Adaptive Spatial Modulation Using Huffman Coding

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Outline

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2. System Model
3. Huffman Coding Based Signal Mapping
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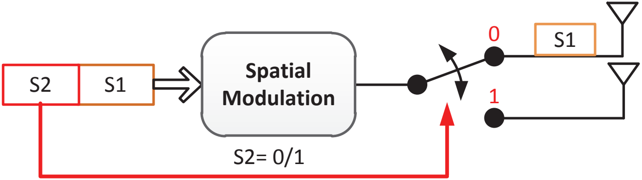
Spatial Modulation



- Benefits
  - Low hardware cost: only one RF-chain needed
  - Low-complexity signal processing
  - High spectral and energy efficiency
- Challenges
  - No transmit diversity
  - Poor anti-fading ability: transmission scheme is independent of the specific channel

[1] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: challenges, opportunities and implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

Motivations

The application of spatial modulation requires favorable propagation conditions. What can we do to enhance the system performance?

- Diagonal precoder designs for spatial modulation [2][3];
  - Difficult to implement: NP-hard;
  - Cause high peak-to-average power ratio among the transmit antennas.
- **Huffman coding based adaptive spatial modulation;**
  - A unified single RF chain transmission scheme that generalizes both *transmit antenna selection* and *spatial modulation*;
  - Both diversity and antenna index benefit obtained;
  - Equal power for all the transmit antennas.

[2] W. Wang and W. Zhang, " Diagonal precoder designs for spatial modulation," *Proc. IEEE Int. Conf. Commun.*, London, UK, Jun. 8-12, 2015.
[3] P. Yang, Y. L. Guan, Y. Xiao, M. Di Renzo, S. Li, and L. Hanzo, "Transmit precoded spatial modulation: Maximizing the minimum Euclidean distance versus minimizing the bit error ratio," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 2054-2068, Mar. 2016.

Outline

System Model

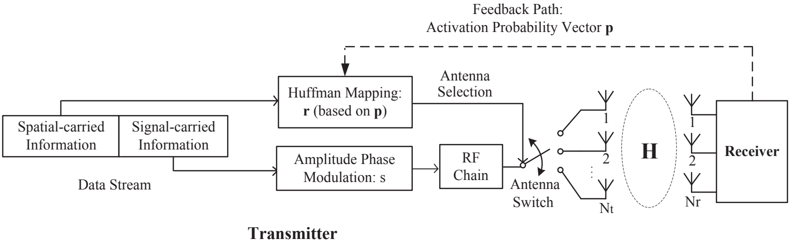


Figure: Structure of Huffman coding based adaptive spatial modulation

The data stream is split into two independent streams.

- Signal information is conveyed via the APM signal s
- Antenna information decides which antenna is activated to send s
  - The specific Huffman mapping scheme is decided by $\mathbf{p}$
  - The optimal $\mathbf{p}$ is dependent on channel $\mathbf{H}$

System Model

The transmitted signal $\mathbf{x}$ is

$$\mathbf{x} = \underbrace{(0 \quad 0 \quad \cdots \quad 0 \quad s \cdots \quad 0 \quad 0)^T}_{\text{One out of } \mathrm{N_t} \text{elements is nonzero}} \tag{1}$$

and (1) can be decomposed and rewritten as

$$\mathbf{x} = \mathbf{r} \cdot s \tag{2}$$

The antenna vector $\mathbf{r}$ is chosen from

$$C_{\mathbf{r}} = \{\mathbf{e}_1, \ \mathbf{e}_2, \ ..., \ \mathbf{e}_{N_t}\} \tag{3}$$

$\mathbf{e}_i$ is an $N_t \times 1$ vector with the i^{th} element being 1 and the rest 0. The probability of selecting the i^{th} antenna is

$$\mathrm{Prob}(\mathbf{r} = \mathbf{e}_i) = p_i, \quad i = 1, \ 2, \ \cdots, \ N_t \tag{4}$$

The amplitude phase modulated (APM) signal s can be

- Complex Gaussian distributed, i.e., $s \sim \mathcal{CN}(0, 1)$
- QAM modulated signal, e.g., BPSK, QPSK, 8PSK, 16QAM.

System Model

- In conventional spatial modulation, the probability vector $\mathbf{p}$ is

$$\mathbf{p} = \left[\frac{1}{N_t}, \frac{1}{N_t}, \cdots, \frac{1}{N_t}\right] \tag{5}$$

Up to $\log_2 N_t$ bits extra information can be conveyed by antenna index.

- In transmit antenna selection, the probability vector $\mathbf{p}$ is

$$\begin{aligned} p_j &= 1, \quad j = \text{argmax}_{\text{i}}\{\|\mathbf{h}_{\text{i}}\|\} \\ p_i &= 0, \quad \forall i \neq j \end{aligned} \tag{6}$$

Only the strongest transmit antenna j is selected to convey the signal information and no information is conveyed via antenna index.

- Mapping schemes for other values of $\mathbf{p}$?

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Huffman Mapping

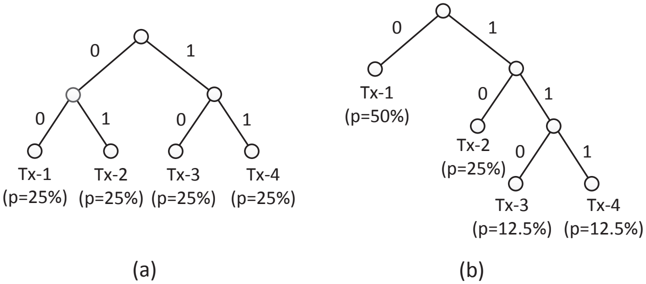

Figure: Huffman trees corresponding to (a) $\mathbf{p} = \left[\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}\right]$ (i.e., conventional SM), (b) $\mathbf{p} = \left[\frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}\right]$

Huffman Mapping

Table: HUFFMAN MAPPING SCHEME FOR $\mathbf{p} = \left[\frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}\right]$

Bit Sequence	Spatial Symbol ($\mathbf{r}$)	Probability ($\mathbf{p}$)
0	Tx-1 ($\mathbf{e}_1$)	50%
10	Tx-2 ($\mathbf{e}_2$)	25%
110	Tx-3 ($\mathbf{e}_3$)	12.5%
111	Tx-4 ($\mathbf{e}_4$)	12.5%

- Table 1 is a bijective function between the binary bits and antenna index, no codeword is a prefix of any other codeword
- The incoming antenna information bits are sequentially detected and then mapped into different transmit antenna indices
- The transmitted antenna information is up to $\frac{1}{2} \times 1 + \frac{1}{4} \times 2 + \frac{1}{8} \times 3 + \frac{1}{8} \times 3 = 1.75$ bits, when $\mathbf{p} = \left[\frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}\right]$.

Mapping Scheme Selection

- The objective of adaptive spatial modulation is to find $\mathbf{p}$ that optimizes system performance, i.e.,

$$\begin{cases} \max_{\mathbf{p}} & C(\mathbf{p}) \\ s.t. & \mathbf{p} \in \mathbb{P} \end{cases} \tag{7}$$

$C(\mathbf{p})$ is the channel capacity that consists of signal carried information and antenna index carried information.
What is the optimal tradeoff that leads to the maximized $C(\mathbf{p})$?

- Due to the binary nature of the proposed Huffman coding scheme, the feasible domain of $\mathbf{p}$ is a discrete set which can be represented as

$$\mathbb{P} = \left\{ \mathbf{p} \middle| \sum_{i=1}^{N_t} p_i = 1, p_i \in \{0, 1, 2^{-1}, \cdots, 2^{-\beta}\} \right\} \tag{8}$$

and β $(0 \leq \beta \leq N_t - 1)$ is an integer and is related to transmission codebook size.

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Capacity Bounds

- The channel capacity C is upper bounded by

$$C^+ = \underbrace{\sum_{i=1}^{N_t} p_i \log_2(1+\rho||\mathbf{h}_i||^2)}_{I(s;\mathbf{y}|\mathbf{r})} + \underbrace{\sum_{i=1}^{N_t} p_i \log_2 \frac{1}{\sum_{j=1}^{N_t} p_j e^{-D(f_i(\mathbf{y})||f_j(\mathbf{y}))}}}_{I^+(\mathbf{r};\mathbf{y})} \tag{9}$$

where

$$D(f_i(\mathbf{y})||f_j(\mathbf{y})) = \ln\frac{1+\rho||\mathbf{h}_j||^2}{1+\rho||\mathbf{h}_i||^2} + \frac{\rho||\mathbf{h}_i||^2-\rho||\mathbf{h}_j||^2}{1+\rho||\mathbf{h}_j||^2} + \frac{\rho^2||\mathbf{h}_i||^2||\mathbf{h}_j||^2\sin^2(\angle(\mathbf{h}_i,\mathbf{h}_j))}{1+\rho||\mathbf{h}_j||^2}$$

- The channel capacity C is lower bounded by

$$C^- = \underbrace{\sum_{i=1}^{N_t} p_i \log_2(1+\rho||\mathbf{h}_i||^2)}_{I(s;\mathbf{y}|\mathbf{r})} + \underbrace{\sum_{i=1}^{N_t} p_i \log_2 \frac{1}{\sum_{j=1}^{N_t} p_j B_{ij}}}_{I^-(\mathbf{r};\mathbf{y})} \tag{10}$$

where

$$B_{ij} = \frac{\sqrt{(1+\rho||\mathbf{h}_i||^2)(1+\rho||\mathbf{h}_j||^2)}}{1+\frac{\rho}{2}(||\mathbf{h}_i||^2+||\mathbf{h}_j||^2)+\frac{\rho^2}{4}||\mathbf{h}_i||^2||\mathbf{h}_j||^2\sin^2(\angle(\mathbf{h}_i,\mathbf{h}_j))}$$

Capacity Bounds

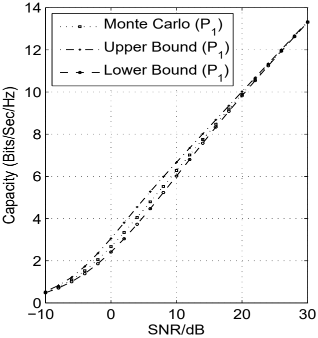

Figure: Capacity bounds comparison for $\mathbf{p}_1 = [\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}], N_r = 2, N_t = 4$

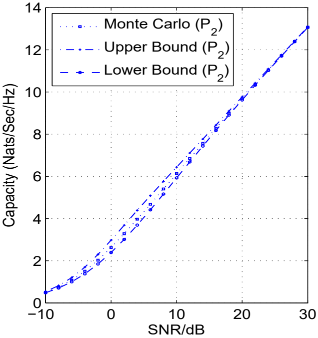

Figure: Capacity bounds comparison for $\mathbf{p}_2 = [\frac{1}{2}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}], N_r = 2, N_t = 4$

The capacity bounds are tight in asymptotic low SNR regime and high SNR regime.

Outline

Capacity Comparison

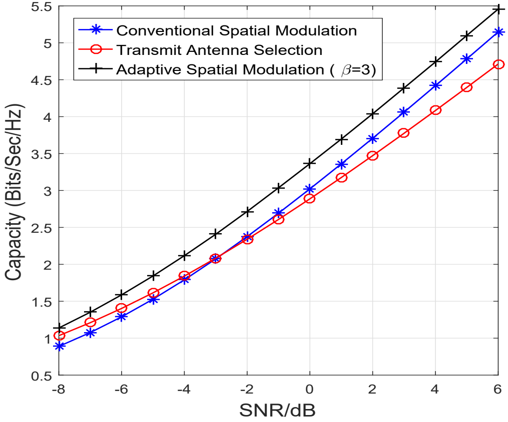

Figure: Capacity comparison ($N_t = 4, N_r = 2$)

Capacity comparison with reduced codebook size

Table: CARDINALITY OF $\mathbb{P}$ WHEN $N_t = 4$

β	0	1	2	3
$\|\mathbb{P}\|$	4	10	23	35

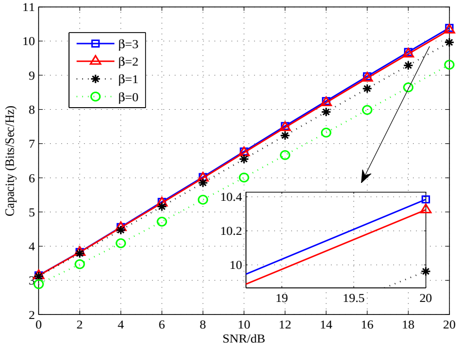

Figure: Capacity comparison with different values of β ($N_t = 4, N_r = 2$)

Outline

Conclusion

- A unified adaptive transmission scheme for single-RF chain MIMO is proposed in this paper. With Huffman mapping, the transmitter can activate each transmit antenna with different probabilities so as to optimize the performance.
- Numerical results show that the adaptive spatial modulation offers performance improvement over both conventional spatial modulation and transmit antenna selection.

Questions

Thank you