Maximum Likelihood Decoding for Non-Synchronized UHF RFID Tags

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***Abstract*— In Radio Frequency Identification (RFID) systems, when multiple tags reply at the same slot, collision occurs. The tags reply are with different data and also different rates. The rate tolerance between the tags reply reaches to +/-22% of the nominal value of the rate which plays a significant role for the stability and the efficiency of RFID systems. This variation in the tags reply rates inhibit to use the ML receiver which is very sensitive to the rate variation between collided replies. This paper focuses on decoding the collided tags with different rates in the RFID systems using Maximum Likelihood (ML) receiver. A new algorithm is proposed to make the ML receiver is insensitive the rate tolerance between the tags reply. The simulations show that the dual receive antennas ML receiver that is used to recover two collided tags over Rayleigh channel is not affected by the rate tolerance. The receiver performance is compared with the previous proposed dual antenna receivers, Minimum Mean Square Error (MMSE), Zero Forcing (ZF), and Ordered SUccessive Cancellation (OSUC). The proposed receiver outperforms the other types of receivers as it has the largest diversity gain.**

I. Introduction

Radio Frequency Identification (RFID) is an automatic identification system that uses wireless communications to identify objects. Nowadays, large amount of RFID tags are used in supply chain for product identification [1], or sensor networks [2], where the cost and energy are critical. One of the biggest RFID challenges is the capability to resolve collisions.

All the RFID tags are within the reading area of the reader are scheduled using Frame Slotted Aloha (FSA). As a result of that, only a single tag response can be decoded successfully, and in case of more than single tag reply at the same slot, the collision occurs, therefore the total slot will be discarded [3]. On the other hand, the diversities of transmitted signals from different collided tags, mainly on channel coefficient and data rates, may affect the stability and efficiency of RFID system severely. In UHF RFID systems, the data rate variations are much more crucial than in other communication systems and if they are not taken into consideration, it would be very difficult to make a correct decoding, leading to an inefficient communication [4]. These data rate variations appear from two factors that can not be mitigated in practical systems. Firstly, due to low cost, RFID tags use a slow system clock for the digital base-band operation, resulting in a measurement error for the parameters that are transmitted by the reader to determine the tag data rate. In the EPCglobal Class-1 Gen-2 RFID protocol, this tag reply rate is called Backscatter Link Frequency (BLF) [5]. Secondly, the tag clock frequency is usually affected by manufacturing process variations, which also contribute to the BLF variations. Based on the standard, a maximum BLF tolerance of $\pm 22\%$ is allowed with a BLF range from $[40] kHz$ to $[640] kHz$ [5]. However, most of previous researches that focus on collision recovery for RFID system assume that the collided tags have the same BLF which is not valid assumption anymore.

Different groups paid attention on slots with colliding RFID tag replies. Angerer et al. [6] proposed an algorithm for channel estimation for two colliding tags to be encoperated with single and multiple antennas techniques to separate the collided tags. However, they did not take the tolerance in the BLF into account in his simulation. Also he did not use the optimum receiver because of BLF tolerance. Kimionis et al. [7] proposed a collision recovery technique to separate two and three collided tags based on the tag reply encoding scheme properties. The proposed algorithm will completely fail, if the tolerance of the BLF is taken into consideration. Kaitovic et al. [8] proposed a channel estimation technique that could be used to separate up to eight collided tags per slot. However, this technique is not compatible with the EPCglobal Class-1 Gen-2 RFID protocol and also the rate tolerance is not taken into consideration.

In this paper, we present a collision recovery technique based on Maximum Likelihood (ML) receiver with taking into consideration the BLF tolerance. The ML decoding is very sensitive to the rate tolerance between the collided symbols, so the proposed algorithm is used to mitigate this sensitivity. The collision recovery technique is tested with two collided tags with different tolerance values as based on [6], there is no channel estimation technique compatible with the standard [5] for more than two tags.

This paper is organized as follows. Section 2 explains the most important basics of the EPCglobal standard. In Section 3, The proposed ML decoding technique is presented. In Section 4, the simulation results are discussed. Finally, the conclusion is drawn in Section 5.

(a) FM0 base-functions

(b) FM0 sequences

Fig. 1: FM0 encoding scheme

Fig. 2: Communication between a reader and two tags

II. EPCGLOBAL CLASS-1 GEN-2

According to the EPCglobal standard [5], the tag uses either FM0 (bi-phase space) or Miller to encode its data. As the FM0 encoding offers the higher data rate, most of the readers use this encoding scheme and this paper focuses on it. The basis functions $s_n(t)$ follow an FM0 (bi-phase space). In FM0 encoding, the pulse shapes $s_n(t)$ for the symbols are selected among four pulse shapes as shown in figure 1a, where $s_0(t)$ and $s_1(t)$ represent data-0 and $s_2(t)$ and $s_3(t)$ represent data-1. The symbols are arranged to feature a level transition at each boundary. For example, the pulse $s_0(t)$ can only be followed by $s_0(t)$ or $s_2(t)$, but not by the symbol $s_1(t)$ or $s_3(t)$ to keep the feature of a level transition between symbols as shown in figure 1b.

According to the standard, the nominal symbol duration value depends on the tag reply encoding technique. It is a multiple of the inverse of the BLF. In case of FM0 encoding, the symbol period is related to the BLF by: $T = 1/BLF$ as shown in figure 1b.

III. ML DECODING FOR COLLIDED TAGS

A. System Model

Figure 2 shows the basic communication between two tags and a RFID reader, equipped with N_R receive antennas. In passive RFID systems the communication is half-duplex. The reader provides the RFID tags with energy in form of a continuous carrier transmission. During this energy signal the reader sends some specific commands to the tags to tell them about the rate they should reply with, the modulation technique that should be used, and the number of available slots. Then the tags use the reader information to backscatter their IDs. Because of this type of communication link, the channel that each tag reply faces is a backscatter channel. The backscatter channel is a forward channel (reader to tag) and a backward channel (tag to reader) multiplied to each other. In [9], the authors proposed a two-way Rician channel model for RFID scenarios based on carried out channel measurements. They also showed that since Rician factor strongly depends on the environment, a better fit to the measurement data was achieved by applying a double Rayleigh distribution. We can describe the system by equation (1)

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ represents $N_R \times R$ channel matrix with channel elements $h_{ij} = h^f_j \cdot h^b_{ij}$, y is the $N_R \times 1$ complex valued received signal vector, x denotes $R \times 1$ the modulation signal vector from tags, and n is the $N_R \times 1$ AWGN at receive antennas. In this work, we assume that the transmit and receive antennas of the reader are perfectly isolated so there is no carrier leakage.

B. ML Decoding for Non-Synchronized Collided Tags

The objective of the receiver is to obtain an estimate of the modulation signal of tags, $\mathbf{x}$, from the given received data in $\mathbf{y}$ over Additive White Gaussian Noise (AWGN) with noise variance σ_n^2, through channel $\mathbf{H}$. There are a wide variety of techniques for doing this but as stated in the introduction this work will only be concerned with the maximum likelihood (ML) detector. The ML detector has the desirable property that, it minimizes the probability of error,

$$P_e \triangleq P(\mathbf{x} \neq \hat{\mathbf{x}}) \tag{2}$$

Minimizing the probability of error is equivalent to maximizing the probability of correctly estimating $\mathbf{x}$, i.e. $P(\mathbf{x} = \hat{\mathbf{x}} \mid y, \mathbf{H})$. To maximize the probability of correctly estimating we have to maximize the probability density function of $\mathbf{y}$ given $\mathbf{x}$, and $\mathbf{H}$, $P(\mathbf{y} \mid \mathbf{x}, \mathbf{H})$ [10]

$$P(\mathbf{y} \mid \mathbf{x}, \mathbf{H}) = \frac{1}{\pi^{N_R} \sigma_n^{2N_R}} exp\left(-\frac{1}{\sigma_n^2} \left\| y - \mathbf{H}\mathbf{x} \right\|^2\right) \tag{3}$$

Equation (3) is referred to as the ML criterion and the detector given by

$$\hat{\mathbf{x}} = arg \max_{\mathbf{x} \in X} P(y \mid \mathbf{x}, \mathbf{H}) = arg \min_{\mathbf{x} \in X} \left\| y - \mathbf{H}\mathbf{x} \right\|^2 \tag{4}$$

The ML detector is the optimum receiver from performance point of view. However, the performance of the receiver is severely affected with the non-synchronization of the received symbol which is the case in the RFID system as shown figure 3. In this paper we propose an algorithm that makes the ML receiver does not care about the synchronization between received symbols. Figure 3 shows two collided with two different symbol duration, T_1 and $T_2$where $T_1 < T_2$, and $T_i = \frac{1}{BLF_i}$. The problem of non-synchronized tags is that the symbol of the tag that has a lower symbol duration T_1 overlaps two symbols of the tag that has an higher symbol duration T_2. For example the second symbol of Tag1 overlaps the second symbol of Tag2 in an interval equals to $T_2 - 2\delta$ and δ of the first symbol, where $\delta = T_2 - T_1$. The overlap between symbol i of Tag1 and symbol i of Tag2 equals to $T_2 - i \cdot \delta$. In addition to the overlap between symbol i of Tag1 and symbol $i-1$ of Tag2 equals to $(i-1) \cdot \delta$. Based on the this formulation of the rate tolerance problem, we designed an

Fig. 3: ML decoding for non-synchronized tags

Fig. 4: Bit Error Ratio for two receive antennas receiver in Rayleigh fading channel in collision slots of two tags with 0, 5, and 22% BLF tolerance

algorithm to solve the problem. First, we have assumed that BLF_1 and BLF_2 are accurately estimated using MUSIC algorithm [11]. Then the generated vector x will contain two elements as we are taking two collided tags as an example. Assume we are talking about decoding symbol i of Tag1; the first element in vector x will be a symbol i of Tag1 with symbol length T_1, and the second element is $T_2 - i\delta$ of symbol i and $(i-1)\cdot\delta$ of symbol $i-1$. This process would be repeated till the end of Tag1 symbols, then the remaining part of Tag2 symbols can be decoded separately as in this part there is no collision. The decision on Tag1 symbols can be taken directly, but the symbols of Tag2 should be reconstructed first and then decoded using regular correlator receiver.

IV. Simulation Results

For the sake of a simple comparison, we assume that the equivalent channel matrix $\mathbf{H}$ follows a Rayleigh fading. The single Rayleigh channel coefficient are independent zero mean circularly symmetric complex Gaussian random variables with normalized energy $E\{|h_i|^2\} = 1$, which indicates the two collided tags have the same average path loss. Figure 4 shows the performance of the proposed ML receiver with dual antennas when the tolerance in BLF equals to 0, 5, and 22% and how the performance is not affected by the value of tolerance. In the simulation, both tags of uncoded random data are decoded depending on the average received SNR $\gamma = \frac{1}{N_R}\sum_j \bar{\gamma}_j$, where $\gamma_j = |h_{ij}|^2 x_i^2/\sigma_i^2$ is the instantaneous SNR at antenna j for tag i, and $\bar{\gamma}_j = E\{\gamma_j\}$. Additionally to disturbance by noise, each stream is interfered by the second tag responding in the same slot, with the same average power. The channel coefficients are estimated by Angerer method [6].

Figure 5 shows the performance of various dual antenna receivers. As expected, the simple Zero Forcing (ZF) receiver shows the worse performance than the Minimum Mean Square Error (MMSE) and Ordered SUccessive Cancellation (OSUC) [6]. Furthermore, the proposed ML receiver outperform all other receivers that are proposed by [6] by at least $[3]dB$ and also that was expected as the ML decoding is the optimum receiver.

Fig. 5: Bit Error Ratio for two receive antennas receiver in Rayleigh fading channel in collision slots of two tags

V. Conclusions

In this paper, a novel algorithm for decoding two collided and non-synchronized tags using ML decoding. The algorithm mainly depends on generating different basis functions instead of regular basis function that are used when the tags are synchronized. The receiver is tested in a Rayleigh fading channel with AWGN to see the effect of tolerance on it. The simulation shows that the tolerance of BLF has no effect on the receiver performance. The receiver is compared with the ZF, MMSE, and OSUC receivers that were proposed by [6]. The proposed receiver has a diversity gain of order N_R while the MMSE and ZF has a diversity gain of order 1 and the OSUC has a diversity gain of order between 1 and N_R. The simulation of the proposed receiver is verified by simulating the other receivers in the same environment and give the same results of [6].

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