Benefits of Compressed Sensing Multi-user Detection for Spread Spectrum Code Design

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Abstract. In sporadic machine-to-machine (M2M) communication, for the Code Division Multiple Access (CDMA) system with random access, applying compressed sensing (CS) algorithms to communication processes is a solution of multi-user detection (MUD). Many papers have shown that compressed sensing multi-user detection (CS-MUD) brings the benefits of jointly detecting activity and data. This paper focuses on the benefits of CS-MUD to the design of spread spectrum code in CDMA systems. Simulations show that CS-MUD brings two advantages in the spread spectrum code design: (1) There exist code sets with short code length can accommodate more users. (2) Code sets design is not limited to the design requirements of pseudo-random sequences, and the CS measurement matrix can be used as the code set. That is, CS-MUD provides a new idea for design and selection of spread spectrum code sets.

Keywords: Compressed sensing · Multi-user detection
Spread spectrum code design

1 Introduction

Effective machine-to-machine (M2M) communication for performing specific tasks is an important part in future communication. So communication processing design which is compatible with communication requirements and characteristics for physical layer in M2M communication has been the research direction of concern.

1.1 CS-MUD for M2M Communication

In a sensor network where large numbers of users can be accessed, the data transmission rate is low and only a portion of the total users implement access operations at some moment. Therefore, in order to improve data transmission efficiency, transmission of control information, such as resource allocation information, should be avoided. This requires the data fusion node to perform user activity detection and data detection. According to the communication requirements and characteristics described above, facilitated by the sparse feature of user activity, the technology that applies compressed sensing (CS) to a multi-user detection (MUD) process is called compressed sensing multi-user detection (CS-MUD).

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In sporadic transmission, only a portion of the total users are active at a given time. Here, if view the non-active users send zeros, then the vector stacked by all users' data is a sparse vector. So MUD can be performed by using the sparse signal reconstruction characteristic of CS algorithm. With the sparsity of user activity, many achievements have been made in the combination of CS technology and MUD technology. Most of them are based on direct sequence spread spectrum (DSSS) communication mode and received data at chip rate. The CS problem is constructed on the basis of the data received at the chip rate, and joint detection of user activity and data is carried out. Based on the assumption of different communication system architectures or the use of multiple information, there have been many improvement schemes for user activity detection, data detection and user capacity expansion. Such as, to consider multi-path channel [1] or asynchronous transmission [2], and to establish received signal model in the corresponding case. For improving the accuracy of activity detection and data detection, the temporal correlation feature of activity can be used to improve the activity detection accuracy [1]. Bayesian algorithm, information based on finite modulation symbol set and tree search algorithm are adopted to improve detection performance [3]. Combined with channel coding and decoding, soft method is used in detection [4, 5]. Channel estimation is introduced into the detection process to detect activity, data and channel state simultaneously [6].

1.2 Paper Focus and Contribution

Bockelmann points out that "With respect to communications, two properties of CS are especially interesting in M2M scenarios: both data and activity can be reconstructed at the same time and reconstruction is possible for underdetermined equation systems [1]." As mentioned above, many papers have shown that CS-MUD can provide good joint detection of activity and data for the Code Division Multiple Access (CDMA) system. The detection performances of different active probabilities and different overload conditions have been studied [7]. Some papers also consider the influences on the detection performance that exerted by different codes or the designs of spread spectrum code under the considered system model [8]. However, according to the existing knowledge, there is no discussion about the benefits of CS-MUD for spread spectrum code design in sporadic communication. In this paper, for overloaded CDMA system, the CS-MUD performances based on group orthogonal matching pursuit (GOMP) algorithm are simulated under different spread spectrum code sets and different active probabilities of users. And the results are compared with the performances of the minimum mean-square-error (MMSE) algorithm when using m-sequences as spread spectrum codes in fully loaded system. Simulations show that, for the considered active probability and overload condition, on the premise that the total number of users is the same and the detection performance is similar, compared to typical spread spectrum codes, code sets with shorter code length which are based on CS measurement matrices can be found. Although compared with the typical spread spectrum code sets, such as m-sequences, the code set based on the CS measurement matrix has poorer auto-correlation and cross-correlation performance, using the measurement matrix as the code set and supplemented by appropriate CS detection algorithm can achieve better detection performance. That is, the MUD process based on appropriate CS detection algorithm does not harshly require the code set has very good auto-correlation and cross-correlation performance. From this and the fact that CS detection allows overload condition, it can be seen that, for sporadic communication in CDMA systems, CS-MUD brings two advantages in the spread spectrum code design: (1) There exist code sets with short code length can accommodate more users. (2) Code sets design is not limited to the design requirements of pseudo-random sequences, and the CS measurement matrices can be used as the code sets. That is, CS-MUD provides a new idea for the design and selection of spread spectrum code sets.

1.3 Organization and Notation

The rest of the paper is organized as follows. Section 2 illustrates the system model considered in this paper. Section 3 contains the simulation conditions, results and discussions based on the system model. Finally, the conclusion is given in Sect. 4.

The notation employed in this paper is as follows. I is a set of indices that indicate active users and I^c is the complementary set. $A^{L \times N}$ denotes that matrix A has L rows and N columns. For matrix A, $A_{i,j}$ represents the element in row i, column j.

2 System Model

Considering a sensor network with star topology, there are some ordinary sensors that have specific tasks and a data fusion node which allows complex signal processing in the network. When an ordinary sensor has a demand to communicate with the data fusion node, it sends the data to the data fusion node according to the established transmission mode. That is, random access mode is implemented. The received data is processed by the data fusion node and MUD is carried out, including activity detection and data detection. Of course, sporadic communication is considered. At a given time, only a portion of the total users send data to the data fusion node.

Adopt CDMA communication mode. Suppose the total number of users is represented by N. Each user is assigned a specific spread spectrum code of length L. The code set which consists of all users' spread spectrum codes is represented by matrix $A^{L \times N}$. A column of the matrix represents a spread spectrum code, $s_n(t)\ 1 \leq n \leq N$, used by a specific user. Active users adopt Binary Phase Shift Keying (BPSK) modulation mode and modulate their symbols to spread spectrum code waveforms. The symbol sent by an active user is represented as $b_n \in \{1, -1\}$ for $n \in I$, where I contains indices of active users. Non-active users can be considered as sending zeros. That is, $b_n = 0$ for $n \in I^c$. The data of a user is transmitted in frame structure, and when a user is active, an entire frame of data is sent, i.e., the user activity is unchanged in one frame time. The frame length is represented by M. A frame contains M symbols. This paper assumes that all users' active probabilities are independent and identical. It is represented by $pa\,(0 < pa < P)$. The upper limit of active probability, P, here ensures the sparsity of communication. Of course, the active probability of each user can be different, or the active probabilities of different users are related, which has concern with the specific communication scene and is not considered in this paper.

To consider the frames are received synchronously. MUD input is the result of multi-path compensation, attenuation compensation and other front-End processing. It is a superposition signal of the active users' baseband signals that pass through the equivalent Additive White Gaussian Noise (AWGN) channel.

$$y = \sum_{n=1}^{N} b_n s_n(t) + w(t)\ t \in [0, T]. \tag{1}$$

$w(t)$ is Gaussian noise with zero mean and variance σ^2, T is the symbol duration time.

3 Simulation and Discussion

Based on the above system model, the performances of CS-MUD with GOMP algorithm are simulated under different spread spectrum code sets and different active probabilities for an overload condition. In the simulations, the total number of users is $N = 127$. The spread spectrum code length of each user is $L = 80$, so overload degree is $\frac{L}{N} \approx 0.63$. The frame length of active users is $M = 100$. The active probabilities considered in this paper are 0.3 and 0.4. Because the activity of each user is in frame form, the sparse form of the sparse vector obtained by all users' symbols is structured. Therefore the sparse structure of the sparse vector can be used to conduct CS-MUD with GOMP algorithm. The details of GOMP algorithm can refer to [1].

Of course, in order to compare with the traditional method, the traditional pseudo-random sequence, m-sequence, is used as the spread spectrum code set under the corresponding active probabilities, and the performances of MUD based on MMSE algorithm are simulated. In the experiments, the simulations of traditional detection method take fully loaded condition into account. That is, for traditional detection method, there is $L = N = 127$.

3.1 CS Measurement Matrices Considered in Simulations

Simulations show the performances of CS-MUD when three CS measurement matrices are used as spread spectrum code sets with active probabilities of 0.3 and 0.4 respectively. The three CS matrices are two Toeplitz matrices based on two different generation element sets and a Bernoulli matrix.

Restricted Isometry Property (RIP) [9] is a well-known condition that should be satisfied by CS measurement matrix. Bernoulli matrix and Toeplitz matrix can satisfy the RIP condition with high probability. They are constructed as follows.

(1) Bernoulli matrix: Construct a matrix $A^{L \times N}$. Each element in the matrix obeys the Bernoulli distribution independently.

$$A_{i,j} = \begin{cases} +\frac{1}{\sqrt{L}}\, p = \frac{1}{2} \\ -\frac{1}{\sqrt{L}}\, p = \frac{1}{2} \end{cases}. \tag{2}$$

(2) Toeplitz matrix: If $r = N + L - 1$, to construct Toeplitz matrix $A^{L \times N}$. Its basic structure is as follows.

$$A = \begin{bmatrix} a_N & a_{N-1} & \cdots & a_1 \\ a_{N+1} & a_N & \cdots & a_2 \\ \vdots & \vdots & \ddots & \vdots \\ a_{N+L-1} & a_{N+L-2} & \cdots & a_L \end{bmatrix}. \quad (3)$$

It can be seen that the Toeplitz matrix is constructed by r generation elements. In this paper, two Toeplitz matrices based on two different generation element sets are constructed. The generation elements of Toeplitz matrix 1 obey the Bernoulli distribution independently. The generation elements of Toeplitz matrix 2 come from a pseudo-random sequence.

3.2 Discussion

From Figs. 1 and 2, it can be seen that, for the considered active probability and overload condition, compared with the MUD scheme based on traditional long m-sequences and MMSE algorithm, A MUD scheme with appropriate CS algorithm and short spread spectrum codes that come from CS measurement matrix can achieve the same or even better detection performance while supporting the same number of total users. This shows that in the consideration of communication scenario, performance requirements, communication processing and system model, a code set with short codes based on CS measurement matrix can be chosen as spread spectrum code set.

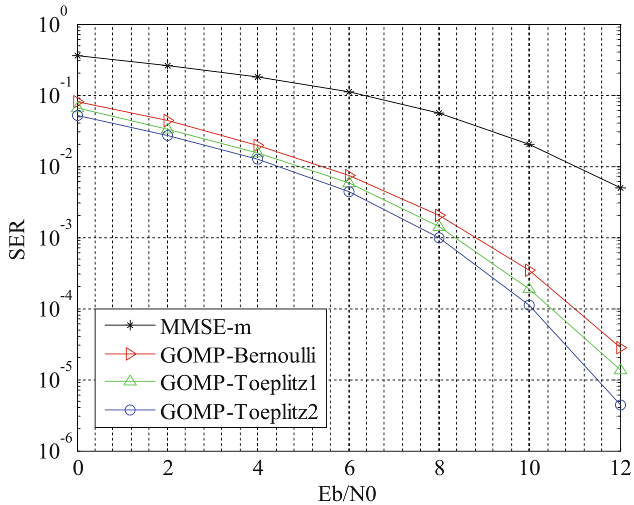

Fig. 1. SER simulation results for $L = 80$, $N = 127$, $pa = 0.3$.

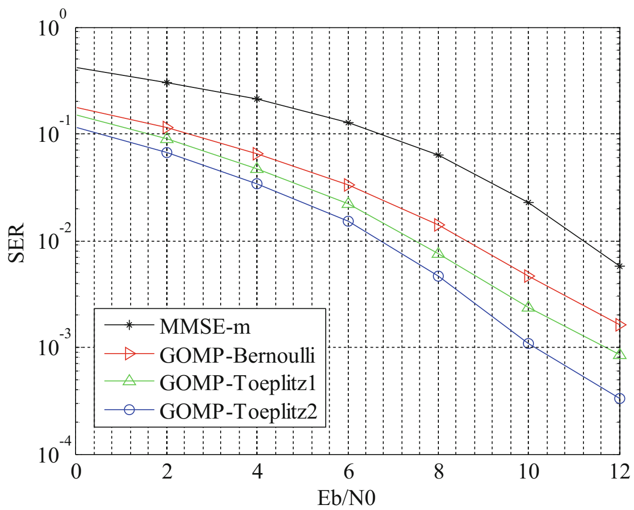

Fig. 2. SER simulation results for L = 80, N = 127, pa = 0.4.

It is a fact that different CS measurement matrices have different impacts on the performance of CS algorithms. This also can be seen in the two figures. If a CS algorithm is to be applied to the process of communication, it must be compatible with the whole communication process. Therefore, on the basis of the above discussions, we can consider the characteristics of communication signals and the characteristics of processing in communication, then design and select the spread spectrum code sets for communication systems that combine with the CS algorithms.

The good performances of CS-MUD based on GOMP algorithm are related to system model. The assumption that the signal before entering the detector has experienced attenuation compensation and multi-path compensation makes the equivalent channel model an AWGN channel. So that GOMP algorithm has such a good performance. In other system models, the performances of the GOMP algorithm might not be so good. The purpose of the experiments is to indicate that, under the considered active probability, front-End processing method of receiver and CS algorithm, on the premise that the detection performance is not bad and the number of users is the same, compared with the traditional MUD based on pseudo-random codes and MMSE algorithm, we can find the spread spectrum code sets that come from CS measurement matrices and of shorter lengths and various forms. That is, CS-MUD provides a new idea for the design and selection of spread spectrum code sets.

4 Conclusion

In this paper, we focus on the benefits of CS-MUD for spread spectrum code design in CDMA systems when sporadic communication is considered. Simulation results show that, for the considered active probability and the same total number of users, compared with traditional MUD, CS-MUD can achieve better detection performance based on appropriate system structure, front-End processing of receiver, measurement matrix and CS algorithm. And because the CS algorithm can deal with overload condition, the code length can be shortened. That is, CS-MUD provides a new idea for the design and selection of spread spectrum code sets.

Many papers assume that the detector has known the channel state information of each user, but the way and process of channel state acquisition as well as its conjunction with the detection process have great influence on the detection performance. Moreover, the design and selection of spread spectrum code set and its adaptability to synchronization and channel estimation also have an impact on the system performance. The design of receiver's each part that is compatible with the performance of the selected spread spectrum code set needs to be considered. This remains to be done for further studies.

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References

1. Bockelmann, C., Schepker, H.F., Dekorsy, A.: Compressive sensing based multi-user detection for machine-to-machine communication. Trans. Emerg. Telecommun. Technol. **24**, 389–400 (2013)
2. Schepker, H.F., Bockelmann, C., Dekorsy, A.: Coping with CDMA asynchronicity in compressive sensing multi-user detection. In: 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), pp. 1–5. IEEE Press (2013)
3. Monsees, F., Bockelmann, C., Wubben, D., Dekorsy, A.: Compressed sensing Bayes risk minimization for under-determined systems via sphere detection. In: 2013 IEEE 77th Vehicular Technology Conference (VTC Spring), pp. 1–5. IEEE Press (2013)
4. Schepker, H.F., Bockelmann, C., Dekorsy, A.: Efficient detectors for joint compressed sensing detection and channel decoding. IEEE Trans. Commun. **63**, 2249–2260 (2015)
5. Bockelmann, C.: Iterative soft interference cancellation for sparse BPSK signals. IEEE Commun. Lett. **19**, 855–858 (2015)
6. Schepker, H.F., Bockelmann, C., Dekorsy, A.: Exploiting sparsity in channel and data estimation for sporadic multi-user communication. In: The Tenth International Symposium on Wireless Communication Systems, pp. 1–5. VDE Press (2013)
7. Schepker, H.F., Dekorsy, A.: Sparse multi-user detection for CDMA transmission using greedy algorithms. In: 2011 8th International Symposium on Wireless Communication Systems, pp. 291–295. IEEE Press, Aachen (2011)
8. Abebe, A.T., Kang, C.G.: Compressive sensing-based random access with multiple-sequence spreading for MTC. In: 2015 IEEE Globecom Workshops (GC Workshops), pp. 1–6. IEEE Press (2015)
9. Candes, E.J., Tao, T.: Decoding by linear programming. IEEE Trans. Inf. Theory **51**, 4203–4215 (2005)