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LETTER

Underdetermined RFID tag anti-collision based on bounded component analysis

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SUMMARY Radio Frequency Identification (RFID) is one of the key technologies of the Internet of Things. However, during its application, it faces a huge challenge of co-frequency interference cancellation, that is, the tag collision problem. The multi-tag anti-collision problem is modeled as a Blind Source Separation (BSS) problem from the perspective of system communication transmission layer signal processing. In order to reduce the cost of the reader antenna, this paper uses the boundedness of the tag communication signal to propose an underdetermined RFID tag anti-collision method based on Bounded Component Analysis (BCA). This algorithm converts the underdetermined tag into the signal collision model is combined with the BCA mechanism. Verification analysis was conducted using simulation data. The experimental results show that compared with the nonnegative matrix factorization (NMF) algorithm based on minimum correlation and minimum volume constraints, the bounded component analysis method proposed in this article can perform better. Solving the underdetermined collision problem greatly improves the effect of eliminating co-channel interference of tag signals, improves the system bit error rate performance, and reduces the complexity of the underdetermined model system.

key words: *RFID, Anti-collision, Co-channel interference elimination, Blind source separation, Bounded component analysis*

1. Introduction

Radio Frequency Identification (RFID) is a typical automatic identification technology that uses wireless radio frequency for non-contact two-way data communication [1] and uses wireless radio frequency to read and write recording media (electronic tags or radio frequency cards), thereby achieving the purpose of target identification and data exchange. It consists of three parts: a computer, readers, and tags [2]. All tags communicate with the reader through the same wireless channel. If there are multiple tags within the range of a reader, the backscattered signals of the tags will be mixed, and the reader cannot obtain the correct signal sent by the tag, thereby reducing the RFID recognition efficiency of the system. Tag collision occurs. In order to solve this problem, specific methods must be used to avoid collisions, namely anti-collision algorithms [3].

The most commonly used anti-collision algorithms are the ALOHA-based anti-collision algorithm and the binary search-based anti-collision algorithm. Both algorithms are based on Time Division Multiple Access (TDMA) and are easy to construct, but these algorithms may take a certain amount of time and have the possibility of losing tags.

Blind Source Separation (BSS) [4-6] offers a fresh approach to RFID tag anti-collision technology in light of the issues with the conventional anti-collision algorithm. Numerous tags anti-collision algorithms based on BSS that have been put out in the literature [7-11] increase reading rates and shorten the time needed to recognize a lot of tags. It fundamentally solves the ALOHA algorithm's "tag starvation" problem, that is, a specific tag may not be recognized for a long time, and also ensures the stability and security performance of the algorithm. However, when the number of tags is greater than the number of reader antennas, it is difficult to separate the correct signal due to the uncertainty of its reception hybrid model. Regarding the difficulty of this situation, some algorithms have been studied to solve it [12-15].

Therefore, in order to reduce the cost of the reader antenna and continue to study the tag collision problem under underdetermined conditions, this paper proposes an RFID tag anti-collision method based on Bounded Component Analysis (BCA) [16]. BCA can separate independent sources as well as dependent sources. The features of signals released by radio frequency tags are used to distinguish the collision-mixed signals. Because the transmitted signals have distinct boundaries and the necessary additive decomposition may be reasonably satisfied even in tiny samples, these qualities are particularly appealing in communications and allow RFID tag anti-collision. Bounded Component Analysis is an unsupervised technique that assumes the bounded properties of components and the additive decomposition of convex sets that support observations. Later, based on those who came before, a series of BCA algorithms such as [17–19] were proposed. This makes the algorithm suitable for many real signals, such as digital communication constellations, natural images, harmonic oscillations with sub-Gaussian properties, sparse signals with a super-Gaussian distribution, etc.

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The BCA-based RFID tag anti-collision method takes into account the influence of nonlinear factors on the radio frequency tag device. The boundedness based on the original transmitted signal reduces the error caused by correlation and reduces the algorithmic implementation complexity.

2. RFID tags collision signal model

The tag collision problem occurs when multiple tags communicate with the reader at the same time. Assuming that there are n tag responses in a query period, the signal matrix (original signal) of tag backscattering can be described as: $\mathbf{S}=[s_1,s_2,...,s_n]^T$, where the subscript n represents the n-th tag signal and the tag signal matrix $\mathbf{S}\in\mathbb{R}^n$. Assuming that the reader has an antenna, then the signal (observation signal) received by the reader can be described as: $\mathbf{X}=[x_1,x_2,...,x_m]^T$, where the subscript m represents the signal received by the m-th reader antenna, and the received signal matrix $\mathbf{X}\in\mathbb{R}^m$. Consider the m-dimensional process of an observation $\mathbf{X}(t)$, which is additively decomposed into a signal component $\tilde{\mathbf{X}}(t)$ and a noise component $\mathbf{N}(t)$. The signal $\tilde{\mathbf{X}}(t)$ is again decomposed into n component processes $\mathbf{X}_i(t), i=1,2,...,n$, producing the following additive model of the observations:

$$\mathbf{X}(t)=\underbrace{\mathbf{X}_1(t)+\cdots+\mathbf{X}_n(t)}_{\tilde{\mathbf{X}}(t)}+\mathbf{N}(t) \tag{1}$$

Due to the uncertainty of the wireless channel, the received signal $\mathbf{X}$ and the backscattered signal $\mathbf{S}$ differ greatly. The influence of the wireless channel can be described as a mixing matrix $\mathbf{A}$ in the BSS domain, where $\mathbf{A}\in\mathbb{R}^{m\times n}$. Therefore, the BSS model equation is as follows:

$$\mathbf{X}=\mathbf{AS} \tag{2}$$

Considering the noise of the wireless channel environment, equation (2) can be modified as:

$$\mathbf{X}=\mathbf{AS}+\mathbf{N} \tag{3}$$

where $\mathbf{N}$ is $m\times n$ Gaussian white noise matrix.

In equation (3), the mixing matrix $\mathbf{A}$ is unknown. We need to solve this problem in a blind situation. In this case, blind separation based on bounded component analysis is a good choice. It can estimate the source signal only from the received mixed signal based on some statistical characteristics. The BSS algorithm always calculates the separation matrix $\mathbf{W}$ through an independent mechanism, non-negative conditions or bounded conditions. The separation matrix $\mathbf{W}$ satisfies the equation:

$$\mathbf{WA}\approx\mathbf{I} \tag{4}$$

Ideally, $\mathbf{I}$ is the identity matrix. Assuming that the output matrix after separation is $\mathbf{Z}$, the equation holds:

$$\mathbf{Z}=\mathbf{WX} \tag{5}$$

Combining formulas (3) and (5), we can get:

$$\mathbf{Z}=\mathbf{WX}=\mathbf{W}(\mathbf{AS}+\mathbf{N})=\mathbf{WAS}+\mathbf{WN} \tag{6}$$

Substituting formula (4) into (6), we get:

$$\mathbf{Z}=\mathbf{WAS}+\mathbf{WN}\approx\mathbf{S} \tag{7}$$

The above is the mathematical description of the RFID tag collision model based on BSS. In this model, it is worth noting that different numbers of tags (n) and reader antennas (m) will determine different model structures. When the number of tags is less than or equal to the number of reader antennas, that is, $n\le m$, then the BSS will be an overdetermined or deterministic model. In contrast to the overdetermined or deterministic case, an underdetermined model is obtained when $n>m$. In underdetermined models, methods based on NMF and BCA are commonly used. Considering the technical advantages of BCA and the bounded characteristics of RFID signals, BCA will become a positive method to separate underdetermined RFID hybrid models. The remainder of this article will be devoted to solving this vexing underdetermined tag collision problem in RFID systems.

3. Tags anti-collision based on BCA

In general, the observational data and the mixing model in equation (3) do not provide enough information to identify mixing systems or sources. For simplicity, the BCA hypotheses are initially proposed in terms of source and mixture vectors. However, it is useful to relate them to an equivalent set of BCA assumptions that can be formulated directly in terms of the components of the observations:

(1) (Bounded components) The components of the observation $\mathbf{X}_1,\mathbf{X}_2,...,\mathbf{X}_n,\mathbf{N}$ are bounded, so their convex supports are convex: $\mathcal{S}_{\mathbf{X}_1},\mathcal{S}_{\mathbf{X}_2},...,\mathcal{S}_{\mathbf{X}_n},\mathcal{S}_{\mathbf{N}}\in\mathcal{K}_{\mathbb{R}}^m$.

(2) (Direct decomposition) We assume that the convex support of the observation can be decomposed into:

$$\mathcal{S}_{\mathbf{X}}=\mathcal{S}_{\mathbf{X}_1}\oplus\cdots\oplus\mathcal{S}_{\mathbf{X}_n}\oplus\mathcal{S}_{\mathbf{N}} \tag{8}$$

(3) (Available noise descriptors) Some key statistics of the noise, such as the covariance matrix $\sum_{\mathbf{N}}$ or its convex support $\mathcal{S}_{\mathbf{N}}$, are known or can be reasonably estimated from observations.

Since this article aims to solve blind source separation under underdetermined conditions, the BCA algorithm based on perimeter matching is used to solve the RFID tag collision problem, namely BCA-PM (Perimeter Matching) [16], based on the observation value projection perimeter least squares fit. The identifiability and separability of mixtures in underdetermined mixtures are guaranteed. The algorithm uses the whitening matrix $\mathbf{W}$ to consider the main eigenvectors of the covariance matrix when mapping the sample vectors, thereby improving the selected projection set.

Since the whitened mixing matrix $\mathbf{A}'$ has fewer degrees of freedom than $\mathbf{A}$, it is more computationally efficient to determine $\hat{\mathbf{A}}'$ (the estimate of $\mathbf{A}'$) and then obtain an estimate of the mixing system using:

$$\hat{\mathbf{A}} = \mathbf{W}^H(\mathbf{W}\mathbf{W}^H)^{-1}\hat{\mathbf{A}}' \tag{9}$$

Based on the above analysis, the steps to implement RFID tag anti-collision using the BCA-PM method are summarized as follows:

(1) First whiten the observation matrix $\mathbf{X}$ to obtain the whitened matrix $\mathbf{W}$.

(2) Use the whitening matrix to map the adoption vector $\mathbf{h}_j$ in the whitening space and the normalized vector $\mathbf{b}_j$ in the observation value correlation space:

$$\mathbf{b}_j = \frac{\mathbf{W}^H\mathbf{h}_j}{\|\mathbf{W}^H\mathbf{h}_j\|} = \mathbf{W}^H\mathbf{b}_j' \tag{10}$$

where $\mathbf{b}_j' = \frac{\mathbf{h}_j}{\|\mathbf{W}^H\mathbf{h}_j\|}$. We group it into matrix $\mathbf{B}' = (\mathbf{b}_1', \mathbf{b}_2', \ldots, \mathbf{b}_q') \in \mathbb{R}^{m\times q}$. The observations are then projected onto these vectors, producing an output vector:

$$\mathbf{Y} = \mathbf{B}'^H\mathbf{W}\mathbf{X} \tag{11}$$

Then the sample perimeter is obtained:

$$L_{y_j} = 2(\max_t\{y_j(t)\} - \min_t\{y_j(t)\}) \tag{12}$$

(3) The cost function of BCA based on perimeter matching can be expressed as:

$$J(\hat{\mathbf{A}}', L_{\hat{r}}) = \left\| L_y - \hat{L}_y \right\|_{\mathbf{P}}^2 \tag{13}$$

Among them, the estimated perimeter is:

$$\hat{L}_y = |\hat{\mathbf{G}}^{(i)}|^T\mathbf{1}_n + \bar{L}_{\hat{r}}\mathbf{1}_q \tag{14}$$

where the global mixing matrix $\hat{\mathbf{G}}^{(i)H} = \mathbf{B}'^H\hat{\mathbf{A}}'^{(i)}$, noise estimate perimeter:

$$\bar{L}_{\hat{r}} = \max\left\{\frac{1}{q}\sum_{j=1}^{q}(L_{y_j} - |\hat{\mathbf{g}}_j|^T\mathbf{1}_n)\right\} \tag{15}$$

And $\mathbf{P}$ is defined as:

$$\mathbf{P} = \begin{cases} \mathbf{I} - \frac{1}{q}1_q1_q^T, & \bar{L}_r > 0 \\ \mathbf{I}_q \quad , & \bar{L}_r = 0 \end{cases} \tag{16}$$

Taking the global hybrid system G as the optimization variable, the BCA-PM loss function can be viewed as an indirect measure of the fit between the true values $(|\mathbf{G}|, L_r)$ and their estimated values $(|\hat{\mathbf{G}}|, \bar{L}_{\hat{r}})$:

$$J(\hat{\mathbf{A}}', L_{\hat{r}}) = \left\| L_y - \hat{L}_y \right\|_{\mathbf{P}}^2 = \|(|\mathbf{G}| - |\hat{\mathbf{G}}|)\mathbf{1}_n + (L_r - \bar{L}_{\hat{r}})\mathbf{1}_q\|_{\mathbf{P}}^2 \tag{17}$$

(4) Using the natural gradient descent iterative algorithm, the update rules for the whitened mixing matrix can be obtained:

$$\hat{\mathbf{A}}'^{(i+1)} = \hat{\mathbf{A}}'^{(i)} - \mu^{(i)}(\mathbf{B}'\mathbf{B}'^H)^{-1}(\mathbf{B}'\nabla_{\hat{\mathbf{G}}^T}J_0(\hat{\mathbf{G}}^H)) \tag{18}$$

The iteration step size is calculated as follows:

$$\mu^{(i)} = \frac{\eta^{(i)}\mathcal{H}(\hat{\mathbf{G}}^{(i)H})}{\|\nabla_{\hat{\mathbf{G}}^T}\mathcal{H}(\hat{\mathbf{G}}^{(i)H})\|_{\mathbf{I}_n}^2} = \eta^{(i)}\frac{J_0(\hat{\mathbf{G}}^{(i)H})}{\|\mathbf{P}_{\mathbf{B}'^H}\nabla_{\hat{\mathbf{G}}^T}J_0(\hat{\mathbf{G}}^{(i)H})\|_{\mathbf{I}_n}^2} \tag{19}$$

Iterate continuously through the above equation, and then bring the obtained estimated whitening mixing matrix $\hat{\mathbf{A}}'$ into equation (9) to calculate the estimated mixing matrix $\hat{\mathbf{A}}$. Finally, multiply the observed signal matrix $\mathbf{X}$ and the estimated mixing matrix to obtain the estimated useful signal:

$$\hat{\mathbf{S}} = \mathrm{pinv}(\hat{\mathbf{A}})\mathbf{X} \tag{20}$$

In summary, this section takes advantage of the boundedness of the tag's original signal and noise signal to analyze the complete process of mixed signal separation after tag collision using the bounded component analysis method to address the RFID multi-tag collision problem.

4. Simulation analysis

This paper simulates the entire communication process of the RFID system and verifies the effectiveness of the proposed method. (Simulation conditions: 5 tags, 3 reader antennas, tag data length of 2000bit, channel noise is Gaussian white noise).

In order to further illustrate the correctness of the overall source separation of the algorithm, this paper uses Equation (21-22) to calculate the correlation coefficient between the source signal and the separation signal to evaluate the method performance. We compare the proposed method with other NMF algorithms [15,20-22] when used in RFID systems. As can be seen from Fig. 1, compared with other NMF algorithms, the BCA_PM algorithm performs better when used for RFID anti-collision.

$$\mathrm{cov}(\mathbf{S},\mathbf{Z}) = E[\mathbf{S} - E(\mathbf{S})]E[\mathbf{Z} - E(\mathbf{Z})] = E(\mathbf{SZ}) - E(\mathbf{S})E(\mathbf{Z}) \tag{21}$$

$$corrcoef(\mathbf{S},\mathbf{Z}) = \frac{\mathrm{cov}(\mathbf{S},\mathbf{Z})}{\sqrt{\mathrm{cov}(\mathbf{S},\mathbf{S})\,\mathrm{cov}(\mathbf{Z},\mathbf{Z})}} \tag{22}$$

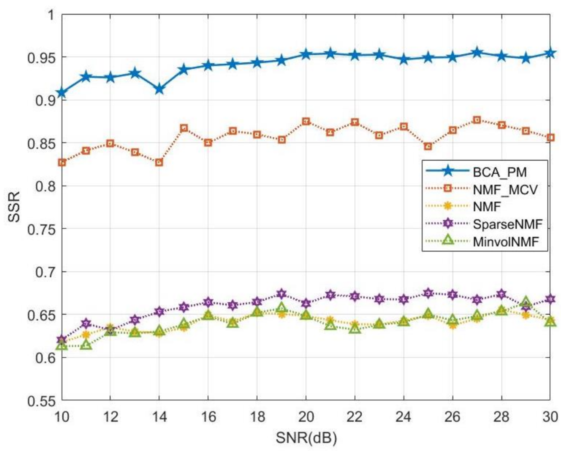

Fig. 1 Correlation coefficient under different signal-to-noise ratios

The calculation formula for BER intuitively reflects the quality of channel transmission (eq. 23). The BER is an important indicator for evaluating the performance of digital communication systems. As shown in Fig. 2, the method used in this article has better bit error rate performance than other NMF algorithms.

$$BER = \frac{\text{number of error bits}}{\text{total number of bits}} \quad (23)$$

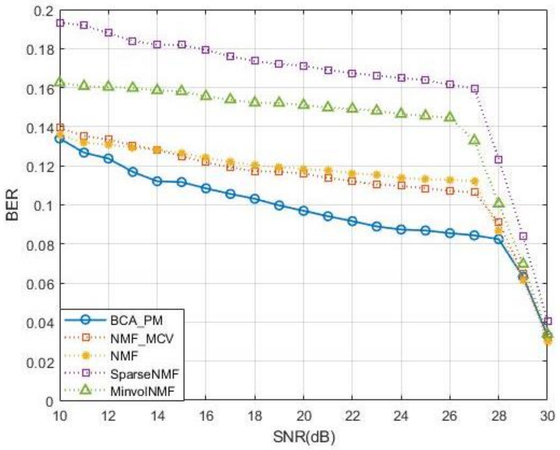

Fig. 2 Bit error rates under different signal-to-noise ratios

This paper also analyzes and studies the Mean Square Error (MSE). The simulation results are shown in Fig. 3. The results show that using the BCA_PM algorithm as the anti-collision algorithm for the RFID system has the smallest error, further proving that the performance of the new algorithm is better than other representative algorithms.

$$MSE = \frac{1}{n}\sum_{i=1}^{n} w_i(\mathbf{z}_i - \mathbf{s}_i)^2 \quad (24)$$

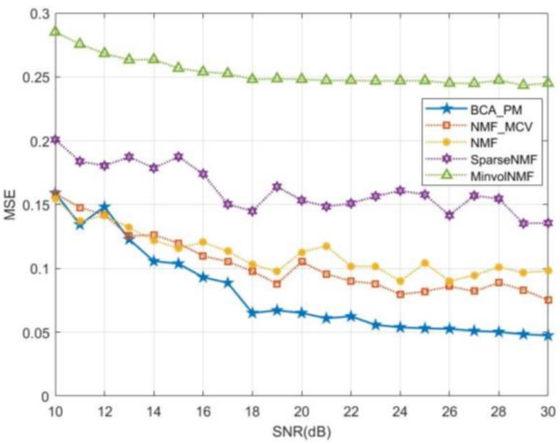

Fig. 3 Mean square error of different signal-to-noise ratios

Author collects some time complexity results from different algorithms in table 1. Based on the results in the table, we can easily see that the complexity of the proposed algorithm is lower than other representative methods.

Table 1 Algorithm time complexity (/s)

Algorithm	Max	Mean	Min
BCA_PM	**0.3471**	**0.1810**	**0.0847**
MCV_NMF	39.9180	39.4917	39.1437
NMF	1.5583	1.4055	1.2243
MinvolNMF	0.4188	0.2787	0.2640

In summary, the tag anti-collision algorithm based on BCA_PM can improve the overall performance of the RFID system.

5. Conclusion

Aiming at the anti-collision problem of underdetermined receiving hybrid RFID systems, this paper uses a blind identification criterion based on least squares fitting of a set of projected perimeters of observed values, namely BCA_PM. In practical applications, the backscattered signal of the tag, that is, the original signal, is bounded. This algorithm uses the bounded characteristics of the source signal as a constraint for algorithm development, so that the proposed BCA_PM algorithm can correctly estimate the source signal. This algorithm can achieve higher throughput than traditional algorithms. Compared with the MCV_NMF [13] algorithm, which has the best tag signal separation effect in recent years, the BCA_PM algorithm has better performance and improves the separation performance of the algorithm.

Collision between RFID system tags is essentially co-channel interference in wireless communications. Although the BCA_PM algorithm used in this article has made good improvements to RFID underdetermined collisions, in future work, the performance of the algorithm under low signal-to-noise ratio needs to be optimized, as well as considering the single-channel separation under extreme circumstances. Anti-collision algorithms are worth studying.

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