Maximum Likelihood Decoding for Non-Synchronized UHF RFID Tags

Hamed Salah, Hazem A. Ahmed, Joerg Robert, Albert Heuberger

Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Information Technology (Communication Electronics)

{hamed.kenawy, hazem.a.elsaid, joerg.robert, albert.heuberger}@fau.de

Abstract—In Radio Frequency Identification (RFID) systems, when multiple tags reply within the same slot, collisions occur. Furthermore, the tags reply with different data and also with different rates. The rate tolerance between the tag replies reaches up to +/- 22% of the nominal value of the rate. This plays a significant role for the stability and the efficiency of RFID systems. This variation in the tag reply rates inhibits the use of Maximum Likelihood (ML) receivers, which are very sensitive to rate variations between collided replies. This paper focuses on decoding collided tags with different rates in RFID systems using an optimized ML receiver. A new algorithm is proposed to make the ML receiver insensitive to the rate tolerance between the tag replies. Simulations show that the dual receive antennas ML receiver that is used to recover two collided tags over a Rayleigh channel is not affected by the rate tolerance. The receiver performance is compared with previously proposed dual antenna receivers, i.e. MMSE, ZF, and OSUC. The proposed receiver outperforms the other receiver types and offers the highest diversity gain.

I. INTRODUCTION

Radio Frequency Identification (RFID) is an automatic identification system that uses wireless communications to identify objects. Nowadays, large amounts of RFID tags are used in supply chains 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 tag collisions.

All RFID tags within the reading area of a reader are scheduled using Frame Slotted Aloha (FSA). As a result, only a single tag response can be decoded successfully. In case of multiple simultaneous tag replies within the same slot a collision occurs. Therefore, the total slot normally will be discarded [3]. On the other hand, the diversities of transmitted signals from different collided tags, mainly on channel coefficients 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. 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 $40\,\text{kHz}$ to $640\,\text{kHz}$. However, most of the previous research focusing on collision recovery for RFID

system assumes that the collided tags have the same BLF and are fully synchronized, which is not valid assumption.

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. The algorithm can be used with single and multiple antennas to separate the collided tags. However, they did not take the BLF tolerance in into account in their simulations. Additionally, they did not use the optimum ML receiver, because of the BLF variations. 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 account.

In this paper, we present a collision recovery technique based on a Maximum Likelihood (ML) receiver that especially considers the BLF tolerance. Generally, ML decoding is very sensitive to rate variations between the collided symbols. Hence, the proposed algorithm is used to mitigate this sensitivity. The collision recovery technique is tested with two collided tags and 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 conclusions are drawn in Section 5.

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. Hence, this paper is only focusing on FM0. Using FM0 encoding, the pulse shapes $s_n(t)$ for the symbols are selected among four possible 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 symbols $s_1(t)$ 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
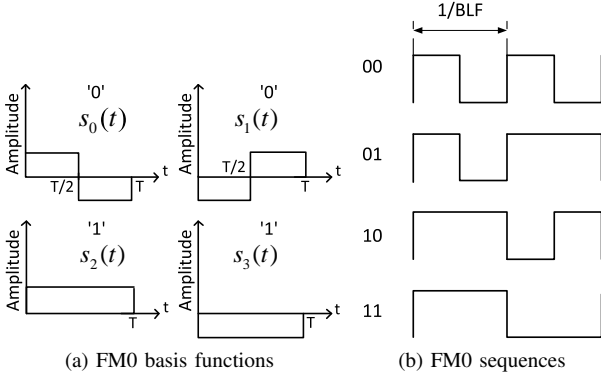
Figure 1: FM0 encoding scheme

(a) FM0 basis functions

(b) FM0 sequences

Figure 2: Communication between a reader and two tags

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 an 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. Within this energy signal the reader modulates some specific commands to the tags, e.g. to tell them about the rate they should reply with, the modulation technique that should be used, or the number of available slots. Then the tags use the reader information to backscatter their IDs. Because of this type of communication link, the tag reply channel is a so-called 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 channel measurements. They also showed, 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)

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \mathbf{n} \qquad (1)$$

where $\mathbf{H}$ represents $N_R \times R$ channel matrix with channel elements $h_{ij} = h_j^f \cdot h_{ij}^b$, 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 wo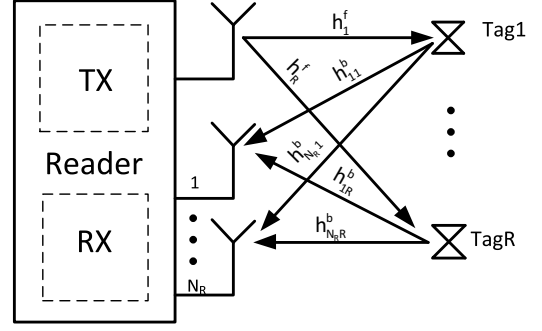rk will only be concerned with the maximum likelihood (ML) detector. The ML detector has the desirable property that, it minimizes the probability of error:

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

Minimizing the probability of an error is equivalent to maximizing the probability of correctly estimating $\mathbf{x}$, i.e. $P(\mathbf{x} = \hat{\mathbf{x}} \mid \mathbf{y}, \mathbf{H})$. 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]

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

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

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

The ML detector is the optimum receiver from the performance point of view. However, the performance of the receiver is severely affected by the non-synchronization of the received symbols, which is the case in the RFID system as shown figure 3. In this paper we propose a ML algorithm that does not require synchronization between received symbols. Figure 3 shows two collided tags with two different symbol durations 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 the higher symbol duration T_2. For example, the second symbol of Tag1 overlaps the second symbol of Tag2 in an interval that 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, 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 algorithm to solve the problem. First, we have assumed that BLF_1 and BLF_2 are accurately estimated, e.g. by using the MUSIC algorithm [11]. Then the generated vector x will contain two elements as we are taking two collided tags. Assume we are talking about decoding symbol i of Tag1: The first element in vector $\mathbf{x}$ 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.
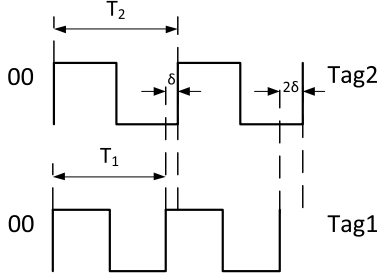
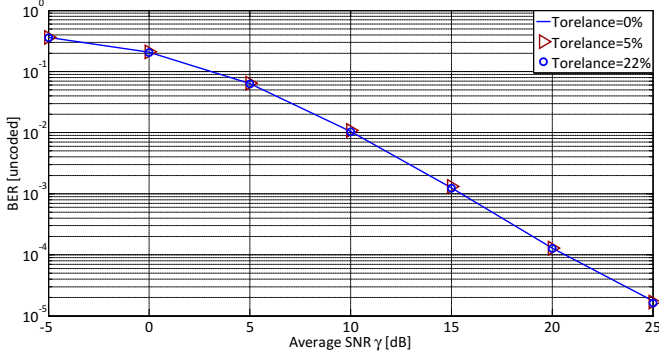Figure 3: ML decoding for non-synchronized tags

Figure 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

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

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 coefficients are independent zero mean circularly symmetric complex Gaussian random variables with normalized energy $E\{|h_i|^2\} = 1$. This indicates that 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 of the BLF equals to 0, 5, and 22%. It is clearly visible that the performance is not affected by the level of the tolerance. In the simulation, both tags transmit uncoded random data, and they 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's method [6].

Figure 5 shows the performance of various dual antenna receivers. As expected, the simple Zero Forcing (ZF) receiver shows the worse performance. The Minimum Mean Square Error (MMSE) and the Ordered Successive Cancellation (OSUC) offer better results [6]. However, our proposed ML receiver outperforms, as expected, all other receivers that are proposed by [6] by at least $3\,\mathrm{dB}$.

V. CONCLUSIONS

In this paper, we propose a novel algorithm for the decoding of two collided and non-synchronized RFID tags using ML decoding. The algorithm mainly depends on generating different basis functions instead of regular basis function that are used
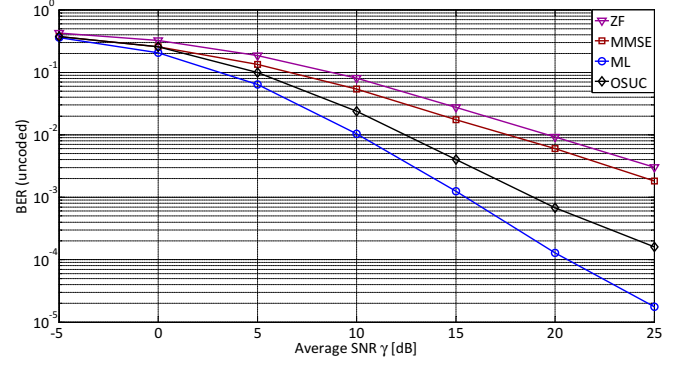
when the tags are synchronized. The performance of the receiver is simulated in a Rayleigh fading channel with AWGN. The simulations shows that the tolerance of the BLF has no effect on the receiver performance. The receiver is compared with the ZF, MMSE, and OSUC receivers that were proposed by [6]. 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 Ordered Successive Cancellation (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].

REFERENCES

[1] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*. John Wiley & Sons Ltd, 2003.

[2] G. Vannucci, A. Bletsas, and D. Leigh, "A software-defined radio system for backscatter sensor networks," *IEEE Transactions on Wireless Communications*, vol. 7, pp. 2170–2179, June 2008.

[3] M. Bueno-Delgado, J. Vales-Alonso, and F. Gonzalez-Castao, "Analysis of dfsa anti-collision protocols in passive rfid environments," in *35th Annual Conference of IEEE Industrial Electronics, 2009. IECON '09.*, pp. 2610–2617, Nov 2009.

[4] P. Wei, B. Li, Y. Yang, H. Min, and J. Wang, "Synchronization with timing recovery loop in uhf rfid reader receivers," in *17th IEEE International Conference on Electronics, Circuits, and Systems (ICECS), 2010*, pp. 1148–1151, Dec 2010.

[5] "EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860MHz - 960MHz version 1.2.0," EPCglobal Inc., 2007.

[6] C. Angerer, R. Langwieser, and M. Rupp, "RFID Reader Receivers for Physical Layer Collision Recovery," *IEEE Transactions on Communications*, vol. 58, no. 12, pp. 3526–3537, 2010.

[7] J. Kimionis, A. Bletsas, A. Dimitriou, and G. Karystinos, "Inventory time reduction in gen2 with single-antenna separation of fm0 rfid signals," in *IEEE International Conference on RFID-Technologies and Applications (RFID-TA), 2011*, pp. 494–501, Sept 2011.

[8] J. Kaitovic, R. Langwieser, and M. Rupp, "A smart collision recovery receiver for rfids," *EURASIP Journal on Embedded Systems*, vol. 2013, no. 1, 2013.

[9] A. Lazaro, D. Girbau, and D. Salinas, "Radio link budgets for uhf rfid on multipath environments," *IEEE Transactions on Antennas and Propagation*, vol. 57, pp. 1241–1251, April 2009.

[10] J. G. Proakis and M. Salehi, *Digital Communications, 5th Edition*. McGraw-Hill, 2007.

[11] C. Angerer, R. Langwieser, and M. Rupp, "Evaluation and exploration of RFID systems by rapid prototyping," *Personal and Ubiquitous Computing*, vol. 16, no. 3, pp. 309–321, 2012.