Hybrid TOA/AOA Cooperative Localization in Non-line-of-sight Environments

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***Abstract*—The majority of the location estimation error in wireless communication systems comes from the effect of non-line-of-sight (NLOS) propagation. NLOS identification and correction are the main techniques of mitigating the NLOS impact on positioning accuracy. In this paper, we propose a cooperative localization algorithm that combines the hybrid time of arrival (TOA) / angle of arrival (AOA) measurements of all identified line-of-sight (LOS) base station (BS) - mobile station (MS) links with the TOA measurements of MS-MS links. Different cost functions are described according to the NLOS detection results based on existing identification methods. We also present a NLOS correction model which can be carried out when the destination MS to be located is completely in NLOS propagation, whereas some BS - cooperative MS links are in LOS conditions. Simulation results demonstrate that the proposed algorithm outperforms other existing hybrid localization techniques, and its accuracy increases with the number of LOS BS-MS links, as well as the NLOS detection accuracy.**

I. Introduction

In recent years, there have been growing interests in the wireless location techniques, driven not only by emergency services but also by potential applications, for instance, location-based services and location-based system performance optimization. The dominant radio location techniques based on received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), or a combination of two of the above (e.g. [1],[2]), can achieve high accuracy under the line-of-sight (LOS) propagation. However, the LOS probabilities decrease with longer distance between the base station (BS) and the mobile station (MS) [3]. None-line-of-sight (NLOS) propagation introduces a bias in the TOA, TDOA, and AOA measurements and also results in an extra power loss. The performance of location techniques mentioned previously degrade evidently in NLOS scenarios. Therefore, it is significant to find methods to mitigate the NLOS bias.

Two classes of methods exist in the literature for solving the NLOS problem, namely the identification and correction. Güvenc and Chong [4] present a good survey on the two kinds of existing methods. The former class is to identify the NLOS conditions first and then to eliminate the NLOS corrupted measurements. The work in [4] analyzes a residual test algorithm in detail, and the method in [5] is based on the distribution of channel parameters which exploits the Rician factor estimation, while Xu and Zekavat [6] exploit space-frequency correlation features of MIMO-OFDM systems to identify NLOS conditions. Yu et al. [7] investigate NLOS propagation by employing the statistical decision theory and derive a joint TOA- and RSS- based identification method. The second class of NLOS solutions include the filtering based methods [8], the constrained optimization techniques [9], and the power delay doppler profile fingerprinting based methods [10].

Hearability is another issue that affects the accuracy of the deployed location scheme. Hybrid techniques that utilize combinations of available TOA, TDOA, RSS and AOA measurements to solve the location can be useful in hearability-challenged conditions especially when the number of available BS is limited. In [11]–[14], hybrid TOA/AOA positioning (HTAP) is proposed that using the combination of TOA and AOA measurements to locate the MSs. The results in [11] show that the location error obtained by HTAP increases when distance between BS and MS is getting large, and it is mostly feasible in micro-cellular environments where the effect of the angular error would be reduced. Venkatraman et al. in [12] utilize non-linear constrained optimization to achieve the hybrid positioning accuracy gains, while the authors in [13][14] exploit the scatterer information to improve the estimation of the MS's coordinates.

Recently, many researchers are considering cooperative localization approach [15][16]. Since the destination MS (DM) to be located can obtain information from both BSs and other cooperative MSs (CMs) within communication range, cooperative localization can offer increased accuracy and coverage [15]. Frattasi et al. [16] present a RSS-aided hybrid TOA/AOA algorithm (RHTA) that combines and weights the long- and short-range location information in a non-linear least square minimization procedure. However, it is difficult to get the optimal weighting factor to mitigate the NLOS error in practice.

In this paper, we propose another cooperative hybrid localization method that utilizes all of the TOA/AOA measurements of the identified LOS BS-MS links, combining with the TOA measurements of the MS-MS links, to estimate the location of the DM. In the case that there are none LOS propagation between DM and all BSs whereas there exists LOS DM-CM links, a correction method is illustrated to modify the

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initial location estimation of the DM. However, it should be noted that the techniques of NLOS identification is beyond the scope of this paper, one can site this work in [4]–[7].The remainder of this paper is organized as follows. Section II presents the model of TOA and AOA measurements error. Section III describes the proposed method, and the NLOS correction scheme is also demonstrated. Section IV discusses the simulation results to show the advantages of the proposed strategies. Finally, the concluding remarks and future work are provided in Section V.

II. NLOS ERROR MODELS

Assuming that the network is fully connected that both the TOA and AOA measurements are available for all of BS-MS links, and the mobile stations can work together to perform TOA measurements.

A. Major Sources of TOA Error

The TOA measurement error comes from two major sources: one is additive noise which is caused by measuring equipment such as synchronization error and timing errors, the other is multipath signals and NLOS propagation. Then the TOA measurement model can be considered as:

$$t = t_{los} + t_{noise} + t_{nlos} \tag{1}$$

where t is the time of flight of BS-MS link or MS-MS link, t_{los} is the time of arrive when the link is under line of sight propagation condition. t_{noise} is an additive Gaussian random variable with zero mean and variance $\sigma^2_{t_{noise}}$, and t_{nlos} is the measurement error caused by the NLOS propagation, which is considered to satisfy the exponential delay profile, and its probability density function can be expressed as:

$$p(t_{nlos}) = \tau_{rms} \exp(-\frac{t_{nlos}}{\tau_{rms}}) \tag{2}$$

where τ_{rms} is *rms* delay spread defined as [17]:

$$\tau_{rms} = T_1 d^{\varepsilon} y \tag{3}$$

where T_1 is the median value of *rms* delay spread at one kilometer, d is the distance between MS and BS, ε is an exponent with value between 0.5 and 1, y is a lognormal variable with zero mean and standard deviation σ_y that lies between 4-6 dB.

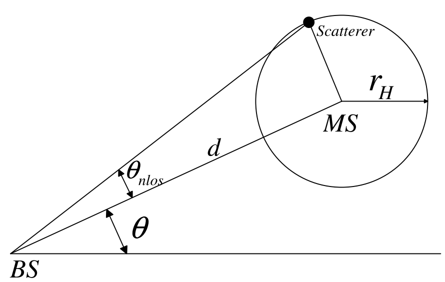

Fig. 1. Ring of scatterers model

B. Major Sources of AOA Error

Since the signal faces reflections/diffractions/scattering from different physical scatterers at different locations in a cellular environment, the AOA measurements also suffers from measuring device/technique and NLOS propagation. The former error could be reduced with the development of angle estimation algorithm, and it is modeled to be gaussian random variable $N(0, \sigma^2_{a_{noise}})$. However, the latter error depends on the propagation environment and the model is given in Figure 1. In this model, the scatterers are uniformly distributed on a ring which is centered around the MS with a radius r_H. The radius r_H is a random variable equal to $c\tau$, c is the velocity of light and τ is the excess delay determined by equation 2. Then the probability density function of NLOS AOA error θ_{nlos} is [18]:

$$\begin{gathered} f(\theta_{nlos}) = \frac{2d\cos(\theta_{nlos})}{\pi r_H^2} \\ \theta_{nlos} \in [-\arcsin(\frac{r_H}{d}), \arcsin(\frac{r_H}{d})] \end{gathered} \tag{4}$$

where d denotes the true distance between BS and MS.

III. PROPOSED ALGORITHM

The future-generation network would be hybrid broadband networks that integrate different network topologies and platforms including cellular network, WLAN, and PAN as well as mobile ad hoc networks. We consider a cellular ad hoc heterogeneous wireless network topology with several available serving BSs and a cluster consisting of DM and its neighboring CMs. It is assumed that the prior information on NLOS propagation of each BS-MS link is available so that the cooperative hybrid localization algorithm can localize the DM with only LOS measurements to achieve an improved accuracy. This type of information can usually come from some identification methods [4]–[7] which can be performed before carrying out the position estimation. In the following section, we presents a NLOS correction model to modify the initial location estimation of DM which is completely in NLOS propagation whereas some CMs' initial location can be obtained with LOS measurements.

A. NLOS Correction Model

As shown in [11], HTAP algorithm performs worse when the distance between BS and MS increase, even a little AOA error would introduce a large location error. Thus a NLOS correction model, as illustrated in Figure 2, may be applied to modify the initial location estimation of the DM.

Let MS_k $[x_k,\ y_k]$, k = 0, 1, ..., n be the coordinates of the DM (k = 0) and CM_k (k = 1, 2, ..., n), respectively, where n is the number of CMs. Similarly, denote $[X_i,\ Y_i]$, i = 1, 2, ..., m as the coordinates of the BSs, and m is the number of BSs. Assuming that d_{ik} and R_{ik} are respectively the measured TOA range and the true distance between BS_i and MS_k. θ_{ik} denotes the measured AOA for BS_i-MS_k link. As showed in [3], the LOS probability approximates to 1 when the distance between transmitter and receiver is less than 30m. In an ad hoc mode, the short range measurement l_{jk} is estimated by TOA measurement based on WLAN and UWB or other wireless technologies. Comparing to the large NLOS error in long range measurements, the short range measurement error in LOS condition could be ignored in this model.

For each MS, the initial estimated location can be obtained from the HTAP algorithm [11]. Denotes that $DM^{'}[x_0^{'}, y_0^{'}]$is the first DM's coordinate estimate when the entire DM-BSs links are NLOS propagation, and CM_k's initial location $[x_k^{'}, y_k^{'}]$ is obtained with only identified LOS measurements. It can be observed in literature [4] that the average NLOS error is usually much greater than the average gaussian measurement noise. Hence, we define the circular area, which is centered on the CM_k with a radius l_{0k}, as the trust region. When $DM^{'}$ locates outside the scope of the trust region, the DM's initial estimated location can be modified as the intersection point $DM^{''}[x_0^{''}, y_0^{''}]$ of the line segment $DM^{'}$-CM_k and the edge of the trust region. According to the triangular relationship, the distance DM-$DM^{'}$ is larger than DM-$DM^{''}$, and the modified DM's coordinate can be calculated as

$$
\begin{aligned}
x_0^{''} &= x_k^{'} + \frac{(x_0^{'} - x_k^{'})l_{0k}}{\sqrt{(x_0^{'} - x_k^{'})^2 + (y_0^{'} - y_k^{'})^2}} \\
y_0^{''} &= y_k^{'} + \frac{(y_0^{'} - y_k^{'})l_{0k}}{\sqrt{(x_0^{'} - x_k^{'})^2 + (y_0^{'} - y_k^{'})^2}}
\end{aligned} \tag{5}
$$

Then the modified initial coordinate of the DM can be used for the minimization optimization, as exposed in the next subsection.

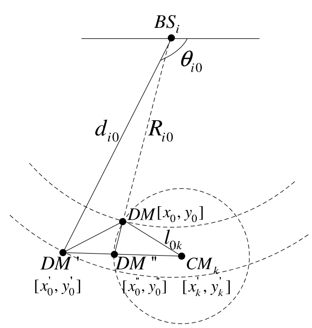

Fig. 2. The model of initial estimated location modification

B. Location Estimation Procedure

Taking into account all the BS-MS links NLOS identification results, the cost function to be minimized in order to determine the final location of the DM can be divided into the following different conditions:

1) None of the BS-MS Links are LOS: When all the MSs are NLOS, we estimate the DM's location using the conventional cooperative hybrid TOA/AOA positioning (Co-HTAP) algorithm. The differences from RHTA described in [16] are that MS-MS short range is calculated by the TOA measurement and the weights γ are all set unit ($\gamma = 1$). Hence, the objective function to be minimized is defined as:

$$
F(\mathbf{x}) = \sum_{i=1}^{m}\sum_{k=0}^{n}(f_{ik}^2(\mathbf{x}) + g_{ik}^2(\mathbf{x})) + \sum_{j=0}^{n}\sum_{k=0}^{n}\xi_{jk}^2(\mathbf{x}), j \neq k \tag{6}
$$

where

$$
\begin{aligned}
f_{ik}(\mathbf{x}) &= d_{ik} - \sqrt{(X_i - x_k)^2 + (Y_i - y_k)^2} \\
g_{ik}(\mathbf{x}) &= \theta_{ik} - \arctan(\frac{Y_i - y_k}{X_i - x_k}) \\
\xi_{jk}(\mathbf{x}) &= l_{jk} - \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2}
\end{aligned}
$$

and $\mathbf{x} = [x_0, y_0, x_1, y_1, ..., x_n, y_n]$ are the final location estimates of the DM and CMs.

2) Only Some of the DM-BS Links are LOS: In this case, if there only exist one LOS DM-BS link, we can use the HTAP algorithm to obtain the final location of the DM. Otherwise, the cost function is defined as:

$$
F(\mathbf{x}) = \sum_{i \in C}(f_{i0}^2(\mathbf{x}) + g_{i0}^2(\mathbf{x})) \tag{7}
$$

where $\mathbf{x} = [x_0, y_0]$, and C is the set of BS which is not corrupted by NLOS propagation to at least one of the MSs.

3) Some of the CM-BSs Links are LOS: Under this circumstance, the DM-BSs links may exist LOS propagation or not. When DM is total NLOS, the first location estimate of the DM can be modified by the NLOS correction model. Then we can form the cost function as follows:

$$
F(\mathbf{x}) = \sum_{i \in C}\sum_{k \in U_i, U_i \subset U}(f_{ik}^2(\mathbf{x}) + g_{ik}^2(\mathbf{x})) + \sum_{j \in U}\sum_{k \in U}\xi_{jk}^2(\mathbf{x}), j \neq k \tag{8}
$$

Where U_i denotes the set of MS which exists a LOS link with BS_i. U includes the DM and all of the CMs whose first location estimate can utilize the LOS AOA/TOA measurements, and $\mathbf{x} = [x_0, y_0, ..., x_k, y_k, ...]$, $k \in U$.

Accordingly, the initial position estimation method is also divided into two cases. If there is only one available $BS_i - MS_k$ link, the location can be calculated as:

$$
\begin{aligned}
x_k &= X_i + d_{ik}\cos\theta_{ik} \\
y_k &= Y_i + d_{ik}\sin\theta_{ik}
\end{aligned} \tag{9}
$$

or else we can use a least squares approach to solve the equations described as follows:

$$
\mathbf{A}\mathbf{x} = \mathbf{b} \tag{10}
$$

where

$$
\mathbf{A} = \begin{bmatrix} X_i - X_j & Y_i - Y_j \\ ... & ... \\ X_i - X_m & Y_i - Y_m \\ \sin\theta_{ik} & -\cos\theta_{ik} \\ \sin\theta_{jk} & -\cos\theta_{jk} \\ ... & ... \\ \sin\theta_{mk} & -\cos\theta_{mk} \end{bmatrix}
$$

,

$$\mathbf{b}=\frac{1}{2}\begin{bmatrix} d_{jk}^2-d_{ik}^2+K_i-K_j \\ \ldots \\ d_{mk}^2-d_{ik}^2+K_i-K_m \\ 2(X_i\sin\theta_{ik}-Y_i\cos\theta_{ik}) \\ 2(X_j\sin\theta_{jk}-Y_j\cos\theta_{jk}) \\ \ldots \\ 2(X_m\sin\theta_{mk}-Y_m\cos\theta_{mk}) \end{bmatrix}$$

$K_i = X_i^2 + Y_i^2$, $\mathbf{x}^T = [x_k, y_k]$, $i \neq j \neq m$, $i, j, m \in C_k$, and where C_k is the set of available BS for MS_k. The MS position can be calculated as:

$$\mathbf{x} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \tag{11}$$

IV. SIMULATION RESULTS

To evaluate the performance of the proposed approach, the simulation environments are considered as a hexagonal urban micro cell of 1000m of radius, the serving BS located at $[0, 0]$, and other six BSs are uniformly spaced around it with the same size. Because of symmetry, 1000 DMs are distributed uniformly in the area specified by $0 < \theta < \pi/2$, $0 < R < 1000m$ in polar coordinate system. For each DM, one cluster of 30m of radius has been taken into account. The DM is placed in the cluster center and the other CMs are uniformly generated around it. Table I gives the value settings of the parameters in urban area mentioned earlier in section II.

TABLE I
SIMULATION PARAMETERS

PARAMTERS	VALUES
$(c \times \sigma_{t_{noise}}, \sigma_{a_{noise}})$	$(10m, 2^o)$
$(T_1, \varepsilon, \sigma_y)$	$(0.4s, 0.5, 3dB)$

Three sets of experiments are conducted to evaluate the performance of the proposed algorithm and the effects of the variations of critical parameters on position estimation, such as the effect of the number of the CMs, the effect of the number of available BSs, and the effect of the probability of error detection (Ped) of NLOS propagation.

We determine the performance of the positioning algorithm with the average location error (ALE). The algorithm runs 100 times, and then the ALE for each DM can be obtained by comparing estimated positions with actual positions. Figure 3 shows the cumulative distribution functions (cdfs) of the ALE of the algorithms for the cases when the total probabilities of LOS BS-MS propagation (P_{los}) are 0.1, 0.3 and 0.5 while the number of BSs is $m = 3$ and the number of CMs is $n = 5$. We observe that the cooperative localization method performs better than non-cooperative HTAP, and the proposed algorithm achieves the best accuracy gains. In the simulation, the weights γ of RHTA presented in [16] are all set unit. The results show that HTAP sometimes obtains less location error than RHTA because the latter incorporates all measurements including large BS-CMs NLOS error for positioning when BS-DM link may be LOS. It happens more frequently when P_{los} increases. We can also observe that all of the algorithms lose in positioning accuracy when P_{los} decreases since the number of BS-MS links corrupted by NLOS propagation trends to be rising. Especially, when $P_{los} = 0.1$, both DM and CMs are more likely completely in NLOS conditions, and the accuracy gains of the proposed algorithm is restricted by the Co-HTAP, the performance of which is close to the RHTA in this simulation.

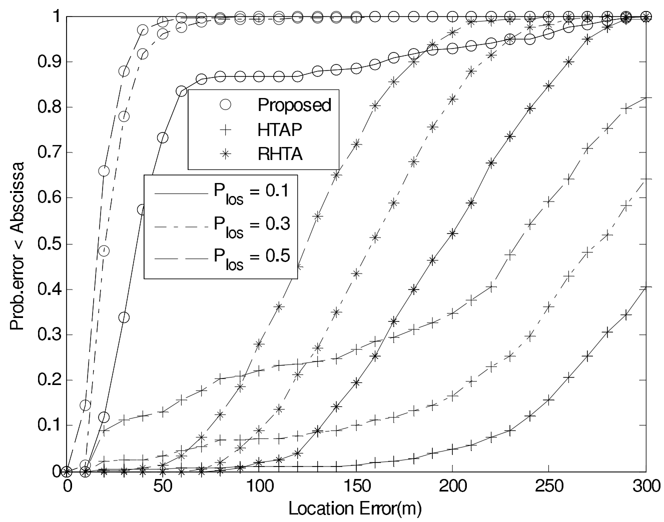

Fig. 3. The cdf of the location error of the proposed algorithm, HTAP and RHTA ($\gamma = 1$) when $m = 3$ and $n = 5$.

Figure 4 presents the average ALE versus the number of BS and the number of CM while $P_{los} = 0.1$. The results indicate that using more number of BS and CM can decrease the position error since there might be more LOS BS-MS links in real environments, and even if DM is completely NLOS, the location estimate can be modified by the NLOS correction model mentioned in section III, as long as there exists at least one LOS BS-CM link.

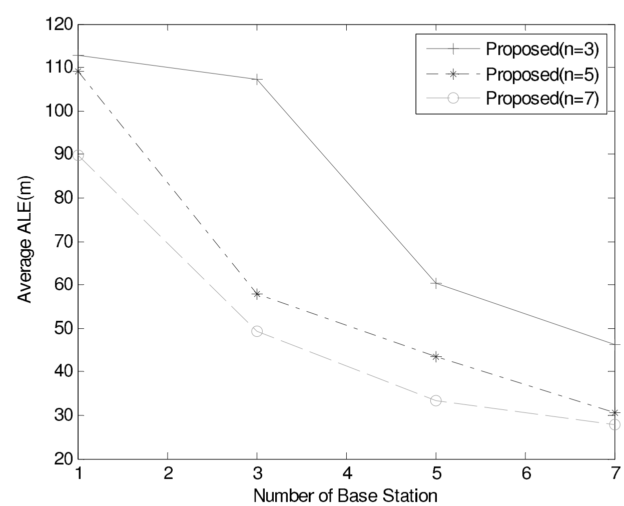

Fig. 4. Effects of number of CM and BS on position estimation accuracy when $P_{los} = 0.1$.

Denoted that if the identification is correct, the localization accuracy is what we can obtain from the proposed algorithm, but there is often the possibility of wrong identification which is referred as Ped. It includes two types of misjudgment of NLOS propagation. One is that BS-MS link is LOS, but detection results is NLOS, whereas the other is that BS-MS link is NLOS, but detection results is LOS. Figure 5 shows the effect of Ped on the location accuracy when the true $P_{los} = 0.3$, $m = 3$, and $n = 5$. It can be observed that the 67-percentile of location errors is less than 30m without wrong NLOS identification. In contrast, it achieves the 67-percentile of location error being less than 115, 160,185m when Ped = 0.1, 0.2 and 0.3, respectively. The performance of the proposed algorithm becomes worse because of higher probability of incorporating large NLOS error or discarding the LOS measurements for positioning.

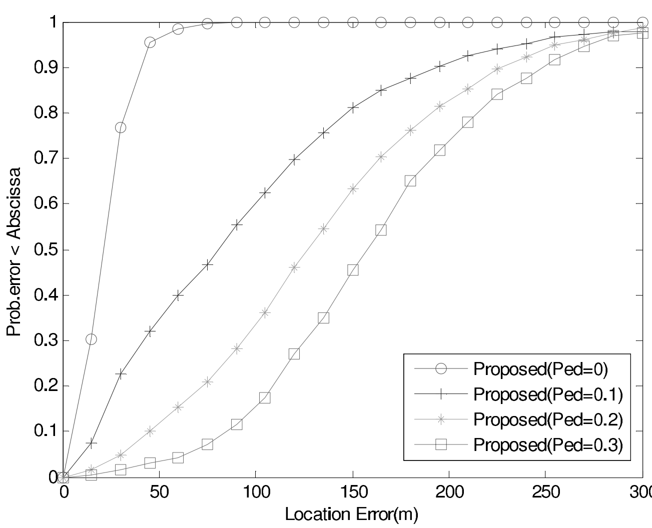

Fig. 5. Effects of probability of error detection (Ped) on localization performance when $P_{los} = 0.3$, $m = 3$, and $n = 5$.

V. CONCLUSION

In this paper, we have proposed a cooperation localization scheme that utilizes the long range hybrid TOA/AOA measurements and short range TOA measurements to estimate the position. Three kinds of objective functions to be minimized to get the final location have been studied which are based on the results of NLOS identification. A NLOS correction model has been also introduced to mitigate the NLOS error. Analysis and simulation have shown that more accuracy position estimation can be achieved when the method is adopted. However, the performance of the algorithm proposed mostly depends on the accuracy of NLOS identification methods. Hence, in future work, we plan to focus on the study of a more precise and robust NLOS identification methods.

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