Separation of overlapping RFID signals by antenna arrays

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***Abstract*— Radio Frequency Identification (RFID) is a technology to wirelessly transmit the identity of tagged objects. For long-range (UHF) systems with multiple tags, the tag replies may overlap. Current solutions are based on collision avoidance using MAC protocols (e.g. slotted ALOHA and binary tree algorithms). This can be a time-consuming process. In this paper, it is shown how an antenna array in combination with blind source separation techniques can be used to separate multiple overlapping tag signals. The source signals are modeled as Zero Constant Modulus (ZCM) signals, and the corresponding ZCM algorithms are tested on synthetic and measured data sets.**

Index Terms—RFID, beamforming, blind source separation

I. Introduction

Radio frequency identification (RFID) is a generic term that is used to describe a system that transmits the identity (in the form of a unique serial number) of an object or person wirelessly, using radio waves. RFID has become a key technology in mainstream applications that help the efficient tracking of manufactured goods and materials by technology achievements in microelectronics and communications. Unlike barcode technology, RFID does not require a line of sight. Some uses of RFID technology can be found in general application areas such as security and access control, transportation and supply chain management.

An RFID system includes three primary components: a transponder (tag), a transceiver (reader) and a data collection device. The operation of RFID systems often involves a situation in which numerous transponders are present in the reading zone of a single reader at the same time. The reader's ability of processing a great quantity of tags simultaneously for data collection is important. If multiple tags are activated simultaneously, their messages can collide and cancel each other at the reader. This situation will require a retransmission of the tag IDs, which results in a waste of bandwidth and increases the overall delay in identifying the objects. A mechanism for handling tag collisions is necessary.

Currently employed mechanisms are collision avoidance methods and act at the MAC level (similar to the situation in networking). E.g., the ISO standard uses a slotted ALOHA protocol. If tags collide, they are instructed to wait a random time up to a certain maximum—which is doubled at each iteration until no collisions are reported [1]. In other standards, spread spectrum or similar techniques are used to deterministically separate reader and tag transmissions, when permitted by local regulations. A brief summary of anti-collision methods can be found in [2].

The collision problem has hardly been studied from a signal processing perspective. If the reader is equipped with an antenna array, we arrive at a MIMO problem (”multiple input-multiple output”), and it may be possible to separate the overlapping collisions based on differences in the spatial locations of the tags. The system setup is shown in Fig. 1. In this paper we describe the data model for RFID signals according to the widely used ISO 18000-6C standard, verify whether such signals admit Blind Source Separation algorithms, based on synthetic data and actual measurements, and study the performance of a source separation algorithm (AZCMA).

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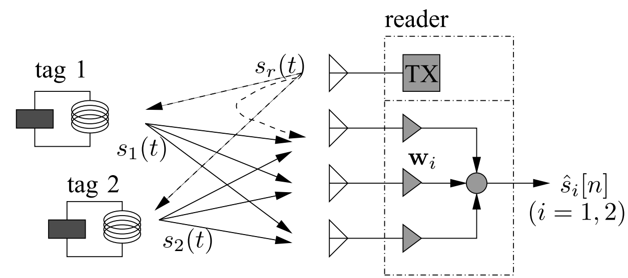

Fig. 1. Blind Source Separation scenario. The reader receives multiple overlapping tag signals, plus a copy of its own transmitted signal. A beamformer is used to recover each of the tags.

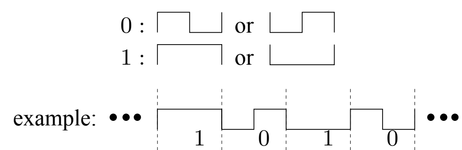

Fig. 2. FM0 symbol encoding [3]

II. Preliminary

An RFID system includes three primary components: a transceiver (interrogator, reader), a transponder (tag, label), and a data collection device (computer) connected to a database system. The interrogator transmits a ”reader request” message to a tag by a modulated RF signal. RFID systems may operate in several frequency bands; in this paper we are interested in UHF systems (300 MHz–3 GHz, typically 868 MHz in Europe and 915 MHz in the USA), which are used for long range systems (larger than 1 m). The return signal is generated via backscatter, by creating an impedance mismatch which causes the antenna to reflect back some of the energy towards the reader, which can detect this using a sensitive radio receiver. By modulating this signal, the tag ID is transmitted back to the reader. The actual return signal can be very small (80 to 90 dB below the reader signal).

A current world wide standard is ISO 18000-6C, which includes EPCglobal Class 1 Generation 2 amendments from 2006 [3], [1]. In this standard, the simplest symbol encoding (single-reader mode) is a baseband frequency modulation (FM0), which inverts the baseband phase at every symbol boundary; a logical 0 has an additional mid-symbol phase inversion (Fig. 2). The data rate ranges from 40 kbps to 640 kbps.

RFID tag response frames contain either 16 or 128 binary symbols; the short frame is used during the contention phase where collisions can occur. The transmitted tag response is a data packet consisting of a preamble (6 or 18 symbols, see Fig. 3) followed by the encoded

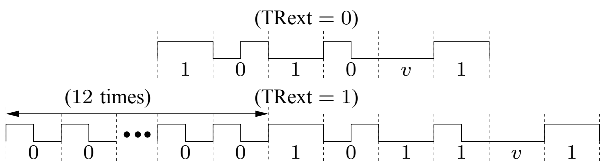

Fig. 3. FM0 preambles (two choices defined by parameter TRext) [3]

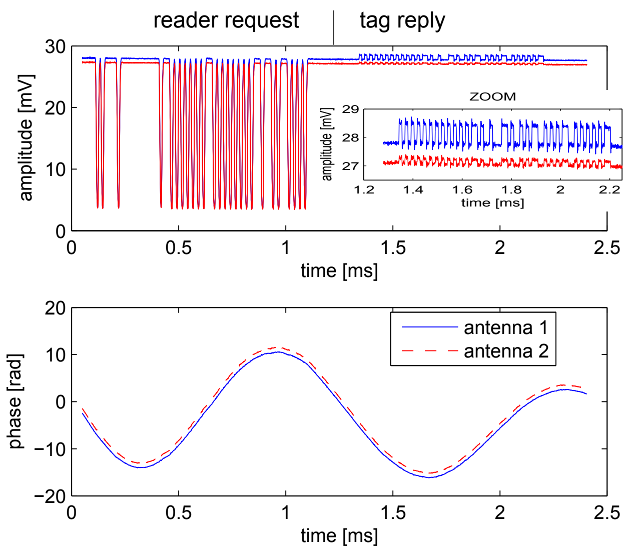

Fig. 4. Baseband amplitude and phase of a measured RFID reader and tag reply signal (2 antennas). Superimposed on the tag signal is the strong unmodulated reader carrier signal that provides power to the tags. Oscillator drift causes significant phase fluctuations.

data symbols.

Current collision avoidance solutions depend on a slotted ALOHA or a binary tree splitting algorithm to identify the tags. These methods cannot decode tag responses if more than one tag responds at the same time. Tags transmit in a randomly selected slot with index between 0 and a maximum that is iteratively adjusted until all tags have been acknowledged by the reader. Even with two times more slots than tags, the probability that at least one collision occurs during the acquisition interval can be high (e.g. 88% for 8 tags, 16 slots), thus leading to long decoding times.

In this paper, we consider the use of an array of antennas at the receiver. By linearly combining the outputs of the antennas, the aim is to separate the signals and thus to remove the mutual interference. A collision only occurs if there are more tags than antennas. The improvement in decoding time can be better than linear in the number of antennas (e.g. for 8 tags, 8 slots, 2 antennas, the duration of the first contention period is halved and the remaining probability of a collision is reduced to 50%).

III. Data Model

Following one of the possibilities in the ISO standard, we consider tag responses as amplitude modulated signals with symbol period $T = 25\mu$s. As discussed in Section II, the messages are coded binary sequences $b[n] \in \{0, 1\}$, modulated on a carrier $f_c = 868$ MHz which is derived from the transmitted reader signal. The tolerance on this carrier frequency is about 20 kHz, and as seen in Fig. 4, oscillator drifts prevent the exact demodulation of the carrier to baseband, unless adaptive carrier tracking is employed. As a result, there will

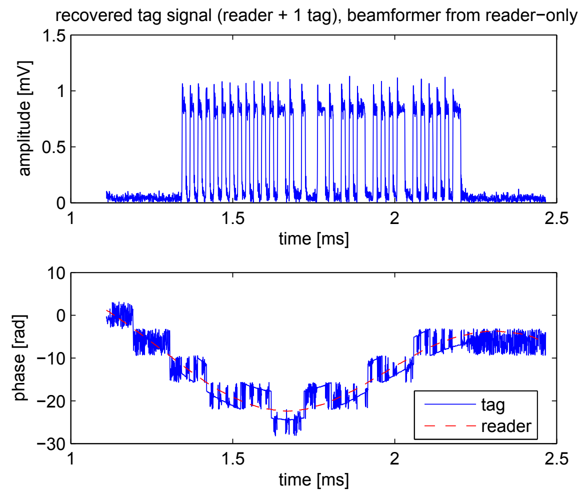

Fig. 5. Amplitude and phase of recovered tag signal for the dataset in figure 4 (reader + 1 tag); the beamformer is computed from the interval in which only the reader signal is present. The recovered phase somewhat follows that of the reader, but can be considered as random.

be a residual carrier frequency (common for the reader and the tags). It appears from experimental data that each tag will also have its own "random" phase fluctuations, thus we will model the received signal of the ith tag as

$$s_i[n] = b_i[n] \exp(j\phi_i[n]) , \tag{1}$$

with $b_i[n]$ the binary message of the ith tag, and $\phi_i[n]$ a random phase. The received signal samples are either equal to zero or they lie on the unit circle: $s[n] = 0$ or $|s[n]| = 1$. Such signals are called Zero Constant Modulus (ZCM) signals.

A strong copy of the reader signal will also be present at the receiver, but since it is unmodulated, it is a Constant Modulus (CM) signal of the form

$$s_r[n] = \exp(j2\pi f_r nT) , \tag{2}$$

with f_r the residual carrier frequency (possibly slowly varying).

After demodulation to baseband, it is sufficient to consider a narrowband data model with tag signals that are 100% overlapping.

With d tags, a mixture of d independent source signals plus the reader signal are impinging on the receiver antenna array, consisting of M elements. The antennas should be separated by at least half a wavelength (15 cm) and preferably by much more. The baseband antenna signals are sampled at rate $1/T$ and stacked in vectors $\mathbf{x}[n]$ of size M. After collecting N samples, a data matrix $\mathbf{X} = [\mathbf{x}[1], \cdots, \mathbf{x}[N]]$ is created, consisting of N complex valued vector samples from the M antennas. The multipath delay spread will be small relative to the sampling period, so that a narrowband observation model is applicable:

$$\mathbf{X} = \mathbf{AS} + \text{noise} = \mathbf{a}_r\mathbf{s}_r + \mathbf{a}_1\mathbf{s}_d + \cdots + \mathbf{a}_d\mathbf{s}_d + \text{noise} . \tag{3}$$

Here, $\mathbf{A} = [\mathbf{a}_r, \mathbf{a}_1, \cdots, \mathbf{a}_d]$ contains the array response vectors of the reader signal and the d tag signals, and $\mathbf{S} = [\mathbf{s}_r^T, \mathbf{s}_1^T, \cdots, \mathbf{s}_d^T]^T$ contains the signal samples of the reader and the d tags.

Since the antennas will be in the near field and multipath is likely to be present, we will not consider any structure of the array response vectors. To enable source separation using beamforming, we will assume that the submatrix $[\mathbf{a}_1, \cdots, \mathbf{a}_d]$ is tall or square, and of full column rank. The reader array response vector $\mathbf{a}_r$ should be linearly independent to each of the $\mathbf{a}_i$.

Ideally, after downmodulation $\mathbf{s}_r$ is a constant signal, $\mathbf{s}_r = [1, 1, \cdots, 1]$. In practice, it is not constant but we can say it is a constant modulus signal (viz. (2)). It is often reasonable to assume that it is known.

IV. Separation algorithms

Given $\mathbf{X}$, our aim is to derive beamformers $\mathbf{w}_i$ $(i = 1, \cdots, d)$ to recover each of the sources $\mathbf{s}_i$ as $\hat{\mathbf{s}}_i = \mathbf{w}_i^H \mathbf{X}$.

A. Separating the tag signals

If $M \geq d+1$, then $\mathbf{A}$ is tall or square, and we assume it is of full rank $d+1$. Since all sources including the reader signal are ZCM sources, we can apply the "Algebraic ZCM Algorithm" (AZCMA) derived by Van der Veen and Tol in [4], or one of its variants [5].

Briefly, if $s[n]$ is a Zero Constant Modulus source, the ZCM property can be written as

$$s[n](s[n]^* s[n] - 1) = 0\,, \qquad n = 1, \cdots N\,. \tag{4}$$

Inserting $s[n] = \mathbf{w}^H \mathbf{x}[n]$ gives

$$\mathbf{w}^H \mathbf{x}[n]\mathbf{x}[n]^H \mathbf{w}\mathbf{w}^H \mathbf{x}[n] = \mathbf{w}^H \mathbf{x}[n]\,, \quad n = 1, \cdots, N\,. \tag{5}$$

Using properties of Kronecker products, we can separate the unknown $\mathbf{w}$ from the known $\mathbf{x}[n]$, which results in N cubic equations

$$(\bar{\mathbf{x}}[n] \otimes \mathbf{x}[n] \otimes \bar{\mathbf{x}}[n])^H (\bar{\mathbf{w}} \otimes \mathbf{w} \otimes \bar{\mathbf{w}}) = \frac{1}{\alpha} \mathrm{vec}(\mathbf{I}_d \otimes \bar{\mathbf{x}}[n])^H (\bar{\mathbf{w}} \otimes \mathbf{w} \otimes \bar{\mathbf{w}}) \tag{6}$$

where the overbar denotes complex conjugation, $\mathbf{I}_d$ is a $d \times d$ identity matrix, vec is an operator that stacks the columns of its matrix argument into a single vector, $\otimes$ is the Kronecker product, and we have introduced a nuisance parameter $\alpha = \|\mathbf{w}\|^2 = \mathbf{w}^H \mathbf{w}$. Define matrices $\mathbf{P}_1$, $\mathbf{P}_2$ with rows $(\bar{\mathbf{x}}[n] \otimes \mathbf{x}[n] \otimes \bar{\mathbf{x}}[n])^H$ and $\mathrm{vec}(\mathbf{I}_d \otimes \bar{\mathbf{x}}[n])^H$, respectively. Then the ZCM separation problem is seen to be equivalent to finding all solutions $(\alpha, \mathbf{y})$, $\alpha \neq 0$ to

$$\alpha \mathbf{P}_1 \mathbf{y} \;=\; \mathbf{P}_2 \mathbf{y}\,, \quad \text{where } \mathbf{y} = \bar{\mathbf{w}} \otimes \mathbf{w} \otimes \bar{\mathbf{w}}\,. \tag{7}$$

This is a matrix pencil problem (generalized eigenvalue problem with nonsquare matrices), and can be solved. After finding solutions $\mathbf{y}_i$ (one for each tag), these can be factored into the corresponding $\mathbf{w}_i$. To ensure an overdetermined system of equations, we require $\mathbf{P}_1$ and $\mathbf{P}_2$ to be "tall", i.e., $N \geq (d+1)^3$. There are a number of other implemenentation details that are listed in [4], [5].

In this algorithm, the reader signal does not have to be known; it is found as one of the sources (see later in Fig. 7 for an example). While convenient, this implies that one antenna dimension is lost on the reader signal, and that more samples are needed to ensure $\mathbf{P}_1$ and $\mathbf{P}_2$ are tall. Thus, we will look for techniques to remove the reader signal in advance.

B. Filtering out the reader signal

Assume $M \geq d$. In many cases the receiver will have access to the transmitted reader signal. With $\mathbf{s}_r$ known, we can try to remove the reader signal by either subtracting it or by projecting it out.

1) Subtraction: Assuming the tag signals are weak and approximately orthogonal to $\mathbf{s}_r$, we can estimate $\mathbf{a}_r$ by correlation:

$$\hat{\mathbf{a}}_r = \mathbf{X}\mathbf{s}_r^H / \|\mathbf{s}_r\|^2\,. \tag{8}$$

Then the reader signal is removed by setting

$$\mathbf{X}' = \mathbf{X} - \hat{\mathbf{a}}_r \mathbf{s}_r\,. \tag{9}$$

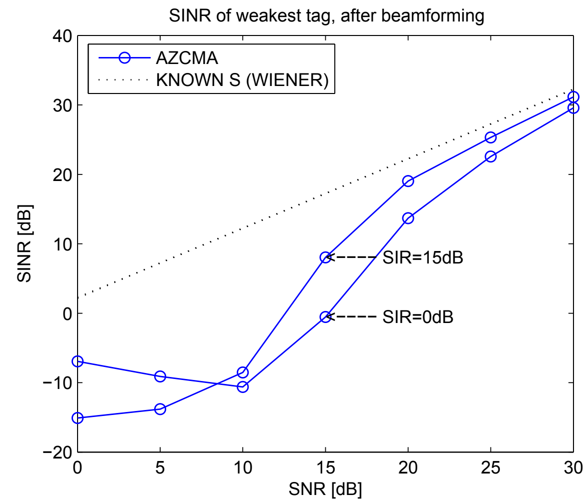

Fig. 6. SINR at the output of the beamformer vs. input SNR

2) Column span projection: A very good estimate of $\mathbf{a}_r$ can also be obtained from intervals in the received signal where there are no tag responses (e.g. during and immediately after the modulated reader signal). Collect a data matrix $\mathbf{X}_r$ or samples that are known to contain only the reader signal. This is a rank-1 matrix, and the dominant left singular vector (obtained from an SVD) is an estimate of $\mathbf{a}_r$, up to scaling. We can subsequently form a projection matrix

$$\mathbf{P}_c = \mathbf{I} - \hat{\mathbf{a}}_r \hat{\mathbf{a}}_r^H / \|\hat{\mathbf{a}}_r\|^2 \tag{10}$$

and project out the reader signal as

$$\mathbf{X}' = \mathbf{P}_c \mathbf{X}\,. \tag{11}$$

This technique was used to suppress the reader signal in the dataset of Fig. 4, resulting in the recovered tag signal in Fig. 5. It is not necessary that the reader signal is known; however, the projection will lead to the loss of one antenna dimension.

If the reader signal *is* known, we can work with an augmented data matrix

$$\mathbf{X}_a = \begin{bmatrix} \mathbf{X} \\ \mathbf{s}_r \end{bmatrix} \tag{12}$$

(as if there is a reference antenna that contains only the reader signal), and apply the above techniques without loss of an antenna dimension.

3) Row span projection: Assuming the reader signal $\mathbf{s}_r$ is approximately orthogonal to all transponder signals, we can form the projection matrix $\mathbf{P}_r = \mathbf{I} - \mathbf{s}_r \mathbf{s}_r^H / \|\mathbf{s}_r\|^2$ and set

$$\mathbf{X}' = \mathbf{X}\mathbf{P}_r\,. \tag{13}$$

The resulting reader-free data matrix is almost equivalent to (9) except that now the tag signals are replaced by $\mathbf{s}_i' = \mathbf{s}_i \mathbf{P}_r$. For constant reader signals ($\mathbf{s}_r = [1, \cdots, 1]$), the effect of this projection is a removal of the mean value of the tag signal, a similar effect occurs for CM reader signals. This implies that there is a potential loss of the ZCM property of the tag signal, although this effect is negligible for longer data sequences (with sufficiently random phase rotations, the tag signal is zero-mean; equivalently, the tag signal is approximately orthogonal to the reader signal).

V. Simulations

To assess the performance of the AZCMA source separation algorithm, a simulation setup as in Fig. 1 is considered. There are

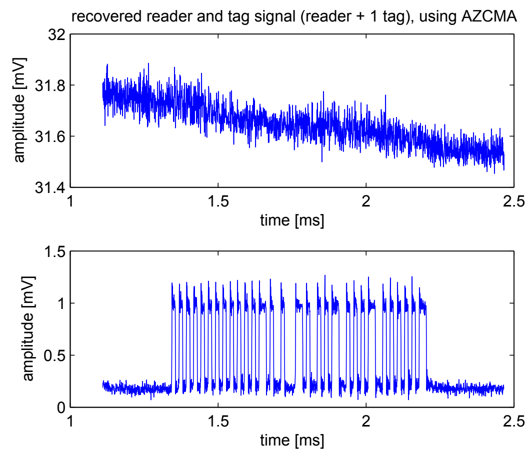

Fig. 7. Recovered reader and tag signal for the dataset in figure 4 (reader + 1 tag); beamformer computed using AZCMA

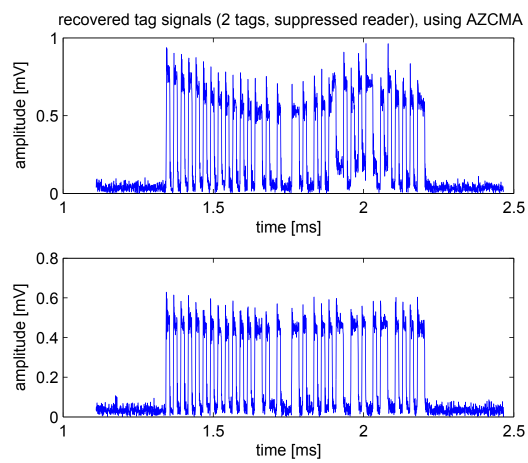

Fig. 8. Recovered tag signals (dataset with 2 tags and suppressed reader signal); beamformers computed using AZCMA

$M = 2$ antennas and $d = 2$ tags. The distance between the antennas is equal to half wavelength, the tag signals arrive at $0°$ and $50°$, respectively, and there is no multipath. It is assumed that the reader signal has been suppressed. The tag signals contain a preamble of 18 symbols (Fig. 3) followed by a random sequence of 16 bits, encoded using FM0 as in Fig. 2; the resulting datalength is $N = 68$ samples. Each tag sample is modified by an arbitrary phase shift. Complex white Gaussian noise is added. Two different Signal to Interference Ratios (SIRs) are considered: the power of tag 2 is 0 dB and 15 dB above the power of tag 1.

The resulting separation performance is shown in Fig. 6, in terms of the Signal to Interference plus Noise Ratio (SINR) at the output of the beamformer, versus the input Signal to Noise Ratio (SNR). Only the worst SINR of the two tags is shown. The performance is compared to that of an optimal beamformer where the source signals are completely known (i.e., $\mathbf{W}^H = \mathbf{S}\mathbf{X}^H(\mathbf{X}\mathbf{X}^H)^{-1}$). For sufficiently large SNR, the performance of the algorithm approaches that of the optimal beamformer. For lower SNR, the performance is quickly limited by the inherent noise enhancement in the algorithm (caused by taking the 3rd order moments in Eqn. (6)).

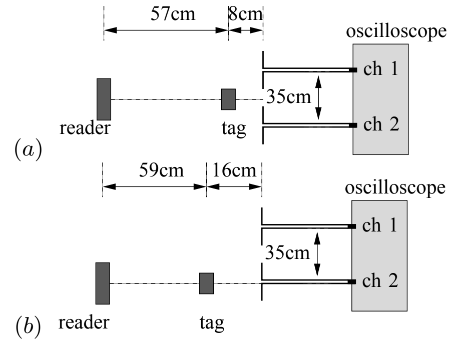

Fig. 9. Experimental setup (1 tag, 2 receiver antennas)

VI. Experiments

Measurement data was obtained and provided by Thomas Plos at the RFID Center (PROACT) at TU Graz. The setup was as shown in Fig. 9 (one tag and a reader, placed in two configurations). The setup has 2 antennas which are connected to the channels of a digital storage oscilloscope, sampling at a rate of 250MS/s. Demodulation to baseband, lowpass filtering and downsampling was done offline.

The tag was placed quite close to the antenna. This is because of limitations in the present setup, in particular a limited resolution of the oscilloscope. In an actual reader, the reader signal would typically be filtered away by a notch filter before amplification and sampling.

Fig. 7 shows the result of applying AZCMA to a dataset (containing the reader signal and a single tag signal), it is seen that the signals are quite nicely separated. Fig. 8 shows the result of applying AZCMA to an offline created mixture of the two tag signals as recovered from the two single-tag datasets. Separation is achieved although it is not perfect (the input SIR is 0 dB, the resulting output SIR is about 8 dB for one tag, and 25 dB for the other).

VII. Conclusions

The shown algorithm, AZCMA, is effective at high SNR, but is limited at lower (and more realistic) SNRs. Nonetheless, separation using beamforming techniques certainly seems feasible. Since the tags have a known preamble, an alternative algorithm that generates less noise enhancement would be to use ACMA [6] on combined segments where the preamble bits are known to be “1” (i.e., CM).

Acknowledgement

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References

[1] D.M. Dobkin and D.J. Kurtz, “Overview of EPCglobal class 1 generation 2 and comparison with 1st generation EPCglobal standards,” tech. rep., RFID Solutions Online, Feb. 2006. Online, via http://www.rfidsolutionsonline.com/.

[2] Liang Biao, Hu Ai-qun, and Qin Zhong-Yuan, “Trends and brief comments on anti-collsion techniques in radio frequency identifcation systems,” in *Proc. 6th Int. Conf. on ITS Telecommunications*, 2006.

[3] ISO/IEC 18000-6, “Parameters for air interface communications at 860 MHz to 960 MHz, amendment 1: Extension of type C and update of type A and B,” tech. rep., ISO, Geneva, 2006.

[4] A.J. van der Veen and J. Tol, “Separation of zero/constant modulus signals,” in *Proc. IEEE ICASSP*, (Munich (Germany)), pp. 3445–3448, IEEE, Apr. 1997.

[5] N. Petrochilos and A.J. van der Veen, “Algebraic algorithms to separate overlapping Secondary Surveillance Radar replies,” *IEEE Tr. Signal Processing*, vol. 55, pp. 3746–3759, July 2007.

[6] A.J. van der Veen and A. Paulraj, “An analytical constant modulus algorithm,” *IEEE Tr. Signal Processing*, vol. 44, pp. 1136–1155, May 1996.