Block Turbo code modulation for MB-OFDM-based cognitive radio to suppress its side-band interferences

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Abstract

To suppress the side-band interferences caused by multiband orthogonal frequency division multiplexing (MB-OFDM)-based cognitive radio systems, a mathematical expression of the side-band signal is derived. Based on this expression, the constraints among the transmitted symbols, which help to suppress the interferences, are obtained. Combined with the constraints, a type of block Turbo code modulation scheme is proposed. In the modulation scheme, the side-band interferences are attenuated quickly. Compared with other techniques, in this scheme, the interference suppression is implemented more easily and sufficiently. Simultaneously, the bit error rate (BER) performance can be improved. Theoretical analyses and simulation results show that it is highly applicable for MB-OFDM-based cognitive radio systems to suffer from Rayleigh fading.

Keywords  MB-OFDM, cognitive radio, block Turbo code modulation, BER performance

1  Introduction

The idea of applying block Turbo code modulation into MB-OFDM-based cognitive radio systems is has two reasons. One is the BER performance of Turbo coded systems, which can approach Shannon limit because it utilizes the idea of coding randomly [1]. The other is that through designing, the check relationships of block codes can embody the constraints, which help to suppress the side-band interferences caused by cognitive radios. This new idea is originated from the problem that cognitive radio systems are required to resolve, which will be depicted in detail as follows.

To avoid disturbing other narrow band radio services nearby, cognitive systems keep watch over the surrounding radio environment. A type of detect and avoid (DAA) scheme can be used [2]. When a certain range of frequency band is detected being occupied by other services, cognitive radio systems reduce the transmission power on that frequency band. A deep spectral notch will be generated by cognitive radio systems whenever necessary. With this scheme, frequency resources are utilized efficiently and flexibly [3–4].

There has been research on methods of decreasing the interference power on the occupied frequency band. First, the subcarriers of cognitive radio systems on that band should be tuned off. However, this is not enough because the signals of the neighboring subcarriers are attenuated with the form of Sa function. This attenuation rate is not high enough, and the final effect is that the interference power caused by these neighboring subcarriers is still high and consequently cannot reach an acceptable level. To solve this problem, an active interference cancellation (AIC) technique is proposed [5] that inserts two special tones at the edge of interference band. By this method, the interference can be cancelled sufficiently, but the receiver side needs to know the position of AIC tones. Several studies [6–7] make use of the property that the signals generated by two successive subcarriers have nearly equal amplitude, and propose that two symbols with the same amplitude but different positive-negative sign are carried by two successive subcarriers, and thus the interferences can be cancelled effectively. Different from these proposals, in this article, a general interference mathematical expression is presented, and based on the expression, a set of constraints are obtained. Through combining the constraints with Turbo code modulation not only the BER performance of cognitive radio systems is improved but also the side-band interferences in other radio services are suppressed sufficiently. Actually, the adjacent frequency coding scheme in Refs. [6–7] can be regarded as one special case of the analysis.
results in this article.

The remainder of the article is organized as follows. In Sect. 2, the mathematical expression of interferences is derived and the constraint relationships among the transmitted symbols are determined. Based on this result, the designing process of block Turbo code modulation is described through a simple example in Sect. 3. Following that, the BER performance of this scheme is analyzed and simulated in Sect. 4. Finally, conclusions are presented.

2 Constraints to suppress side-band interferences

2.1 Constraints derivation

Orthogonal frequency division multiplexing (OFDM) signal during one symbol period can be described as:

\[ x(t) = x_i(t) + x_q(t) = g_T(t) \sum_{n=0}^{N-1} (a_n \cos(\omega_n t + \phi) + b_n \sin(\omega_n t + \phi)) \]  

(1)

where \( g_T(t) \) is defined as:

\[ g_T(t) = \begin{cases} \sqrt{1/T} & 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases} \]

\( T \) is the period of OFDM symbols. \( a_n, b_n \) represent horizontal and vertical coordinates of one symbol point in a constellation, respectively. As for quadrature phase-shift keying (QPSK), with the unit amplitude, \( a_n, b_n \in \{-1/\sqrt{2}, 1/\sqrt{2}\} \). Parameter \( m \) is the index of subcarriers. \( N \) is the number of subcarriers. \( \omega_p \) is frequency offset. \( \omega_p + \omega_n \) is central frequency of subcarrier. \( \phi \) is the original phase. \( \omega \) is frequency.

Conduct Fourier transform on the in-phase term of Eq. (1) and select the component of positive frequency axis, the following can be obtained:

\[ X_i(j\omega) = \sum_{n=0}^{N-1} a_n \frac{1}{2} \sqrt{T} \sin \left( \frac{\omega - \omega_p - \omega_n}{2} T \right) e^{-j(\omega_p - \omega_n) T} \]  

(2)

With \( \omega_T = (m+1) \times 2\pi \), the absolute value of Eq. (2) is:

\[ |X_i(j\omega)| = \left| \sum_{n=0}^{N-1} a_n \frac{1}{2} \sqrt{T} \sin \left( \frac{\omega - \omega_p - \omega_n}{2} T - (m+1)\pi \right) e^{j(\omega_p - \omega_n) T} \right| \]

\[ = \left| \sum_{n=0}^{N-1} a_n \frac{1}{2} \sqrt{T} \sin \left( \frac{\omega - \omega_p - \omega_n}{2} T \right) \right| \]

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\[ = \left| \sum_{n=0}^{N-1} a_n \frac{1}{2} \sqrt{T} (\omega - \omega_p - \omega_n) \sin \left( \frac{\omega - \omega_p}{2} T \right) \right| \]

\[ \frac{\sum_{n=0}^{N-1} a_n \omega_p^{N-1} - \sum_{n=0}^{N-1} a_n (A - m) \omega_p^{N-2} + \ldots}{\sqrt{T} \prod_{n=0}^{N-1} (\omega - \omega_p - \omega_n)} \sin \left( \frac{\omega - \omega_p}{2} T \right) \]  

(3)

where \( A = \sum_{n=0}^{N-1} m \). Eq. (3) represents the amplitude of the in-phase component. The first multiplying term is the envelope of the sine function. Clearly, if the envelope term can decrease quickly, correspondingly, the side-band power will be attenuated quickly, and thus the interference is suppressed sufficiently. For a single subcarrier signal, the envelope in the frequency domain decreases with the rate of \( 1/\omega_p \). However, if several subcarriers are composed as a whole, the envelope of the composed signal may decrease with the rates of \( 1/\omega_p^2, 1/\omega_p^3, \ldots \).

To explain in detail, as for the envelope term in Eq. (3), the highest power terms in the denominator and numerator are \( \omega_p^N \) and \( \omega_p^{N-1} \), respectively. Hence, when the first term of the numerator is equal to zero, that is,

\[ \sum_{n=0}^{N-1} a_n = 0 \]  

(4)

the highest power term in the numerator becomes \( \omega_p^{N-2} \), then the envelope decreases with the rate of \( 1/\omega_p^3 \). Further, if the second term is also equal to zero: \( \sum_{n=0}^{N-1} a_n (A - m) = 0 \), combined with Eq. (4), the following can be obtained:

\[ \sum_{n=0}^{N-1} a_n (N - m - 1) = 0 \]  

(5)

Then, the highest power term in the numerator becomes \( \omega_p^{N-3} \), as a result, the envelope decreases with the rate of \( 1/\omega_p^4 \). Suppose if the third, fourth terms ... are all equal to zeros, then the envelope will decrease more quickly. However, more constraints are required among the transmitted symbols. The result is similar to the quadrature term of Eq. (3). Fig. 1 illustrates a comparison among the signals with three different attenuation rates.
2.2 Power spectrum density comparison

In this subsection, the power spectrum density (PSD) comparison is presented among the MB-OFDM signals, which are modulated by symbol sequences $a$, $b$, and $c$, respectively. Symbols in sequence $a$ are mutually independent. The constraints will be imposed on the signal symbol sequence $b$ and $c$. Symbols of sequence $b$ and $c$ are divided into many blocks. Each block contains eight symbols. The difference is that each block of symbols in sequence $b$ satisfies the only constraint Eq. (4) and in sequence $c$ satisfies both constraints Eqs. (4) and (5). The MB-OFDM scheme will be taken for an example, which is proposed by MB-Alliance for IEEE 802.15.TG3a. In the scheme, the first subband has the bandwidth of 528 MHz and contains 128 subcarriers. Assume that the frequency band starting from the eightieth subcarrier to the eighty-eighth is occupied by other narrow band radio services, and the corresponding 8 subcarriers, 33 MHz in total, will be tuned off by cognitive radio systems. The simulation results of the average PSD are presented in Fig. 2. Fig. 2(a) shows sequence $a$ after tuning off 8 subcarriers; Figs. 2(b) and (c) are the results of sequence $b$ and $c$, respectively, after tuning off 8 subcarriers.

![Fig. 2](image)

It can be seen from Fig. 2 that:
1) The attenuation rate of side-band signal becomes higher and higher from Figs. 2(a) to (c).
2) As for the frequency notch, the depth does not reach 20 dBm for sequence $a$. However, for the sequences $b$ and $c$, which conform to constraint Eq. (4) and constraints Eqs. (4)–(5), respectively, the depth approximately 40 dBm/MHz and exceeds 40 dBm/MHz correspondingly.

3 Block Turbo code modulation

Turbo encoder consists of two or more component encoders. A group of information bits and its interleaved version are sent into the component encoders. The outputs from these encoders are combined together as the final encoded bits. In this article, the Turbo code idea is applied into the modulation scheme. The objects dealt with are not bits but signal symbols.

3.1 Description of product code modulation

Product code can be regarded as one type of block Turbo code. First, a train of 0, 1 bits are mapped into signal symbols. Then, the symbols are sent into a check-symbol generator. The outputs are the corresponding check-symbols for a block of information-symbols, as Fig. 3 shows. Finally, the information-symbols, the row and column check-symbols form a block of coded symbols.

![Fig. 3](image)

Fig. 4 illustrates the structure of a block of symbols. The information-symbols and the generated check-symbols satisfy the constraint relationship Eq. (4) or both Eqs. (4) and (5), and thus through this code modulation scheme, two aims are achieved, that is, improvement of BER performance and side-band interferences suppression.
3.2 Check relationship design

In this subsection, the design process of product codes is described through a simple example with eight symbols in one block. They are four information-symbols and four check-symbols. QPSK modulation scheme is utilized, and the average symbol energy is equal to 1. Fig. 5 shows the relationships among these symbols. For this equation, the parameter values cannot be uniquely determined. Here, let $p = -1/2, q = -1/2, p_1 = -1/2, q_1 = -1/2, p_2 = -1/2$. To have the average symbol energy equal to 1, through calculation, a value of $\sqrt{3}/2$ should be multiplied with each symbol. Then, $\sqrt{3}a_0/2, \sqrt{3}a_1/2, \sqrt{3}a_2/2, \sqrt{3}a_3/2, a_4$ are information-symbols, $a_5 = -\sqrt{3}(a_0 + a_2)/4, a_6 = -\sqrt{3}(a_1 + a_3)/4$ are row check-symbols, and $a_7 = -\sqrt{3}(a_0 + a_1)/2, a_8 = -\sqrt{3}(a_2 + a_3)/2$ are column check-symbols.

If a higher rate of $1/\omega^2$ is required, the constraint Eq. (5) needs to be satisfied further. Substitute Eqs. (6)–(9) into Eq. (5) and the following can be obtained:

$$\frac{1}{4} + \frac{K L}{4N_0}\sum_{i=1}^{L} \exp \left( -\frac{K \overline{E}_s |x_i - \hat{x}_i|^2}{4N_0} \right) \leq 1$$

(12)

where $x_i, \hat{x}_i$ are symbols, $\overline{E}_s$ is the symbol energy averaged over fading amplitude, $K$ is the ratio of signal energy between the direct and scattered components. As $K = \infty$, which is corresponding to AWGN channels.
Eq. (12) can be rewritten as:

$$P(x \to \hat{x}) \leq \exp \left( -\frac{E_s}{4N_0} \sum_{i=1}^{L} |x_i - \hat{x}_i|^2 \right)$$

(13)

and $K = 0$ is corresponding to Rayleigh channels, then Eq. (12) can be rewritten as:

$$P(x \to \hat{x}) \leq \prod_{i=1}^{L} \frac{1}{1 + \frac{E_s}{4N_0} |x_i - \hat{x}_i|^2}$$

(14)

and 0 is corresponding to Rayleigh channels, then

According to these expressions, the following conclusions can be drawn:

1) Over AWGN channels, based on Eq. (13), the BER performance is guided by the minimum squared Euclidean distance.

2) Over Rayleigh channels, based on Eq. (14), the BER performance is guided by the smallest number of symbols (donated as $L_{\text{min}}$) at nonzero Euclidean distance between two symbol sequences. It is also guided by the product $P$ of these distances.

3) Over general Rician channels, it is guided by the minimum squared Euclidean distance, $L_{\text{min}}$ and $P$.

Based on these conclusions, when the average symbol energy is unchanged, the following can be seen:

1) As for AWGN channels, the minimum Euclidean distance is the essential factor for the performance. The curve II in Fig. 6(a) is very close to curve III because the minimum distance is not increased even though the proposed code modulation scheme is adopted in the system. Compared with curve I, the performance represented by curve III is improved, which is attributed to the enlarged minimum distance by the code modulation scheme.

2) As for Rayleigh fading channels, the dominant parameter is $L_{\text{min}}$. As it becomes larger from the original value of 1 to the value of 5 (corresponding to curve I) or 3 (corresponding to curve II), the performance is improved remarkably, as shown in Fig. 6(b). BER decreases quickly with the increase of signal-to-noise ratio (SNR). It is for this reason that the upper bound decreases with the $L_{\text{min}}$th power of SNR, as can be seen from Eq. (14).

3) While for general Rician channels, the performances are between the upper two results, as shown in Fig. 6(c).

Similar to the presented example, a much larger symbol block can be used and more check-symbols can be generated so that the BER performance can be further improved. At the same time, with more constraint conditions satisfied, the side-band interferences can be attenuated more quickly.

5 Conclusions

Cognitive radios need to suppress the interferences in other protected narrow band radio services sufficiently and easily. However, because of the existence of side-band power, the only measure of tuning off the subcarriers on the occupied frequency band is not enough. To resolve this problem, the mathematical expression of side-band signal, which is generated by neighboring subcarriers, is derived. Based on this expression, the constraints satisfied to decrease the side-band interferences are obtained. Following these, a type of block Turbo code modulation scheme combined with these constraints is proposed. With this joint design, the BER performance is improved, and simultaneously, the requirement of suppressing side-band interferences is satisfied. Besides, simulation results and theoretical analyses of the BER performance show that the scheme is more effective for signals suffering from fading channels than that of AWGN channels.
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References


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