Accurate relative position indicator for tracking-based position estimation system

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Abstract: A relative position indicator (RPI) system with radial antenna array (RAA) is proposed and experimentally demonstrated for use in a tracking-based position estimation system (PES). Utilizing radial vectors generated by both received signal strength (RSS) and azimuth direction of each antenna element in the RAA, accurate direction and distance-to-target can be obtained simultaneously. The proposed RPI system using a radial vector sum and a simple equalization process can mitigate the gain mismatch problem, which was a serious problem in previous tracking-based PESs.

Keywords: position estimation, received signal strength, direction of arrival

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Network-based position estimation systems (PESs) have been considered a good solution for location awareness services [1, 2, 3]. However, due to multipath and non-line-of-sight propagation in wireless channels, network-based PESs exhibit a trade-off between cost and accuracy. On the other hand, a tracking-based PES with a mobile tracer can provide both low cost and high accuracy in various applications such as pet locators, criminal tracking systems, and missing-child locators. A previous study of a tracking-based PES with a portable tracer made of rotatable unidirectional antennas showed that active target tracking was possible with Bayesian inference, based on a priori received signal strength (RSS) data [4]. However, a PES using a unidirectional antenna exhibited the gain mismatch problem caused by unsharp patterns, back-lobes, and side-lobes, generating considerable errors in direction and distance estimation [5]. In this paper, we propose and demonstrate a novel relative position indicator (RPI) system composed of a radial antenna array (RAA) and using radial vector signal processing. This system attempts to estimate the relative position (i.e., both direction and distance of the target) accurately using only RSS data from the RAA. Using the symmetric structure of the RAA and radial vector signal processing, we can mitigate the gain mismatch problem, and thereby, high accuracy is achieved using the proposed RPI.

2 Radial vector array with Cardioid pattern

The RSS is a random variable with Gaussian distribution and depends on both the gain pattern $g(\Phi)$ and the incident power $P(d)$, where Φ and d are the incident angle and the distance, respectively [6]. It has been reported that given a smaller circular array, the RSS of each antenna is more dependent on the direction of the antenna [7]. As shown in Fig. 1 (a), the RAA is a small circular antenna array consisting of an even number N of directional antennas. In this case, the antennas are arranged every $\Delta\Phi = 2\pi/N$, and the azimuth direction of the k^{th} antenna (a_k) is given by $\Phi_k = (k-1)\Delta\Phi$. Accordingly, the unit azimuth direction vector p_k and the gain pattern of the k^{th} antenna are given by $\cos\Phi_k \vec{x} + \sin\Phi_k \vec{y}$ and $g(\Phi-\Phi_k)$, respectively. Then, the radial vector of the k^{th} antenna is defined as follows.

$$\vec{r}_k = s_k \vec{p}_k = [g(\Phi - \Phi_k) + P(d) + X]\big(\cos\Phi_k \vec{x} + \sin\Phi_k \vec{y}\big), \qquad (1)$$

where, s_k is the RSS of the k^{th} antenna and X is the Gaussian random variable.

Fig. 1 (b) shows the measured gain pattern of a general-purpose antenna used in the RAA. The measured data is compared with the Cardioid gain pattern $g(\Phi)=G_o[(1+\cos\Phi)/2]^m$ for m=1, 2, and 3. Here, the parameter G_o is the maximum gain values, and m is the directivity index. The Cardioid gain approximates the main lobe in general, and it is widely

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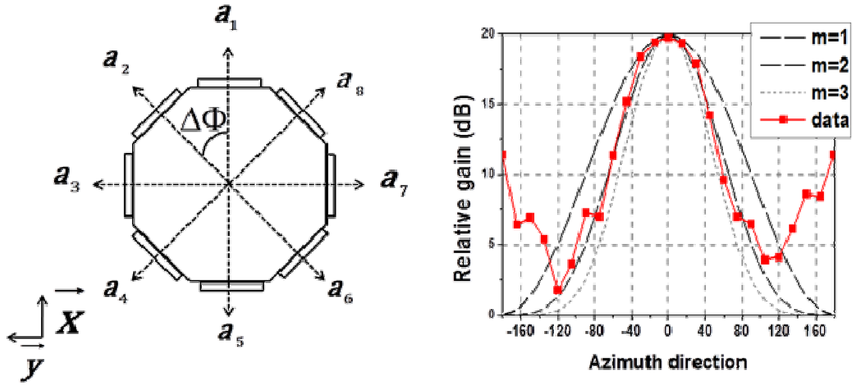

(a) (b)

Fig. 1. (a) Schematic of radial antenna array for the proposed RPI system, (b) Measured relative gain pattern of an antenna in the array and calculated Cardioid gain pattern with different directivity indexes m.

used as the radiation pattern for the direction-of-arrival applications [7]. As shown in Fig. 1 (b), the measured gain pattern shows that $G_o = 20\,\text{dB}$ and the main lobe is close to the Cardioid pattern with m = 2, although back-lobes exist if $|\Phi|$ is greater than 90°. The correlation between the RSS data acquired by each antenna in the RAA is proportional to λ/D, where λ is the wavelength and D is the diameter of the array [8]. However, if D is larger than $\lambda/2$, the mutual coupling between antenna elements can be ignored [9]. Also, an experimental work by Cidronali et al. [10] showed that the mutual coupling was not significant for neighboring patch antennas with $D \approx 5.5\,\text{cm}$. Since our fabricated RAA has D of 20 cm, which is much larger than $\lambda/2$, the mutual coupling and gain deformation of antenna elements in the RAA are neglected in this study. Actually, the gain deformation has not been appeared in the measured gain pattern shown in Fig. 1 (b).

3 Direction and distance estimation in RAA

Considering the given condition, the radial vector is expressed by

$$\vec{r}_k = \left[G_O\left(\frac{1+\cos(\Phi-\Phi_k)}{2}\right)^2 + P(d) + X\right]\left(\cos\Phi_k\vec{x} + \sin\Phi_k\vec{y}\right). \quad (2)$$

Then, we define the characteristic direction vector of the RAA, which is the sum of radial vectors as expressed in Eq. (3).

$$\vec{R} = \sum_{k=1}^{N}\vec{r}_k = \sum_{k=1}^{N} s_k\vec{p}_k = K_R\left(\cos\Phi\vec{x} + \sin\Phi\vec{y}\right) + X_M, \quad (3)$$

where K_R is the magnitude of the characteristic direction vector given by $G_oN/4$. X_M is random variable, which generates a direction and distance error in characteristic direction vector. It is noted that K_R is independent of the distance, because P(d) values in all radial vectors are canceled out in the vector sum of a symmetric RAA. On the other hand, the numerical average of the RSS values in the RAA (K_d) is a function of the distance,

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irrespective of the direction because the characteristic direction vector guarantees equal values of K_R for all directions. This average is given by

$$K_d = \frac{1}{N}\sum_{k=1}^{N} s_k = \frac{3}{8}G_o + P(d) + X_d\,, \tag{4}$$

where X_d is the average of random variables. For the implemented RAA (G_o = 20 dB, N = 8), K_R and K_d are 40 dB and 7.5+P(d)+X_d dB, respectively.

4 Radial vector equalization and RPI system

Fig. 2 shows the proposed RPI system with the three basic blocks of radial vector generation, radial vector equalization (RVE), and position estimation. First, radial vector generation is performed as previously explained. A moving average filter (MAF) in this block is applied to reduce the randomness of the received signal. Next, RVE is performed to solve the gain mismatch problem generated by back- and side-lobes. Although K_R is ideally supposed to be a constant, gain mismatch due to back-lobes can be observed. As shown in Fig. 1 (b), if the azimuth angle of maximum RSS Φ_M is considered to be 0°, the RSS's of the antenna elements with the angle less than 90° carry accurate target information without any perturbation of back-lobes. On the contrary, those with the angle greater than 90° are perturbed by back-lobes. Moreover, the back-lobe problem is serious if the angle is greater than 120°. Therefore, RVE is applied for the RSS's of antenna elements having azimuth angles greater than 90° with respect to Φ_M. If the k^{th} antenna in the RAA is perturbed by the back-lobes (i.e. $|\Phi_M - \Phi_k| > 90°$), the RSS value of s_k can be compensated using the accurately measured s_{k+4}. In this case the location of the $(k+4)^{th}$ antenna is where the maximum RSS is or its neighboring. From Eqs. (1) and (2), the compensated s_{ck} is obtained by the following relationship.

$$\begin{aligned} s_{ck} - s_{k+4} &= g(\Phi_M - \Phi_k) - g(\Phi_M - \Phi_{k+4}) \\ &= G_O\left(\frac{1+\cos(\Phi_M - \Phi_k)}{2}\right)^2 - G_O\left(\frac{1+\cos(\Phi_M - \Phi_k + \pi)}{2}\right)^2 \\ &= G_O\cos(\Phi_M - \Phi_k). \end{aligned} \tag{5}$$

Finally, the numerical average and sum of radial vector can be simply calculated to perform the position estimation using the equalized RSS (s_{ck}) and radial vector (r_{ck}).

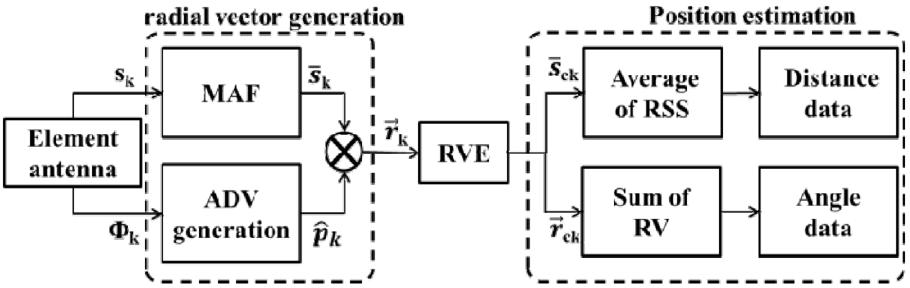

Fig. 2. The proposed RPI system with three basic blocks.

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5 Experiment results and discussion

The RPI system is realized using a small RAA consisting of eight general-purpose antennas. The RAA has a radius of 20 cm. Each antenna has the gain pattern shown in Fig. 1 (b). For signal transmission and detection, CC2430 IEEE 802.15.4 zigbee modules were used. Fig. 3 shows the experimental results for position estimation with a distance variation ranging from 10 to 110 m in line-of-sight space ($\Phi = 0$). Fig. 3 (a) and (b) show the measured position results without and with the RVE, respectively. Considering large signal fading, the log-distance model is applied in the distance estimation [2].

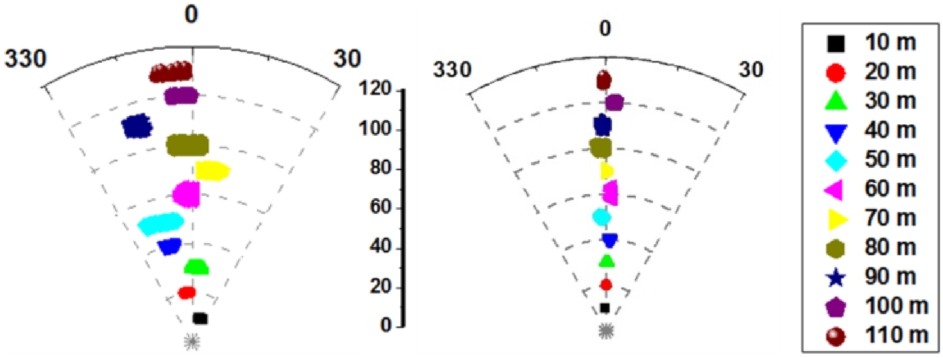

Fig. 3. (a) Measured distances and directions (Φ=0) ranged from 10 to 110 m and (a) without and (b) with the RVE processes. For simplicity, only data within the standard deviation σ are displayed.

At the measurement of 110 m, for example, if the MAF and the RVE are not used in the RPI, the average distance (A_d) and the average angle (A_Φ) are measured to be 110.20 m and -4.01° with a standard deviation (σ_d and σ_Φ) of 6.65 m and 15.46°, respectively. Relatively accurate distance estimation is obtained even without the MAF and the REV owing to the symmetric structure of the RAA. For all distances, the A_d values were relatively close to the real values with a maximum of 8.6% deviation. If only the MAF is applied, σ_d in A_d is reduced to 5.5% in the worst case. However, although σ_Φ is reduced, no improvement in A_Φ is observed. As shown in Fig. 3 (a), without RVE, A_Φ and σ_Φ fluctuates significantly from -14.78° to 20.15° and from 2.30° to 7.95°, respectively. On the other hand, if the RVE is applied, great improvement in A_Φ and σ_Φ are observed as shown in Fig. 3 (b). For example at the measurement of 110 m, A_d and σ_d are slightly enhanced (110.03 m and 2.42 m respectively), whereas A_Φ, and σ_Φ are significantly enhanced (-0.48°, and 0.58°, respectively). Without RVE, a reduction and fluctuation in K_R from the theoretical constant value (40 dB in this case) occurs because of the gain mismatch problem, which is critical in the determination of the incident angle. Without RVE, the measured average and σ of K_R are severely fluctuated from 9.69 to 23.25 dB and from 0.54 to 1.41 dB, respectively. With RVE, it is confirmed that the K_R values are 40 ± 0.1 dB (almost constant) for all distances with $\sigma < 0.05$ dB, showing the validity of our proposed RPI system.

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6 Conclusions

For radial vector generation, a theoretical calculation to determine the position is carried out and an RAA using general-purpose antennas with a Cardioid pattern is realized. To mitigate the gain mismatch problem due to the side- and back-lobes, simple RVE is developed and employed. The experimental results show that the proposed RPI system can provide nearly ideal characteristics and significantly improve accuracy both in terms of distance and direction. Consequently, it is believed that the proposed RPI system can be utilized as a simple but efficient PES.

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