Signal Coding in Physical Layer Separation for RFID Tag Collision

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Abstract—**In an ultra-high-frequency (UHF) radio frequency identification (RFID) system, direct separation for tag collision on a physical layer can improve the efficiency of the tag identification. Many coding methods can be adopted in the RFID system. Different codes have different link frequencies and have an impact on the separation on the physical layer. This paper analyses the performance of FM0 and Miller code for the physical-layer separation. Firstly, collision tag signals are mapped to an IQ constellation plane, and then a clustering algorithm and a matched filter are performed to separate the collision signal. Finally, the separated signal will be recovered via Miller and FM0, respectively. Experimental results show that, Miller code has better performance of bit error rate (BER) and higher separation efficiency for tag collision than FM0 code when the subcarrier frequency of the both codes is the same.**

Keywords—RFID; tag collision; Miller; FM0

I. INTRODUCTION

Ultra high frequency (UHF) radio identification (RFID) is a non-contact electronic tag identification technology. As one kind of technique in internet of thing (IoT), RFID is widely used in the management of products. In UHF RFID systems, passive tags use backscatter communication method and thus have simple structure and low cost [1]. From ISO18000-6C protocol, when multiple tags communicate with the reader using passive backscattering in a shared channel, signal collisions will be inevitable. Traditional anti-collision algorithms use the idea of random multiple access and are performed on mainly on a media access control (MAC) layer[2-8]. However, these methods cannot separate the tag signals in the collision time slots, and the identification efficiency is not optimal. The separation of the tag signal on a physical layer can directly identify the tag signal from the collision signal, and thus has higher tag identification efficiency than the traditional MAC layer methods.

Clustering methods can solve the separation of collision tags on the physical layer, and will be divided into supervised clustering and unsupervised clustering. Unsupervised clustering has higher complexity and requires higher hardware cost. Unsupervised clustering methods have lower complex and easier to implement. The supervised method first maps the received signals from the reader onto an in-phase quadrature (IQ) plane, and then calculates the distance from each point to the center of each cluster. With the minimum distance, each point can be classified into the corresponding cluster. The center of clusters can be estimated in the prefix signal of each

tag. The separated signal obtained by the clustering method is passed through a matched filter to obtain a baseband signal.

II. FM0 CODEC METHOD

As described above, the existing physical-layer collision separation algorithm mostly uses FM0 to encode and decode the baseband signal. The FM0 coding principle is shown in Figure 1, which shows the basic functions and an encoding example for generating the first-order FM0 code, i.e. M=0. The FM0 coding rule is that the phase between any two adjacent symbols must be inverted, and the phase at the center of the symbol 0 must also be inverted.
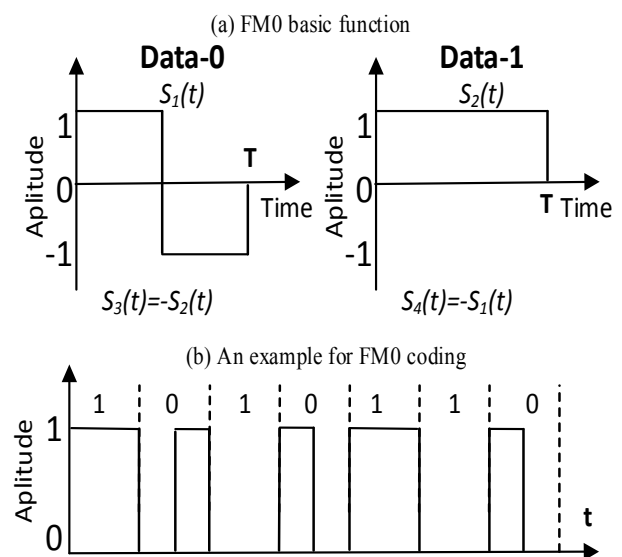

FIGURE I. FM0 BASIC FUNCTION AND ENCODING

In the FM0 coding example of FIGURE 1, there is a phase inversion between symbols 1 and 0 or 0 and 1. At the same time, there is a phase inversion at the center of symbol 0. On the other hand, there is no phase inversion at the center of symbol 1. Therefore, from the FM0 coding principle, decoding only needs to determine whether there is a phase inversion at the center of the symbol.

III. QUESTIONS RAISED

According to the ISO18000-6C protocol, RFID tag signal can be encoded from baseband signals via FM0 or Miller codes.

Each kind of code can select a different baseband link frequency (BLF), i.e. symbol rate, with a minimum of 40Khz and a maximum of 320Khz. In addition, we can also use DataRate to represent the transmission speed of each code, defined as the ratio of BLF to the number of subcarriers in each symbol, s expressed as:

$$DataRates = BLF / s \qquad (1)$$

From (1), given the same DataRate, the code with more subcarriers per symbol will have higher BLF. Similarly, given

The same BLF, the code with more subcarriers per symbol will have lower DataRate. Generally, Miller code can contain 2, 4 or 8 subcarriers per symbol, while FM0 code has only one subcarrier. Therefore, if the DataRate of the both is the same, FM0's BLF is higher than Miller code.
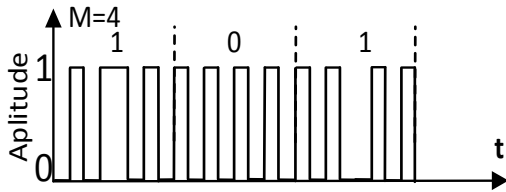
After baseband signals are Miller encoded, there is a phase inversion between two consecutive symbols 0, and a phase inversion in the middle of a symbol 1. Figure 2 shows the basic function and an example of Miller code.
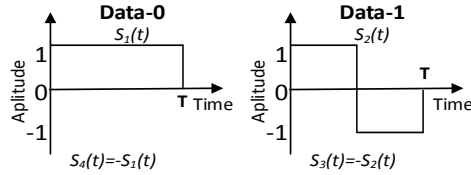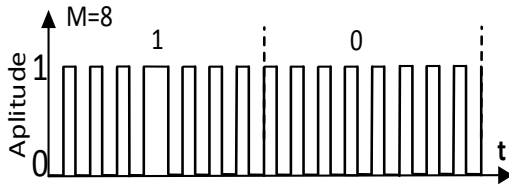

(a) Miller basic function
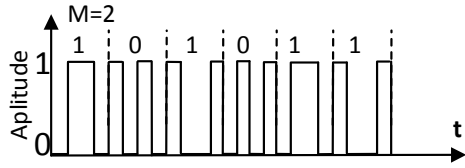
(b) An example for Miller2 (M=2)

(c) An example for Miller4 (M=4)

(d) An example for Miller8 (M=8)

FIGURE II. MILLER BASIC FUNCTION AND ENCODING

After collision signals are separated, the separation signals are processed through a matched filter to obtain the output signal with the largest signal-to-noise ratio (SNR). Then, original symbols are obtained via Miller decoding. Because each symbol of Miller code has more subcarriers, some noise can be cancelled after the matched filter. On the contrary, FM0 code has fewer subcarriers, and thus the noise eliminated through the matched filter is not much.

IV. ALGORITHM

A. System Model

In UHF RFID systems, the communication between tags and a reader uses backscatter modulation. The tag acquires the information from the carrier transmitted by the reader and the energy required to transmit the information itself. The reader selects the code mode and data transfer rate by initializing the inventory command (Query). The tag switches between 0 and 1 depending on the transmitted data and can be controlled by the reflection coefficient of the antenna. The communication principle between the reader and the tags is as shown in Figure 3. When there are N tags in the same time slot, the reader will receive the superimposed signals of the N tags [12, 13, 14]. The reader downconverts the superimposed signals to baseband signals. The baseband signal is a complex signal, which can be shown as
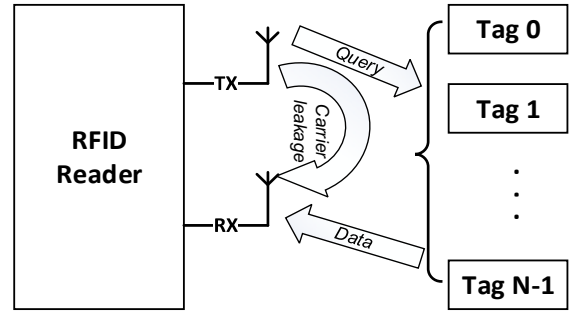

FIGURE III. THE PRINCIPLE OF COMMUNICATION BETWEEN THE READER AND THE TAG

$$z_{L}(t) = \sum_{n=0}^{N-1} h_n c_n(t) + L + \xi(t) \qquad (2)$$

Where

- $h_n = h_n^f h_n^b \sqrt{\triangle\sigma_n}$ and usually the channel can be regarded as a linear time-invariant channel with flat fading in a short communication time

- h_n^f and h_n^b are the downlink channel coefficients (reader to tag) and the uplink channel coefficients (tag to reader) , respectively

- $\triangle\sigma_n$ represents a standardized complex radar cross-section coefficient,

- $\xi(t)$ is an additive white Gaussian noise superimposed on the receiver's receiving end,

- $c_n(t)$ is a switch key signal expressed as

$$c_n(t) = \sum_{k=0}^{K-1} d_{n,k} g_{a_n}(t - ka_n - b_n)$$
(3)

- K is a symbol block length,

- a_n and b_n denote symbol periods and symbol delay, usually $b_n \neq b_m$ [6 - 11],

- $d_{n,k} \in \{0,1\}$ is the binary sequence.

- $g_{a_n}(t)$ is pulse waveform for modulation .

From ISO-18000-6C[14] standard, tags have a silent period before the information is backscattered. That is, the tags are in absorbed energy state, and the reader receives only the carrier leakage of the reader. The carrier leakage value L can be estimated during this time. Since this problem has been solved better in [12], this paper assumes that L is known. Then equation (1) becomes

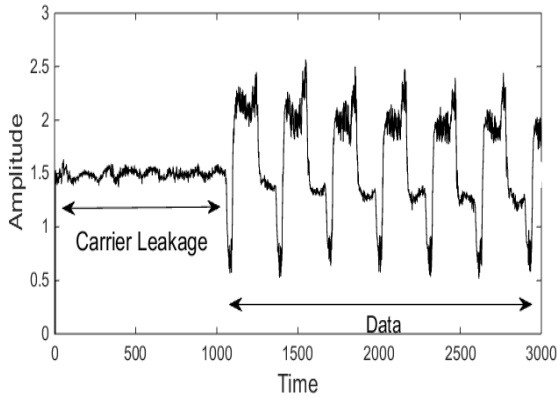$$z(t) = \sum_{n=0}^{N-1} h_n c_n(t) + \xi(t)$$
(4)

FIGURE IV. AN EXAMPLE FOR CARRIERLEAK

B. Collision Label Separation Method

In (4), $z(t)$ is a complex baseband signal, which is superimposed signal on the reader each tag, after IQ demodulated[8,12,13]. And, the channel coefficient h_n in (4) is a linear time-invariant channel in a short time and thus can be expressed as

$$h_n = r_n e^{j\theta_n}$$
(5)

Where r_n is the channel attenuation coefficient, θ_n is a phase. If two tags transmit signals simultaneously in one time slot and the channel coefficients corresponding to these tags are h_1 and h_2 , respectively, then four clusters will appear on a complex plane shown in Figure 5 after the signal is demodulated by IQ. In theory, the centers of the clusters are respectively:

$$L, c_1(t)h_1 + L, c_2(t)h_2 + L, c_1(t)h_1 + c_2(t)h_2 + L$$
(6)

And the corresponding two tags are respectively transmitted with symbols (0,0), (1,0), (0,1), (1,1). When the channel coefficients are known, we can separate the superimposed tag signals via clustering methods.
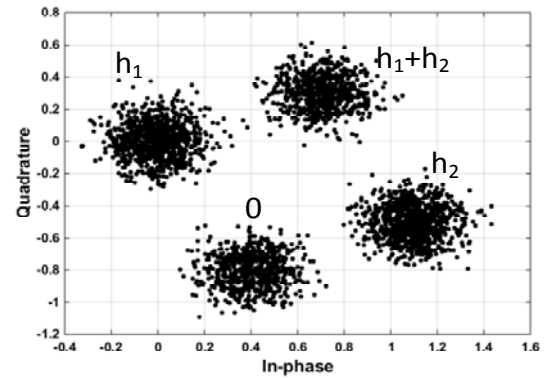

FIGURE V. BASEBAND SIGNAL CONSTELLATION IN AN IQ PLANE

Clustering methods are divided into supervised clustering and unsupervised clustering. Generally, the unsupervised clustering method has higher computational complexity and does not suit engineering applications. However, the supervised clustering method requires estimating the channel coefficients in advance to determine each clustering center. Since the channel coefficients have been accurately estimated in [13], it is assumed that the channel coefficients are known. If the channel coefficients are known, all points on the complex plane can be made a decision via Euclidean distance expressed as

$$d = \| \mathbf{Z}(t) - \mathbf{C}(i) \|_2$$
(7)

Where $\mathbf{Z}(t)$ is the vector consisting of the I and Q paths of the received signal, and $\mathbf{C}(t)$ is the center of the i-th cluster in which $\{i \mid i=1, 2, 3, 4\}$. The point closest to the Euclidean distance of a cluster center will belong to the cluster. Then, the binary symbols $c_n(t)$ of a tag are recovered from its belonging cluster.

C. Miller Decoding

The baseband signals separated on the physical layer will contain low-frequency noise. Here, we use a matched filter to reduce the noise so that the output signal satisfies the principle of maximum SNR. That is

$$\mathbf{X}_{MF}(t) = \mathbf{X}(t) \otimes \mathbf{H}(t) \qquad (8)$$

Where $\mathbf{H}(t)$ is an impulse response function of the matched filter, which is mirroring one cycle of $\mathbf{X}(t)$ and shifting one cycle. Eq. (8) explains that the output of the matched filter is in fact to convolving the separated signal with an impulse response function and $\mathbf{H}(t)$ can be expressed as pual to baseband signal $\mathbf{X}(t)$ one cycle of mirroring and then panning t_0 units. In this pape

$$\mathbf{H}(t) = k\mathbf{X}_a(t_0 - t) \qquad (9)$$

Where $k=1$, $t_0=T$ and $\mathbf{X}_a(t)$ is a cycle of $\mathbf{X}(t)$. Resampling the output of the matched filter will obtain a subcarrier sequence with Miller code. From ISO-18000-6C, the value of M in the command Query sent by the reader will determine that each bit contains 2, 4, or 8 subcarrier cycles. Next, the Miller subcarrier sequence will be XOR operated with the system's synchronous clock (CLK) to remove the subcarriers. The first cycle of the synchronous clock is high. The signal waveform obtained at this time is similar to the signal of the FM0 code. Figure 6 shows the baseband signal after subcarrier removal.
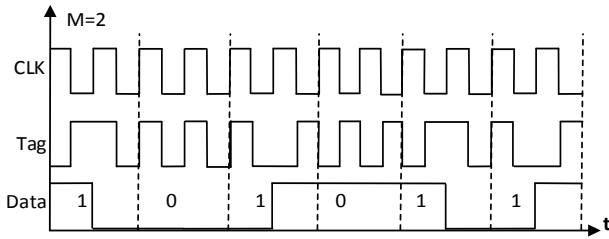

FIGURE VI. ELIMINATION OF SUBCARRIER IN MILLER2 CODE

As specified in ISO 18000-6C, the duty ratios of symbol 0 and symbol 1 range from 45% to 55%. Since the theoretical value is 50%, the phase decision cannot be made only at half of an cycle, $T/2$ and the decision region needs to be extended to $[0.45T, 0.55T]$ Figure 7 shows Miller decoding result and FM0 decoding result after the matched filter.
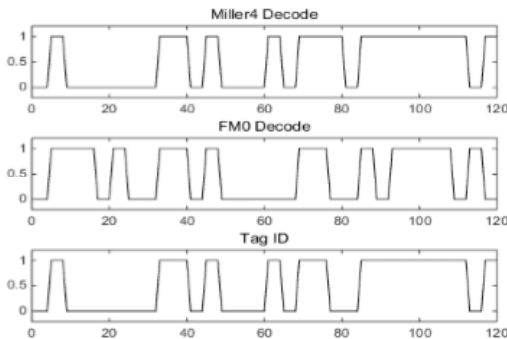

FIGURE VII. COMPARISON OF THE MILLER AND FM0 CODE THROUGH A MATCHED FILTER

D. Miller Decoding Step

Step 1: the separated tag signal through a matched filter is resampled. Assuming that the baseband signal's symbol period is T, the matched filter's resampling period is T/2.

Step 2: the baseband Miller code's subcarriers can be eliminated via XOR operation, where the resampled signal is XOR operated with a square wave of frequency BLF*s in which s is specified from the value of M in the command Query.

Step 3: Detect the preamble. The Miller coded preamble has been specified as "010111", from which the preamble can be determined and the starting position of the decoding is also determined.

Step 4: A decision is made in each cycle of the baseband Miller code to obtain tag symbol. Baseband Miller decoding is similar to FM0 decoding. If the first half period of the symbol is T1 and the second half period is T2, the tag symbol can be obtained through a decision, where the sampling value is determined at time T2 of the previous symbol, and at time T1 and T2 of the current symbol. The decoding can be seen in Table 1.

TABLE I. DECODING MILLER BASEBAND SIGNAL

Sample value in previous symbol half period T2	*Sample value in current symbol half period T1*	*Sample value in current symbol half period T2*	*Decoding result*
1 or 0	0	0	0
1 or 0	1	1	0
0	0	1	1
1	1	0	1

V. SIMULATION EXPERIMENT

A. System Parameter Settings

In this computer simulation experiment, the performance comparison between FM0 and Miller2, Miller4, and Miller8 codes is given. The simulation experiment is carried out on the baseband signal, and the number of readers is assumed to be 1 and the number of collision tags is 2. All the simulation results are repeated 10,000 times independently, and the average of the results is given. All parameters are set according to ISO18000-6C and literature [6, 8, 12, 13]. The specific parameters are set as follows

(1) Channel: a linear time-invariant channel with flat fading in an identification period, and according to the literature[13,15], the path fading coefficients of each tag are not the same, i.e. $E(|h_i|^2) \neq E(|h_j|^2)$, when i≠j.

(2) Symbol block length: the symbol(bit) block length K of tag is set to 96, according to ISO18000-6C[14].

(3) Duty cycle: use the standard value of ISO18000-6C protocol[14], 50%.

(4) Reader receiver antenna: 1.

(5) DataRate: all of FM0 and Miller code adopt the same DataRate.

The simulation experiment process is as follows. (1) Perform FM0, Miller2, Miller4 and Miller8 encoding on the baseband tag signal, respectively and then transmit them through complex channel. (2) Map the collision tag signal to an IQ plane to form a constellation of four clusters in Figure 4. Since the channel of the tag is assumed to be known, the four cluster center points can be determined. In this paper, the Euclidean distance is used to make a decision for the separation of the collision signal. (3) Let the separated baseband signal through a matched filter and obtain the signal with the largest output SNR. (4) Performing FM0, Miller2, Miller4, and Miller8 decoding on the separated signals, respectively, and then calculate bit error rate and separation efficiency.

B. Bit error Rate

In this section, the performance of FM0 and Miller codecs is evaluated by the bit error rate of conflict label separation. The bit error rate of label separation is defined as

$$BER = c_k / c_t \times 100\% \quad (10)$$

Where c_k is the number of error bits in separated tag signal, c_t is the total number of bits, i.e. the symbol block length.
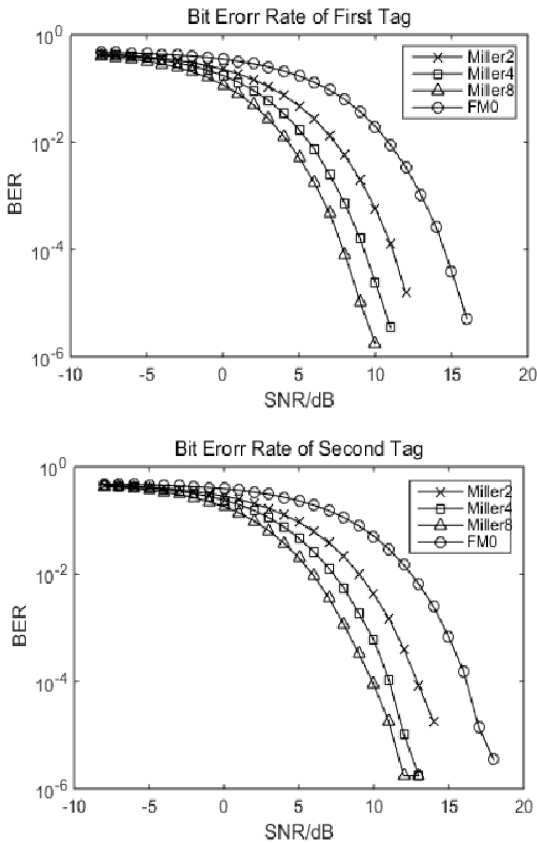

FIGURE VIII. RESULTS OF BERS FOR FM0, MILLER2, MILLER4 AND MILLER8

Figure 8 gives the BERs of FM0 and Miller for the first separated tag signal and the second tag under different SNR when all of codes adopt the same DataRate, where

(1) Miller2: each bit contains 2 subcarriers with a link frequency of BLF=2*DataRates.

(2) Miller4: each bit contains 4 subcarriers with a link frequency of BLF=4*DataRates.

(3) Miller8: each bit contains 8 subcarriers with a link frequency of BLF=8*DataRates.

(4) FM0: each bit contains no subcarriers with a link frequency of BLF=DataRates.

It can be seen from Figure 8 that the BERs of FM0, Miller2, Miller4 and Miller8 decrease with SNR. At lower SNR (from -10dB to -5dB), these codes have higher separated BERs and the collision tag signal at this time is difficult to be decoded. The reason is that, at lower SNR, the separation performance of the collision tag mainly depends on the performance of the matched filter, and the matched filter has a higher BER at lower SNR. On the other hand, at higher SNR (from 5dB to 20dB), the BERs of these codes drastically decrease. In particular, Miller8 has a lower bit error rate than Miller4, while Miller4 has a lower bit error rate than Miller2. The higher bit error rate is FM0 coding, because the Miller code has subcarriers, which is equivalent to an increase in the number of retransmissions bits. When a matched filter is used, the more subcarriers are encoded, the smaller the noise contained in the output signal, and the lower BER. However, it can be seen from eq. (1) that increasing the number of subcarriers reduces the bit rate, so it is necessary to find a compromise in increasing the number of subcarriers and the bit rate to obtain a suitable BER.

C. Separation Efficiency

This sub-section uses tag separation efficiency to evaluate the performance of FM0 and Miller code. The tag separation efficiency is defined as

$$\eta_e = n_b / n_a \quad (11)$$

Where n_b is the number of successfully decoded separated collision tags, and n_a is the total number of collisions tag. The code with higher separation efficiency has better performance. In the experiment, the decoded bits of each tag are compared with the real tag bits, and even if there is only one bit error for a tag, the tag will be considered to be incorrectly decoded.
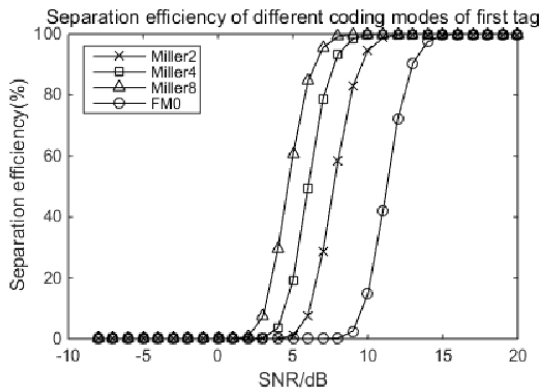
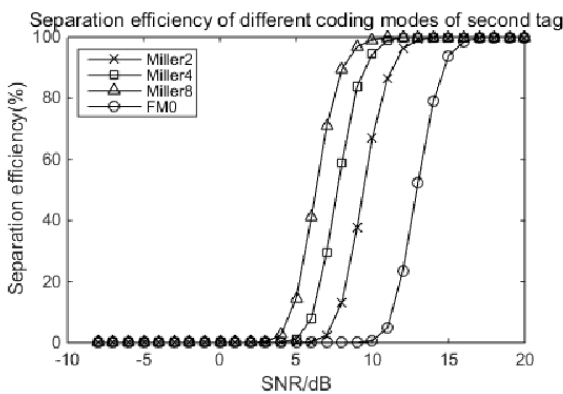FIGURE IX. RESULTS OF BERS FOR FM0, MILLER2, MILLER4 AND MILLER8

FIGURE X. RESULTS OF SEPARATION EFFICIENCIES FOR FM0, MILLER2, MILLER4 AND MILLER8

Figure 9 shows the separation efficiency curves of FM0, Miller2, Miller4 and Miller8 under different SNR. It can be seen from the figure that when SNR is 5dB, the separation efficiency of all codes is lower than 40%. This result means that the separation efficiency of FM0 and Miller codec is lower at lower SNR. However, as the signal-to-noise ratio increases, the separation efficiency of all codes increases. When SNR is 10 dB, the separation efficiency of Miller code is over 95%, while the separation efficiency of FM0 code is lower than that of Miller code. In addition, as can be seen from the figure, when SNR exceeds 15dB, the separation efficiency of Miller8 firstly arrive at 95%, followed by Miller4, Miller2 and FM0. Therefore, under the same *DataRate*, the separation efficiency of FM0 codec does not surpass be those Miller codes.

VI. CONCLUSION

For the separation of UHF RFID collision tags on the physical layer, this paper analyses the impact of Miller code and FM0 code on the separation performance. It can be concluded from the simulation experiment that, since several subcarriers are added to each bit of Miller code, the accuracy and efficiency of the collision tag separation can be improved. However, in order to ensure higher separation performance, the subcarriers will increase. The increase will result in a lower bit transfer rate. Therefore, when obtaining higher separation performance, the Miller code will have a lower transmission rate than the FM0 code.

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