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BICM With OFDM System

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Abstract:

Caire, Taricco and Biglieri presented a detailed analysis of bit interleaved coded modulation, a simple and popular technique used to improve system performance, especially in the context of fading channels. This paper deals with transmission schemes for BICM-OFDM system. In low-mobility scenarios the channel state can be accurately tracked by both the transmitter and the receiver and the performance can be improved adapting the signalling to the instantaneous channel spectral shape. In the BICM-OFDM scheme, nearly optimal performance can be achieved by bit loading and power allocation, i.e. assigning a different constellation (number of bits) and different power to each subcarrier and each channel access according to the channel frequency response.

1.Introduction

Orthogonal frequency division multiplexing (OFDM) has been shown to combat ISI extremely well by converting the frequency selective channel into parallel flat fading channels. On the other hand, bit interleaved coded modulation (BICM) was shown to have high performance for flat fading Rayleigh channels. Combination of BICM and OFDM was shown to exploit the diversity that is inherited within the frequency selective fading channels. In other words, BICM-OFDM is a very effective technique to provide diversity gain, employing frequency diversity.

Bit-interleaved coded modulation (BICM) provides a pragmatic approach to coded modulation and has received attention in broadband transmission due to its bandwidth and power efficiency. Key to the success of the BICM paradigm is its applicability in a wide range of scenarios, achieved by separating modulation and demodulation from channel coding and decoding. The BICM receiver demodulates groups of bits, each group mapped to a single data-symbol and transmitted over a memory less channel, and passes the resulting soft reliability information to a subsequent binary decoder; the soft information is usually represented by log-likelihood ratios (LLRs). In the binary decoder, bits within such groups are treated as independent, an assumption typically motivated by the inclusion of a bitwise interleaver.

2.Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) originated from the need of efficient communications through frequency-selective fading channels. A channel is frequency selective if the frequency response of the channel changes significantly within the band of the transmitted signal. While, a constant frequency response is called flat fading, orthogonal frequency-division multiplexing (OFDM), essentially identical to coded OFDM (COFDM) and discrete multi-tone modulation (DMT), is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate intersymbol interference (ISI). This mechanism also facilitates the design of single frequency networks (SFNs), where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

2.1.Principles Of Operation

In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and the receiver; unlike conventional FDM, a separate filter for each sub-channel is not required.The orthogonality requires that the sub-carrier spacing is $\Delta f = \frac{k}{T_U}$Hertz, where T_U seconds is the useful symbol duration (the receiver side window size), and k is a positive integer, typically equal to 1. Therefore, with N sub-carriers, the total pass band bandwidth will be $B \approx N \cdot \Delta f$ (Hz).

The orthogonality also allows high spectral efficiency, with a total symbol rate near the Nyquist rate for the equivalent baseband signal (i.e. near half the Nyquist rate for the double-side band physical passband signal). Almost the whole available frequency band can be utilized. OFDM generally has a nearly 'white' spectrum, giving it benign electromagnetic interference properties with respect to other co-channel users.

3.Bit-Interleaved Coded Modulation (BICM)

BICM can be obtained by using a bit interleaver, π, between an encoder for a binary code C and an N-dimensional memory less modulator over a signal set $\chi \subseteq C$ of size $|\chi| = M = 2^m$ with a binary labelling map $\mu : \{0, 1\}^m \rightarrow \chi$. During transmission, the code sequence c is interleaved by π, and then mapped onto signal sequence $x \in \chi$. The signal sequence x is then transmitted over the channel.

The bit interleaver can be modelled as $\pi : k' \rightarrow (k, i)$ where k’ denotes the original ordering of the coded bits $c_{k'}$, k denotes the time ordering of the signals x_k transmitted, and i indicates the position of the bit ck’ in the label of x_k.

Let χ^i_b denote the subset of all signals x ∈ χ whose label has the value b ∈ {0, 1} in position i. Then, the ML bit metrics can be given by [1]

$$\lambda^i(y_k, b) = \begin{cases} \max\limits_{x \in x_b^1} \log p\theta_{k'}(y_{k'}|x), & \text{perfect CSI} \\ \max\limits_{x \in x_b^1} \log p(y_{k'}|x), & \text{no CSI} \end{cases} \qquad (1)$$

Where $\theta_{k'}$ denotes the channel state information (CSI) for the time order k.

The ML decoder at the receiver can make decisions according to the rule

$$\underline{\hat{c}} = \arg\max_{\underline{c} \in C} \sum_{k} \lambda^i (y_{k'}, c_k) \qquad (2)$$

4.Proposed System

Figure 1, depicts the system block diagram including the coding, interleaving, mapping and power allocation stages. Following a BICM scheme, the coded bits are bit-interleaved and delivered to the modulation and power allocation stages.

$$y_q(n) = H_q\sqrt{p_q(n)}x_q(n) + w_q(n)$$

$$q = 1, \ldots\ldots, Q \qquad (1)$$

Where $w_q(n)$ is the additive complex white Gaussian noise term of zero mean and variance σ^2, independent among sub channels. At the receiver, the suboptimum detector computes the bit log-likelihood ratios (LLR's) of the transmitted bits, de interleaves and delivers them to the decoder.

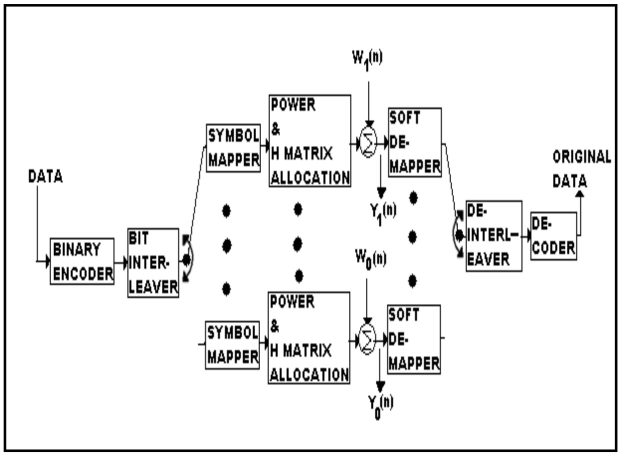

Figure 1: System architecture

According to the irregular modulation and power scheme, we allow the transmission of symbols belonging to different constellations with different allocated power within the same sub channel, and we let this configuration to be different for each sub channel. If more than one constellation is used within a sub channel, the order in which the bits are mapped to them is predefined and, therefore, known at both transmitter and receiver. Let α_{iq} be the fraction of symbols transmitted through the q-th sub channel that belong to constellation $\mathcal{C}_i$, and let p_{iq} be the power allocated to each one of them. According to their definition, these parameters must fulfill:

$$\alpha_{iq} \geq 0, p_{iq} \geq 0 \text{ and}$$

$$\sum_{i=1}^{N} \alpha_{iq} \leq 1 \qquad (2)$$

For q = 1, ...,Q and i = 1, ...,N. If α_{iq} = 0, then constellation $\mathcal{C}_i$ is not employed in the q-th channel. If $\sum_{i=1}^{N} \alpha_{iq} = 0$ then the q-th sub channel is not used and if $0 < \sum_{i=1}^{N} \alpha_{iq} < 1$ then it is used during a fraction of the channel accesses. Note that this formulation can be mathematically seen as a continuous relaxation of the usual bit allocation, in which $\alpha_{iq} \in \{0, 1\}$ (i.e., only one constellation can be used per sub channel).

The objective of this paper is the derivation and analysis of a bit loading and power allocation algorithm that maximizes the mutual information for the system set-up. Using the parameters previously defined, the power allocated to and the MI of the q-th sub channel are obtained as the weighted averages of the individual values for each constellation,

$$P_q = \sum_{i=1}^{N} \alpha_{iq} p_{iq} \qquad (3)$$

$$\overline{I_q} = \sum_{i=1}^{N} \alpha_{iq} I_i \left(p_{iq}\gamma_q\right) \qquad (4)$$

Where $\gamma_q = \left|H_q\right|^2 / \sigma^2$ is a measure of the sub channel reliability (the SNR with unit transmitted power) and $I_i(\mu) = I_i\,(x;LLR(b_1), ..., LLR(b_{mi}))$ is the MI between the transmitted symbols and the corresponding bit LLR's at the demodulator output for the i-th constellation when it is employed in an AWGN channel with SNR μ.

Finally, the total MI averaged over all sub channels is

$$\bar{I} = \frac{1}{Q} \sum_{Q=1}^{Q} \bar{I}_q \qquad (5)$$

and the average constellation size is

$$\eta = \frac{1}{Q} \sum_i \sum_q \alpha_{iq}\, m_i \qquad (6)$$

The optimum bit loading and power allocation is defined as the one that maximizes the MI in (5) with respect to α_{iq} and p_{iq}subject to the constraints in (2) and the average power constraint, that is,

$$\max_{\{\alpha_{iq}\},\{p_{iq}\}} \frac{1}{Q} \sum_{q=1}^{Q} \sum_{i=1}^{N} \alpha_{iq} I_i \left(p_{iq}\gamma_q\right) \qquad (7a)$$

$$\text{S.T.} \qquad \alpha_{iq} \geq 0,\ p_{iq} \geq 0 \qquad i = 1, \ldots, N$$

$$q = 1, \ldots., Q \qquad (7b)$$

$$\sum_{i=1}^{N} \alpha_{iq} \leq 1 \quad q = 1, \ldots\ldots, Q \qquad (7c)$$

$$\frac{1}{Q} \sum_{q=1}^{Q} \sum_{i=1}^{N} \alpha_{iq} p_{iq} \ \leq P_T \qquad (7d)$$

Where, P_T is the maximum available power at transmitter. Introducing the average power allocated per sub channel defined in (3) into these equations, one can observe that the joint optimization of the parameters for all sub channels can be formulated as a two step optimization. The first step is the optimization of the power allocation and bit loading for a single AWGN channel. Let us consider a generic AWGN channel with reliability γ and allocated power P. In this case, we drop the sub index q indicating the sub channel and, therefore, we denote the parameters as α_i and p_i instead of α_{iq} and p_{iq}.

If we introduce the normalized power parameters $p'_i = p_i/P$, then the first optimization can be expressed as a function of the SNR $\mu = P_\gamma$ as

$$\bar{I}_{\circ}(\mu) = \max_{(p'i),(\alpha_i)} \sum_{I=1}^{N} \alpha_i \, I_i(p'_i \, \mu) \qquad (8a)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} \alpha_i \, p'_i = 1 \qquad (8b)$$

together with the inequality constraints (7b) and (7c). The second step consists in the following problem of power allocation over parallel sub channels:

$$\max_{\{P_q\}} \frac{1}{Q} \sum_{q=1}^{Q} \bar{I}_{\circ}\left(\gamma_q P_q\right) \qquad (9a)$$

$$\text{s.t.} \frac{1}{Q} \sum_{i=1}^{N} P_q \leq P_T \qquad (9b)$$

Hence, in the second step no bit loading must be done.

5.Conclusion

This way, the concepts of orthogonal frequency division multiplexing (OFDM) and bit interleaved coded modulation (BICM) in digital transmission system are explained. BICM-OFDM scheme, nearly optimal performance can be achieved by bit loading and power allocation, i.e. assigning a different constellation (number of bits) and different power to each subcarrier and each channel access according to the channel frequency response. BICM-OFDM systems can be employed for performance optimization with channel state information at the transmitter.

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