Current summary of research: Analysis of Delayed Bit Interleaved Coded Spatial Modulation

Abstract—

I. Introduction

About BICM

For achieving higher spectral efficiencies coded modulation combines higher order modulation with channel coding.

Bit Interleaved Coded Modulation (BICM) [1] creates code-diversity at individual bit level. This is achieved by bit-wise interleaving at encoder output. This breaks the correlation induced by the modulation and adds additional redundancy against bit errors.

About DBICM

Delayed Bit Interleaved Coded Modulation (DBICM) is an extension of BICM. Interleaved codeword is segmented into $log_2(M) = m$ parts and a pre-defined delay sequence of length m (for eg: [0 1 0 ... 1]) will determine which segments will be delayed. Initially decoded segments of a particular codeword can be used to demap symbols containing segments of the same codeword. This improves the performance.

- In other words, extrinsic information generated from decoder can be used again for better demapping of symbols [2], which leads to improved accuracy in information bit estimation.

About DBICM with spatial modulation

Recently spatial modulation has drawn increased attention as a special case of index modulation. Added performance from DBICSM compared to BICSM is shown using BER simulations in the recent paper [3].

Expected contribution

- Target is to combine the concepts of [4] and recently published [3].
- A capacity analysis is performed on how delay patterns can be designed with the available spatial bits and modulation bits. Spatial bits and modulation bits have unique bit-channel capacities. Bit channel capacities can follow interesting properties that can be proven mathematically. If such patterns exist they can be used to speed up the process of finding optimum delay scheme.
- After the capacity analysis is complete, polar code construction (selection of unfrozen bits) can be optimized considering the bit-channel capacities [5] of DBICSM.

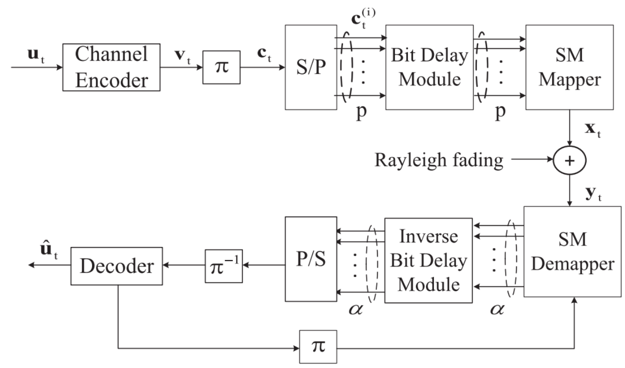

Fig. 1: DBICSM System model used in [3]

II. Capacity analysis of DBICSM system

According to [6], for generalized spatial modulation (GSM) with no bit-interleaving, sum channel capacity (sum of all bit-channels) can be either calculated using simulation or upper/lower bounded using closed-form expressions.

DBICM bit-channel capacity expression is available in [7]. This is also given as an expectation which can simulated over multiple random realizations.

BICSM bit-channel capacity expression is not available in the literature.

A. *Deriving the bit-channel capacity expression for BICSM*

Bit-channel capacity for BICM is given by [1],

$$C_{i,\mathrm{BICM}} = 1 - \mathop{\mathbb{E}}_{b,\mathbf{y}} \left[\log_2 \frac{\sum_{\mathbf{z}\in\mathcal{X}} p(\mathbf{y} \mid \mathbf{z})}{\sum_{\mathbf{z}\in\mathcal{X}_b^i} p(\mathbf{y} \mid \mathbf{z})} \right] \tag{1}$$

The derivation of this is based on the definition of average mutual information (AMI).

$$I_{XY} = \sum_{i,j} P_{XY}(x_i, y_j) \log_2 \left[\frac{p_{XY}(x_i, y_j)}{p_X(x_i)\, p_Y(y_j)} \right] \tag{2}$$

BICM-MIMO capacity expression for λ^{th} bit-channel is given by [8],

$$
\begin{aligned}
I\left(b^\lambda;\mathbf{r}\mid\mathbf{H}\right) &= H\left(b^\lambda\right) - H\left(b^\lambda\mid\mathbf{r},\mathbf{H}\right)\\
&= 1-\mathbb{E}_{b^\lambda\mid\mathbf{r},\mathbf{H}}\left(\log_2\frac{\sum_{\hat{b}^\lambda\in\{0,1\}} p\left(\mathbf{r}\mid\hat{b}^\lambda,\mathbf{H}\right)}{p\left(\mathbf{r}\mid b^\lambda,\mathbf{H}\right)}\right)
\end{aligned} \quad (3)
$$

Bit-channel capacities of BICSM can be derived using properly selecting the hypersymbols attributable to 0 and 1 bits.

For example consider a 2×2 BICSM ($n_t = 2$ and $n_r = 2$) system consisting of $p' = 3$, $p'' = 1$ and $n_a = 1$. Where p' is the number of bits pertaining to a single modulated symbol. In this example 8 PSK is considered. $p'' = log_2\lfloor\binom{n_t}{n_a}\rfloor$ is the number of bits required to represent the selected number of antennas for transmission using n_a antennas out of n_r antennas for spatial modulation.

The system is capable of transmitting a hypersymbol that is attributable to $p'' + p' \times n_a = 4$ bits. Each bit will have its unique bit-channel capacity. We denote the index of these four bits using b_i where $i = 1,..,4$. Obtaining bit-channel capacity of symbol bits b_2, b_3 and b_4 can be performed similar to BICM-MIMO bit-channel capacity calculation (3).

Next tasks

1) Obtain formula and implement BICSM capacity for above described system.
2) Implement DBICM capacity.
3) Implement DBICSM capacity.

Proving the following claims

1) Proving that all spatial bits have similar capacities.
2) Even though we use $p'' = log_2\lfloor\binom{n_t}{n_a}\rfloor$ spatial bits, we have $\binom{n_t}{n_a}$ possible antenna selections. Prove that any selection $\lfloor\binom{n_t}{n_a}\rfloor$ out of $\binom{n_t}{n_a}$ will result in same capacity.

B. Deriving the bit-channel capacity expression for DBICSM

Bit-channel capacity for DBICM system is mentioned in [7].

$$
\begin{aligned}
C^{\mathbf{T}}_{k,\mathrm{DBICM}} &= I(b;\mathbf{y}\mid\mathcal{D})\\
&= 1-\frac{1}{2^{|\mathcal{D}|}}\sum_{\mathbf{b}_{\mathcal{D}}\in\mathbb{F}_2^{|\mathcal{D}|}} \mathop{\mathbb{E}}_{b,\mathbf{y}\mid\mathcal{D}}\left[\log_2\frac{\sum_{\mathbf{z}\in\chi^{\mathcal{D}}_{\mathbf{b}_{\mathcal{D}}}} p(\mathbf{y}\mid\mathbf{z})}{\sum_{\mathbf{z}\in\chi^{k,\mathcal{D}}_{b,\mathbf{b}_{\mathcal{D}}}} p(\mathbf{y}\mid\mathbf{z})}\right]
\end{aligned} \quad (4)
$$

III. Possibility using polar codes as the channel coding block after completing capacity analysis

After referring to following papers [5], [9], [10], it was identified that polar codes can also be used for the channel coding block. It is yet to decide which channel coding scheme will be used.

Mapping the bits belonging to bit-channel groups into polarized unfrozen bits is a time consuming problem that can be solved exhaustively using $N!/((\frac{N}{m})!)^m$ of trials [5]. Developments in this regard are available in [9], [10].

IV. Evaluating performance

BER curves will be used to evaluate the performance of optimized schemes.

References

[1] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE transactions on information theory*, vol. 44, no. 3, pp. 927–946, 1998.

[2] H. Ma, W. Leung, X. Yan, K. Law, and M. Fossorier, "Delayed bit interleaved coded modulation," in *2016 9th International Symposium on Turbo Codes and Iterative Information Processing (ISTC)*. IEEE, 2016, pp. 86–90.

[3] Y. Liu, H. Du, S. Zhao, and J. Wen, "Delayed bit-interleaved coded transmission for spatial modulation," *IEEE Communications Letters*, 2023.

[4] Y. Liao, M. Qiu, and J. Yuan, "Design and analysis of delayed bit-interleaved coded modulation with ldpc codes," *IEEE Transactions on Communications*, vol. 69, no. 6, pp. 3556–3571, 2021.

[5] D.-M. Shin, S.-C. Lim, and K. Yang, "Mapping selection and code construction for 2^m-ary polar-coded modulation," *IEEE Communications Letters*, vol. 16, no. 6, pp. 905–908, 2012.

[6] T. L. Narasimhan and A. Chockalingam, "On the capacity and performance of generalized spatial modulation," *IEEE Communications Letters*, vol. 20, no. 2, pp. 252–255, 2015.

[7] X. Yan, R. G. Machado, K. Huang, F. Gabry, M. Fossorier, H. Hafermann, H. Zhang, I. Land, and W. Leung, "Capacity analysis of delayed bit interleaved coded modulation," in *2018 IEEE 10th International Symposium on Turbo Codes & Iterative Information Processing (ISTC)*. IEEE, 2018, pp. 1–5.

[8] M. R. McKay and I. B. Collings, "Capacity and performance of mimo-bicm with zero-forcing receivers," *IEEE Transactions on communications*, vol. 53, no. 1, pp. 74–83, 2005.

[9] K. Chen, K. Niu, and J.-R. Lin, "An efficient design of bit-interleaved polar coded modulation," in *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2013, pp. 693–697.

[10] X. Wu, M. Qiu, and J. Yuan, "Delayed bit-interleaved polar coded modulation with superposition gray labeling," in *2021 IEEE Globecom Workshops (GC Wkshps)*, 2021, pp. 1–6.