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Full Length Research Paper

A constrained equalization scheme for mobile location in non-line-of-sight environments

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Mobile location techniques in wireless communication networks have received significant attention in recent years. One of the main problems impeding accurate location estimation is non-line-of-sight (NLOS) propagation. In this paper, we propose a novel method by incorporating constrained optimization algorithm with an equalization scheme, where the weights are derived from root mean square delay spread, which is an environment-dependent parameter describing the multipath dispersion of radio channel. Since both the channel information and constrained condition are exploited, this method can improve the location accuracy as shown in the provided simulation results.

Key words: Non-line-of-sight (NLOS), mobile location, constrained equalization scheme.

INTRODUCTION

Determining the position of a mobile station (MS) in wireless communication system becomes a popular issue in recent years. One of the major driving forces is due to the U.S. Federal Communications Commission (FCC) released a mandate requiring all wireless service providers to provide location information of a wireless 911 caller for Enhenced-911 (E-911) safety services (FCC, 1996). With the popularization of wireless services, more and more people call for emergence services by wireless phone (NENA). Location information of wireless caller permits rapid response which can help the callers who are disoriented, disabled, unable to speak, or do not know their location, etc. In addition to emergency services, the mobile location information can be useful in cellular system design and management, or other location-based applications such as mobile yellow pages, route guidance, and traffic information (Caffery, 2000). A new survey of mobile location techniques can be seen in (Gezici, 2008).

However, one of the main problems impeding accurate location estimation is non-line-of-sight (NLOS) propagation. In dense urban environment, the received signal often propagates through reflected, diffracted, or scattered paths due to buildings and other obstacles, and then excess path length in range measurement and the bias of angle of arrival will be imposed (termed the NLOS error). For range measurements, the NLOS error is the order of hundreds of meters and hardly affects the location accuracy (Gezici, 2008; Gui et al., 2011; Silventoinen and Rantalainen, 1996). Great efforts have been made to solve this problem in the past few years and several approaches based on range measurement have been proposed in (Silventoinen and Rantalainen, 1996; Wylie and Holtzman, 1996; Woo et al., 2000; Khajehnouri and Sayed, 2003; Jeong et al., 2001; Caffery and Stuber, 1998; Al-Jazzar et al., 2002; Greenstein et al., 1997; Chen, 1999). One example is the equalization scheme, in which the topology of network (Khajehnouri and Sayed, 2003) or the relationship between root mean square (*r.m.s.*) delay spread and the mean excess delay (Khajehnouri and Sayed, 2003) was used to equalize the measurements. The other example is constrained Non-linear Least Squares (NL-LS) algorithms (Caffery and Stuber, 1998), which consider the fact that the measured range estimates are always greater than the true values due

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Abbreviations: NLOS, Non-line-of-sight; **MS,** mobile station; **FCC,** Federal Communications Commission; **CDF,** cumulative distribution function; **PDF,** probabilitydensity function.

to NLOS propagation. These methods can improve the location accuracy to some extent under their own required conditions. In this paper, we focus on the integrated application of equalization scheme and constrained optimization algorithm with range measurements.

NLOS ERROR MODEL AND ROOT MEAN SQUARE DELAY SPREAD

Let d_i denote the direct range between MS and the i-th base station (BS). The range measurement between MS and BS can be modeled as:

$$r_i = d_i + n_i + l_i,\ \ i = 1,\ 2, \ldots, M. \tag{1}$$

where n_i is the measurement noise and l_i is the excess range due to NLOS propagation, M is the number of BSs participated in mobile location. The measurement noise is often modeled as zero-mean Gaussian random variable with relatively small standard deviation, whereas l_i is always positive and can be modeled by exponential distribution as (Lee, 1993):

$$f(l_i) = \begin{cases} \frac{1}{c\tau_{rms}^i}\exp\left(-\frac{l_i}{c\tau_{rms}^i}\right), & l_i > 0 \\ 0, & \text{otherwise} \end{cases}, \tag{2}$$

where c is the speed of light, and τ_{rms} is the *r.m.s.* delay spread. The *r.m.s.* delay spread is a crucial parameter to quantify the time dispersive properties of radio channels and depends on the environment (Greenstein et al., 1997). It is commonly defined as:

$$\tau_{rms} = \sqrt{\frac{1}{K}\sum_{i=1}^{K}\left(\tau_i - \bar{\tau}\right)^2}, \tag{3}$$

where τ_i is the delay measurement, $\bar{\tau}$ is the mean delay.

Actual data reported by Motorola and Ericsson (Jeong et al., 2001) showed that l_i is essentially correlated with τ_{rms}. Considering this correlation, Forcellini and Trintinalia (2005) have proposed method to correct the measured distances. In this paper, the *r.m.s.* delay spread is utilized to equalize the range measurements. The constrained optimization algorithm is then applied to obtain the location estimation. It can be expected that the performance of proposed constrained equalization scheme would be better than the methods utilizing only the constrained optimization algorithm in (Caffery and Stuber, 1998) or the equalization scheme in (Khajehnouri and Sayed, 2003).

CONSTRAINED EQUALIZATION SCHEME

Consider that, the measurement noise, n_i, is relatively smaller than the NLOS error and can be neglected, we have:

$$l_i = r_i - d_i,\ \ i = 1, 2, \ldots, M. \tag{4}$$

Then the probability density function (PDF) of l_i should be a function of the MS location denoted by *x*. The equation 2 can be rewritten as:

$$f(r_i \mid \mathbf{x}) = \begin{cases} \frac{1}{c\tau_{rms}^i}\exp\left(-\frac{r_i - d_i}{c\tau_{rms}^i}\right), & r_i - d_i > 0 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Assuming each BS measures the range independently, and then the joint PDF is:

$$f(\mathbf{r} \mid \mathbf{x}) = \prod_{i=1}^{M} f(r_i \mid \mathbf{x}), \tag{6}$$

where $\mathbf{r} = \begin{bmatrix} r_1 & r_2 & \cdots & r_M \end{bmatrix}$ is a vector containing all the range measurements.

Let $w_i = c\tau_{rms}^i$, the likelihood function of $\mathbf{x}$ can be expressed as follow:

$$L(\mathbf{x}) = \ln f(\mathbf{r} \mid \mathbf{x}) = \sum_{i=1}^{M}\ln\left(\frac{1}{w_i}\right) - \sum_{i=1}^{M}\frac{r_i - d_i}{w_i}. \tag{7}$$

Then we can pose the problem to estimate the MS location by solving:

$$\hat{\mathbf{x}} = \arg\min_{\tilde{\mathbf{x}}} \sum_{i=1}^{M}\frac{r_i - d_i}{w_i}$$
$$s.t.\ \ r_i - d_i > 0,\ i = 1, 2, \cdots, M \tag{8}$$

Here, the *r.m.s.* delay spread is utilized to equalize the range measurements and the fact that the error due to NLOS propagation delay is always positive is utilized as the constrained condition. For the solution of the constrained optimization problem (8), we can use the SQP (Sequential Quadratic Programming) method, which essentially reduces a nonlinear optimization problem with nonlinear constraints to a sequence of constrained least-squares problems.

Although, the proposed method is derived from exponential distribution (2), the *r.m.s.* delay spread is

Table 1. Model parameters for different environment types.

Environment	$T_1(us)$	ε	$\sigma_y(dB)$
Bad Urban	1.0	0.5	4
Urban	0.4	0.5	4
Suburban	0.3	0.5	4
Rural	0.1	0.5	4

dependent on the environment parameters, especially is correlated with the excess range due to NLOS propagation, this method is independent of the assumption of the NLOS error model as long as the measurement noise n_i is smaller than the NLOS error and can be neglected.

PERFORMANCE EVALUATION

Computer simulations have been carried out to evaluate the performance of the proposed method using a mobile positioning scenario with four BSs of known coordinates (0, 0), (3750, 2500), (3750, -2500) and (0, 5000) m. The measurement noise at each BS is assumed as a zero-mean white Gaussian process with variance 100 m. The position of MS is uniformly distributed within a circle centered at the origin. The radius of the circle is 2000 m. Each result is a statistics of 5000 independent runs and the *r.m.s.* delay spread is a statistics of 1000 measurements for each run. We compared the location error of the constrained equalization scheme with unconstrained LS algorithm, constrained LS algorithm (Caffery and Stuber, 1998) and residual weighting algorithm (Chen, 1999).

The first set of simulation is performed to verify the availability of the proposed method on various environments. The NLOS error is modeled as (2) and a statistical model from measurements characterized in (Greenstein et al., 1997) is chosen for the *r.m.s.* delay spread, which is:

$$\tau_{rms} = T_1 d^{\varepsilon} y \,, \tag{9}$$

Where:

T_1 = The median value of the r.m.s. delay spread at $d = 1\text{Km}$.
d = The distance between the MS and the BS in kilometers.
ε = The path loss exponent (PLE) that lies between $0.5 \sim 1.0$.
y = A lognormal random variable, that is, $10\log y$ is a Gaussian random variable having zero mean and a standard deviation σ_y which lies between $2 \sim 6\text{dB}$.

The choice of these parameters depends on different type of environments, which are listed in Table 1. Figure 1 shows plots of the cumulative distribution function (CDF) of location error at each environment. It is seen that the location estimate performances of all algorithms degrade dramatically with the increase of NLOS error. However, the proposed method can still improve the location accuracy in rural environment, suburban environment, urban environment and bad urban environment.

In the second set of simulation, the NLOS error l_i is modeled by Rayleigh distribution instead of exponential distribution to evaluate the effect of the assumption of NLOS error model, that is, the PDF of l_i is:

$$f(l_i) = \begin{cases} \dfrac{l_i}{u^2}\exp\left(-\dfrac{l_i^2}{2u^2}\right), & l_i > 0 \\ 0, & \text{otherwise} \end{cases} . \tag{10}$$

Then the variance of l_i is:

$$\sigma_{l_i}^2 = \frac{4-\pi}{2}u^2 . \tag{11}$$

Figure 2 shows a plot of the root mean square error (RMSE) against the standard deviation (SD) of Rayleigh distribution. The root mean square error is defined as $\text{RMSE} = \sqrt{E\left[\left\|\mathbf{x}-\hat{\mathbf{x}}\right\|_2^2\right]}$, where $E[\cdot]$ denotes the expectation and $\|\cdot\|$ denotes the norm operation. As shown in Figure 2, the proposed method is superior to unconstrained LS algorithm, constrained LS algorithm and residual weighting algorithm in terms of RMSE when the measurement noise can be neglected.

CONCLUSION

In this paper, we propose a constrained equalization scheme to improve the location accuracy in NLOS propagation environments. This work shows that utilizing the channel information rightly can efficiently improve the location accuracy. For measuring the channel parameters, however, network analyzers or sophisticated channel sounders may be required. To be broadly applicable, a further investigation should be focused on the development of efficient channel parameter estimation techniques with standard equipment and NLOS based location algorithms to overcome the NLOS error in NLOS environment.

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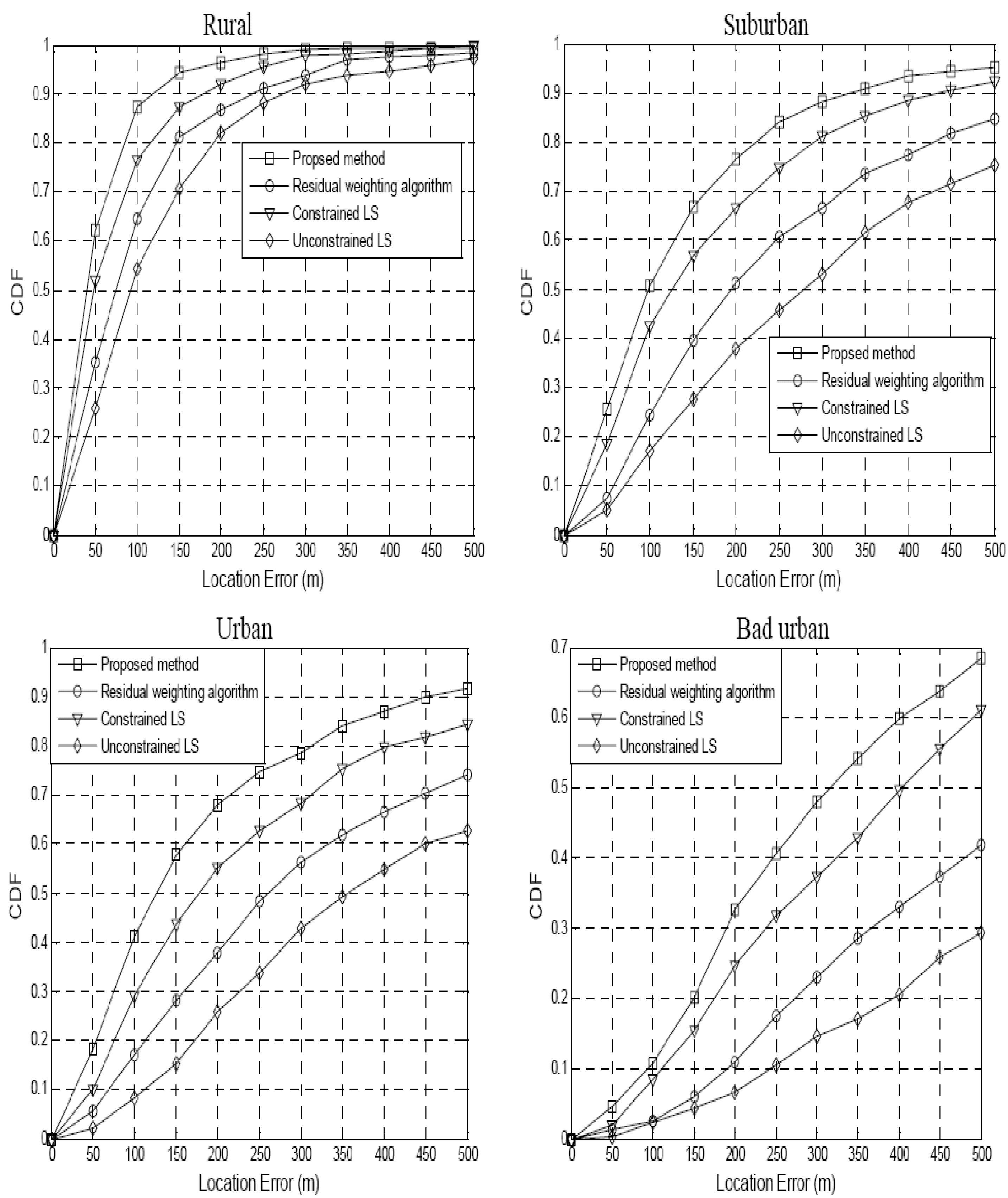

Figure 1. The CDF of location error for proposed constrained equalization scheme, unconstrained LS algorithm, constrained LS algorithm and residual weighting algorithm in different environment types are given in Table 1.

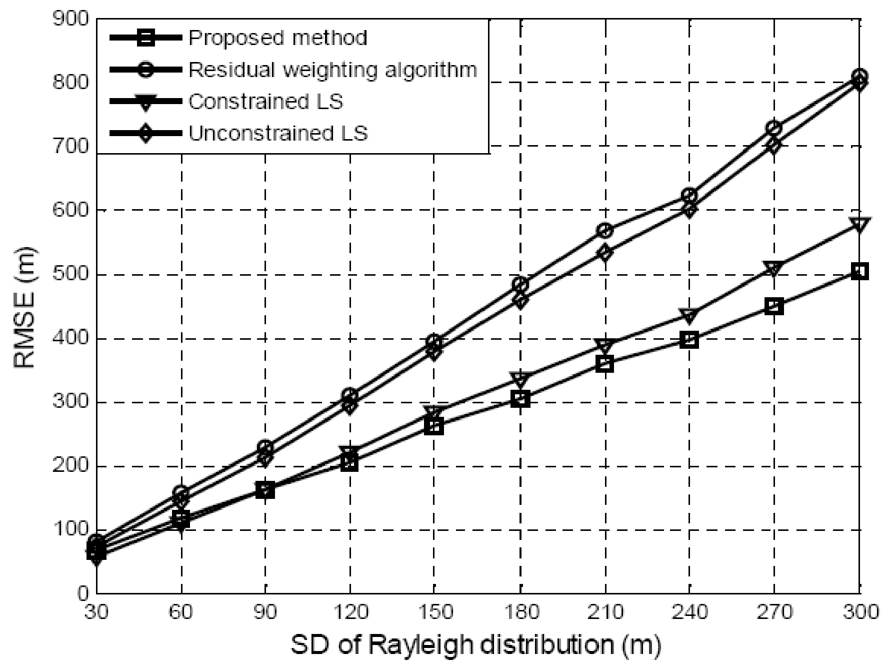

Figure 2. RMSE against the standard deviation of Rayleigh distribution.

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