Full-Duplex Generalized Spatial Modulation: A Compressed Sensing-Based Signal Detection

(Invited Paper)

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Abstract—In this paper, we propose a novel low-complexity signal detection technique based on compressed sensing for a full-duplex generalized spatial modulation (FD-GSM) system, where a communication node transmits data symbols via some antennas and receives data symbols via the remaining antennas at the same time. Thus, each antenna operates as either transmitter or receiver in each symbol time, which implies FD-GSM can be implemented with half-duplex antennas. In particular, *parallel orthogonal matching pursuit (POMP)* algorithm is exploited as a sparse signal recovery algorithm for detecting GSM signals. The self-interference (SI) due to full-duplex operation is assumed to be completely removed by help of the recently proposed SI cancellation techniques. The proposed signal detection technique significantly outperforms the conventional OMP algorithm in terms of symbol error rate (SER). Interestingly, there exists an optimal number of active antennas for maximizing effective throughput.

Index Terms—Full-duplex radio, generalized spatial modulation, sparse signal recovery, compressed sensing, massive MIMO.

I. Introduction

Full-duplex (FD) communication has been received much interest in both industry and academia due to its possibility to achieve double throughput without additional frequency resources. Recently, the effect of self-interference (SI) from transmit antennas to receive antennas, the most challenging technical issue of the FD communication, has been known to be significantly alleviated with several advanced signal processing techniques including [1]. More recently, FD multiple-input multiple-output (FD-MIMO) systems have been investigated in [2], [3]. In [2], a FD-MIMO system has been proposed, where the SI is significantly decreased at antennas by symmectric antenna spacing techniques, but $4N_t$ antennas are required at each node for achieving spatial N_t FD-MIMO operation. In [3], it was shown that the N_t spatial FD-MIMO operation can be possible without addtional antennas and N_t antennas are enough to both transmit and receive data simultaneously. However, it is worth noting that the computational complexity scales linearly with the number of antennas and the complexity issue may be challenging if the large number of antennas are utilized as in massive MIMO systems [4], [5].

On the other hand, (generalized) spatial modulation (GSM) has been proposed as another way of utilizing multiple an-

tennas, coping with demerits of the conventional MIMO techniques [6], [7]. The basic idea of GSM is to activate a subset of transmit antennas out of all antennas for transmitting data, and the indices of the activated antennas impliciticity convey information in addition to the traditional symbol modulation. Thus, the total number of transmitting bits is given by

$$N_b = \lfloor \log_2 \binom{N_t}{n_t} \rfloor + n_t \log_2 \lfloor |\mathbb{A}| \rfloor, \tag{1}$$

where N_t, n_t, and $\mathbb{A}$ denote the total number of transmit antennas, the number of active transmit antennas, and modu-latino alphabet, respectively. For example, $\mathbb{A} = \{-1, +1\}$ for BPSK modulation. The GSM matches well with the massive MIMO technique since it effectively reduces the required number of *RF chains* which is known to be the most expensive component in mobile communication systems. However, the receiver complexity for estimating the indices of the active transmit antennas significantly increases as the number of transmit antennas increases.

There existed an attempt to combine FD operation and the SM in a 2×2 MIMO system [8], where a single antenna is used as a transmitter and the other antenna is used as a receiver. In other words, each antenna operates with half-duplex mode, i.e., either transmitter or receiver. In this paper, we consider the FD-GSM system where each node activates n_t antennas to transmit data out of N_t ($n_t < N_t$). Hence, ($N_t - n_t$) antennas operate with a receiver mode. In particular, we proposed a low-complexity signal detection technique based on compressed sensing, called *parallel orthogonal matching pursuit (POMP)*, to estimate the indices of the active transmit antennas. Simulation results show that the proposed technique significantly outperforms the conventional detection technique in terms of symbol error rate (SER).

II. System Model

In this paper, we assume that each node is equipped with the same number of antennas, N_t, and thus the wireless channel between nodes is modelled as $\mathbf{H} \in \mathbb{C}^{N_t \times N_t}$ whose elements are assumed to be an identical and independent complex Gaussian random variable with zero mean and unit variance. In addition, quasi-static fading is assumed, i.e., channel coefficients are constant during a single GSM symbol
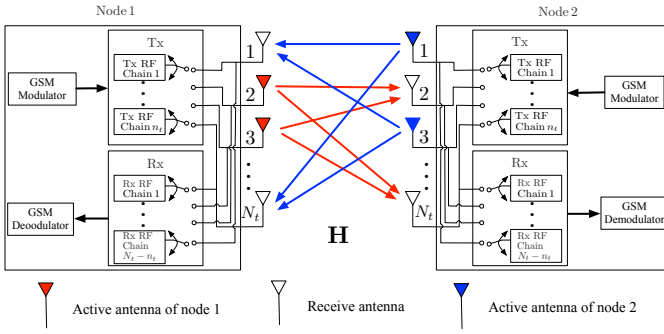
Fig. 1. System model of FD-GSM when $n_t = 2$.

and change independently over GSM symbols. The channel matrix is assumed to be known to the receiver via reference signals. Each node employs the GSM for transmission, and thus it transmits n_t symbols from a modulation alphabet $\mathbb{A}$ via n_t activated antennas out of N_t antennas. The other $N_t - n_t$ antennas operate as receiver antennas. The SI is assumed to be perfectly removed at each node. Fig. 1 illustrates FD-MIMO channel model where GSM is used in each node and $n_t = 2$. In Fig. 1, the second and the third antennas are activated in node 1 and transmit data to node 2, and the first and the third antennas are activated in node 2 and transmit data to node 1. The total number of transmitting bits over the FD-GSM system is given by

$$ N_b^{\mathsf{FD}} = 2 \left(\left\lfloor \log_2 \binom{N_t}{n_t} \right\rfloor + n_t \log_2 \lfloor |\mathbb{A}| \rfloor \right), \qquad (2) $$

where double throughput can be achievable if the same signal detection performance is guaranteed compared with the half-duplex (HD) GSM system.

Without loss of generality, node 1 is assumed to activate the first n_t antennas to transmit data. Then, the last $N_t - n_t$ antennas of node 1 receive data from node 2. The received signal vector at node $i \in \{1, 2\}$ from node $j \in \{1, 2\}$ is given by

$$ \mathbf{y}_i = \mathbf{H}_{ij} \mathbf{x}_j + \mathbf{z}_i, \qquad (3) $$

where $\mathbf{H}_{ij} \in \mathbb{C}^{(N_t - n_t) \times N_t}$, $\mathbf{x}_j \in \mathbb{C}^{N_t \times 1}$, and $\mathbf{z}_i \in \mathbb{C}^{(N_t - n_t) \times 1}$ denote the wireless channel matrix from all antennas of node j to the $(N_t - n_t)$ receive antennas of node i, transmit symbol vector of node j, and thermal noise vector at $(N_t - n_t)$ receive antennas of node i with zero mean and the covariance $N_0 \mathbf{I}_{N_t - n_t}$, respectively. Note that $\mathbf{x}_j$ has n_t non-zero elements out of N_t elements.

With the optimal maximum-likelihood detector (MLD) at node 1, the detection rule is given by

$$ \hat{\mathbf{x}}_j^{\mathsf{ML}} = \arg \min_{\mathbf{x}} \| \mathbf{y}_i - \mathbf{H}_{ij} \mathbf{x} \|_2^2, \qquad (4) $$

where the number of candidates for $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is approximately given by $\binom{N_t}{n_t} \cdot |\mathbb{A}|^{n_t}$. For example, when $N_t = 16$, $n_t = 2$, $|\mathbb{A}| = 4$ (QPSK modulation), then $N_b^{\mathsf{FD}} = 20$ but the number of candidates for $\mathbf{x}$ is approximately given by 1920 for each node. Although the the MLD achieves the optimal performance, it requires tremendous amount of

computations at each node because it searches all possible candidates and may not be feasible in practical wireless communication systems. If n_t becomes large, then N_b tends to increase, but the signal detection performance for the GSM may be deteriorated because the number of receive antennas at each node decreases. Considering effective throughput that is defined the number of successfully decoded at receiver, there may exist the optimal n_t for given N_t and $\mathbb{A}$.

III. GSM Signal Detection with Parallel OMP

Compressed sensing has been known as a revolutionary technique for reconstructing a sparse signal by finding solutions of under-determined linear systems. Orthogonal matching pursuit (OMP) [9] has been known as a representative greedy algorithm owing to its simplicity and competitive performance. In this section, we propose a low-complexity signal detection technique for the FD-GSM system based on parallel OMP (POMP) algorithm [10] which was proposed to supplement the conventional OMP algorithm for sparse signal recovery. In the FD-GSM system, the signal detection problem is to obtain the transmit signal vector $\mathbf{x}_j$ of node j from the received signal vector $\mathbf{y}_i$ at node i by referring to (3). Recall that $\mathbf{H}_{ij} \in \mathbb{C}^{(N_t - n_t) \times n_t}$, and (3) becomes under-determined linear system. Considering that $n_t \ll N_t$ in general GSM systems, the transmit signal vector can be regarded as a *sparse* signal of which almost elements are zero.

Overall procedure of the proposed signal detection technique is summarized in Algorithm 1. In the algorithm, $\mathbf{H}_{\Lambda_t^m} \in \mathbb{C}^{(N_t - n_t) \times |\Lambda_t^m|}$ denotes a submatrix of $\mathbf{H}_{ij}$ that only contains columns indexed by Λ_t^m. As explained in Algorithm 1, multiple columns (M) from the channel matrix $\mathbf{H}_{ij}$ are selected in the first iteration, which have a high correlation value with the received signal vector $\mathbf{y}_i$. Then, conventional OMP processes are carried out in parallel, on the basis of the selected columns in the first iteration. The detection performance becomes improved as M increases, but the computational complexity increases linearly with M. Note that the proposed signal detection algorithm has much smaller complexity than the optimal MLD, even though it has M times higher complexity than the conventional OMP algorithm.

IV. Simulation Results and Discussions

In this section, the signal detection performances of ML, OMP, and the proposed algorithm are compared in terms of SER via extensive simulations. We assume that $N_t = 8$ and $n_t = 3$. In addition, QPSK modulation is assumed to be used for symbol modulation, and thus the resultant number of transmitting bits of FD-GSM system per channel use is equal to 30 according to (2). As shown in Fig. 2, the proposed detection technique significantly outperforms the conventional OMP algorithm. For example, the SER of OMP algorithm is equal to 0.035, while that of the proposed algorithm with $M = 4$ is equal to 0.001, when $\mathsf{SNR} = 30$dB. The SER of the proposed algorithm has similar slope with that of the optimal MLD in medium SNR regime, i.e., $\mathsf{SNR} \in [5$dB, 10dB$]$. Both the proposed algorithm and the conventional OMP algorithm

Algorithm 1 Proposed signal detection algorithm based POMP for a FD-GSM system

1: Input:
2: $\quad$ $\mathbf{y}_i$: Received signal
3: $\quad$ $\mathbf{H}_{ij}$: Channel matrix
4: $\quad$ $\mathbf{h}_k$: k-th column of $\mathbf{H}_{ij}$
5: $\quad$ n_t : The number of active antennas
6: $\quad$ M : The number of parallel OMP blocks
7: Initialize:
8: $\quad$ $t = 0, \mathbf{r}_t^m = \mathbf{y}_i, \Lambda_t^m = \emptyset, \Omega = \{1, 2, \ldots, N_t\},$
9: $\quad$ $m \in \{1, 2, \ldots, M\}$
10: Iteration:
11: **for** $t = 1$ to n_t **do**
12: $\quad$ **for** $m = 1$ to M **do**
13: $\quad\quad$ **if** $t == 1$ **then**
14: $\quad\quad\quad$ $\lambda_t^1 = \arg\max_{i \in \Omega} \left| \langle \mathbf{r}_{t-1}^1, \mathbf{h}_k / \|\mathbf{h}_k\|_2 \rangle \right|^2$
15: $\quad\quad\quad$ $\lambda_t^2 = \arg\max_{i \in \Omega \setminus \{\lambda_t^1\}} \left| \langle \mathbf{r}_{t-1}^2, \mathbf{h}_k / \|\mathbf{h}_k\|_2 \rangle \right|^2$
16: $\quad\quad\quad$ $\vdots$
17: $\quad\quad\quad$ $\lambda_t^M = \arg\max_{i \in \Omega \setminus \{\lambda_t^1, \ldots, \lambda_t^{M-1}\}} \left| \langle \mathbf{r}_{t-1}^M, \mathbf{h}_k / \|\mathbf{h}_k\|_2 \rangle \right|^2$
18: $\quad\quad$ **else**
19: $\quad\quad\quad$ $\lambda_t^m = \arg\max_{i \in \Omega \setminus \{\lambda_{t-1}^m\}} \left| \langle \mathbf{r}_{t-1}^m, \mathbf{h}_k / \|\mathbf{h}_k\|_2 \rangle \right|^2$
20: $\quad\quad$ **end if**
21: $\quad\quad$ $\Lambda_t^m = \Lambda_{t-1}^m \cup \{\lambda_t^m\}$
22: $\quad\quad$ $\mathbf{P}_t^m = \left\{ \left(\mathbf{H}_{\Lambda_t^m}\right)^T \mathbf{H}_{\Lambda_t^m} \right\}^{-1} \left(\mathbf{H}_{\Lambda_t^m}\right)^T$
23: $\quad\quad$ $\hat{\mathbf{x}}_t^m = \mathbf{P}_t^m \mathbf{y}_i$
24: $\quad\quad$ $\hat{\mathbf{y}}_t^m = \mathbf{H}_{\Lambda_t^m} \hat{\mathbf{x}}_t^m$
25: $\quad\quad$ $\mathbf{r}_t^m = \mathbf{y}_i - \hat{\mathbf{y}}_t^m$
26: $\quad$ **end for**
27: **end for**
28: Decision:
29: $\quad$ $\hat{m} = \arg\max_m \|\mathbf{r}_{n_t}^m\|_2^2$
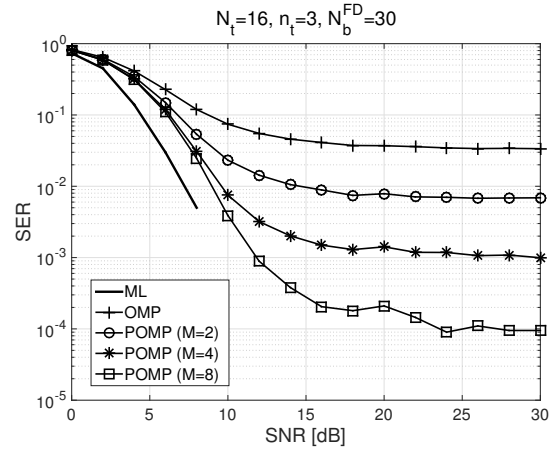30: $\quad$ $\hat{\mathbf{x}}_j^{\mathrm{POMP}} = \mathbf{P}_{n_t}^{\hat{m}} \mathbf{y}_i$

Fig. 2. BER performance of the proposed low-complexity signal detection algorithm when $N_t = 16$, $n_t = 3$, $|\mathbb{A}| = 4$ (QPSK modulation).
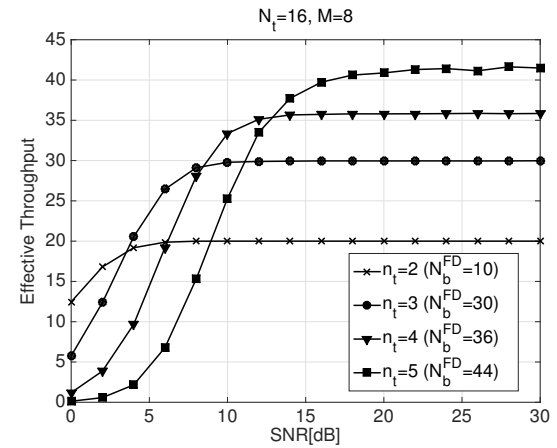

Fig. 3. Effective throughput of the proposed signal detection algorithm for varying SNR when $M = 8$, $N_t = 16$, $|\mathbb{A}| = 4$ (QPSK modulation), and $n_t = 2, 3, 4, 5$.

has a error floor which is common in low-complexity signal detection techniques, and channel coding technique may be combined with the proposed algorithm for achieving better SER performance.

Fig. 2 shows the effective throughput of the proposed POMP algorithm, where the effective throughput is defined as $N_b^{\mathrm{FD}}(1 - P_e)$. P_e denotes the SER. The maximum value of the effective throughput becomes N_b^{FD} and it tends to be larger as n_t becomes large. However, for a given SNR value, there exists a optimal n_t that achieves the maximum effective throughput due to the corresponding SER. In addition, the number of receive antennas becomes smaller as n_t increases, and it negatively affects the SER performance. Thus, n_t needs to be carefully chosen.

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