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Influence of Multiple Tags' Distribution on the Reading Performance of RFID-MIMO System Based on CRB

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Abstract. A testing method is investigated for performance evaluation and optimization of radio frequency identification and multi-input multi-output (RFID-MIMO) system based on Cramer-Rao Bounds (CRB). Based on the channel model of RFID-MIMO system, a CRB estimator of antenna azimuth in single antenna multiple tag system is obtained. A simulation on the CRB of different number of tags is made. In this research, we study the relationship between the CRB of multiple tags' distribution and the reading performance. Moreover, a quantitative index of optimization is proposed by multiple tags analysis. The antenna selection technique of RFID-MIMO system is analyzed. The feasibility of this method is verified by comparing the optimal and the suboptimal antenna selection technique. This study provides an effective reference for the evaluation and optimization of RFID-MIMO system.

Keywords: antenna azimuth, Cramer-Rao, multiple tags, reading performance, RFID-MIMO

1 Introduction

In recent years, as one of the core of internet of things (IOT), radio frequency identification (RFID) has been widely used. With the rapid development of RFID and Multi-Input Multi-Output (MIMO) communication, RFID-MIMO system has attracted a wide spread attention in the IOT industry. In RFID, MIMO technology improves reliability of the system by using near field spatial multiplexing and far field spatial diversity to eliminate the interference. Common MIMO system uses several frequencies through multiple channel links while MIMO channel has multiple links operating at the same frequency, which can lengthen RFID reading distance, reduce the bit error rate of the system and improve the reading efficiency of RFID tag and the signal bandwidth doesn't increase [1-2]. For RFID-MIMO system, Terasaki made experiments on passive MIMO transmission with load modulation. The results indicated that the transmission rate of passive MIMO was up to 2 times higher than that of Single-Input Single-Output (SISO) with the same transmission power when the distance between the reader and the tag was 0.5m. These results also indicate that passive MIMO offers high-speed data transmission even when the distance is doubled [3]. He studied the performance of MIMO RFID backscattering channels, and found out that these properties of the MIMO RFID channel are significantly different from that of other types of cascaded channels such as keyhole and double scattering [4]. In order to get effective biased estimators of the RFID multiple tag system, Yu took the linear and nonlinear functions in the measurement of RFID tags as a paradigm to study the equivalence between the bias-corrected estimators and biased estimators [5]. Aouadi and Belgacem presented an evaluation of MIMO antennas, with analysis of the mutual coupling, correlation coefficient, diversity gain and correlation efficiency. They found that the use of the novel LHM (Left Handed Metamaterial) with multiple bands after fractional removal of substrate was suitable for MIMO antenna system [6]. Xu studied the uplink transmission in MIMO systems with antenna correlation and proposed a very efficient scheme in multi-user uplink MIMO system with distributed channel information [7]. However, few studies have been done about the influence of multiple

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tags' distribution on the reading performance in RFID-MIMO system. Therefore, this paper focuses on the multiple tags' distribution in RFID-MIMO system.

In the MIMO system, the frequency deviation between transmitter and receiver is mainly caused by the error between the transmitter and the receiver, and the Doppler shift caused by the motion of the mobile station. The problem of multi frequency deviation in MIMO system makes it more complicated to estimate the frequency deviation correctly, and it has become a joint estimation of multi parameter. The multi parameter joint estimation based on ML principle can almost approximate the ideal performance with the increase of signal to noise ratio, so it becomes a very practical estimation method [8]. However, the above method has high complexity. Therefore, suboptimal quasi maximum likelihood algorithm is also a common method for the study of multi parameter estimation [9-10]. Considering the parameter estimation of the MIMO system, Cramer-Rao Bound (CRB) determines a lower limit for any unbiased variance of estimator, which means that it is impossible to obtain the unbiased estimator when the variance is less than the lower limit. Meanwhile, the CRB provides a standard of comparing the performance of unbiased estimator. In [11], Wang studied the CRB for joint RSS/DoA-Based Primary-User localization in cognitive radio networks. Bekkerman studied the CRB for estimating parameters of coherently distributed targets (CDT) using MIMO radars [12]. Jagannatham discussed the Cramer-Rao bound based mean-squared error and throughput analysis of superimposed pilots for semi-blind multiple-input multiple-output wireless channel estimation [13]. In [14], Kalkan calculated the CRB for target position and velocity estimations for widely separated MIMO radar. However, at present, the research on CRB in the MIMO system is mainly focused on the study of the beam and the estimated CRB. There are fewer reports on the RFID-MIMO system, especially the impact of the size of CRB on the reading performance of the RFID- MIMO system. Therefore, on the basis of the above research, this paper introduces the MIMO system into the field of RFID, and constructs a channel model of the RFID-MIMO system. Besides that, in the paper, CRB will be applied to the field of parameter estimation in the RFID-MINO system. The CRB of different tag numbers is simulated by computer to obtain the CRB corresponding to the number of different tags in the case of orthogonal and coherent signals. Finally, by studying the relationship between multi-tag distribution CRB and reading performance, the paper analyzes the effect of multi-tag distribution on reading performance in RFID-MIMO system based on CRB.

2 Channel Model

Consider a RFID-MIMO system composed of M antennas coordinate of $Z_m = (x_m, y_m)^T (m = 1,\ldots,M)$. Let antenna azimuth angle θ denotes the angle between the tag and the vertical plane of the antenna arrays. The space between two tags is d_a times of wavelength, and the space between two antennas is d_b times of wavelength. The schematic diagram of the structure of RFID-MIMO system is shown in Fig. 1.

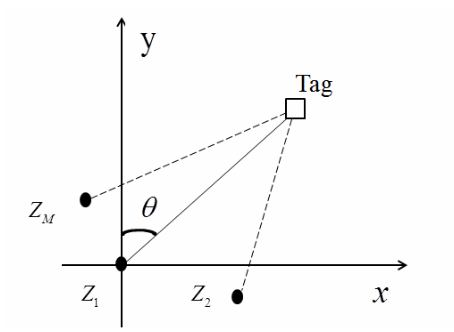


Fig. 1. The schematic diagram of the structure of RFID-MIMO system

Let the column vector $s[n]$ represents the baseband signal transmitted by antenna unit when n represents the time. So a echo signal of the target received by the receiving array is given by

$$y[n] = \alpha A(\theta) s[n] + w[n] (n = 1 \ldots N) \quad \textbf{(1)}$$

where α is the complex amplitude corresponding to the tag, $A(\theta)$ is the corresponding response matrix, $w[n]$ is the noise matrix, and $A(\theta)$ can be defined as

$$A(\theta) = a(\theta) a^T(\theta) \quad \textbf{(2)}$$

The coherent matrix of the transmitted signal is given by

$$R_s = \begin{bmatrix} 1 & \beta_{12} & \cdots & \beta_{1M} \\ \beta_{21} & 1 & \cdots & \beta_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{M1} & \beta_{M2} & \cdots & 1 \end{bmatrix} \quad \textbf{(3)}$$

where $a(\theta)$ denotes the steering vector, which is the complex correlation coefficient between the ***i***th ani *j*th tag. When the transmit beam of antenna points to the normal direction, the correlation coefficient's phase of transmitted signal is zero, and $\beta_{ij} = \beta_{ji} = \beta$ ($\beta \in [0,1]$). Therefore, when the coherent signal is transmitted, $\beta = 1$. However, when the orthogonal signal is transmitted, $\beta = 0$.

In the white Gaussian noise (WGN) environment, $SNR = N|\alpha|^2/\delta^2$ is signal-to-noise ratio, N is the sampling point, δ^2 is the variance of the sampling signal, and $|\alpha|$ represents the complex amplitude of the received signal. Then the estimation of the CRB for the single tag's space parameter can be expressed as [9]

$$CRB(\theta) = \frac{1}{2SNR\left(M\dot{a}^H(\theta) R_s^T \dot{a}(\theta) + a^H(\theta) R_s^T a(\theta) \left\| \dot{a}(\theta) \right\|^2 - \frac{M\left| a^H(\theta) R_s^T \dot{a}(\theta) \right|^2}{a^H(\theta) R_s^T a(\theta)} \right)} \quad \textbf{(4)}$$

From Eq.(4), CRB is inversely proportional to signal-to-noise ratio $N|\alpha|^2 / \delta^2$, namely the greater the sampling point, the higher the signal-to-noise ratio, the smaller the CRB, and the better the estimation performance for RFID-MIMO system. The CRB is related to the steering vector of the signal $a(\theta)$ and the number of tags. When the number of tags is given, different CRB can be obtained by changing the waveform of transmitted signal. Therefore, the CRB can be used as a criterion of waveform optimization.

If α is unknown and the transmitted signal is orthogonal to each other, the coherent matrix of the transmitted signal R_s is unit matrix. Hence, the CRB in Eq.(4) can be written as

$$CRB(\theta) = \frac{1}{8NM\frac{|\alpha|^2}{\sigma^2}\left(\sum_{k=-(M-1)/2}^{(M-1)/2} k^2 \right) (\pi \cos\theta)^2 \left(d_b^2 + d_a^2 \right)} \quad \textbf{(5)}$$

It can be shown from Eq.(5), when the transmitted signal is orthogonal to each other, CRB is related to the space between two tags, antenna unit and the number of tags. And with the increasing of the space between two tags, the CRB decreases. Therefore, we can obtain better CRB by increasing the space between two tags.

If α is already precisely known, we only need to estimate θ and δ^2. As estimation of δ^2 doesn't affect the estimation of θ, the estimation of the CRB can be expressed as [12]

$$CRB(\theta) = \frac{1}{2SNR\left(M\dot{a}^H(\theta) R_s^T \dot{a}(\theta) + a^H(\theta) R_s^T a(\theta) \left\| \dot{a}(\theta) \right\|^2 \right)} \quad \textbf{(6)}$$

where ||•|| is the norm of a matrix.

The CRB always increase with the estimation of more parameters, because the steering vector considers the center of tag unit as the reference point. When the transmitted signal is orthogonal, the item 3 of the denominator in (4) will be equal to 0, the formula (4) will be equal to (6). Therefore whether the target range is known, it has no effect on the CRB estimation of RFID-MIMO system which transmits orthogonal signal.

In time division duplex (TDD) adaptive MIMO system, channel reciprocity is an inherent characteristic of TDD system channels [1]. In TDD system, uplink and downlink channels work in the same frequency. Therefore, on the path that electromagnetic waves transmit, electromagnetic waves which return and go in two directions will through the same reflection, refraction, diffraction and other physical disturbance. Accordingly, it can be assumed that uplink and downlink channels have the same fading characteristics, so we can put the channel state of the uplink channels as channel state of the downlink channels, which is to say that uplink and downlink channels have reciprocity. Let H_u denote the uplink channel state matrix detected on the uplink, and H_d denote the downlink channel state matrix detected on the downlink, so the uplink and downlink channel reciprocity of TDD

$$H_u = H_d^T \quad \textbf{(7)}$$

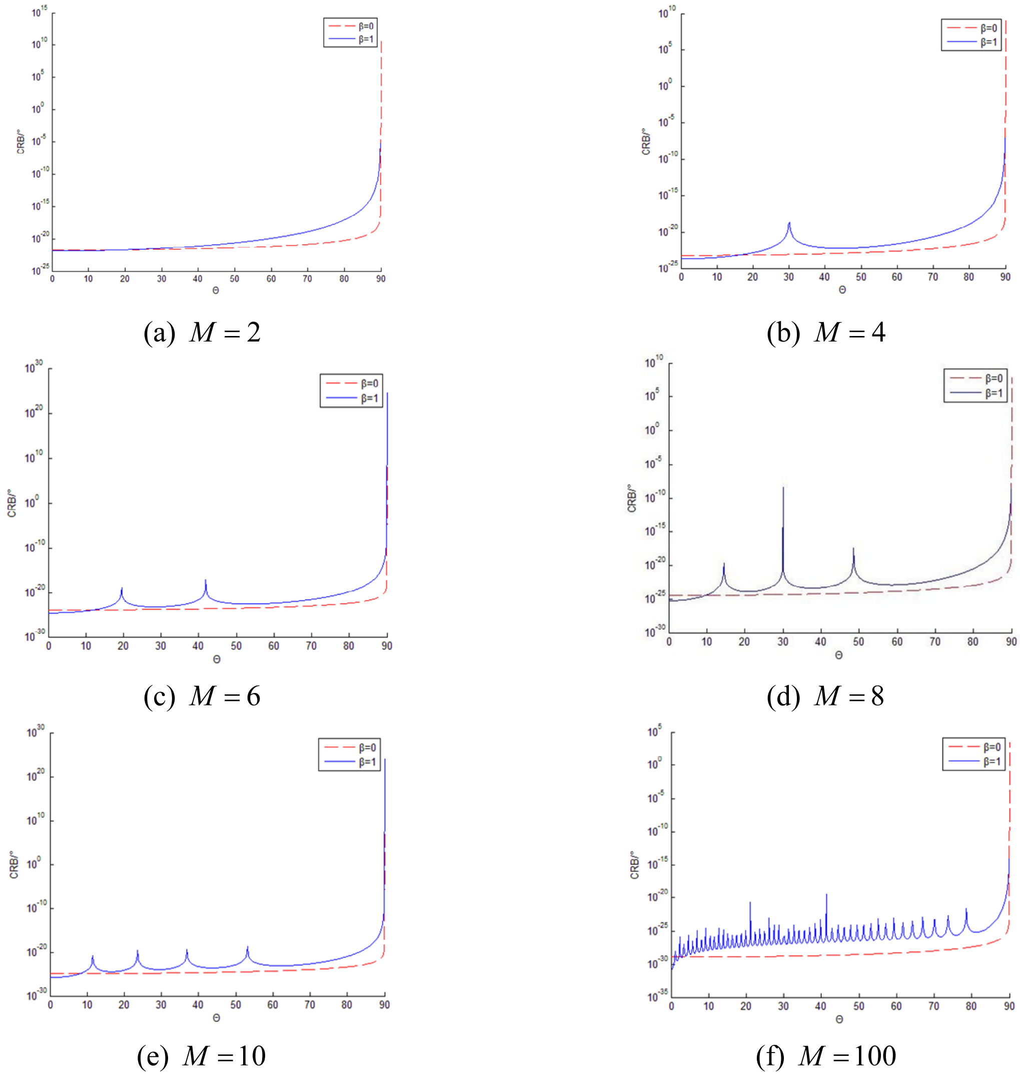
where the superscript T represents the matrix transpose.

Because of the reciprocity theorem, RFID-MIMO system has a plurality of tags and the plurality of antennas which corresponded to a plurality of output and input, and tag along with the antenna works in the same frequency, so it can be shown that the channels of the antenna and the tag also have reciprocity. Therefore, the equation (4) is introduced into RFID-MIMO system, which represents the number of antennas. For the RFID-MIO system with channel reciprocity, we can use equation (4) to represent the CRB estimator of antenna azimuth in single-antenna multiple tag system, when M is the number of tags.

3 Computer Simulation and Analysis

In this section, we imitate the CRB estimator of antenna azimuth in RFID-MIMO system by computer simulating. We can assume that RFID-MIMO system is composed of lined-up tag unit, the space between two tags is half a wavelength, and the centroid is at the origin.

The CRB simulation diagram is shown in Fig. 2, where the reader antenna transmits the orthogonal ($\beta = 0$) and coherent ($\beta = 1$) signals, the number of tags are 2, 4, 6, 8, 10, and 100 respectively, and the signal-to-noise ratio is SNR=20dB It is shown that:



(a) $M = 2$ (b) $M = 4$

(c) $M = 6$ (d) $M = 8$

(e) $M = 10$ (f) $M = 100$

Fig. 2. CRB under different number of tags

(1) When the antenna azimuth angle θ is close to 90°, the CRB is very large. Regardless of the number of tags or antenna's transmitted signal is orthogonal or coherent, the estimation couldn't be done effectively, which results in a poor reading performance of tags.

(2) When the reader antennas transmit orthogonal signal, with the changing of antenna azimuth angle θ, the CRB is relatively stable, and there is no interference between the reflected signal of two tags. Therefore, the estimation accuracy remains unchanged, and the reading performance of tags is relatively stable.

(3) When the reader antennas transmit coherent signal, with the increase of the antenna azimuth θ, interference between two tags' reflected signal gradually increases which leads to the decrease of the estimation accuracy and CRB increases. Therefore, tags' reading performance declines. And due to the more concentrated interference in a few degrees, the estimation accuracy decreases remarkably. Hence, the peak of the CRB appears at a certain angle, and the peak number increases with the increase of the number of tags. When the number of tags is 8, the distributions of tags and antenna are shown in Fig. 3. At this case of Fig. 3, the CRB is the largest and the RFID-MIMO system has the worst reading performance.

(4) In addition, the increase of the number of tags decreases the whole system's CRB, which improves the estimation accuracy and the reading performance of tags.

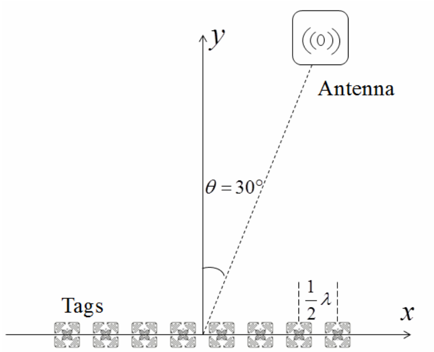


Fig. 3. Schematic diagram of tag and antenna position when the tags have the worst reading performance

4 Antenna Selection Techniques

4.1 Optimal Antenna Selection Technique

In RFID-MIMO system, channel capacity improves with the increasing number of RFID tags and antennas. However, the main disadvantage of RFID-MIMO system is the additional high cost for more radio frequency (RF) modules. Generally, RF modules include low noise amplifier (LNA), down converter and analog-digital converter (ADC). In order to reduce the cost of multiple RF modules, fewer RF modules are used than the number of reader antennas by applying the antenna selection techniques. A point-to-point distribution of the antenna selection is shown in Fig. 4, where only Q RF modules are used to support M_R reader antennas ($Q < M_R$). Therefore, the selected Q RF modules corresponding to Q antennas in M_R reader antennas.

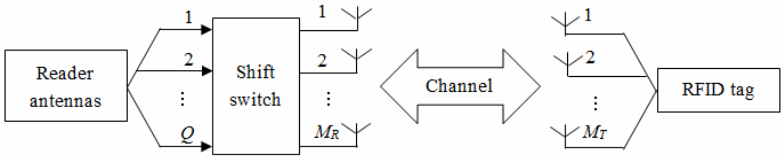


Fig. 4. Antenna selection: Q RF modules and MR reader antennas

As Q antennas are chosen from M_R reader antennas, Q column of matrix $H \in \mathbb{C}^{M_R \times M}$ represents efficient channel, p_i represents the selected serial number (i, $i = 1, 2, \cdots, Q$) and $H_{\{P_1, P_2, \cdots, P_Q\}} \in \mathbb{C}^{M_T \times Q}$

represents the efficient channel. Let $x \in \mathbb{C}^{Q\times 1}$ represent the space-time code or spatial multiplexing data flow which is mapped to Q selected antennas, the received signal y could be expressed as

$$y = \sqrt{\frac{E_x}{Q}} H_{\{p_1, p_2, \cdots, p_Q\}} x + z \tag{8}$$

where E_x is the energy of the transmitted signal and $z \in \mathbb{C}^{M_T \times 1}$ is the additive noise vector. The system capacity in (8) depends on the reader antennas and the corresponding number.

Q antennas could be chosen from M_R reader antennas to make the channel capacity reach the maximum. When the total transmitted power is P, the channel capacity of Q selected reader antennas can be expressed as

$$C = \max_{R_{xx}, \{p_1, p_2, \ldots, p_Q\}} \log_2 \det\left(I_{M_T} + \frac{E_x}{QN_0} H_{\{p_1, p_2, \ldots, p_Q\}} R_{xx} H^H_{\{p_1, p_2, \ldots, p_Q\}} \right) bps/Hz \tag{9}$$

where R_{xx} is the covariance matrix of $Q \times Q$. If all the selected transmitted antennas have the same power, $R_{xx} = I_Q$. Therefore for $\{p_i\}_{i=1}^{Q}$, the channel capacity can be described as

$$C_{\{p_1, p_2, \ldots, p_Q\}} = \log_2 \det\left(I_{M_T} + \frac{E_x}{QN_0} H_{\{p_1, p_2, \ldots, p_Q\}} H^H_{\{p_1, p_2, \ldots, p_Q\}} \right) bps/Hz \tag{10}$$

The best selection of Q antennas can be realized by calculating Eq.(10) with all possible combinations of antennas. In order to maximize system's capacity, antenna with maximum capacity must be selected as

$$\left\{ p_1^{opt}, p_2^{opt}, \cdots, p_Q^{opt} \right\} = \arg \max_{\{p_1, p_2, \cdots, p_Q\} \in A_Q} C_{\{p_1, p_2, \cdots, p_Q\}} \tag{11}$$

where A_Q represents the set formed by all possible combinations of Q selected antennas

$$|A_Q| = \begin{pmatrix} M_R \\ Q \end{pmatrix} \tag{12}$$

The simulation of Eq. (10) and the curve of channel capacity are shown in Fig. 5. The channel capacity of different reader antennas (M_R = 2, 6, 10, 20) and tags (M_T = 2, 6, 10, 20) as a function of *SNR* are plotted with different selected antennas Q. It can be seen from the figure that the channel capacity increases linearly with the number of selected antennas. In the case of Fig. 5(d), when *SNR* is less than 12dB, 18 antennas can be selected to ensure the same channel capacity as 20 antennas.

4.2 Complexity-reduced Antenna Selection

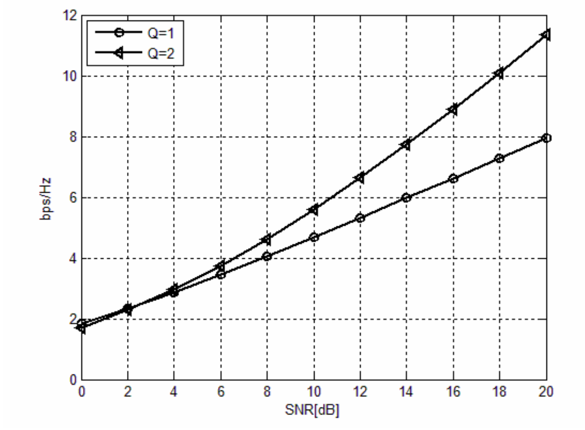
As mentioned in the previous subsection, a set of all possible antenna combinations with Q selected antennas is obtained in Eq. (12). However, when M_R is very large, all possible antenna combinations in Eq. (11) may involve the enormous complexity depending on the total number of available reader antennas. The reading speed and efficiency will be greatly reduced in practical application. In order to reduce its complexity, we may need to resort to the sub-optimal method.

Additional antenna can be selected in ascending order of increasing the channel capacity. The first antenna with the highest capacity is selected as

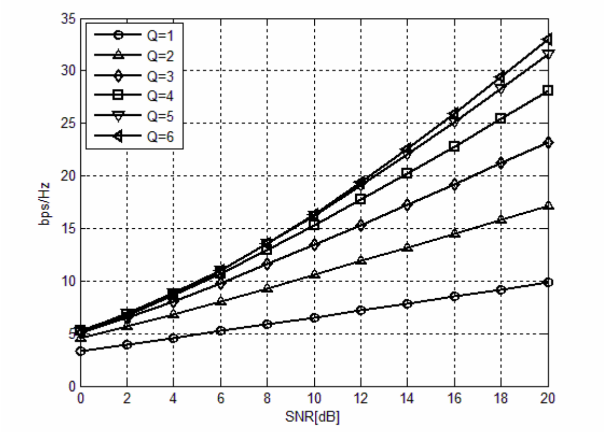
$$p_1^s = \arg\max_{p_1} C_{\{p_1\}} = \arg\max_{p_1} \log_2 \det\left(I_{M_R} + \frac{E_x}{QN_0} H_{\{p_1\}} H^H_{\{p_1\}} \right) \tag{13}$$

Given the first selected antenna, the second antenna is selected such that the channel capacity is maximized

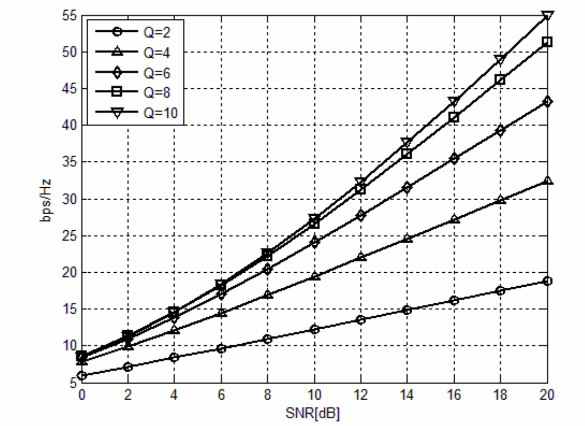
$$p_2^s = \arg\max_{p_2 \neq p_1^s} C_{\{p_1^s, p_2\}} = \arg\max_{p_2 \neq p_1^s} \log_2 \det\left(I_{M_R} + \frac{E_x}{QN_0} H_{\{p_1^s, p_2\}} H^H_{\{p_1^s, p_2\}} \right) \tag{14}$$



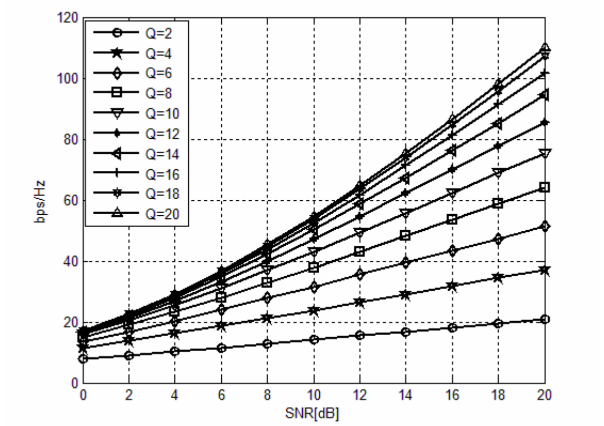
(a) $M_T = M_R = 2$, $Q = 1, 2$



(b) $M_T = M_R = 6$, $Q = 1, 2, 3, 4, 5, 6$



(c) $M_T = M_R = 10$, $Q = 2, 4, 6, 8, 10$



(d) $M_T = M_R = 20$, $Q = 2, 4, 6, 8, 10, 12, 14, 16, 18, 20$

Fig. 5. Channel capacity when using the optimal antenna selection techniques

After the nth iteration which provides $\{p_1^s, p_2^s, \cdots p_n^s\}$, the capacity with an additional antenna, antenna v, can be updated as

$$C_v = \log_2 \det\left(I_{M_R} + \frac{E_x}{QN_0} H_{\{p_1^s, p_2^s, \dots p_n^s\}} H^H_{\{p_1^s, p_2^s, \dots p_n^s\}} \right) + \log_2\left(1 + \frac{E_x}{QN_0} H_{\{v\}} \left[I_{M_R} + \frac{E_x}{QN_0} H_{\{p_1^s, p_2^s, \dots p_n^s\}} H^H_{\{p_1^s, p_2^s, \dots p_n^s\}} \right]^{-1} H^H_{\{v\}} \right) \quad \mathbf{(15)}$$

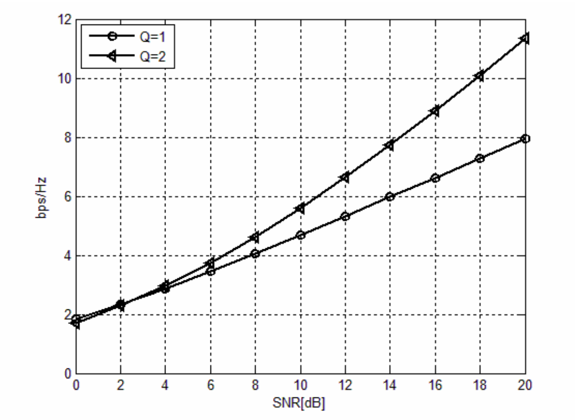
The additional (n+1)th antenna is the one that maximizes the channel capacity in Eq. (15), that is,

$$p_{n+1}^s = \arg \max_{v \notin \{p_1^s, p_2^s, \dots p_n^s\}} C_v = \arg \max_{v \notin \{p_1^s, p_2^s, \dots p_n^s\}} H_{\{v\}} \left(\frac{QN_0}{E_x} I_{MR} + H_{\{p_1^s, \dots p_n^s\}} H^H_{\{p_1^s, \dots p_n^s\}} \right)^{-1} H^H_{\{v\}} \quad \mathbf{(16)}$$

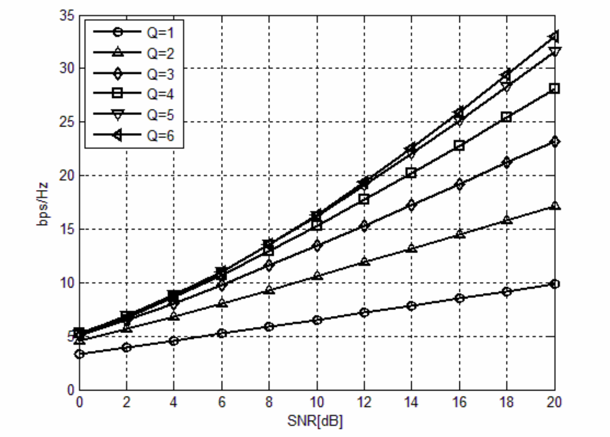
This process continues until all Q antennas are selected, (i.e., continue the iteration Eq. (16) until $n + 1 = Q$).

Meanwhile, the same process can be implemented by deleting the antenna in descending order of decreasing channel capacity. When $Q = M_R - 1$, the selection method in descending order produces the same antenna index set as the optimal antenna selection method. When $Q = 1$, however, the selection method in ascending order produces the same antenna index as the optimal antenna selection method and achieves better performance than any other selection methods.

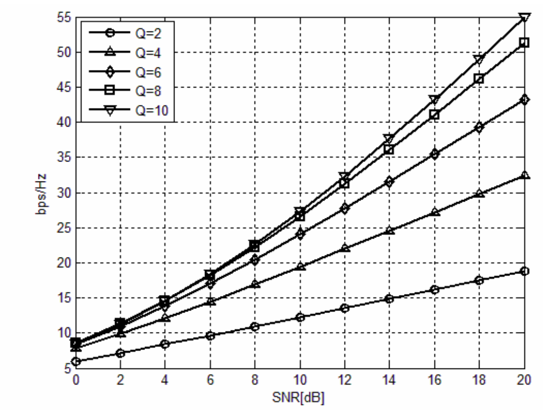
The simulation of Eq. (15) and the curve of channel capacity are shown in Fig. 6. The channel capacity of different reader antennas ($M_R = 2, 6, 10, 20$) and tags ($M_T = 2, 6, 10, 20$) as a function of SNR are plotted with different selected antennas Q. Comparing the curves in Fig. 6 with those in Fig. 5, we can see that the suboptimal antenna selection method in Eq. (15) achieves almost the same channel capacity as the optimal antenna selection method in Eq. (10). Because of the decreasing of the complexity, the calculation speed is greatly improved. However, when the number of reader antennas is very large, the channel capacity of the suboptimal antenna selection will be significantly smaller than the optimal antenna selection.



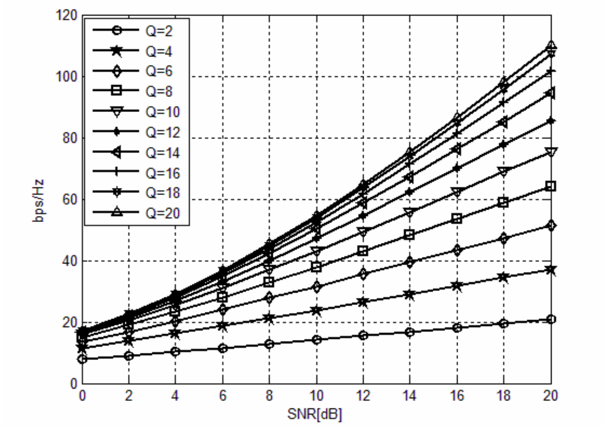
(a) $M_T = M_R = 2$, $Q = 1, 2$



(b) $M_T = M_R = 6$, $Q = 1, 2, 3, 4, 5, 6$



(c) $M_T = M_R = 10$, $Q = 2, 4, 6, 8, 10$



(d) $M_T = M_R = 20$, $Q = 2, 4, 6, 8, 10, 12, 14, 16, 18, 20$

Fig. 6. Channel capacity when using the complexity-reduced antenna selection

Table 1. Computation time and relative error of different antenna selection techniques

M	Optimal antenna selection (OAS)/s	Suboptimal antenna selection (SAS)/s	% of OAS's earning	Relative error
6	3.778240	2.450044	64.85%	0.012%
10	9.633543	4.689665	45.68%	0.024%
20	77.049178	18.976021	24.63%	0.065%
50	1021.68677608	124.374018	12.17%	0.214%

To compare two different antenna selection techniques, a simulation of computation time and relative error are shown in Tab.1. Let $M = M_R = M_T$ and $Q = 2$, it can be seen that the percentage of suboptimal antenna selection's computation time reduces and the relative error increases with the increase **o**f *M*. This is confirmed that the suboptimal antenna selection has a faster computation speed and a higher efficiency. When the number of reader antennas is very large, the relative error of suboptimal antenna selection will be even greater.

5 Conclusions

In this paper, the channel model of RFID-MIMO system is established based on CRB, and the CRB of a single antenna multiple tag RFID system is estimated which relates to the correlation matrix and steering vectors of tags. The CRB of coherent signal and orthogonal signal are compared by simulation. For the coherent signal, the numerical turns out that the higher the CRB is, the better the reading performance of RFID system is. Moreover, the CRB of coherent signal is lower than orthogonal signal when the antenna azimuth θ is far away from 0°. For the orthogonal signal, a better performance could be obtained by increasing the number of tags. The antenna selection techniques of RFID-MIMO system are studied and the simulation of optimal and suboptimal antenna techniques are made. It can be seen that the channel capacity increases in proportion to the number of selected antennas. When the number of reader antennas and tags is very small, the suboptimal antenna selection achieves almost the same channel capacity as the optimal antenna selection, and the suboptimal antennas selection technique has a faster computation speed and a higher efficiency. This study provides a meaningful reference for the optimization of RFID-MIMO system.

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