designed for communications, not localization. As a result, the network design tends to limit the number of eNodeBs that a UE can hear (or the number of eNodeBs that can hear a UE). This can result in a relatively small number of eNodeBs participating in localization. Collaborative positioning uses the connections between mobiles in order to improve localization performance, thus circumventing the impact of a limited number of base stations. In non-cooperative networks, a UE is localizable when it is connected to at least three non-collinear eNodeBs (for 2-D localization). However in collaborative networks, defining localizability for each UE is more difficult. In fact, in order to determine whether or not a UE is localizable in a cooperative network, it is necessary to analyze the network as a whole. In other words, examining the connectivity of a UE individually cannot determine their localizability in collaborative networks. As a concise definition, a UE is localizable in a cooperative network if it has at least three disjoint paths to three non-collinear eNodeBs [17].

Fig. 5 shows the localizability performance as a function of the SINR threshold and the number of collaborators. The blue curve shows the performance of a network with no collaborator which coincides with the performance of a noncooperative network. The SINR detector threshold in the LTE network for CRS and PRS typically varies between -6 to -14 dB. At -6 dB threshold which is widely used in 3GPP contributions, the UE can be localized about 65% of the time, if the CRS is used. This is the main reason that special positioning subframes are designated in LTE Release 9. If PRS is used to obtain OTDOA measurements, 97% of the time the UE can be localized. On the other hand, if the UE has a single collaborator, the localizability increases significantly in positioning with CRS. At -6 dB threshold, by having only one collaborator, the UE can be localized about 95% of the time which is 30% improvement in comparison with the noncooperative case. The reason is that in most of the time the UE has only two connections to eNodeBs and a collaborator (another UE) can provide enough connections to make the UE localizable. If the UE has more than 3 collaborators, it can be localized all the time using CRS. As the number of collaborators increases, the relative improvement decreases. A large gain can be achieved in terms of localizability, if the UE is collaborating with 1 or 2 other UEs. Cooperation provides less noticeable improvement if PRS is used. However, if the threshold is set to larger SINR levels, cooperation will be more useful. In some applications where very high localization accuracy is required, the SINR threshold can be set to larger levels to achieve more reliable and accurate measurements, as connections with lower SINR levels are less accurate.



(a) CRS

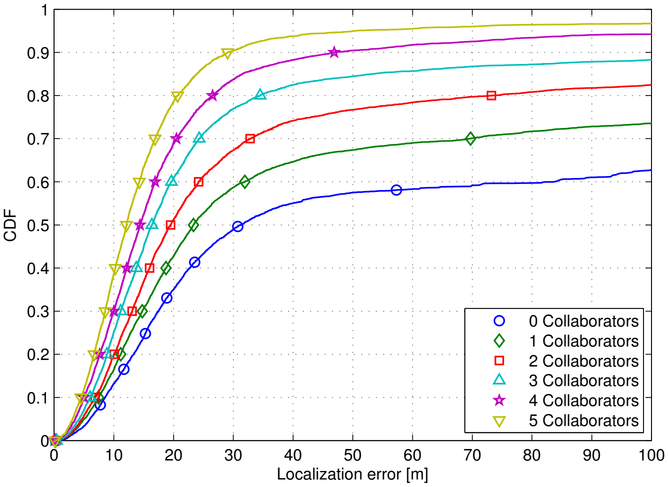


(b) PRS

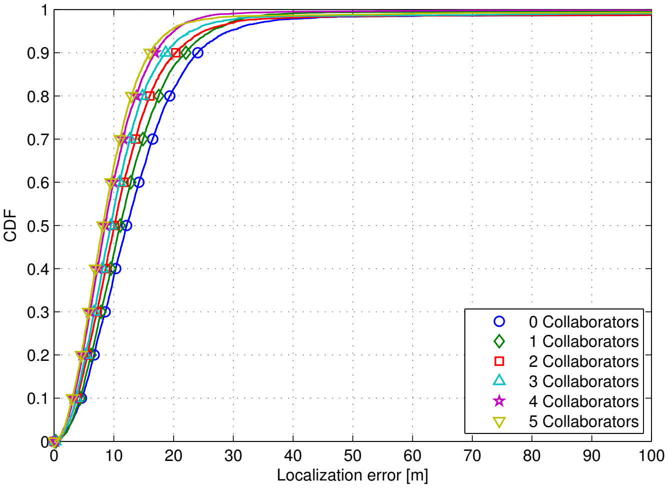
Fig. 5. Localizability versus the SINR threshold and number of collaborators for CRS (reuse of 3) and PRS (reuse of 6).

B. *Localization Accuracy*

Another important benefit of cooperative localization is to improve positioning accuracy. Fig. 6 shows the cumulative distribution function (CDF) of the localization error versus the number of collaborators. Again, zero collaborator represents the noncooperative case. The SINR threshold is fixed at -6 dB. The performance of noncooperative localization is inferior to cooperative localization. There are three main reasons behind the poor performance of the noncooperative localization. First, the UE might not be connected to three eNodeBs. Second, the UE may have at least three connections to eNodeBs but they might have bad geometry. Third, the measurements noise might be very large. In this study, cooperative localization is easily able to overcome these problems. As can be seen by increasing the number of collaborators, the localization



(a) CRS



(b) PRS

Fig. 6. The CDF of localization error versus the number of collaborators. The SINR threshold is set to -6 dB.

accuracy improves significantly when using either CRS or PRS measurements. The main reason for this is that in cooperative networks the UEs have more connections available when collaborating than when only communicating with eNodeBs. Generally speaking, the more connections a UE has, the better the accuracy of its location estimate will be. A large improvement is achieved by having one, two, or three collaborators and the improvement rate decreases beyond 3 collaborators.

VI. CONCLUSION

In this paper, cooperative positioning in LTE systems was studied. Current cellular systems employ only noncooperative positioning methods. A cooperative localization technique was proposed for LTE systems. In the proposed technique, OTDOA measurement method is used for UE-eNodeB connections, while RTT measurement method is used for UE-UE connections. Computer simulations were conducted to show the benefits of the cooperative localization over the traditional noncooperative localization. Results showed that the cooperation among UEs can significantly improve the localizability and positioning accuracy in a LTE network. It was demonstrated that the localizability can be improved by almost 30% by having a single collaborator. Cooperation also improves the positioning accuracy in comparison with noncooperative localization. The improvement is significant where noncooperative localization produces large estimation errors, e.g., when the UE is connected to eNodeBs with bad geometry or the measurement noise is very large.

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