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IEICE Communications Express, Vol.5, No.5, 118–123

An RFID tag identification protocol via Boolean compressed sensing

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Abstract: This paper proposes a tag identification protocol built upon Boolean compressed sensing (CS) for radio frequency identification (RFID) systems. Unlike the conventional CS-based tag identification (CS-ID) protocol, the proposed protocol can cope with flat fading channels without explicit channel estimation. Simulation results show that the proposed scheme requires less amount of bits for successful identification than dynamic framed slotted ALOHA (DFSA) protocol, and that it even outperforms the conventional CS-ID protocol with perfect channel information.

Keywords: RFID tag identification, Boolean compressed sensing, IoT
Classification: Wireless Communication Technologies

References

[1] Y. Zhang, L. T. Yang, and J. Chen, *RFID and Sensor Networks*, CRC Press, Inc. Boca Raton, FL, USA, 2009.
[2] L. D. Xu, W. He, and S. Li, "Internet of things in industries: a survey," *IEEE Trans. Ind. Informat.*, vol. 10, pp. 2233–2243, Nov. 2014. DOI:10.1109/TII.2014.2300753
[3] M. Kaneko, W. Hu, K. Hayashi, and H. Sakai, "Compressed sensing-based tag identification protocol for a passive RFID system," *IEEE Commun. Lett.*, vol. 18, no. 11, pp. 2023–2026, Nov. 2014. DOI:10.1109/LCOMM.2014.2360684
[4] K. Hayashi, M. Nagahara, and T. Tanaka, "A user's guide to compressed sensing for communications systems," *IEICE Trans. Commun.*, vol. E96–B, no. 3, pp. 685–712, Mar. 2013. DOI:10.1587/transcom.E96.B.685
[5] EPC Radio-Frequency Identify Protocols Class-1 Generation-2 UHF RFID

DOI: 10.1587/comex.2016XBL0012
Received January 12, 2016
Accepted February 2, 2016
Publicized February 22, 2016
Copyedited May 1, 2016

IEICE Communications Express, Vol.5, No.5, 118–123

Protocol for Communications at 860 MHz-960 MHz v1.1.0, 2005.
[6] D. Malioutov and M. Malyutov, "Boolean compressed sensing: LP relaxation for group testing," Proc. ICASSP2012, pp. 3305–3308, Mar. 2012. DOI:10.1109/ICASSP.2012.6288622
[7] Y. Kawaguchi, T. Osa, S. Barnwal, H. Nagano, and M. Togami, "Information-based pool size control of Boolean compressive sensing for adaptive group testing," Proc. EUSIPCO, pp. 2280–2284, Sept. 2014.
[8] R. Kawasaki, K. Hayashi, and M. Kaneko, "Pool size control for adaptive group testing via Boolean compressed sensing with solution space reduction," Proc. APSIPA ASC 2015, Dec. 2015.
[9] *Matlab Optimization Toolbox User's Guide*, Math Works, 2015.

1 Introduction

Radio Frequency Identification (RFID) [1] is a system for reading and writing data onto tag devices using wireless communications, and is gathering much attention as one of the key technologies for realizing Internet of Things (IoT) [2]. RFID tags can be classified into passive and active tags. A passive tag has no battery and utilizes the radio energy transmitted by the reader for processing and transmitting signals to the reader. On the other hand, an active tag has an on-board battery and can achieve longer distance communications than a passive one. In this letter, we focus on passive tags because of their low cost, thereby enabling many potential applications, such as manufacturing systems, information management systems, and security systems.

Concerning the identification of multiple passive RFID tags, one of the key issues is about coping with the problem of collisions between the signals from different tags. Recently, CS-ID protocol [3], which is based on compressed sensing (CS) [4], has been proposed as an alternative protocol for Dynamic Framed Slotted ALOHA (DFSA) [5], which is widely used for tag identification in such situations. CS-ID takes advantage of the fact that the number of tags in the reader's range is typically far smaller than the size of ID space, and employs two-phase approach for the reduction of computational complexity. Specifically, in phase 1, it divides the ID space into several groups, and specifies those including tags in the reader's range via CS. And in phase 2, it identifies the tags in the reader's range out of the candidates obtained in phase 1 with CS again. It has been shown that CS-ID can achieve tag identification with shorter sensing time than DFSA in additive white Gaussian noise (AWGN) channel, however, it requires explicit channel estimation in flat fading environments, which is often difficult in passive RFID tag identification.

In this paper, we propose a tag identification protocol based on Boolean compressed sensing (Boolean CS) [6], referred to as *BCS-ID*. Since Boolean CS directly estimates the support of sparse Boolean vectors, BCS-ID can achieve tag identification without requiring an explicit estimation of the channel gains between the tags and the reader. We numerically demonstrate that the proposed BCS-ID requires less amount of bits for 99% tag identification than DFSA in flat Rician fading environments, and outperforms the conventional CS-ID protocol with perfect channel information.

DOI: 10.1587/comex.2016XBL0012
Received January 12, 2016
Accepted February 2, 2016
Publicized February 22, 2016
Copyedited May 1, 2016

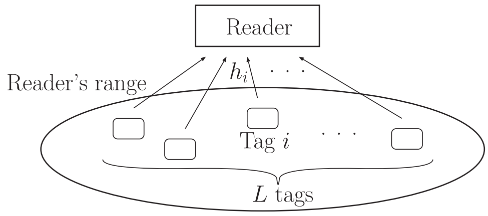

Fig. 1. RFID system

2 System model

Fig. 1 shows the system model considered in this letter. A single reader identifies L RFID tags in its range, where each tag has a unique 16-bit ID and the size of ID space will be $N = 2^{16}$. We define a binary vector $\boldsymbol{x} = [x_1 \cdots x_N]^{\mathrm{T}} \in \{0, 1\}^N$, where $x_i = 1$ or 0 indicates that the tag with ID i is in the reader's range or not, respectively. Moreover, we define a matrix $\boldsymbol{A} = [\boldsymbol{a}_1 \cdots \boldsymbol{a}_N] \in \{0, 1\}^{M \times N}$, where a binary vector $\boldsymbol{a}_i = [a_{1,i} \cdots a_{M,i}]^{\mathrm{T}} \in \{0, 1\}^M$ corresponding to tag i is generated with a hash function [1] by using the ID of tag i as a seed. In the t-th time slot ($t = 1, \ldots, M$), each tag i sends the t-th element of $\boldsymbol{a}_i$ to the reader simultaneously. Then, the observed signal vector at the reader $\boldsymbol{y} \in \mathbb{R}^M$ obtained by stacking the received signals in M time slots is given by

$$\boldsymbol{y} = \boldsymbol{AHx} + \boldsymbol{n}, \tag{1}$$

where $\boldsymbol{H} = \mathrm{diag}(h_1, \ldots, h_N)$, $h_i \in \mathbb{R}$ is the channel gain between the tag i and the reader, and $\boldsymbol{n} \in \mathbb{R}^M$ is an AWGN vector. Note that, although there is no impact on the received signal, we set $h_i = 0$ if the tag i is not in the reader's range. Thus, the problem of the tag identification can be formulated as the estimation of the unknown vector $\boldsymbol{x}$ in (1). If the number of tags L in the reader's range is much less than the size of the ID space $N = 2^{16}$, then $\boldsymbol{x}$ becomes a sparse vector. Taking advantage of the sparsity of $\boldsymbol{x}$, the conventional CS-ID performs tag identification by solving (1) with CS, but it requires the information on the channel gains.

3 Proposed protocol: BCS-ID

In order to perform tag identification without explicit channel estimation, we propose a tag identification method using Boolean CS, named BCS-ID. The proposed BCS-ID is composed of two phases for reducing computational complexity, as in conventional CS-ID.

3.1 Phase 1

We firstly divide the ID space into several disjoint groups of IDs, and specify the groups including at least one ID of tags in the reader's range by using Boolean CS. Phase 1 is composed of the following four steps:

1. All N IDs are hashed into disjoint N/b groups of size b, where b is a divisor of N.
2. Each tag in the reader's range generates a pseudo-random binary vector $\boldsymbol{q}_d = [q_{1,d} \cdots q_{M_1,d}]^{\mathrm{T}} \in \{0, 1\}^{M_1}$ using its group index d ($d = 1, \ldots, N/b$) as the seed of a hash function. Each element of $\boldsymbol{q}_d$ takes zero with probability p

DOI: 10.1587/comex.2016XBL0012
Received January 12, 2016
Accepted February 2, 2016
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Copyedited May 1, 2016

and one with probability $1 - p$. Note that $\boldsymbol{q}_d$ is common for all tags in the same group, since the group index is used as the seed.

3. In time slot t ($t = 1, \ldots, M_1$), each tag sends bit $q_{t,d}$, i.e., the t-th element of $\boldsymbol{q}_d$, to the reader. After M_1 time slots, the received signal vector at the reader $\boldsymbol{y}_1 \in \mathbb{R}^{M_1}$ is given by

$$\boldsymbol{y}_1 = [y_{1,1} \cdots y_{M_1,1}]^{\mathrm{T}} = \boldsymbol{Q}\boldsymbol{g} + \boldsymbol{n}_1, \tag{2}$$

where $\boldsymbol{Q} = [\boldsymbol{q}_1 \cdots \boldsymbol{q}_{N/b}]$, $\boldsymbol{g} = [g_1 \cdots g_{N/b}]^{\mathrm{T}}$, $g_d = \sum_{i=1}^{N} h_i e_{d,i}$,

$$e_{d,i} = \begin{cases} 1 & \text{if (the tag with ID } i) \in \text{(group } d) \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

and $\boldsymbol{n}_1 \in \mathbb{R}^{M_1}$ is a zero-mean AWGN vector with variance σ_{n}^2.

4. Let $\boldsymbol{y}_1^{\mathrm{B}} = [y_{1,1}^{\mathrm{B}} \cdots y_{M_1,1}^{\mathrm{B}}]^{\mathrm{T}} \in \{0,1\}^{M_1}$ and $\boldsymbol{g}^{\mathrm{B}} = [g_1^{\mathrm{B}} \cdots g_{N/b}^{\mathrm{B}}]^{\mathrm{T}} \in \{0,1\}^{N/b}$ be the binary versions of $\boldsymbol{y}_1$ and $\boldsymbol{g}$, respectively, i.e.,

$$\begin{cases} y_{t,1}^{\mathrm{B}} = 0 & \text{if } |y_{t,1}| \le \gamma_{\mathrm{th}} \\ y_{t,1}^{\mathrm{B}} = 1 & \text{otherwise} \end{cases} \quad \text{and} \quad \begin{cases} g_d^{\mathrm{B}} = 0 & \text{if } g_d = 0 \\ g_d^{\mathrm{B}} = 1 & \text{otherwise,} \end{cases} \tag{4}$$

where γ_{th} is a threshold. Assuming sufficiently high received signal-to-noise ratio (SNR), we have

$$\boldsymbol{y}_1^{\mathrm{B}} = \boldsymbol{Q} \vee \boldsymbol{g}^{\mathrm{B}}, \tag{5}$$

where $\vee$ is the Boolean product of a matrix and a vector, and the reader can estimate the groups including tag IDs in the reader's range by solving Boolean CS problem,

$$\underset{\tilde{\boldsymbol{g}} \in \mathbb{R}^{N/b}}{\text{minimize}} \, \|\tilde{\boldsymbol{g}}\|_1 \text{ subject to } \boldsymbol{0} \le \tilde{\boldsymbol{g}} \le \boldsymbol{1},\ \boldsymbol{Q}_{\mathcal{P}}\tilde{\boldsymbol{g}} \ge \boldsymbol{1},\ \boldsymbol{Q}_{\mathcal{N}}\tilde{\boldsymbol{g}} = \boldsymbol{0}, \tag{6}$$

where $\boldsymbol{Q}_{\mathcal{P}}$ and $\boldsymbol{Q}_{\mathcal{N}}$ are matrices composed of the rows of $\boldsymbol{Q}$ corresponding to $y_{t,1}^{\mathrm{B}} = 1$ and $y_{t,1}^{\mathrm{B}} = 0$, respectively.

3.2 Phase 2

Let P be the number of groups having tag IDs in the reader's range obtained in phase 1. Since the number of candidate tags is at most bP, we denote the set of their indexes as $\mathcal{I} = \{i_1, \ldots, i_{bP}\}$. In phase 2, we specify tag IDs in the reader's range from the reduced ID space $\mathcal{I}$ with the following three steps:

1. Tag i in the reader's range generates a pseudo-random binary vector $\boldsymbol{r}_i = [r_{1,i} \cdots r_{M_2,i}]^{\mathrm{T}} \in \{0,1\}^{M_2}$ using its tag ID $i \in \mathcal{I}$ as the seed of a hash function. Each element of $\boldsymbol{r}_i$ takes zero with probability p and one with probability $1 - p$.
2. In time slot t ($t = 1, \ldots, M_2$), tag i sends bit $r_{t,i}$ to the reader. After M_2 time slots, the received signal vector at the reader $\boldsymbol{y}_2 \in \mathbb{R}^{M_2}$ is given by

$$\boldsymbol{y}_2 = [y_{1,2} \cdots y_{M_2,2}]^{\mathrm{T}} = \boldsymbol{R}\boldsymbol{H}_{\mathcal{I}}\boldsymbol{z} + \boldsymbol{n}_2, \tag{7}$$

where $\boldsymbol{R} = [\boldsymbol{r}_{i_1} \cdots \boldsymbol{r}_{i_{bP}}]$, $\boldsymbol{H}_{\mathcal{I}} = \mathrm{diag}(h_{i_1}, \ldots, h_{i_{bP}})$, $\boldsymbol{z} = [z_{i_1} \cdots z_{i_{bP}}]^{\mathrm{T}}$,

$$z_i = \begin{cases} 1 & \text{if tag } i \text{ exists in the reader' s range} \\ 0 & \text{otherwise,} \end{cases} \tag{8}$$

and $\boldsymbol{n}_2 \in \mathbb{R}^{M_2}$ is a zero-mean AWGN vector with variance σ_{n}^2.

DOI: 10.1587/comex.2016XBL0012
Received January 12, 2016
Accepted February 2, 2016
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Copyedited May 1, 2016

3. Let $\boldsymbol{y}_2^{\mathrm{B}} = [y_{1,2}^{\mathrm{B}} \cdots y_{M_2,2}^{\mathrm{B}}]^{\mathrm{T}} \in \{0,1\}^{M_2}$ be the binary version of $\boldsymbol{y}_2$ in the same manner as phase 1. Since $\boldsymbol{H}_{\mathcal{I}}$ is a diagonal matrix, assuming high SNR, we have

$$\boldsymbol{y}_2^{\mathrm{B}} = \boldsymbol{R} \vee \boldsymbol{z}. \tag{9}$$

Thus, the reader can estimate the tag IDs in the reader's range by solving the problem of Boolean CS,

$$\underset{\tilde{\boldsymbol{z}} \in \mathbb{R}^{bP}}{\text{minimize}} \, \|\tilde{\boldsymbol{z}}\|_1 \text{ subject to } \boldsymbol{0} \leq \tilde{\boldsymbol{z}} \leq \boldsymbol{1},\ \boldsymbol{R}_{\mathcal{P}}\tilde{\boldsymbol{z}} \geq \boldsymbol{1},\ \boldsymbol{R}_{\mathcal{N}}\tilde{\boldsymbol{z}} = \boldsymbol{0}, \tag{10}$$

where $\boldsymbol{R}_{\mathcal{P}}$ and $\boldsymbol{R}_{\mathcal{N}}$ are matrices composed of the rows of $\boldsymbol{R}$ corresponding to $y_{t,2}^{\mathrm{B}} = 1$ and $y_{t,2}^{\mathrm{B}} = 0$, respectively.

3.3 Selection of *p*

In the proposed method, the parameter p is selected so that the information obtained by a single observation is maximized, which can be achieved when the number of zeros in the binary observation, such as $\boldsymbol{y}_1^{\mathrm{B}}$ and $\boldsymbol{y}_2^{\mathrm{B}}$, is the same as that of ones. Note that a similar approach has been originally proposed for the pool size control in adaptive group testing [7, 8]. The probability that a single binary observation y^{B} becomes zero can be approximated by the probability that all bits sent by L tags are zero, i.e., $\Pr(y^{\mathrm{B}} = 0) \approx p^L$, thus we set $p = 1/\sqrt[L]{2}$ in the proposed scheme.

4 Simulation results

In this section, we demonstrate the performance of the proposed BCS-ID via computer simulations conducted by using a computer with 1.7 GHz Intel Core i7 and 8 GB memory. In the simulations, 500 realizations of flat Rician fading channels with K-factor of 10 and average received SNR of 30 dB are used to obtain the average performance. Moreover, the number of tags L is assumed to be known to the reader, and the function `linprog` in MATLAB Optimization Toolbox [9] is used to solve (6) and (10).

Fig. 2 shows the required number of bits (in other words, the sensing time) $M_1 + M_2$ for the detection of 99% tags and the average computation time of the detection with proposed BCS-ID versus the group size b. The number of tags is set to be $L = 15$ and the channel gains are assumed to be unknown to the reader. For the case with $b = 1$, which means that the tag identification is completed by

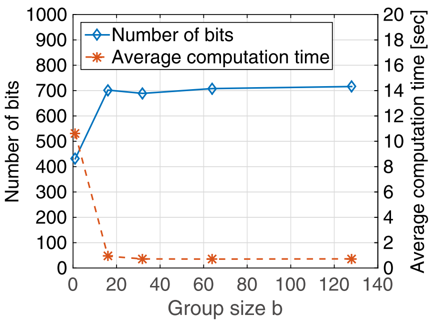

Fig. 2. Required number of bits $M_1 + M_2$ and average computation time of BCS-ID ($L = 15$)

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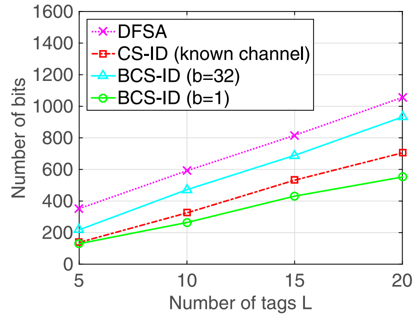

Fig. 3. Required number of bits $M_1 + M_2$

phase 1 only, the required number of bits is the lowest among the other values of b, but it requires a large computation time (around 10.5 seconds in our system). By using $b > 1$, we can reduce the computational complexity at a certain cost of the required number of bits.

Fig. 3 shows the required number of bits for the detection of 99% of the tags with DFSA, CS-ID with $b = 32$, and the proposed BCS-ID versus the number of tags L. Note that channel gains are assumed to be known to the reader only for the case with

CS-ID. From the figure, we can see that BCS-ID requires less number of bits than DFSA. Moreover, BCS-ID with $b = 1$ even outperforms CS-ID with perfect channel information and optimized parameters.

5 Conclusion

In this paper, we have proposed an RFID tag identification protocol based on Boolean CS, referred to as BCS-ID. The proposed BCS-ID can perform identification without explicit channel estimation, unlike the conventional CS-ID. Moreover, simulation results show that BCS-ID can achieve much better performance than DFSA.

Acknowledgments

This research was supported by Japan Science and Technology Agency (JST) through Global Science Campus (GSC).

DOI: 10.1587/comex.2016XBL0012
Received January 12, 2016
Accepted February 2, 2016
Publicized February 22, 2016
Copyedited May 1, 2016