The Application of DOA Estimation Approach in Patient Tracking Systems with High Patient Density

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Abstract—In this paper, an improved localization method named three-uniform-linear-array localization is proposed for patient track systems. Three receivers adopting a smart antenna technique cooperate with each other to locate the patients using the angulation positioning method. In order to be able to track patients in environment with high patient density, a high-resolution direction-of-arrival (DOA) estimation algorithm for the coexistence of noncircular and circular signals is proposed. First, the maximal and common noncircularity rated signals are preliminarily estimated. Second, based on the noise space block matrix, the DOAs of these signals are re-estimated with high accuracy. Then, the covariance matrix of the maximal and common noncircularity rated signals is reconstructed. The contributions of these signals are eliminated after performing a subtraction operation on the covariance matrix of the received data and only those of circular signals remain. Finally, the DOAs of circular signals are obtained. Results of simulations and real tests demonstrate the effectiveness and performance of the proposed algorithm.

Index Terms—Angulation positioning method, direction-of-arrival (DOA) estimation, noncircular and circular signals, patient tracking system.

NOMENCLATURE

AM Amplitude modulation.
AWG Arbitrary waveform generator.
BPSK Binary phase shift keying.
DPC Data processing center.

ESPRIT Estimation of signal parameters via rotational invariance techniques.
HRNC-MUSIC High resolution noncircular multiple signal classification.
MUSIC Multiple signal classification.
NC-MUSIC Noncircular multiple signal classification.
QAM Quadrature amplitude modulation.
QPSK Quadrature phase shift keying.
RFID Radio frequency identification.
RSSI received signal strength indicator.
SCS Spatial compressive sensing.
SD Standard deviations.
SVD Singular value decomposition.
TDOA Time difference of arrival.
TOA Time of arrival.
TUL Three uniform linear arrays localization.
UCA Uniform circular array.
ULA Uniform linear array.
UQPSK Unbalanced quadrature phase shift keying.

I. INTRODUCTION

As we all know, population aging is nowadays growing to a worldwide concern. In the U.S. alone, between 2000 and 2010, the population of 65 years old and over increased at a faster rate (15.1%) than the total population (9.7%) [1]. With this general trend, critical issues like the quality of life and healthcare for senior citizens are rapidly rising. Pervasive healthcare technologies, such as automated wearable sensor devices, are invaluable tools for regular and noninvasive monitoring and tracking of risk population groups, which include the elderly who may suffer from involuntary falls, arrhythmia or dementia [2]. With the rapid development of wireless communication [3], remote diagnosis and tracking of patients have been gaining great interest in telemedicine systems [4]. For the indoor situation with high density of patients such as hospitals, sanitarium, and mental institution, if some emergency conditions happen to patients such as heart attack, cerebral hemorrhage, etc., wearable or even implantable body sensors can send distress signals via mobile devices. Thus, a high-resolution localization method is needed to monitor and track multiple patients simultaneously. Then, the location information can be delivered to the emergency personnel in time. If the position of patient is not known, the rescue time could be delayed. The patient may fall into dangerous condition, which could even endanger live.

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A. Related Work

CodeBlue, a commonly used software infrastructure, developed by Harvard University to address the problem of sensor nodes’ extreme resource limitations, is regarded as the beginning of sensor network used in emergency response. Based on MoteTrack, a robust radio frequency (RF)-based localization system, the rescuers could determine patients’ locations within a building and track them using RSSI method [5]. Then, a real-time patient monitoring system has been constructed based on CodeBlue. For outdoor location, the GPS is used to provide geolocation; for indoor location, the MoteTrack system is adopted. However, one patient has to be taken care by one doctor, which means that the wireless network has to be established by the emergency doctor manually one after another. Moreover, MoteTrack needs to install three location beacons to locate the patient, and the location region was limited [6]. The Fleck Nano wireless sensor platform for mobile inertial movement sensing has been used to locate a patient and monitor their physical status in an indoor environment. In addition, it consumes minimal computation resources that can be used to complement other sensor platforms [7]. However, only one patient can be monitored and tracked at one time. A wireless wearable sensing system of real-time monitoring patients within a building on a continuous basis is designed in [2]. The sensors that collect data of the patient are integrated to a necklace worn by each patient. The tracking routers are installed at strategic points inside the building. However, this system is only suitable for indoor localization. Bluetooth is another wireless technology for connecting devices and exchanging data over short distances. Bluetooth cell-based positioning has been proposed, and the device can be located in the cell area of which Bluetooth signal is detected to be the strongest [8]. Bluetooth beacons and a pedestrian dead reckoning technique have been fused to provide meter-level positioning without additional infrastructure. However, the effective distance is restricted [8], and the estimation accuracy is not high [9]. The RFID technology is used to locate patients in different areas [10]. However, the handheld RFID reader is needed as the gateway. An accurate vehicle self-localization method has been proposed based on extended finite impulse response filtering [11], this method can be applied to patient tracking as well. However, the location region is still limited. Patient tracking systems for the use in the pediatric emergency department are systematically reviewed in [12]. Also, a patient-tracking system for emergency departments is evaluated in [13].

For direction-of-arrival (DOA) estimation, receivers are designed to receive the signals transmitted by the mobile devices carried by the patients. However, different mobile devices may use different modulation modes. The signals of widely used modulation modes, such as BPSK and AM, are noncircular signals. Their unconjugated covariance matrix is not equal to zero. This is different from the QAM and QPSK signals, i.e., circular signals. Thus the unconjugated covariance matrix of noncircular signals can be utilized to improve the performance of DOA estimation. To the best of our knowledge, the algorithm that can handle the general case in which both circular and noncircular sources coexist is first proposed in [14]. It is based on the well-established MUSIC algorithm [15]. By exploiting the difference between the circularity of noncircular and circular signals, the maximum number of detectable directions by the method proposed in [16] is twice that by MUSIC. However, the noncircular signals amount to the maximal noncircularity rated signals in this paper [14]–[16]. These algorithms cannot estimate the direction-of-arrivals (DOAs) of the common noncircularity rated signals with high accuracy.

The RSSI method has been used for indoor positioning [5]. However, the attenuation of the signal strength could be changed due to the complex condition of the channel, i.e., disaster scene. The estimation accuracy of patient’s location could be severely degraded. TOA [17] is a method that tries to estimate the patient’s position based on the travel time of a signal. However, clock synchronization is one of the challenges involved in the TOA. In [18], a novel algorithm based on DOA estimation has been proposed for the localization of partial-discharge (PD) sources in substations. Planar location of PD sources can be obtained by solving the intersecting point of two lines coming from two different DOAs. The time difference in TDOA estimation [19] is replaced by the phase difference in DOA estimation. The benefit of DOA or TDOA compared to TOA is that only the anchor nodes’ phases (clocks) needs to be synchronized between each other. Compared with the RSSI method, the different attenuations of the signal strengths almost not affect the estimation result of patient’s location. Thus, the DOA estimation algorithm reported in this paper can also be applied in the localization of PD sources.

B. Contribution

In [18], two arrays are utilized to locate the patient’s position. However, the mirror ambiguity exists, which means that when the DOAs of incident signals are estimated, the signals may come from both sides of ULA. In this paper, based on angulation positioning method, an improved patient tracking method is proposed based on three receivers (ULAs), and the mirror ambiguity is avoided. However, different mobile devices of patients may use different modulation modes such as BPSK (noncircular signals) and QPSK (circular signals). In order to execute the patient tracking method in places with high density of patients, a high-resolution DOA estimation algorithm for the noncircular (the maximal and common noncircularity rated) and circular signals is proposed. Different types of signals are estimated separately. The angular resolution is improved, which means more patients can be tracked. The performance of the proposed algorithm is evaluated extensively by simulation and real tests. When signal-to-noise ratio (SNR) and snapshot number are 3 dB and 300, respectively, the computation time of the proposed algorithm is about 0.12 s. The presumably spatial resolution of tracking is about 4°, which means we can distinguish two patients when their distance is longer than 0.6 m (patient density is about one person per square meter).

C. Notation

In this paper, the operator $(·)^*$, $(·)^T$, $(·)^H$, $(·)^\dagger$, and $E\{·\}$ denote conjugate, transpose, conjugate transpose, Moore–Penrose inverse, and expectation, respectively. The boldface letters are
reserves for matrices and vectors. $(\cdot)_{ii}$ is the diagonal entry at the $i$th row and $i$ column of a matrix. $(\cdot)_{nm}$ and $(\cdot)_{in}$ are the matrix or vector corresponding to the maximal and common noncircularity rated signals. $I_M$ is an $M \times M$ identical matrix.

**D. Outline**

This paper is organized as follows. The system architecture and localization method are elaborated in Section II. The high-resolution DOA estimation algorithm is proposed in Section III. The simulation and real test verification are given in Section IV. The conclusions are drawn in Section V.

**II. SYSTEM ARCHITECTURE AND LOCALIZATION ALGORITHM**

**A. System Architecture**

Wearable or even implantable body sensors have been widely used to monitor the health status of patients or elderly people, which bridge the physical world and electronic systems. These wearable and implantable body sensors form the body sensors networks; acceleration, pulse oximetry, electroencephalogram, ECG, electromyogram, blood pressure, and some other physiological signals can be recorded by their corresponding sensors. Then, all the recorded data are delivered to the gateway such as mobile phone, mobile device, etc. [20]. The system architecture has been demonstrated in [21]. In the patient tracking system, as receivers contain multiple antenna elements, thus the smart antenna (SA) technique is adopted. The advantage of the SA technique is that the DOAs of multiple patients can be estimated simultaneously as shown in Fig. 1. Receivers are deployed on the top of buildings (hospitals, nursing home), which are far from the patients. The advantage of this deployment is that the signals transmitted by the gateway can be delivered to the receivers based on 5G-link. Then, the data received by the receivers would be delivered to a DPC. The cloud computation technique can be used in the DPC. This system can be used to monitor and track the patients who have mental or Alzheimer’s diseases as well. These patients could not remember the way to home and cause other problems. The caregivers can find them easily based on this patient tracking system.

**B. Localization Algorithm**

Based on the angulation positioning method [22], when any two receivers receive the signal sent by the mobile device, the position of the patient could be located. The mobile device sends signal in a fixed time interval; then, the position of the patient can be tracked. Each patient has a unique ID; thus, multiple patients can be distinguished. If the elevation estimation is ignored and only azimuth estimation is considered, then any two receivers can give two distinguishing directions. The intersecting point of two rays from different directions measured by two receivers in the identical plane can be regarded as the patient’s location. However, the mirror ambiguity exists in this method as given in [18].

Three receivers (ULAs) are installed at the top of buildings. Assume the projection of patient in the plane of ULAs is $S'$. The reference points of three ULAs are A, B, and C, respectively. Due to the mirror ambiguity, the incident signal may come from two sides of ULA; this can be seen in Fig. 2. The intersecting point of two rays can be regarded as the location of patient’s location in principle. It can be seen that $S'$ is the intersecting point of two rays as well. However, $S'$ is not the actual location of patient. Thus, another ULA is arranged to estimate the DOA of incident signal in order to confirm the actual location of patient. $S$ is the intersecting point of three rays, which is regarded as the actual location of patient.

$\theta_1$, $\theta_2$, and $\theta_3$ can be estimated by using the algorithm proposed in Section III. The coordinates of reference points A, B, and C corresponding to ULA1, ULA2, and ULA3 are $(0,0)$, $(0,y_B)$, and $(x_C,0)$, respectively. It can be shown that $S'$ is the actual position of patient, and $S''$ is a fake one. Based on the measurements of ULA1 and ULA2, we have

$$\tan \theta_1 = \frac{y}{x}, \quad \tan \theta_2 = \frac{y - y_B}{x}. \quad (1)$$

Then, the coordinates of $(x_{S''},y_{S''})$ can be calculated as

$$x = \frac{y_B}{\tan \theta_1 - \tan \theta_2}, \quad y = \frac{y_B \tan \theta_1}{\tan \theta_1 - \tan \theta_2}. \quad (2)$$

Based on the measurements of ULA1 and ULA3, the coordinates of $(x_{S'},y_{S'})$ can be calculated as

$$x = \frac{1}{1 + \tan \theta_1 \tan \theta_3} x_C, \quad y = \left( \frac{\tan \theta_1}{1 + \tan \theta_1 \tan \theta_3} \right). \quad (3)$$
If $\mathbf{s}$ is the actual position of the patient, then (2) is equal to (3). On the other hand, the calculated coordinates of the fake patient do not satisfy these conditions. Hence, the actual position of the patient can be decided with three ULAs together.

### III. DOA Estimation With High Resolution for Circular and Noncircular Signals

For the reason that the modulation modes among different mobile devices carried by patients may be different because of the different equipment suppliers, a high-resolution DOA estimation algorithm for noncircular and circular signals is proposed, which can simultaneously track multiple patients with mobile devices using different modulation modes and make the patient tracking system suitable for places with high patient density.

When the incident signals comprise noncircular signals (include the maximal and common noncircularity rated signals) and circular signals, the noncircular characteristic of the non-circular signals can be used for estimating the DOA of different types in turn.

Assume $q$ uncorrelated narrowband sources impinge on the ULA with $M$ elements, and the distance between adjacent elements is $d$. The received data vector $\mathbf{x}(t)$ at time $t$ is given by

$$\mathbf{x}(t) = \mathbf{A}s(t) + \mathbf{n}(t)$$

where $\mathbf{A} = [a_1, a_2, \ldots, a_q]$ is the $M \times q$ steering matrix, $s(t) = [s_1(t), s_2(t), \ldots, s_q(t)]$ is a $q \times 1$ signal vector and $\mathbf{n}(t)$ is the $M \times 1$ additive white Gaussian noise vector with zero means and variance $\sigma_n^2$. The steering vector of the $i$th signal is $a_i(\theta_i) = [1, e^{j \theta_i}, \ldots, e^{j(M-1)\theta_i}]^T$, and $\theta_i = \frac{\pi d \sin \theta_i}{\lambda}$, where $\lambda$ is the wavelength of the incident signals.

According to the received data vector $\mathbf{x}(t)$, the covariance matrix of $\mathbf{x}(t)$ is expressed as

$$\mathbf{R} = \mathbb{E}\{\mathbf{x}(t)\mathbf{x}^H(t)\} = \mathbf{A} \mathbf{R}_s \mathbf{A}^H + \sigma_n^2 \mathbf{I}_M$$

where $\mathbf{R}_s$ is the signal covariance matrix.

$$\mathbf{U}_N^H \mathbf{a}(\theta_i) = 0, i = 1, 2, \ldots, q.$$ Obviously, when $\theta \neq \theta_i, i = 1, 2, \ldots, q$, we have $\mathbf{a}^H(\theta) \mathbf{U}_N \neq 0$. Based on the orthogonality between signal and noise subspace, the conventional MUSIC estimator involves minimizing its null-spectrum function

$$f(\theta) = \|\mathbf{a}^H(\theta) \mathbf{U}_N\|_F^2 = \mathbf{a}^H(\theta) \mathbf{U}_N \mathbf{U}_N^H \mathbf{a}(\theta).$$

The spatial spectrum can be expressed as

$$f(\theta) = \frac{1}{\mathbf{a}^H(\theta) \mathbf{U}_N \mathbf{U}_N^H \mathbf{a}(\theta)}$$

where $\mathbf{U}_N$ is the estimator of noise subspace. This is the conventional MUSIC algorithm.

For noncircular signal $s$, it holds that $\mathbb{E}\{s(t)s^*(t)\} = \rho \mathbf{e}^{j\beta}$, $\mathbb{E}\{s(t)s(t)^*\}$, in which $\beta$ is the noncircularity phase, $\rho$ is the noncircular rate. $\rho = 1, 0 < \rho < 1$, and $\rho = 0$ stands for the maximal noncircularity rated signal, the common noncircularity rated signal, and circular signal, respectively.

The signal vector $s(t)$ consists of $q$ signals; its unconjugated covariance matrix $\mathbf{R}'_s = \mathbb{E}\{s(t)s^T(t)\}$ is defined as

$$\mathbf{R}'_s = \mathbb{E}\{s_1(t)s_1(t)^*\}, \ldots, \mathbb{E}\{s_q(t)s_q(t)^*\}$$

$$= \rho \mathbf{e}^{j\beta} \mathbb{E}\{s_1(t)s_1^*(t)\}, \ldots,$$

$$\times \rho \mathbf{e}^{j\beta} \mathbb{E}\{s_q(t)s_q^*(t)\} \overset{\Delta}{=} \mathbf{PBR}_s$$

where $\mathbf{P}$ is a diagonal matrix, whose diagonal entries are the noncircularity rates of the $q$ signals and is defined as $\mathbf{P} = \mathbb{E}\{\rho_1, \rho_2, \ldots, \rho_q\}$. $\mathbf{B}$ is a diagonal matrix, whose diagonal entries are the noncircularity phases of the $q$ signals, and is defined as $\mathbf{B} = \mathbb{E}\{\exp(j\beta_1), \exp(j\beta_2), \ldots, \exp(j\beta_q)\}$.

In particular, when the $q$ signals are all maximal noncircularity rated signals, the noncircularity rate matrix satisfies $\mathbf{P} = \mathbf{I}_q$; when the $q$ signals are all circular signals, the noncircularity rate matrix satisfies $\mathbf{R}'_s = 0$.

According to (4) and (7), the unconjugated covariance matrix $\mathbf{R}'$ of the received data vector $\mathbf{x}(t)$ is expressed as

$$\mathbf{R}' = \mathbb{E}\{|\mathbf{x}(t)\mathbf{x}(t)^T|\} = \mathbf{A} \mathbf{R}_s \mathbf{A}^H + \mathbb{E}\{\mathbf{n}(t)\mathbf{n}^T(t)\}$$

$$= \mathbf{APBR}_s \mathbf{A}^H.$$  

(8)

In practical situations, the maximum likelihood of covariance and the unconjugated covariance matrices are, respectively, estimated by

$$\hat{\mathbf{R}} = \frac{1}{L} \sum_{l=1}^{L} \mathbf{x}(t)\mathbf{x}^H(t), \quad \hat{\mathbf{R}}' = \frac{1}{L} \sum_{l=1}^{L} \mathbf{x}(t)\mathbf{x}^T(t).$$

(9)

### A. DOA Estimation for Common Noncircularity Rated Signals

The number of the maximal noncircularity rated signals, common noncircularity rated signals and circular signals are $q_{nn}, q_{nn} + q_c$, and $q_c$, respectively, and they satisfy $q_{nn} + q_{nn} + q_c = q$. According to (8), the unconjugated covariance matrix $\mathbf{R}'$ of the received data vector $\mathbf{x}(t)$ is rewritten as $\mathbf{R}' = \mathbf{A} \mathbf{R}'_s \mathbf{A}^H = \mathbf{APBR}_s \mathbf{A}^H.$ Then, a Hermite matrix can be constructed as $\mathbf{R}' \mathbf{R}'^H = \mathbf{A} \mathbf{R}'_s \mathbf{A}^H$, where $\mathbf{R}'_s = \mathbf{PBR}_s \mathbf{A}^H$. It can be seen that when the number of incident signals satisfies $q_{nn} + q_{nn} \leq M - 1$, the rank of matrix $\mathbf{R}'$ satisfies $\text{rank}\{(\mathbf{R}' \mathbf{R}'^H)\} = q_{nn} + q_{nn} \leq M - 1$, i.e., $\mathbf{R}'$ is not a full-rank matrix. The SVD is taken on the unconjugated covariance matrix $\mathbf{R}'$, which can be expressed as

$$\mathbf{R}' = \mathbf{Q}_1 \mathbf{A} \mathbf{Q}_2^H = [\mathbf{Q}_1 \mathbf{Q}_2^H] \begin{bmatrix} \mathbf{A}_s & 0 \\ 0 & \mathbf{Q}_2^H \end{bmatrix}$$

(11)

where $\mathbf{Q}_1$ and $\mathbf{Q}_2$ stand for the left and right singular eigenvectors of the matrix $\mathbf{R}'$, respectively. $\mathbf{A}_s$ is a diagonal matrix
whose diagonal entries are constructed by \(q_{\text{nn}} + q_{\text{mn}}\) nonzero singular values. Then, matrix \(R' R^{-H}\) can be rewritten as

\[
R' R^{-H} = [Q_{N1} Q_{N1}^T] \begin{bmatrix} A_0^2 & 0 \\ 0 & Q_{N1}^2 \end{bmatrix}.
\]  

(12)

According to (10) and (12), it can be found that the spaces span \(\{Q_{N1}\}\) and span \(\{A_{\text{mn}} A_{\text{nn}}\}\) are orthogonal based on the orthogonality principle of MUSIC algorithm. Then, the spatial spectrum function \(f_{\text{nc}}(\theta)\) can be constructed as

\[
f_{\text{nc}}(\theta) = a^H(\theta) Q_{N1} Q_{N1}^T a(\theta).
\]  

(13)

This estimated result is regarded as the low DOA estimation, i.e., \(\hat{\theta}_{\text{nc}} = \{\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_{q_{\text{mn}} + q_{\text{nn}}}\}\). For the common noncircularity rated signals, the corresponding manifold matrix is orthogonal to both matrices \(Q_{N1}\) and \(U_{N1}\); thus, the matrix \(W\) is constructed as \(W = [Q_{N1} U_{N1}^T]\). Then, the relationship between the manifold matrix \(A_{\text{nn}}\) for the common noncircularity rated signals and the matrix \(W\) satisfies \(A_{\text{nn}} W^H W = 0\).

In order to improve the estimated accuracy, the column space of the matrix \(W\) needs to be combined, and the unit orthogonalization is taken for the column space. The dimension of the matrix \(W\) is \(M \times (3M - 2q_{\text{nn}} - 3q_{\text{mn}} - 2q_c)\). The SVD is taken on \(W\), i.e., \(W = W_1 A_{\text{nn}}^H\), where the \(M \times M\) matrix \(W_1\) and the \((3M - 2q_{\text{nn}} - 3q_{\text{mn}} - 2q_c) \times (3M - 2q_{\text{nn}} - 3q_{\text{mn}} - 2q_c)\) matrix \(W_2\) are the left and right singular eigenvectors of the matrix \(W\), respectively. Then, the matrix \(W_1\) can be partitioned into block matrices as \(W_1 = [W_{11} W_{12}]\). It can be shown that \(W_{11}\) is orthogonal to the manifold matrix of the common noncircularity rated signals, i.e., \(A_{\text{nn}} W_{11} = 0\). The dimension of the matrix \(W_{11}\) is \(M \times w\), where \(w\) satisfies \(w = \min\{3M - 2q_{\text{nn}} - 3q_{\text{mn}} - 2q_c, M - q_{\text{nn}}\}\). Thus, (13) is satisfied. The spatial spectrum function for the common noncircularity rated signals can be constructed as

\[
f_{\text{nc}}(\theta) = a^H(\theta) W_{11} W_{11}^H a(\theta).
\]  

(14)

According to the \(q_{\text{nn}}\) minimum values obtained by searching (14), the \(q_{\text{nn}}\) DOAs of the common noncircularity rated signals is obtained. The estimated accuracy and resolution performance of spatial spectrum function given in (14) is higher than that of the spatial spectrum function given in (13).

### B. DOA Estimation for Circular Signals

By eliminating the information of noncircular signals in the extended covariance matrix \(R_y\), the DOA of circular signals can be estimated. According to the spatial spectrum function given in (14), the \(q_{\text{nn}}\) DOAs for the common noncircularity rated signals can be estimated as \(\hat{\theta}_{\text{nc}} = \{\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_{q_{\text{nn}}}\}\). Thus, the manifold matrix for the common noncircularity rated signals can be constructed as \(A_{\text{nn}} = A(\hat{\theta}_{\text{nc}})\). According to \(\hat{\theta}_{\text{nc}}\), eliminating \(q_{\text{nn}}\) estimator of the common noncircularity rated signals given in \(\hat{\theta}_{\text{nc}}\), the low-accuracy DOA estimations of \(q_{\text{mn}}\) maximal noncircularity rated signals can be obtained as \(\hat{\theta}_{\text{mn}} = \{\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_{q_{\text{mn}}}\}\).

The low-accuracy manifold matrix estimation of \(q_{\text{mn}}\) maximal noncircularity rated signals can be obtained \(\hat{A}_{\text{nn}} = A(\hat{\theta}_{\text{mn}})\). The matrix \(\hat{A}_{\text{nc}}\) can be defined as \(\hat{A}_{\text{nc}} = [A_{\text{nn}} A_{\text{nn}}]\). The pseudoinverse of matrices \(\hat{A}_{\text{nc}}\) and \(\hat{A}_{\text{nc}}^+\) can be, respectively, found in [16, eq. (17)]. Based on the property of pseudoinverse matrix, \(R'S\) can be partitioned into block matrices as follows:

\[
R'S = (\hat{A}_{\text{nc}}^{-1})^H R' (\hat{A}_{\text{nc}}^+) = [R_1, R_2, R_3, R_4]
\]  

(15)

where \(R_1\) is \(q_{\text{mn}} \times q_{\text{nn}}\) matrix and \(R_2\) is \(q_{\text{nn}} \times q_{\text{nn}}\) matrix. Then, the unconjugated covariance matrix of the common noncircularity rated signals can be estimated as \(\hat{R}_{\text{nn}} = R_4\).

Assuming the noncircularity rated matrix of the noncircular signals is estimated as \(\hat{P}_{\text{nn}}\). Then, the covariance matrix of the common noncircularity rated signals can be estimated as \(\hat{S}_{\text{nn}}(\hat{\theta}_{\text{nc}})_{ii} = \|\hat{P}_{\text{nn}} R_4\|\).

**Remark 1:** The noncircularity rate of the noncircular signals is related to the modulation mode of the signals, e.g., BPSK signal (noncircular one with noncircularity rate of 1), QPSK signal (circular one with noncircularity rate of 0), and UQPSK signal (the common noncircularity rated signal). Since each patient has unique ID, and the information of all patients’ IDs have already stored in the DPC, the information of the modulation mode and noncircularity rate can be embedded in the ID. The receiver can identify ID, which contains the information of the modulation mode and noncircularity rate. Then, the noncircularity rate can be confirmed uniquely.

Based on the estimation manifold matrix \(\hat{A}_{\text{nn}}\), the covariance matrix \(\hat{R}_{\text{nn}}\) and the unconjugated covariance matrix \(\hat{R}_{\text{nn}}\) for the common noncircularity rated signals can be, respectively, estimated as

\[
\hat{R}_{\text{nn}} = \hat{A}_{\text{nn}}\left\|\begin{bmatrix} \hat{P}_{\text{nn}} R_4 \\ \hat{R}_{\text{nn}} \end{bmatrix} \right\|^H \hat{P}_{\text{nn}} R_4 \hat{A}_{\text{nn}}^T.
\]  

(16)

In order to eliminate the effect of the information about the common noncircularity rated signals in the extended covariance matrix \(R_y\), the matrix \(\hat{R}_{\text{nn}}\) can be constructed as

\[
\hat{R}_{\text{nn}} = \begin{bmatrix} \hat{R}_{\text{nn}} \end{bmatrix}^T \begin{bmatrix} \hat{R}_{\text{nn}} \end{bmatrix}.
\]  

(17)

Then, a difference matrix \(R_y - \hat{R}_{\text{nn}}\) can be defined as \(R_y - \hat{R}_{\text{nn}}\). It can be found that the matrix \(R_y - \hat{R}_{\text{nn}}\) only contains the information about the maximal noncircularity rated signals and circular signals. The SVD of the matrix \(R_y - \hat{R}_{\text{nn}}\) is taken as \(R_y - \hat{R}_{\text{nn}} = \hat{U}_N \Sigma_N \hat{U}_N^H + \sigma^2 \tilde{U}_N \tilde{U}_N^H\). The matrix \(\hat{U}_N\) is partitioned into two block matrices \(\hat{U}_N = [\hat{U}_{N1}^T, \hat{U}_{N2}^T]^T\).

The spatial spectrum function of circular signals can be constructed as

\[
f_c(\theta) = a^H(\theta) \hat{U}_{N1} \hat{U}_{N1}^H a(\theta).
\]  

(18)

According to (18), the DOAs of \(q_c\) circular signals can be obtained. The information of the common noncircularity rated signals is eliminated from the extended covariance matrix \(R_y\) in [23]. The array aperture extension is achieved, and the effect that
the common noncircularity rated signals impact on the circular signals is eliminated as well. Thus, both the estimated accuracy and the angular resolution are improved.

C. DOA Estimation for Maximal Noncircularity Rated Signals

For the maximal noncircularity rated signals, it should be noted that the extended steering vectors satisfies
\[
\begin{bmatrix}
a_i(\theta) \\
e^{-j\beta_i}a_i^*(\theta)
\end{bmatrix}^H
\begin{bmatrix}
\bar{U}_{N1} \\
\bar{U}_{N2}
\end{bmatrix} = 0, \quad i = 1, 2, \ldots, q_{nm}. \tag{19}
\]

The DOAs of the maximal noncircularity rated signals lead to the minimum values of the dimension reduction spatial spectrum function given in [23, eq. (12)], i.e.,
\[
f(\theta) = a^H(\theta)\bar{U}_{N1}\bar{U}_{N1}^H a(\theta) - ||a^T(\theta)\bar{U}_{N2}\bar{U}_{N1}^H a(\theta)||. \tag{20}
\]

Then, the minimum values of (20) are corresponding to the DOAs of the circular signals. In order to eliminate the effect of circular signals, (13) is used, which is not suitable for the circular signals, i.e., the orthogonality relationship \(a^H(\theta)Q_{N1} = 0\) between the steering vectors for the circular signals and the component noise space is not held. Thus, the spatial spectrum function for the maximal noncircularity rated signals can be constructed as
\[
f_{nm}(\theta) = a^H(\theta)\left(\bar{U}_{N1}\bar{U}_{N1}^H + Q_{N1}Q_{N1}^H\right)a(\theta) - ||a^T(\theta)\bar{U}_{N2}\bar{U}_{N1}^H a(\theta)||. \tag{21}
\]

Thus, the DOA estimation for the common noncircularity rated, circular and maximal noncircularity rated signals is completed finally.

Remark 2: The proposed method needs knowing the number of the tracking patients to partition the noise subspace and signal subspace correctly. The method proposed in Remark 1 can estimate the number of patients, since each mobile device carried by a patient has a unique ID. We can know the source number when multiple signals simultaneously arrive at the ULA. Thus, the pseudocode of TUL can be summarized as in Algorithm 1.

However, compared with the traditional NC-MUSIC algorithm, there is a limitation in TUL. If the DOAs of maximal and common noncircularity rated signals cannot be estimated correctly based on (13), TUL cannot estimate three types of signals effectively. Thus, based on the relationship between source number and the number of elements of traditional NC-MUSIC algorithm, an extra restriction is needed, i.e., the source number has to satisfy
\[
\begin{aligned}
q' &= q_{nm} + 2(q_e + q_{nn}) \leq 2M - 2 \\
q_{nm} + q_{nn} &\leq M - 1.
\end{aligned} \tag{22}
\]

In theory, three receivers can satisfy the requirement for indoor localization and tracking of patients. However, more receivers should be deployed to guarantee the stability of the system. For outdoor localization and tracking of patients, adequate receivers should be deployed in the region of the place where the patients could go.

Algorithm 1:

1: Input: the snapshot data \(x_i(t), t = 1, \ldots, L\) received by ULA_i, \(i = 1, \ldots, L\) respectively;
2: for \(i = 1 \text{ to } 3\) do
3: judge the modulation mode and estimate the number of the tracking patients(signals) based on Remark 1;
4: Estimate the DOAs \(\hat{\theta}_{i1}, \ldots, \hat{\theta}_i\) of common noncircularity rated signals according to (14);
5: Estimate the DOAs \(\hat{\theta}_{c1}, \ldots, \hat{\theta}_{c2}\) of circular signals according to (18);
6: Estimate the DOAs \(\hat{\theta}_{m1}, \ldots, \hat{\theta}_{mnm}\) of maximal noncircularity rated signals according to (21);
7: end for
8: For one of common noncircularity rated signals transmitted by the mobile device of patients, we can obtain three DOAs \(\hat{\theta}_i, i = 1, \ldots, 3\) from ULA_i, \(i = 1, \ldots, 3\). Calculate the patient’s location according to (2) and (3);
9: Compare the results of (2) and (3). If they are approximately equal to each other, their average value can be regarded as the actual location; if not, it is a fake location. The locations of other patients whose mobile devices transmit common noncircularity rated, circular and maximal noncircularity rated signals can be calculated in the same way.
10: Output: All the positions of patients.

D. Computational Complexity Analysis

We just count the complex multiplication for comparison. For the SCS method stated in [24, Table I], the main computational complexity focuses on Step 2 and the log-likelihood function of (15). For Step 2, it is equivalent to solve a compressed sensing based problem, which can be solved by the simple orthogonal matching pursuit (OMP) algorithm. In each iteration of OMP, we need to solve a least square problem. This would cost \(M^3\), where \(M\) is the number of sensors. \(M\) linear searches are needed as well, this would cost \(J^2\) complex multiplication. For (15), we need to solve a least square problem and perform two matrix multiplications. It would cost \(M^3 + M^2L + (J_0)^2 + M(J_0)^2\), where \(L\) is snapshot number and \(J_0\) is the estimation source number of the \(i\)th iteration. The total computational complexity of SCS is the sum of all the iterations, i.e.,
\[
\sum_{i=1}^{J}[(P + 1)M^3 + PMN + M^2L + (M + 1)(J_0)^2].
\]

For MUSIC, the computational complexity mainly focuses on SVD and spectrum peaking search. The SVD would cost \(M^3\), and the spectrum peaking search would cost \(\lambda(M + 1)(M - q)\), where \(\lambda\) is the number of spectral points of the total angular field of view and \(q\) is the source number. Thus, the total computational complexity of MUSIC is \(M^3 + \lambda(M + 1)(M - q)\). For NC-MUSIC, the only difference
from MUSIC is that the array aperture of NC-MUSIC is twice of that of MUSIC. Thus the total computational complexity of MUSIC is $2(M^3 + J(M+1)(M-q))$. For the proposed HRNC-MUSIC, the computational complexity mainly focuses on SVD, spectrum peaking search, and matrix multiplications. The SVD would cost $M^3 + M^3 + (2M)^3 = 218M^3$. The matrix multiplications would cost $M^3 + M^2L + 4(M-1)^2L + 3(q_{thm} + q_{nn})^2M$. The spectrum peaking search would cost $J(M+1)(M-q_{thm}) + J(M+1)w + J(M+1)(M-q_{thm}) + 3J(M+1)(M-q_{thm}) = J(M+1)(5M-q-3q_{thm})$. Thus, the total computational complexity of HRNC-MUSIC is $19M^3 + J(M+1)(5M-q-3q_{thm}) + M^2L + 4(M-1)^2L + 3(q_{thm} + q_{nn})^2M$.

For ESPRIT, the computational complexity mainly focuses on SVD and matrix multiplications. The SVD of $(M-1) \times (M-1)$ matrix would cost $[2(M-1)]^2$. Another matrix multiplication and the pseudoinverse of matrix would cost $(M-1)^2q + Mq^2$. Thus, the total computational complexity of ESPRIT is $8(M-1)^3 + (q + 4)(M-1)^2 + Mq^2$.

Since $N > J \gg L > M > q$, we can know that the descending order of computational complexity of different algorithms is $SCS > HRNC - MUSIC > NC - MUSIC > MUSIC > ESPRIT$.

### E. Cramér–Rao Bound (CRB) Versus Noncircularity Rate

CRB plays an important role in parametric estimation because the statistical performances of numerous estimation methods are known to be comparable with these bounds under certain mild conditions. CRB for noncircular sources has been given by [28, eq. (3.9)]. However, this result cannot reflect the relationship between CRB and noncircularity rate explicitly. When we only consider one source (patient), we have

$$C_{\theta_1} = \frac{1}{\alpha_1} \left[ \frac{2r_1^{-1} + \|a_1\|^2 r_1^{-2} + \|a_i\|^2 - \|a_1\|^2 \rho_1^2}{\|a_1\|^2 r_1 + 1 + \left(1 - \|a_1\|^2 r_1\right) \rho_1^2} \right]$$

where $\rho_1$ is the noncircularity rate and satisfies $0 \leq \rho_1 \leq 1$, the SNR is defined by $r_1 = \sigma_1^2 / \sigma_n^2$, and $\alpha_1$ is the purely geometrical factor $2a_1^HY_n \Pi a_1' \Pi \alpha_1 \alpha_1'$. In (23), we can know the relationship between CRB and noncircularity rate explicitly. We can derive that the CRB for a noncircular source decreases monotonically as the noncircularity rate increases as follows.

Equation (23) may be written as the following function of $x = \|a_1\|^2 r_1$:

$$C_{\theta_1} = \frac{\|a_1\|^2}{\alpha_1 c} \left( -1 + \frac{a + b}{b + \rho_1^2} \right)$$

with $a = \frac{(1+x)^2}{x^2}, b = \frac{1+x}{1-x}$, and $c = 1 - x$. According to $(a + b)/c = (1 + x)/x^2(1 - x)^2 > 0, C_{\theta_1}$ is a decreasing function of $\rho_1$.

Consequently, for one source, the CRB decreases from $C_{\theta_1} = (1/\alpha_1 r_1)(1 + \|a_1\|^2 r_1)$, ($\rho_1 = 0$ circular case) to $C_{\theta_1} = (1/\alpha_1 r_1)(1 + 1/2\|a_1\|^2 r_1)$, ($\rho_1 = 1$ BPSK case).

### IV. Simulation and Real Test Verification

In this section, numerical results based on MATLAB are shown to demonstrate the performance of the proposed algorithm. In addition, results from a real test of the proposed algorithm are also provided. Assume the uncorrelated narrowband far field incident signals impinge on the ULA (receiver), and the distance between adjacent elements is half a wavelength.

The sparse representation-based method, SCS [24], MUSIC, conventional NC-MUSIC, and ESPRIT algorithm are used for performance comparison with the proposed algorithm, referred to as HRNC-MUSIC. The number of independent trials is $100$. The range of SNR is from 0 to 10 dB. For SCS, the log-likelihood function threshold is fixed at $h_0 = 0.5337$, the size of discrete grids is 180, the probability of false alarm is $10^{-3}$, the regularization parameter is 1, the coarse and fine search resolution is $1^\circ$ and $0.001^\circ$, respectively. For MUSIC, conventional NC-MUSIC and HRNC-MUSIC algorithms, the search grid resolution is $0.01^\circ$. Compared with other algorithms, more parameters are needed to be set for SCS.

#### A. DOA Estimated Accuracy

The DOA estimation accuracy of different algorithms is simulated and analyzed. The root-mean-square error (RMSE) of the estimated parameter $\hat{y}$ can be defined as

$$\text{RMSE}(y) = \sqrt{E[(y - \hat{y})^2]} \approx \sqrt{\frac{1}{L} \sum_{i=1}^{L} (y_i - \hat{y}_i)^2}$$

where $L$ is the number of independent trials. When the incident signal comprises multiple signals, the RMSE is defined as the average value of RMSEs of these signals, i.e., $\text{RMSE} = \frac{1}{L} \sum_{i=1}^{L} \text{RMSE}(\theta_i)$.

The DOA estimation performance curves of different algorithms versus SNR and snapshot number with large angular distance are depicted in Figs. 3 and 4, respectively. Assume that
the directions of two BPSK, one QPSK, and one UQPSK signal are 35°, 55°, 75°, and 95°, which, respectively, impinge on the ULA with five elements. The noncircularity phase of BPSK signals are 10° and 20°, respectively. In this case, the noncircularity phase and rated of UQPSK signal are 40° and 0.5, respectively.

The snapshot number is fixed at 500 in Fig. 3 and the SNR is fixed at 3 dB in Fig. 4.

It can be seen from Fig. 4 that the advantage of the HRNC-MUSIC algorithm is not obvious. The reason is that the spatial spectrum function of the preliminary DOAs does not have the advantage of the virtual array extension. When the relative effects of different types of signals in the received data are small, the NC-MUSIC algorithm still has better estimated performance. Since a discretization grid scheme is used in SCS, the RMSE of SCS is lowest of all based on the joint sparse recovery. The subarray of ESPRIT only exploits four elements, which leads to the poorest performance directly.

The DOA estimation performance curves of different algorithms versus angular distance is depicted in Fig. 7. The angular distance between BPSK signal 35° and QPSK 40° is increased gradually. Meanwhile, The angular distance between QPSK signal 80° and UQPSK signal 75° is increased gradually. The increased angular distance is 1°. The noncircularity phase of BPSK signal is 10°. Other parameters are identical with that of Fig. 3. From Figs. 5 and 6, it can be seen that the advantage of the HRNC-MUSIC algorithm is obvious. This phenomenon is mainly due to the fact that the DOAs of different types of signals are estimated separately. The effect among different types of signals is reduced by the HRNC-MUSIC algorithm. However, for the NC-MUSIC algorithm, different types of signals are estimated simultaneously, and the DOA estimation performance is severely affected by the effect among different types of signals. Regardless of the types of signals, the SCS can perform very well. This is because the support (DOAs) can be accurately recovered based on the mature convex optimization algorithms, even with small angular distances. However, the available array aperture of ESPRIT is smaller than that of MUSIC and HRNC-MUSIC, which lead to the largest RMSE. It can be seen that the RMSE of MUSIC is significantly larger than others with little snapshot (snapshot number less than 100). This is because the performance of MUSIC mainly depends on the two order statistic characteristic of received data, i.e., the covariance matrix calculated by snapshot data. When the snapshot number and the angular distance are both small, the randomness effect of noise is significantly. The noise subspace estimation is occasionally inaccurate. This may lead to the result of large RMSE of MUSIC. However, the ESPRIT exploits the signals subspace, which is not very sensitive to two order statistic characteristic of received data compared with MUSIC, to estimate DOAs. Thus, the RMSE of ESPRIT is smaller than that of MUSIC with small snapshot number and angular distance. In Figs. 3 and 4, the angular distance are larger than that in Fig. 6. In Fig. 5, the snapshot number is much larger than that in Fig. 6. When the snapshot number is large or the angular distance is large, the noise subspace estimation is more accurate than that of signal subspace. Thus, the RMSE of MUSIC is smaller than that of ESPRIT from Figs. 3 and 5.

The DOA estimation performance curves of different algorithms versus angular distance is depicted in Fig. 7. The angular distance between BPSK signal 35° and QPSK 40° is increased gradually. Meanwhile, The angular distance between QPSK signal 80° and UQPSK signal 75° is increased gradually. The increased angular distance is 1°. The noncircularity phase of BPSK signal is 10°. Other parameters are identical with that of Fig. 3. From Figs. 5 and 6, it can be seen that the advantage of the HRNC-MUSIC algorithm is obvious. This phenomenon is mainly due to the fact that the DOAs of different types of signals are estimated separately. The effect among different types of signals is reduced by the HRNC-MUSIC algorithm. However, for the NC-MUSIC algorithm, different types of signals are estimated simultaneously, and the DOA estimation performance is severely affected by the effect among different types of signals. Regardless of the types of signals, the SCS can perform very well. This is because the support (DOAs) can be accurately recovered based on the mature convex optimization algorithms, even with small angular distances. However, the available array aperture of ESPRIT is smaller than that of MUSIC and HRNC-MUSIC, which lead to the largest RMSE. It can be seen that the RMSE of MUSIC is significantly larger than others with little snapshot (snapshot number less than 100). This is because the performance of MUSIC mainly depends on the two order statistic characteristic of received data, i.e., the covariance matrix calculated by snapshot data. When the snapshot number and the angular distance are both small, the randomness effect of noise is significantly. The noise subspace estimation is occasionally inaccurate. This may lead to the result of large RMSE of MUSIC. However, the ESPRIT exploits the signals subspace, which is not very sensitive to two order statistic characteristic of received data compared with MUSIC, to estimate DOAs. Thus, the RMSE of ESPRIT is smaller than that of MUSIC with small snapshot number and angular distance. In Figs. 3 and 4, the angular distance are larger than that in Fig. 6. In Fig. 5, the snapshot number is much larger than that in Fig. 6. When the snapshot number is large or the angular distance is large, the noise subspace estimation is more accurate than that of signal subspace. Thus, the RMSE of MUSIC is smaller than that of ESPRIT from Figs. 3 and 5.
Obviously, it can be seen from Fig. 7 that when the angular distances among different types of signals are small, the RMSE of the HRNC-MUSIC algorithm is smaller than that of NC-MUSIC and MUSIC algorithm. When the angular distances achieve 16°, the DOA estimation performance of NC-MUSIC algorithm outperforms HRNC-MUSIC algorithm. For SCS, the multiresolution grid refinement method guarantees the estimation accuracy in all angular distance. Due to the array aperture loss of ESPRIT compared with other algorithms, it has the largest RMSE.

B. DOA Resolution Probability

In the previous subsection, it only reflects the estimated accuracy when the exact estimation is taken. In this subsection, the resolution probability of different algorithms is evaluated as well. The error estimation is defined as that the algorithm cannot exactly resolve two signals or the error of the DOA estimation is larger than 5°.

The resolution probability curves of different algorithms versus SNR and snapshot number are depicted in Figs. 8 and 9, respectively. In this simulation, the ULA with six elements is used and the directions of two BPSK and one UQPSK signals are 35°, 65°, and 85°, respectively. Other parameters are identical with that of Fig. 3. The snapshot number is fixed at 300 in Fig. 8 and the SNR is fixed at 3 dB in Fig. 9.

From Figs. 8 and 9, it can be seen that the resolution probability of different algorithms increases as the SNR and snapshot increase. The resolution probability of the HRNC-MUSIC algorithm is higher than that of the NC-MUSIC and MUSIC algorithms. The performance of the HRNC-MUSIC algorithm is stable at high SNR and large snapshot number. The resolution probability of SCS is larger than 90% even in low SNR. It performs the best among all algorithms. However, the resolution probability of ESPRIT is poor even in relatively high SNR. The resolution probability of SCS is larger than 85% even with 50 snapshot number, it performs the best among all. However, the resolution probability of ESPRIT is very low at small snapshot number. Even in large snapshot number, the resolution probability cannot reach 100%.

Assume that the directions of one BPSK, two QPSK and one UQPSK signals are 35°, 39°, 79°, and 75°, which, respectively, impinge on the ULA with six elements. Other parameters are identical with that of Fig. 7. Then, the angular distance between BPSK signal 35° and QPSK signal 39° is increased gradually. Meanwhile, the angular distance between QPSK signal 79° and UQPSK signal 75° is increased gradually. The increased angular distance is 1°. The snapshot number is fixed at 300 and the SNR is fixed at 3 dB. From Fig. 10, it can be seen that the resolution probability of different algorithms increases as the angular distance increases. However, compared with the NC-MUSIC and MUSIC algorithms, the effect among different types of signals has less effect on the HRNC-MUSIC, the resolution probability stabilizes at high level. The resolution probability of SCS is almost 100% at all angular distance. However, the resolution probability of ESPRIT reaches 100% when angular distance reaches 16°.

C. Averaged CPU Times

We evaluate the averaged CPU times of SCS method, HRNC-MUSIC algorithm and ESPRIT in the following experiment. Two QPSK signals impinge on the five-element ULA from −15° and 10°. The snapshot number is fixed at 300, and the SNR is fixed at 3 dB. The experiment is carried out in MATLAB.
D. Real Test of the Proposed Localization Algorithm

Table I presents the averaged CPU times of SCS method, HRNC-MUSIC algorithm, and ESPRIT. The SCS method is most time-consuming. While ESPRIT performs the worst of all, it costs the least time of all. Thus, the HRNC-MUSIC is chosen as the DOA estimation algorithm for patient’s localization, since it performs well in estimated accuracy and resolution probability, and it does not cost much time to execute the algorithm.

![Resolution probability versus SNR.](image)

**Fig. 10. Resolution probability versus SNR.**

**TABLE I**

<table>
<thead>
<tr>
<th>Method</th>
<th>CPU Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCS</td>
<td>1.555</td>
</tr>
<tr>
<td>HRNC-MUSIC</td>
<td>0.120</td>
</tr>
<tr>
<td>ESPRIT</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Time unit: seconds.

![Planar diagram of the receivers and patients.](image)

**Fig. 11. Planar diagram of the receivers and patients.**

v.8.3.0 on a PC with a Windows 7 system and a 3-GHz CPU. Table I presents the averaged CPU times of SCS method, HRNC-MUSIC algorithm, and ESPRIT. The SCS method is most time-consuming. While ESPRIT performs the worst of all, it costs the least time of all. Thus, the HRNC-MUSIC is chosen as the DOA estimation algorithm for patient’s localization, since it performs well in estimated accuracy and resolution probability, and it does not cost much time to execute the algorithm.

**D. Real Test of the Proposed Localization Algorithm**

In the previous subsections, the high-resolution performance of HRNC-MUSIC has been tested by simulation. In this subsection, it will be tested in real application. The real test is taken in microwave anechoic chamber. Its height, width, and length are 10, 18, and 5 m, respectively. TUL is compared with the TOA-based algorithm [17] to verify the effectiveness of TUL. A real test example is given in Fig. 11, which is the planar diagram of Fig. 1. Assume that the signals directly reach the receivers. Three receivers (A, B, and C) and 15 (P_i, i = 1, ..., 15) patients are considered for real test. The reference coordinates of the receivers are A(0, 6, 4)m, B(0, 3, 4)m, C(14, 0, 4)m, respectively. The height of these mobile devices is all 1 m. The positions of mobile devices of 15 patients are P_1(8, 3, 1.5)m and P_2(9, 4, 1.2)m, P_3(9, 5, 1.5)m, P_4(8, 4.5, 1.4)m, P_5(7, 4, 1.0)m, P_6(6, 3, 1.2)m, P_7(5, 2.5, 1.1)m, P_8(8, 5.5, 1.2)m, P_9(6, 5, 1.4)m, P_{10}(5, 4, 1.3)m, P_{11}(10, 3, 1.2)m, P_{12}(9, 2, 1.5)m, P_{13}(9.5, 1.1, 3)m, P_{14}(8, 1, 1.4)m and P_{15}(7, 1.5, 1.2)m, respectively. The array configurations of three receivers are five-element patch UCA with radius of 40 mm. The size of patch antenna is 1.25 cm × 1 cm. We use three AWG70000 series AWGs to generate 6-GHz RF signals. Three AWGs generate BPSK, QPSK, and UQPSK signals, respectively. The BPSK, QPSK, and UQPSK signals generated by three AWGs pass three power dividers, which divide one way signal into five ways. Then, five ways BPSK signals are transmitted to five patch antennas, which can model five BPSK signals (P_0 - P_5) generated by patients’ mobile devices. The five-way QPSK and five-way UQPSK signals are transmitted to ten patch antennas, which can model five QPSK signals (P_1 - P_5) and five UQPSK signals (P_{11} - P_{15}) generated by patients’ mobile devices. For the TUL method, the snapshot number is fixed at 100. For TOA localization, three sensors arranged at A, B, and C, respectively, are used to locate the patient’s location based on trilateration, whose detail can be found in [25, Fig. 1]. The two-way ranging method [26] is used to measure the distance between A (B, C) and patient. The waiting time t_reply at patient is 20 μs, A round time t_round at A, B, and C is 100 μs. The frequency of crystal is 125 MHz.

We just give the localization result of P_1 and P_2, the localization accuracy from P_3 to P_{15} is similar to that of P_1 and P_2. Theoretical values of azimuth angles are ϕ_A = −20.56°, ϕ_B = 16.32°, ϕ_C = 7.13°, θ_A = 17.35°, θ_B = 63.43°, θ_C = 20.46°, and ϕ_{A1} = −12.53°, θ_{A1} = 16.89°, ϕ_{B1} = 12.53°, θ_{B1} = 17.17°, ϕ_{C1} = 51.34°, θ_{C1} = 23.63°. The mean values of azimuth estimation results and their SDs for patients’ locations (P_1 and P_2) are shown in Tables II and III, respectively. Patients’ 3-D locations can be obtained using the mean values of azimuths and elevations estimation above by the similar formulation as (2) or (3). The localization results and their errors based on DOA and TOA estimation are shown in Tables IV and V, respectively. It can be seen that the error of DOA based method is smaller than that of TOA estimation.

In theory, the localization accuracy of TOA/TDOA-based method outperforms that of DOA-based method. However, in real application, the frequency offsets of off-the-shelf crystal os-
cillators can still result in time measurement errors, which cause the localization error of TOA. The network time protocol is used to synchronize the time between sensor and the mobile device. In the wireless condition of our real test, the synchronization error in 1 m translates to 9-ns error. Thus, the localization accuracy of TUL is higher than that of TOA-based method.

Remark 3: If the source number estimated by Akaike information criterion, Bayesian information criterion, and minimum description length (MDL) [27] is less than the number of detected signals by identifying ID, it means that multiple signals come from the same direction. The proposed algorithm has to give up the data at this time, since it cannot deal with this condition. Fortunately, the time interval between the transmitted of two signals is very short; the problem cannot lead to severe performance degradation. When the source number equals to the number of detected signals, we can exploit our TUL method smoothly.

From Fig. 10, it can be known that when SNR and snapshot number are 3 dB and 300, respectively, the presumably spatial resolution of tracking is about 4°, which means we can distinguish two patients when their distance is longer than 0.6 m. This distance is small enough with respect to two patients. However, when the distance between two patients is getting close, the estimation accuracy of patients’ location would decrease, this can be seen in Fig. 7. Thus, in order to guarantee the estimation accuracy, the patient density cannot be too high with respect to venue layout. In addition, we can also increase the number of receivers if the distance between two patients is smaller than 0.6 m, but this situation is almost impossible in real world. In other localization-aware application with respect to small things, this localization method could be a good choice.

V. CONCLUSION

In this paper, an improved angulation positioning method named TUL is proposed for patient tracking systems. The DOAs of the maximal noncircularity rated, the common noncircularity rated, and circular signals are estimated separately. The interrelationship among these signals can be reduced significantly, resulting in a higher resolution. The proposed algorithm performs better than traditional MUSIC and NC-MUSIC algorithms in small angular distance. Thus, this localization method can be applied in patient tracking with high density. We will take the nonline-of-sight propagation into consideration and study its avoidance method in the future works.

REFERENCES


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