A Novel Uplink Data Transmission Scheme For Small Packets In Massive MIMO System

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Abstract—Intelligent terminals often produce a large number of data packets of small lengths. For these packets, it is inefficient to follow the conventional medium access control (MAC) protocols because they lead to poor utilization of service resources. We propose a novel multiple access scheme that targets massive multiple-input multiple-output (MIMO) systems based on compressive sensing (CS). We employ block precoding in the time domain to enable the simultaneous transmissions of many users, which could be even more than the number of receive antennas at the base station. We develop a block-sparse system model and adopt the block orthogonal matching pursuit (BOMP) algorithm to recover the transmitted signals. Conditions for data recovery guarantees are identified and numerical results demonstrate that our scheme is efficient for uplink small packet transmission.

I. Introduction

As intelligent terminals such as smart phones and tablets get more popular, they produce an increasing number of data packets of short lengths. Modern mobile applications that produce such small packets include instant messaging, social networking, and other services [1], [2]. Although the lengths of messages are relatively short, small packet services put great burden on the communication network. Two kinds of messages contribute to the traffic of small packets: one is the small packets of conversation produced by active users that occupy only a small percentage of the total online users [2]; the other is the signaling overheads needed to transmit these conversation packets [3].

In current wireless communication systems, a user follows the medium access control (MAC) protocols to obtain the service resources. Either resources are preallocated to the users in a noncompetitive fashion, or certain random access scheme with collision resolution is used. For small and random packets, the reservation-based approach is inefficient in resource utilization due to irregularity of the packets. The collision-resolution based approaches, on the other hand, can suffer from too many retransmissions due to frequent collisions.

Recently, massive multiple-input multiple-output (MIMO) was studied as a way to improve the system throughput of cellular systems [5]- [8]. In massive MIMO systems, the number of antennas at the base station (BS) can be more than the number of active single-antenna users that are simultaneously served. When the number of antennas at BS is large, the different propagation links from the users to the BS tend to be orthogonal, and the large amount of spatial degrees of freedom

are useful for mitigating the effect of fast fading [6], [7]. Overall, massive MIMO technique provides higher data rate, better spectral and energy efficiencies [8]. All these advantages make massive MIMO a promising technique.

In this paper, we propose a novel uplink small packet transmission scheme based on precoding at the transmitters and sparsity-aware detection at the receiver. The main motivation is to allow for a large number of users to transmit simultaneously, although each user may be transmitting only a small amount of data. Besides frame-level synchronization, no competition for resources or other coordinations are required. This saves the signaling overhead for collision resolution, and improves the resource utilization efficiency.

The contributions of our work are as follows:

- 1) block-sparse system model is established: We apply block precoding at each transmitter in time domain, and by considering the user activities, develop a block-sparse system model [9]- [11].
- 2) conditions for signal recovery are given: The result of our analyses about the block orthogonal matching pursuit (BOMP) algorithm is milder than those in the related work in [10]. Furthermore, we characterize the data recovery condition from information theoretic point of view.

Thanks to the precoding operation and our sparsity-aware detection algorithms, our scheme enable the system to support more active users to be simultaneously served. The number of active users can be even more than the number of antennas at BS. This is of great practical significance for networks offering small packet services to a large number of users.

Applications of compressive sensing (CS) to random MAC channels have been considered in [12]- [15]. In [12], CS based decoding scheme at the BS has been used for the multiuser detection task in asynchronous random access channels. A technique based on CS for meter reading in smart grid is proposed in [13], and its consideration is limited to single-antenna systems. Besides, a novel neighbor discovery method in wireless networks with Reed-Muller Codes has been proposed in [15], where CS technique is also adopted. All the referred works depend on the idea that the MAC channel is sparse, and all their works are classified to initial category of CS, where no structure property have been taken into account. This is one of the main distinctions that differentiate our work from the referred ones.

The rest of the paper is organized as follows. In Section II, the system model of block-sparsity are given. In Section III, we introduce the BOMP algorithm to recover the transmitted signals, and discuss performance guarantees for data recovery. Section IV will present the numerical experiments that verify the effectiveness of our scheme.

II. SYSTEM MODEL

Assume the propagation environment is a block-fading channel and the antennas at the BS, as well as the antennas among users, are uncorrelated and uncoupled. We also assume that the transmissions are in blocks and the users are synchronized at the block level. When a terminal has successfully connected to the network, it becomes an online user, and the BS always has the perfect channel state information (CSI) of online users. Our consideration is only limited to uplink small packet transmission for single-antenna users in massive MIMO system.

Consider an uplink system with N mobile users, each with a single antenna, and a base station with M antennas. N_a active users of the total N online users have small packets to send. For small packet services, $N_a < N$, and usually $N_a \gg M$, even with massive MIMO, we may have $N_a > M$. We assume that each frame of transmission consists of T symbols, and T is no longer than the coherent interval of block-fading channel. Let $\mathbf{s}_n \in \mathbb{C}^{d \times 1}$ denotes the symbols to be transmitted by user n, with d < T. User n applies a precoding to \mathbf{s}_n to yield

$$\mathbf{x}_n = \mathbf{P}_n \mathbf{s}_n \tag{1}$$

where \mathbf{P}_n is a complex precoding matrix of size $T \times d$. The entries of \mathbf{x}_n are transmitted in T successive time slots. The received signals at all antennas within one frame can be written as

$$\mathbf{Y} = \sqrt{\rho_0} \sum_{n=1}^{N} \mathbf{h}_n \mathbf{x}_n^T + \mathbf{Z} = \sqrt{\rho_0} \sum_{n=1}^{N} \mathbf{h}_n \mathbf{s}_n^T \mathbf{P}_n^T + \mathbf{Z}$$
 (2)

where ρ_0 is the signal to noise ratio (SNR) of the uplink, \mathbf{Y} is noisy measurement of size $M \times T$, $\mathbf{Z} \in \mathbb{C}^{M \times T}$ represents the additive noise, with i.i.d. circularly symmetric complex Gaussian distributed random entries of zero mean and unit variance, and $\mathbf{h}_n \in \mathbb{C}^{M \times 1}$ represents the channel coefficients from the user n to the base station, without loss of generally, let $h_{mn} \sim \mathcal{CN}(0,1), \ m=1,2,\cdots,M$. Using the linear algebra identity $vec(\mathbf{ABC}) = (\mathbf{C}^T \otimes \mathbf{A}) \, vec(\mathbf{B})$, where vec denotes vectorizing \mathbf{B} by column stacking and \otimes denotes the Kronecker product of two matrices, we can rewrite the received signal as

$$vec(\mathbf{Y}) = \sqrt{\rho_0} \sum_{n=1}^{N} (\mathbf{P}_n \otimes \mathbf{h}_n) \mathbf{s}_n + vec(\mathbf{Z})$$
 (3)

Define $\mathbf{y} := vec(\mathbf{Y})$, $\mathbf{B}_n := (\mathbf{P}_n \otimes \mathbf{h}_n) / \sqrt{M}$ and $\mathbf{B} := [\mathbf{B}_1, \mathbf{B}_2, \cdots, \mathbf{B}_N]$, $\mathbf{s} := [\mathbf{s}_1^T, \mathbf{s}_2^T, \cdots, \mathbf{s}_N^T]^T$. Then we can write the model in (3) as

$$\mathbf{y} = \sqrt{\rho_0 M} \mathbf{B} \mathbf{s} + \mathbf{z} \tag{4}$$

In this formulation, we have assumed that all the users have messages of equal length d. This may not be the case in practice. We view d as the maximum length of the messages of all users within a frame. For the users whose message length is less than d, we assume their messages have been zero-padded to d before precoding. Also, for those users that are not active, we assume their transmitted symbols are all zeros.

Model (4) indicates that the signals to recover present the structure of block-sparsity where transmitted signals are only located in a small fraction of blocks and all other blocks are zeros. We collect all the indices of blocks corresponding to active users to form a set I, with $|I| = N_a$. When precoding matrix \mathbf{P}_n is reasonably designed, matrix \mathbf{B} can meet the requirement for sensing matrix in CS, and this kind of \mathbf{P}_n is of wide range, for instance, Gaussian or Bernoulli matrix. Therefore, model (4) can be viewed as block-sparse model in CS.

A few remarks about the precoding are needed. The precoding scheme is proposed because in reality, T is usually several times longer than the lengths of small packets. Also, the precoding scheme contributes to solving signal recovery problem in the situation where $N_a > M$. Secondly, each user knows its own precoding matrix and the BS knows all precoding matrices of all users. Thirdly, a basic requirement on the precoding matrix is that it should be full column rank, which is a requirement for data recovery. Additionally, in order to balance the power of every symbol of the messages before and after being precoded, each column of \mathbf{P}_n should be normalized to unit energy. And finally, our precoding scheme is different from spreading schemes in [14], where direct sequence spread spectrum (DSSS) is utilized for CS formulation.

III. DATA RECOVERY

A. BOMP Algorithm For Data Recovery

The main idea of BOMP algorithm is that, for each iteration, it chooses a block which has the maximum correlation with the residual signal, and after that, it will use the selected blocks to approximate the original signals by solving a least squares problem. In our scheme, we will adopt the BOMP algorithm to recover the transmitted signal vector s. About the detailed calculation process of BOMP algorithm, we refer readers to article [10].

B. Data Recovery Guarantees

In this section, we will present conditions that guarantee data recovery. Before analyzing conditions for data recovery, some notation and definitions will be introduced first. From the definition of ${\bf B}$, we can see that each column of it is statistically normalized to one when number of antenna M becomes large. Here we expand ${\bf B}$ as

$$\mathbf{B} = \left[\underbrace{\mathbf{b}_{1} \cdots \mathbf{b}_{d}}_{\mathbf{B}_{1}} \underbrace{\mathbf{b}_{d+1} \cdots \mathbf{b}_{2d}}_{\mathbf{B}_{2}} \cdots \underbrace{\mathbf{b}_{(N-1)d+1} \cdots \mathbf{b}_{Nd}}_{\mathbf{B}_{N}}\right]$$
(5)

As in [10], we give the definitions of block-coherence in the form of spectral norm

$$\mu_{\mathbf{B}} := \frac{1}{d} \max_{i \neq j} \left\| \mathbf{B}_i^H \mathbf{B}_j \right\| \tag{6}$$

and sub-coherence as

$$\nu := \max_{1 \le l \le N} \max_{(l-1)d+1 \le i \ne j \le ld} \left| \mathbf{b}_i^H \mathbf{b}_j \right| \tag{7}$$

At the same time define

$$s_l := \min_{i \in I} \|\mathbf{s}_i\|_2 \quad s_u := \max_{i \in I} \|\mathbf{s}_i\|_2$$
 (8)

In the following we will give two theorems to characterize conditions for signal recovery, the proofs of which will be presented in the journal version of this paper.

C. Data Recovery Conditions For BOMP Algorithm

The following theorem characterizes the block-sparse data recovery performance by BOMP algorithm.

Theorem 1: Consider the block-sparse model above, suppose that condition

$$\rho_{0}M[1 - (d - 1)\nu]^{2}s_{l}^{2} > \tau^{2} +\rho_{0}Md\mu_{\mathbf{B}} \{2(N_{a} - 1)[1 + (d - 1)\nu] + N_{a}^{2}d\mu_{\mathbf{B}}\}s_{l}^{2} +2\sqrt{\rho_{0}M}\tau\{(2N_{a} - 1)d\mu_{\mathbf{B}} + [1 + (d - 1)\nu]\}s_{l}$$
(9)

is satisfied, then the BOMP algorithm identifies the correct support of signal vector s and at the same time achieves a bounded error given by

$$\|\widehat{\mathbf{s}} - \mathbf{s}\|_{2}^{2} \le \frac{K\tau^{2}}{\left[1 - (d - 1)\nu - (K - 1)d\mu_{\mathbf{B}}\right]^{2}\rho_{0}M}$$
 (10)

where $\hat{\mathbf{s}}$ is the signal vector recovered by BOMP algorithm, $K \leq \left\lfloor \frac{MT}{d} \right\rfloor$ is the maximum number of iterations for BOMP algorithm, $1-(d-1)\nu-(K-1)d\mu_{\mathbf{B}}>0$ and $\tau=\max_{1\leq j\leq N}\left\|\mathbf{B}_{j}^{H}\mathbf{z}\right\|_{2}$. Remark 1: Since T>d and $MT\gg d$, we can design

Remark 1: Since T>d and $MT\gg d$, we can design orthogonal columns for precoding matrix \mathbf{P}_n of user n, $n=1,2,\cdots,N$, then each block of matrix \mathbf{B} is submatrix with orthogonal columns, meaning $\nu=0$. On the other hand, we have $\tau\gg s_l$ when each nonzero element of \mathbf{s}_n satisfies a reasonable power constrain. Additionally, if $\mu_{\mathbf{B}}=0$, then condition (9) can be simplified as $\rho_0 M s_l^2 > \tau^2 + 2\sqrt{\rho_0 M} \tau s_l \approx \tau^2$, which is milder when compared with [10, Theorem 5], where result $\rho_0 M s_l^2 > 4\tau^2$ is given when applied to our scenario.

Remark 2: In our scheme, when the number of active users are more than that of the antennas at BS, the channel vectors among users are no longer orthogonal or asymptotically orthogonal. However, by our precoding scheme, correlations among columns in B can be smaller than correlations among channel vectors of different users, which means that block-coherence $\mu_{\rm B}$ can still be rather small, as long as precoding is well designed.

D. Condition From Information Point Of View

From the BS's point of view, it is desirable to recover all the information conveyed by s, including number of active users, exact indices of these active users, their transmitted information bits, etc.. When all the information are measured by bits, then The number of bits representing the indices of active users and signal bits of the transmitted messages are respectively $\log_2\binom{N}{N_a}$ and $\sum_{i=1}^{N_a}b_i$. Assume all bits are generated with equal probability, and let S denote the set of bits needed to represent the total information, then we have $|S| \geq \log_2\binom{N}{N_a} + \sum_{i=1}^{N_a}b_i$.

The following theorem characterizes the data recovery problem from information theoretic point of view. Its proof is not included due to lack of space.

Theorem 2: Define p_e as the probability that some error has happened in the recovery of information in set S, then the following condition is necessary for the data recovery

$$|S| \le \frac{1}{1 - p_e} [H(p_e) + \log_2 \det(\mathbf{I}_{MT} + \rho_0 \mathbf{B}_I \mathbf{B}_I^H)]$$
 (11)

IV. NUMERICAL RESULTS

The experimental studies for verifying the proposed scheme are presented in this section. In all simulations, the channel response matrix is i.i.d. Gaussian matrix of complex values and the N_a active users are chosen uniformly at random among all N online users. As for the block-sparse data vectors to be transmitted, we assume quadrature phase shift keying (QPSK) for data modulation. The symbol error rate (SER) and frame error rate (FER) are used as the performance metrics. In all simulations, we do not set the number of antennas to a large value, say one hundred or more, for the sake of simplicity. We will choose the frame length to be a multiple of the maximum length of short messages. We assume that all messages have the same length d unless otherwise specified. We simply design \mathbf{P}_n a random matrix with (v=0) or without $(v\neq 0)$ orthogonal columns, $n=1,2,\ldots,N$.

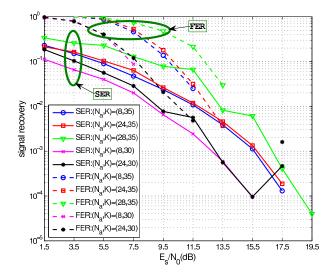


Fig. 1. signal recovery with 8 antennas at BS

Test Case 1: Figure 1 shows the performance of the proposed scheme with 8 antennas at BS, where K is the iterative number for BOMP algorithm. Other parameters are given as (N, d, T, v) = (80, 200, 1000, v = 0). The results indicate that, the SER decreases when E_s/N_0 increases and at the same time, increases when the number of active users becomes larger. For case where iterative number is 35, when the number of active users is lower than a certain number, say 24 in our results, the SER is basically independent of this number. When the number of active users exceeds the certain number, the performance will get a lot worse; see e.g., $N_a = 28$ in our results as an example. Besides, the results we obtain for 8 and 24 active users are nearly identical to those achieved by least square algorithm when active users are already picked out and other $K - N_a$ off-support users are chosen at random. Also in Figure 1, we give results when less iterations are employed for BOMP algorithm. When there are not too many active users, less iterations benefit a lot, just like 30 iterations for 8 active users. But for 24 active users, fluctuations exist which means 30 iterations are not enough to include all the active users.

FER is also presented in Figure 1 with the same parameters as that for SER. In our simulation, the FER is counted as follows: when more than 8 bits in a message are demodulated in error, we claim a frame error, and if the bit errors are equal to or less than 8, we hypothesize that they can be detected and corrected by some channel coding schemes, such as BCH Code. The same trend in performance of FER can be observed as that of SER. As the E_s/N_0 increases, FER decreases quickly and when the E_s/N_0 exceeds a certain value, the FER will be negligible.

The normalized throughput defined as $(1 - P_{FER}) N_a d / (MT)$, where $(1 - P_{FER}) N_a$ is the maximum number of allowed active users in our scheme, P_{FER} is the value of FER; and MT/d is the maximum number of users that can be served when all timeslots of a frame are effectively used for data transmission, which is 40 under the given parameters. Take only the signaling needed for resources competition before data transmission into account, if 24 active users are allowed to be simultaneously served, since our scheme requires no additional signaling messages for data transmission, the throughput will reach 60%; while by conventional random access protocols, if we regard the signaling messages (such as request-to-send (RTS) signaling [4]) as some kinds of small packets we considered, its throughput will be no more than 60%, and if collision happens, which is often the case, the throughput will decrease a step further. Therefore, our scheme will greatly improve the system throughput.

Test Case 2: By Figure 2, we can see that when the number of active users is fixed, the SER increases as the number of online users increases, but the performance degradation is rather small, even when the number of online users has been doubled, nearly no more than 1dB degradation can be observed for 24 active users. By Theorem 2, the number of online users is not the dominant factor to affect the performance under the

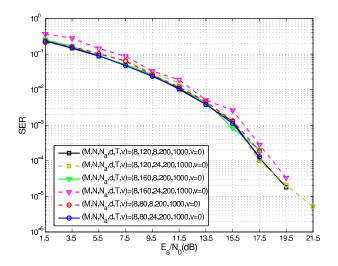


Fig. 2. signal recovery with different numbers of online users

given parameters.

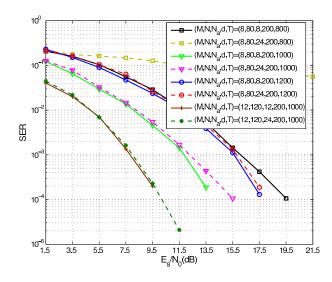


Fig. 3. symbol recovery with different numbers of BS antennas and with different frame lengths

Test Case 3: Figure 3 depicts the performance when BS are equipped with different numbers of antennas, and when frame lengths are different. The results show that, under the same ratio N_a/M , when the number of antennas M increases, the SER performance becomes remarkably better and a higher ratio N_a/M can be accepted, which suggests a higher throughput. With massive MIMO technique, this benefit can be reaped. On the other hand, a big performance gap between antenna numbers of 8 and 12 is observed, for the reason of iterative number demonstrated by Figure 1. More antennas at BS allows a larger iterative number for BOMP algorithm to accommodate more active users, and the big performance gap appears when we set both cases to the same number 35 of iterations. The curves respectively for T=4d, T = 5d and T = 6d show that, the longer the frame length is, the better performance we can achieve, and thus the more users that can be simultaneously served. However, affected by the normalization of columns in precoding matrix, even when the length of frame grows, the benefits diminish. This phenomenon will be observed when parameters are chosen to ensure that MT/(dK) is a constant.

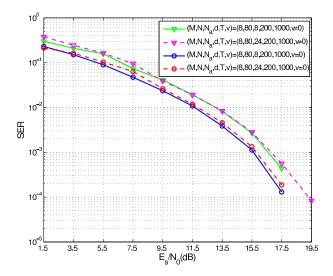


Fig. 4. symbol recovery with or without column orthogonal blocks

Test Case 4: In Figure 4, we examine the performance when each block of the matrix is column orthogonal or not. As we can see, for column non-orthogonal case, nearly 1dB performance degradation is observed when compared with that of column orthogonal case, since the former case will amplify the influence of noise to some degree.

Remark 3: In all simulations, we set the number of antennas at BS just 8 or 12, which is not enough for massive MIMO. In fact, the expected performance of more antennas at BS can be significantly better, as demonstrated by Figure 3.

Remark 4: In all simulations, we have set d as the length of all messages. In practice, this may not be the case. In fact, when different lengths for messages exist and the number of active users is large, it has some performance degradation. We have done the simulation and the result shows that the performance gap is slight under wide conditions.

Remark 5: The results given by our Theorem 1 in terms of allow active users is pessimistic whem compared with our simulation results. For example, under the same conditions of Figure 1, when $E_s/N_0=10dB$, only 1 active user is allowed by (9). This is because in the derivation of Theorem 1, we always consider the least favorable situation.

V. CONCLUSION

In this paper, we propose an uplink data transmission scheme for small packets. The proposed scheme combines the techniques of CS and massive MIMO. Particularly, under the assumption that the BS has perfect CSI of every online user and by a precoding scheme for block signal transmission, we develope a block-sparse system model and adopte BOMP algorithm to recover the transmitted data.

The transmission scheme addressed in this paper is applicable to future wireless communication system. The reason is that small packet plays a more and more important role in data traffic with the wide use of intelligent terminals. The overall throughput of such a system is hampered by small packet because of its heavy signaling overhead. Our scheme will greatly reduce the signaling overhead and improve the throughput of the system.

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