Soft-output ML detector for spatial modulation OFDM systems

Soon Up Hwang^{1a)}, Sungho Jeon², Sangjin Lee¹,
and Jongsoo Seo¹

¹ School of Electrical and Electronic Engineering,
Yonsei University, Seoul 120–749, Korea

² Broadcast Technical Research Institute (BTRI),
Korean Broadcasting System (KBS), Seoul, 150–790, Korea
a) hsu777@yonsei.ac.kr

Abstract: The spatial modulation (SM) divides input data into antenna indexes and data symbols, and transmits data symbols via the specific antenna chosen by the antenna index. Soft decision technology for the SM system has not been developed, and there is room for improving the receive performance. In this paper, soft-output maximum likelihood (ML) detector for antenna index and data bit is derived to recover the desired signals by soft decision. Simulation results show that the conventional SM system with hard decision has a limitation in its performance as compared to SIMO (single-input multiple-output) system. On the other hand, the proposed SM with soft decision outperforms the SM with ML detector based on hard decision.

Keywords: spatial modulation, MIMO based wireless communication system, SIMO, coded OFDM

Classification: Science and engineering for electronics

References

- [1] H. Jiang and P. A. Wilford, “A hierarchical modulation for upgrading digital broadcasting systems,” *IEEE Trans. Broadcast.*, vol. 1, no. 2, pp. 222–229, June 2005.
- [2] R. Ran, J. Yang, and D. Kim, “Multimode precoder design for STBC with limited feedback in MIMO based wireless communication system,” *IEICE Electron. Express*, vol. 6, no. 3, pp. 173–179, Feb. 2009.
- [3] R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, “Spatial modulation,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, July 2008.
- [4] J. Jeganathan, A. Ghayeb, and L. Szczecinski, “Spatial modulation: Optimal detection and performance analysis,” *IEEE Commun. Lett.*, vol. 12, no. 8, pp. 545–547, Aug. 2008.
- [5] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, “V-BLAST : an architecture for realizing very high data rates over the rich-scattering wireless channel,” *Proc. IEEE ISSSE*, Pisa, Italy, pp. 295–300, Sept. 1998.

1 Introduction

As the demand for high-data rate multimedia services grows, several approaches such as increasing modulation order or employing multiple antennas at both transmitter and receiver have been studied to enhance the spectral efficiency [1]. In wireless systems, higher order modulation than 64 quadrature amplitude modulation (QAM) has a limitation due to signal distortion caused by channel fading and background noise. Multiple-input multiple-output (MIMO) technique has been regarded as one of the core techniques to achieve both the data rate increment and performance enhancement [2].

In open-loop schemes, there are generally two approaches to implement MIMO systems. One is to increase the spatial transmit diversity (STD) by means of space-time coding and space-frequency coding. Another is to raise the channel capacity by employing spatial division multiplexing (SDM) that simultaneously transmits independent data symbols through multiple transmit antennas. STD mitigates impairments of channel fading and noise, whereas SDM increases the spectral efficiency.

The open-loop scheme proposed in [3] is called spatial modulation (SM), which enables basically to avoid co-channel interference (CCI) and inter-antenna interference (IAS) as compared to Vertical Bell labs layered space-time (V-BLAST) [5]. In [4], the optimal receiver for SM is described, which is operated on hard decision basis. There has been no literature reporting the performance of SM combined with soft decision. It should be quite desirable to apply powerful forward error correction (FEC) such as Turbo or low density parity check (LDPC) codes for the SM system.

In this paper, soft-output maximum likelihood (ML) detector for antenna index and data bit is derived to recover the desired signals by soft decision. This is useful work to realize the SM for coded systems utilizing multiple antennas because this approach has not been studied enough in practical applications.

2 Spatial modulation

In the SM, input data are divided into antenna indices and data symbols, and a modulated symbol is transmitted through the specific antenna chosen by an antenna index. Once the indices of transmit antennas are perfectly detected at the receiver, the system model is equivalent to SIMO system which has ideally the diversity order of receive antennas. This leads us to avoid spatial correlation at the transmitter. Let us consider $N \times M$ MIMO system combined with SM illustrated in Fig. 1, where M and N are the number of transmit and receive antennas, respectively.

After removing the cyclic prefix (CP) and fast Fourier transform (FFT) operation, the received signal at a subcarrier is represented as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

where $\mathbf{h}_m$ is the channel vector of the m th ($m = 1, \dots, M$) transmit antenna, and the transmitted signal vector $\mathbf{x}$ associated with antenna index m

Fig. 1. Spatial modulation system model.

is written as

$$\mathbf{x} = [0 \ 0 \cdots \underbrace{x_k}_{m\text{-th position}} \ 0 \cdots 0]^T \quad (2)$$

Herein, $x_k (k = 1, \dots, K)$ denotes the complex signal with $E[|x_k|^2] = 1$, and is mapped by QAM format such as QPSK, 16 QAM, etc. $\mathbf{0}_l$ stands for zero vector of $1 \times l$ size. The elements of noise vector $\mathbf{n}$ are additive white Gaussian noise (AWGN) and independent and identically distributed (i.i.d.) with the variance σ^2 .

2.1 Sub-optimal detector (hard decision)

The maximum ratio combining (MRC) is used to detect the transmit antenna index and transmitted symbol, which is expressed as

$$\mathbf{g} = \mathbf{H}^H \mathbf{y} \quad (3)$$

Ideally, the output vector $\mathbf{g}$ is equal to the transmitted vector $\mathbf{x}$ if there is perfect time and frequency synchronization and no noise. In the presence of AWGN and spatial correlation, the antenna index should be estimated prior to detecting the transmitted symbol. By finding the maximum value in Eq. (3), the antenna index is obtained as following:

$$\hat{m} = \arg \max_m \|\mathbf{g}_m\|^2 \quad m = 1, \dots, M \quad (4)$$

where $\mathbf{g}_m$ is the m th element of $\mathbf{g}$ vector. Then, we can demodulate the transmitted symbol x_q by quantizing $\mathbf{g}_{\hat{m}}$ as in [3]. Replacing $\mathbf{H}^\dagger$ with $\mathbf{H}^H$ in Eq. (3), antenna indices also can be more accurately obtained in zero forcing (ZF) scheme. As for estimating antenna indices, it is proven that inverse matrix such as ZF or minimum mean square error (MMSE) is more effective than MRC.

2.2 Optimum detector (hard decision)

Let us assume that the transmitted signals are equally likely. As in [4], the optimal detector based on ML is given as

$$[\hat{m}, \hat{q}] = \arg \max_{m,q} P(\mathbf{y}|\mathbf{H}, \mathbf{x}) \quad (5)$$

where the conditional probability density function (pdf) is represented by $P(\mathbf{y}|\mathbf{H}, \mathbf{x}) \propto \exp(-\|\mathbf{y} - \mathbf{h}_m x_q\|^2 / \sigma^2)$. Antenna indices and data symbols are recovered by the joint detection as Eq. (5). As mentioned above, those schemes are used only for coded systems operated by hard decision.

3 Soft output ML detector for SM

When a wireless communication system employs FEC codes, soft-input soft-output (SISO) decoder is needed to decode the received signals. Apparently, the term ‘soft’ means log-likelihood ratio (LLR). For this reason, SISO decoder should be accompanied by soft-output demapper or detector in order to input equalized signals to SISO decoder. Without loss of generality, soft-output ML detector for SM is derived in this section.

3.1 Soft-output demapper for antenna index

Assuming that the number of transmit antennas M is four and input data are modulated by QPSK, a *posteriori* LLR $L(m^i)$ for the i th antenna bit is expressed as

$$L(m^i) = \log \frac{P(m^i = 1|\mathbf{y})}{P(m^i = 0|\mathbf{y})} = \log \frac{\sum_{\tilde{\mathbf{m}} \in \mathbf{m}_1^i} \sum_{\tilde{x} \in \mathcal{X}} P(\mathbf{y}|\mathbf{m} = \tilde{\mathbf{m}}, x = \tilde{x}) P(\mathbf{m} = \tilde{\mathbf{m}})}{\sum_{\tilde{\mathbf{m}} \in \mathbf{m}_0^i} \sum_{\tilde{x} \in \mathcal{X}} P(\mathbf{y}|\mathbf{m} = \tilde{\mathbf{m}}, x = \tilde{x}) P(\mathbf{m} = \tilde{\mathbf{m}})} \quad (6)$$

where $\mathbf{m}_1^i$ and $\mathbf{m}_0^i$ represent vectors of the antenna indices which have “1” and “0” at the i th bit, respectively. The set of QPSK constellations is defined as $\mathcal{X} \{x \in \mathcal{X} | \pm 1/\sqrt{2} \pm 1/\sqrt{2}\}$.

It is assumed that antenna indices and data symbols are uncorrelated each other. Moreover, antenna bits consisting of antenna indices are equally likely and independent with the aid of bit interleaver. By Bayes’ theorem, Eq. (6) can be simply rewritten as

$$L(m^i) = \log \frac{\sum_{\tilde{\mathbf{m}} \in \mathbf{m}_1^i} \sum_{\tilde{x} \in \mathcal{X}} \exp\left(-\frac{\|\mathbf{y} - \mathbf{h}_{\tilde{\mathbf{m}}} \tilde{x}\|^2}{\sigma^2}\right)}{\sum_{\tilde{\mathbf{m}} \in \mathbf{m}_0^i} \sum_{\tilde{x} \in \mathcal{X}} \exp\left(-\frac{\|\mathbf{y} - \mathbf{h}_{\tilde{\mathbf{m}}} \tilde{x}\|^2}{\sigma^2}\right)} \quad (7)$$

3.2 Soft-output demapper for data symbol

The *a posteriori* LLRs for data symbols are similarly computed as the ones for antenna index. a *posteriori* LLR $L(x^q)$ for the q th bit is given as

$$L(x^q) = \log \frac{\sum_{\tilde{x} \in \mathbf{x}_1^q} \sum_{\tilde{\mathbf{m}} \in \mathbf{m}} P(\mathbf{y}|x = \tilde{x}, \mathbf{m} = \tilde{\mathbf{m}}) P(x = \tilde{x})}{\sum_{\tilde{x} \in \mathbf{x}_0^q} \sum_{\tilde{\mathbf{m}} \in \mathbf{m}} P(\mathbf{y}|x = \tilde{x}, \mathbf{m} = \tilde{\mathbf{m}}) P(x = \tilde{x})} \quad (8)$$

where $\mathbf{x}_1^q$ and $\mathbf{x}_0^q$ denote vectors of the data symbol which have “1” and “0” at the q th bit, respectively. The candidate element $\tilde{\mathbf{m}}$ for antenna index can be one of the set $\{00, 01, 10, 11\}$ since the number of transmit antennas is 4 as mentioned above. Assuming that data bits are generated with equal

probability, Eq. (8) is rewritten as

$$L(x^q) = \log \frac{\sum_{\tilde{x} \in \mathbf{x}_1^q} \sum_{\tilde{\mathbf{m}} \in \mathbf{m}} \exp\left(-\frac{\|\mathbf{y} - \mathbf{h}_{\tilde{\mathbf{m}}} \tilde{x}\|^2}{\sigma^2}\right)}{\sum_{\tilde{x} \in \mathbf{x}_0^q} \sum_{\tilde{\mathbf{m}} \in \mathbf{m}} \exp\left(-\frac{\|\mathbf{y} - \mathbf{h}_{\tilde{\mathbf{m}}} \tilde{x}\|^2}{\sigma^2}\right)} \quad (9)$$

4 Simulation results

Simulation results are shown to analyze BER performances of the SM as compared to SIMO systems, in terms of hard and soft decision. The coded performances of the SM based on hard decision are also examined by ZF and MMSE scheme as well as ML scheme. Computer simulations are performed over COST207-typical urban (TU) channel with Doppler frequency of 30 Hz. The FFT size is set to 256, and the channel matrix is assumed to be perfectly known at the receiver. For error correction codes, convolutional codes with half rate are used where the polynomials are (7, 5) in octal notation. Also, one frame is assumed to consist of one OFDM block for simplicity, and the bit-interleaver is performed randomly.

In Fig. 2, coded BER performances are shown in the event of 4 bits per one subcarrier, where 10^4 iterations are used for each case. It is found that the performance of SM operated by hard decision (ZF) is not better than that of SIMO, because antenna indices are not accurately estimated. There is no guarantee that i.i.d. channel matrixes are always orthogonal. Therefore, a linear detection such as ZF or MMSE scheme has a limitation to estimate antenna indices accurately as compared to ML. It is seen clearly that 4 by 4 SM with hard decision (ZF) does not have full diversity order 4 as compared to 1 by 4 SIMO with hard decision (ZF).

The BER performance of 4 by 4 SM with hard decision (ML) is better than 1 by 4 SIMO with soft decision at the expense of increasing the computational complexity. It is shown that the diversity orders of both schemes are the same. The BER performance of 4 by 4 SM with soft decision is superior to the performance of 4 by 4 SM with hard decision (ML). At $\text{BER}=10^{-4}$, the former outperforms the latter by about 3 dB.

In Fig. 3, coded BER performances are shown in the event of 6 bits per one subcarrier. The overall performances are similar to the cases of 4 bits per one subcarrier except for the modulation order. The BER performance of 4 by 4 SM with soft decision is superior to the performance of 4 by 4 SM with hard decision (ML) by about 3 dB at $\text{BER}=10^{-4}$.

5 Conclusion

In this paper, a MIMO-OFDM system combined with the SM which is operated by soft decision is introduced. In order to practically apply the SM to coded systems, we derived soft-output ML detector based on the SM. Simulation results show that the BER performance of SM with soft decision is superior to that of SM with hard decision (ML) by about 3 dB at $\text{BER}=10^{-4}$,

Fig. 2. Coded BER performances of SM and SIMO (4 bits/subcarrier).

Fig. 3. Coded BER performances of SM and SIMO (6 bits/subcarrier).

when the spectral efficiency is 4 or 6 bits per one subcarrier. The coded BER performances for MIMO OFDM combined with SM are compared to SIMO systems. As a result, the SM system using the derived soft-output ML detector is more effective than the SIMO system. It is also shown that the SM operated by hard decision such as ZF or MMSE equalizer has a limitation in its performance as compared to SIMO system.

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