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S. W. Chen, C. K. Seow and S. Y. Tan

A novel wireless localisation scheme which requires just one reference device to estimate the mobile location is presented. The proposed scheme utilizes the joint Time-of-Arrival (TOA) and Angle-of-Arrival (AOA) estimation of Line-of-Sight (LOS) path measured at both mobile and reference device to construct areas of possible mobile device (APMDs). Intersection of these APMDs will give an estimation of MD location. Simulation in light and heavy multipath environments show that the performance of the proposed single reference localisation scheme dramatically improved the location accuracy as compared with the conventional localisation techniques that use four reference devices.

Introduction: The most significant source of errors in wireless localisation in multipath environment is due to the in-direct or scattered Non-Line-of-Sight (NLOS) paths. Many techniques [1-5] have been developed to reduce the error due to NLOS paths. However, these techniques do not perform satisfactorily if there is insufficient number of LOS reference devices (RDs). For example, the conventional TOA localisation techniques require at least three LOS RDs in 2D localisation. If any RD is in NLOS condition, the localisation accuracy will be seriously degraded. This letter presents a robust and novel method to overcome the above limitations by using just a single RD in LOS to estimate mobile device (MD) location. By measuring LOS path's TOA and AOA at RD and MD, we are able to construct two areas where all possible MD locations reside. This is referred as Area of Possible MD location (APMD). Intersection of these APMDs will give an estimation of MD location. This results in greatly improved localisation accuracy and robustness.

Fig. 1 Geometrical relationship between RD and MD

Theory and formulation: Fig. 1 depicts the geometrical relationship between RD and MD in 2D plane. TOA (t, τ) and AOA (θ, ϕ) were measured at (RD, MD). RD coordinate (x_R, y_R) is known and MD position (x, y) is to be estimated from the measured TOAs and AOAs. The measured TOAs are related to the propagation path lengths which are $d = ct, r = c\tau$ where c is the speed of wave propagation.

The AOA and TOA data values are perturbed by the measurement noise:

$$\begin{aligned} \theta &= \theta^0 + n_\theta, \phi = \phi^0 + n_\phi, d = d^0 + n_d, r = r^0 + n_r \\ n_m &= N(0, \sigma_m) \quad m = \theta, \phi, d, r \end{aligned} \quad (1)$$

where θ^0, ϕ^0 and d^0, r^0 are the true AOA and TOA values of signal path, and n_θ, n_ϕ and n_d, n_r are the measurement noise which are assumed to be zero mean Gaussian random variables with known standard deviation σ_m . $\hat{RD}(\hat{MD})$ denotes the estimated position of RD (MD) because of the measured metrics $\tau(t)$ and $\phi(\theta)$ at MD (RD).

At RD, the APMD can be confined to an enclosed region of possible MD location, NOPQ, within $[\theta - 3\sigma_\theta, \theta + 3\sigma_\theta]$ and $[d - 3\sigma_d, d + 3\sigma_d]$ as shown in Fig. 2(a). Similarly, another APMD, STUV, can be found at MD as shown in Fig. 2(b). Since RD position is known, we can flip the area STUV at MD to the RD side. A smaller APMD, ABCD, can be obtained by overlapping NOPQ and STUV at RD as shown in Fig. 2(c). As illustrated, the enclosed area ABCD shows that the estimated MD location, $\hat{MD}$, is much nearer to the true MD location as compared to Fig. 2(a). Hence, the concept of APMD enhances the accuracy of MD estimation.

Fig. 2 Area of Possible Mobile Device (APMD)

The estimated location of the MD ($\hat{MD}$) can be determined from the intersection area of the APMD, ABCD as shown in Fig. 2 (c). This is done by minimizing the sum of the square of the distance from $\hat{MD}$ to the vertices of the enclosed region i.e. A, B, C and D.

$$J = (\mathbf{CZ} - \boldsymbol{\lambda})^T (\mathbf{CZ} - \boldsymbol{\lambda}) \quad (2)$$

where $\mathbf{C} = [\mathbf{c}_1 \quad \mathbf{c}_2 \quad \dots \quad \mathbf{c}_K]^T$ and $\mathbf{c}_k = \mathbf{I}_{2 \times 2}$. $\boldsymbol{\lambda}$ is the coordinate vectors of these vertices and the location of $\hat{MD}$ is $\mathbf{Z} = [x, y]^T$.

$$\begin{aligned} \boldsymbol{\lambda} &= [\lambda_1, \lambda_2, \dots, \lambda_K]^T \\ &= [x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D]^T \\ &= [x_R + (l_{\max} - 3\sigma_{l_{\max}})\cos(\alpha_{\max} - 3\sigma_{\alpha_{\max}}), y_R + (l_{\max} - 3\sigma_{l_{\max}})\sin(\alpha_{\max} - 3\sigma_{\alpha_{\max}}), \\ &\quad x_R + (l_{\max} - 3\sigma_{l_{\max}})\cos(\alpha_{\min} + 3\sigma_{\alpha_{\min}}), y_R + (l_{\max} - 3\sigma_{l_{\max}})\sin(\alpha_{\min} + 3\sigma_{\alpha_{\min}}), \\ &\quad x_R + (l_{\min} + 3\sigma_{l_{\min}})\cos(\alpha_{\min} + 3\sigma_{\alpha_{\min}}), y_R + (l_{\min} + 3\sigma_{l_{\min}})\sin(\alpha_{\min} + 3\sigma_{\alpha_{\min}}), \\ &\quad x_R + (l_{\min} + 3\sigma_{l_{\min}})\cos(\alpha_{\max} - 3\sigma_{\alpha_{\max}}), y_R + (l_{\min} + 3\sigma_{l_{\min}})\sin(\alpha_{\max} - 3\sigma_{\alpha_{\max}})]^T \end{aligned} \quad (3)$$

$$l_{\min} = \min(d, r), l_{\max} = \max(d, r).$$

$$\alpha_{\min} = \min(\theta, \phi \pm \pi), \alpha_{\max} = \max(\theta, \phi \pm \pi).$$

$$\sigma_{l_{\max}} = \begin{cases} \sigma_d & \text{if } l_{\max} = d \\ \sigma_r & \text{if } l_{\max} = r \end{cases}, \sigma_{\alpha_{\max}} = \begin{cases} \sigma_\theta & \text{if } \alpha_{\max} = \theta \\ \sigma_\phi & \text{if } \alpha_{\max} = \phi \end{cases}$$

$$\sigma_{l_{\min}} = \begin{cases} \sigma_d & \text{if } l_{\min} = d \\ \sigma_r & \text{if } l_{\min} = r \end{cases}, \sigma_{\alpha_{\min}} = \begin{cases} \sigma_\theta & \text{if } \alpha_{\min} = \theta \\ \sigma_\phi & \text{if } \alpha_{\min} = \phi \end{cases}$$

Therefore, the least square solution for (2) will be simply given as

$$\mathbf{Z} = (\mathbf{C}^T \mathbf{C})^{-1} \mathbf{C}^T \boldsymbol{\lambda} \quad (4)$$

Fig. 3 ALE comparison for 10,000 uniformly distributed MD locations with $\sigma_d, \sigma_r = 3$ m, $\sigma_\theta = 5^\circ$ with varying σ_ϕ in multipath environment

Simulation: The accuracy of our proposed single RD localisation scheme is compared to the conventional TOA and TOA/AOA techniques using four RDs in different multipath environments. The simulations are carried out in light and heavy multipath environments in a $20\text{m} \times 20\text{m}$ area. The four RDs are placed at $(0, 0)$, $(0, 20\text{ m})$, $(20\text{ m}, 0)$ and $(20\text{ m}, 20\text{ m})$. The scatterers are assumed to be uniformly distributed in the environments [6]. The probability of NLOS (LOS) paths at each RD is assumed to be 20% (80%) and 40% (60%) [5] for light and heavy multipath environments, respectively. The NLOS path is referred to the scattering path from RD to MD via a scatterer. At the RDs, the TOA standard deviation, σ_d , and AOA standard deviations, σ_θ , are fixed at 3m and 5° respectively [4]. At MD, the TOA standard deviation, σ_r , is 3m while the AOA standard deviation, σ_ϕ , is varied from 5° to 20° . The average location error (ALE) performance comparison is illustrated with 10,000 uniformly distributed MD locations. The conventional TOA and TOA/AOA localisation techniques [1, 2] exploit the mitigation technique [1, 3] to reduce the NLOS error while the TOA location technique in [5] relies on the iterative parallel projection method (PPM). Our proposed scheme and TOA/AOA technique in [4] both employ bi-directional estimation. Our proposed single RD scheme and [4] use only one RD at $(0, 0)$ to estimate the MD location while the rest utilize all four RDs.

Discussion: Fig. 3 demonstrates the ALE performance by comparing our proposed single RD localisation scheme with [4] and the conventional localisation techniques. Our proposed scheme achieves an average error of 3.3 m (4.2 m) in the light (heavy) environment, as compared with an average error of 7.8 m (11.8 m) in Seow and Tan [4], 6.7 m (10.6 m) in Jia and Buehrer [5], 7.7 m (11.7 m) in Wang et al. [1] and 4.5 m (7 m) in Cong and Zhuang [2, 3]. This represents an improvement of more than 27% and 40% in the light and heavy multipath environment respectively. Simulation results show that the margin of accuracy increases as NLOS probability increases. As shown, our proposed localisation scheme outperforms all conventional techniques for all escalations of σ_ϕ using one RD. A similar trend is observed if σ_r is changed from 1 to 5m.

Conclusion: The proposed single RD localisation scheme which exploits the concept of APMD at both RD and MD outperforms the

existing conventional localisation techniques by a significant margin in the multipath environment especially under heavy multipath environment.

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