Sparse Index Multiple Access

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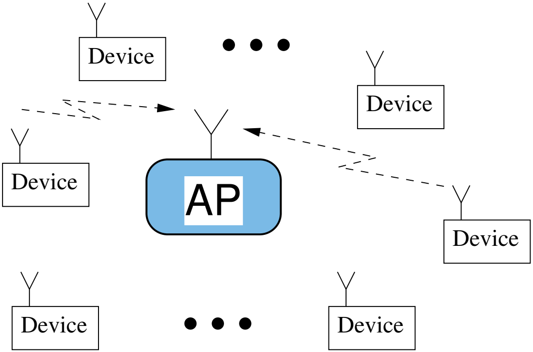
1. Introduction

- Spatial modulation (SM) was proposed for MIMO systems where only few TX antennas are active to transmit signals (Mesleh et al. 2008).
- The notion of SM has been applied to OFDM as index modulation where only few subcarriers are active to transmit signals (Basar et al. 2013).
- Precoding and sparse index modulation (SIM) are employed for index modulation (Choi and Ko 2015).
  - Precoding is to exploit the frequency diversity (for better performances).
  - Sparsity is to use low-complexity detection methods based on the notion of compressive sensing (CS).
- The above approaches are for single-user systems.

- In this paper, we extend SIM to a multiuser system.
- Due to precoding, the resulting system can be seen as a multi-carrier CDMA system with SIM.
- The resulting approach is referred to sparse index multiple access (SIMA).
- Compared with the conventional MC-CDMA, SIMA can have a higher spectral efficiency and better performance (depending on system parameters).
- Due to the sparsity, low-complexity algorithms for multiuser detection are also available.

2. System Model



- An AP and K devices or users
- Uplink transmissions with L subcarriers

The received signal of length $L \times 1$ at the AP or BS over L subcarriers is

$$\mathbf{r} = \sum_{k=1}^{K} \mathrm{diag}(H_{k,0}, \ldots, H_{k,L-1})\mathbf{s}_k + \mathbf{n} = \sum_{k=1}^{K} \mathbf{H}_k \mathbf{s}_k + \mathbf{n},$$

- $\mathbf{H}_k$: $L \times L$ diagonal matrix for the frequency-domain channel from user k
- $\mathbf{s}_k$: the OFDM symbol from user k
- $\mathbf{n}$: the brackground noise vector
- MC-CDMA with spreading (or signature) codes $\mathbf{C}_k$

$$\mathbf{r} = \sum_{k=1}^{K} \mathbf{H}_k \mathbf{C}_k \mathbf{s}_k + \mathbf{n} = \sum_{k=1}^{K} \mathbf{G}_k \mathbf{s}_k + \mathbf{n}.$$

- In the conventional MC-CDMA, $\mathbf{s}_k$ is not sparse.
- In SIMA, $\mathbf{s}_k$ becomes sparse.

$$\begin{aligned} \mathbf{r} &= \sum_{k=1}^{K} \mathbf{G}_k \underbrace{\mathbf{s}_k}_{Q-\text{sparse}} + \mathbf{n} \\ &= [\mathbf{G}_1 \ \cdots \ \mathbf{G}_K] \begin{bmatrix} \mathbf{s}_1 \\ \vdots \\ \mathbf{s}_K \end{bmatrix} + \mathbf{n} \\ &= \mathbf{G}\mathbf{s} + \mathbf{n}, \end{aligned}$$

where $\mathbf{s}$ becomes KQ-sparse.

3. Compressive Sensing Based Estimation

- ML detection:

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}} ||\mathbf{r} - \mathbf{G}\mathbf{s}||^2$$

- An exhaustive approach for the ML detection is computationally prohibitive.
- In addition, the size of $\mathbf{G}$ is $L \times KL$, which results in an underdetermined system
- Thus, ZF or MMSE approach does not work.
- Noting that $\mathbf{s}$ is sparse, we could use CS approaches.
- CS has been extensively studied by Candes, Donoho and so on since 2006.

- A CS-based estimation:

$$\hat{\mathbf{s}} = \arg\min ||\mathbf{r} - \mathbf{G}\mathbf{s}||^2 + \lambda||\mathbf{s}||_1$$

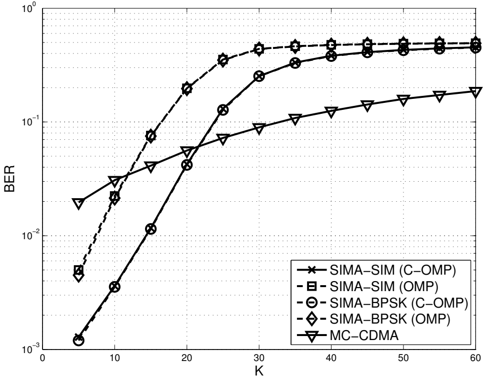
- This problem is a convex problem. However, the computational complexity is high.
- Thus, low-complexity approaches can be used, e.g., the OMP algorithm.
- $\mathbf{s}$ is KQ-sparse with the following property:

$$\mathbf{s} = [\ \underbrace{\mathbf{s}_1^{\mathrm{T}}}_{Q-\text{sparse}} \quad \cdots \quad \underbrace{\mathbf{s}_K^{\mathrm{T}}}_{Q-\text{sparse}}\ ]^{\mathrm{T}}.$$

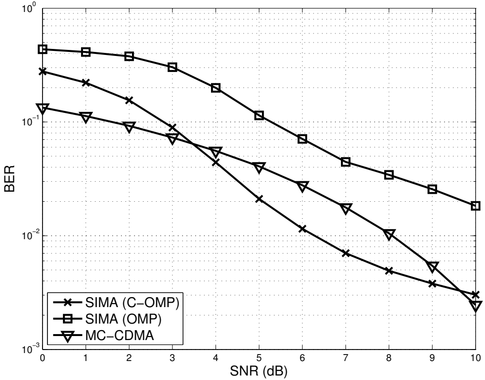
- To exploit this property, we need to modify the OMP algorithm.
- A modified OMP algorithm is presented in the paper.

4. Simulation Results

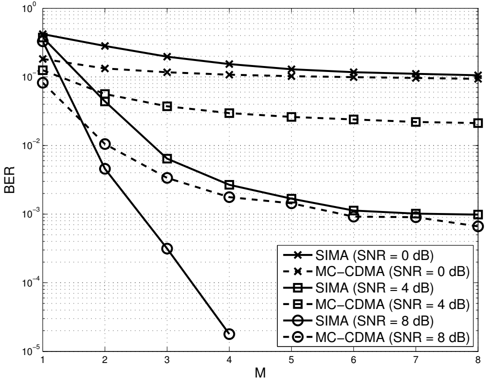
- We consider MC-CDMA for comparison purposes.
- For MC-CDMA, 4-QAM signaling is used for each user.
- In SIMA, messages bits can be delivered by sparse index modulation (SIM) and conventional modulation (BPSK).
- Multiple RX antennas are considered as the BS, (denote by M the number of RX antennas).
- The frequency-domain channel coefficients are assumed to be iid.



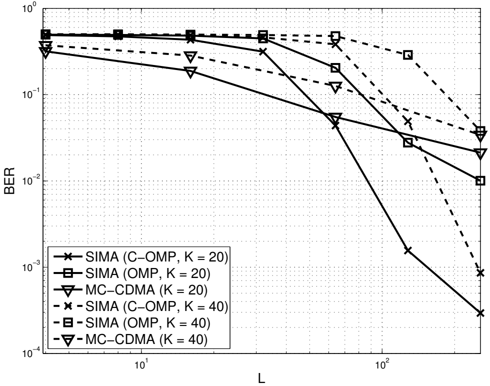
BER performances of SIMA and MC-CDMA for different numbers of users ($L = 64$, $M = 2$, and SNR $= \frac{E_{\text{bit}}}{N_0} = 4$ dB).



BER performances of SIMA and MC-CDMA for various values of SNR $= \frac{E_{\text{bit}}}{N_0}$ *($L = 64$, $M = 2$, and $K = 20$).*



BER performances of SIMA and MC-CDMA for various values of M *(*$L = 64$ *and* $K = 20$*).*



BER performances of SIMA and MC-CDMA for various values of L ($\frac{E_{\text{bit}}}{N_0} = 4$ dB, $M = 2$, and $K \in (20, 40)$).

Note: SIMA has a higher spectral efficiency than MC-CDMA and the gap increases with L.

- In MC-CDMA, the number of bits per user is 2 (as 4-QAM is used).
- In SIMA, the number of bits per user is

$$\log_2(2L) + 1 = 2 + \log_2 L \ (\geq 2).$$

- As L increases, SIMA can transmit more bits.

5. Conclusion

- Sparse index modulation has been extended to a multiple access scheme, called sparse index multiple access (SIMA).
- Since the computational complexity for the ML multi-user detection in SIMA is high, a low-complexity approach has been proposed using a compressive-sensing based estimation method (i.e., OMP algorithm).
- SIMA can provide better performance in most cases and has a higher spectral efficiency than MC-CDMA.
- SIMA has a potential to be used for M2M to support a number of devices with low activity.