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Performance of a frequency-domain OFDM-frame detector[☆]

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ABSTRACT

A frequency-domain algorithm for orthogonal frequency-division multiplexing (OFDM)-frame detection is considered useful when the OFDM system is to operate in a known narrowband interference (NBI) channel, e.g., in a cognitive radio OFDM-based overlay system. While frame detection algorithm based on state-of-the-art time-domain correlation perform poorly in such a channel, we propose a frame detection algorithm based on energy detection in frequency domain. By exploiting the NBI band information obtained during sensing period, the proposed algorithm exhibits strong performance and outperforms other existing frequency-domain OFDM frame detection alternatives even at the signal-to-interference ratio (SIR) below 0 dB. Moreover, simulation results are confirmed by the analytical performance presented as a linear combination of the incomplete gamma function. The weight of each component is a function of the eigenvalues of the matrix associated with the detection metric and the number of summation is proportional to the number of non-zero eigenvalues of the matrix associated with the detection metric.

1. Introduction

Recently, there has been a considerable interest to improve existing spectrum band utilization based on the concept of cognitive radio (CR): sensing the existing spectrum environment, and adapting the signal transmission to the sensing results [1–4] so as not to interfere with other users. In the mean time, the Federal Communications Commission (FCC) has proposed an open spectrum policy allowing secondary users (SUs) to opportunistically access the spectrum bands licensed to primary users (PUs) [5]. CR network is recognized as a promising technology to mitigate spectrum shortage problems in smart grid [6], smart home and the Internet of Things (IoT) [7] applications. Among many CR-based technologies, orthogonal frequency-division multiplexing (OFDM)-based overlay technique [8] is considered a very interesting approach in CR to permit OFDM-based SUs to transmit signals simultaneously with the PUs. With this approach, the SUs can avoid interfering with the PUs by transmitting data only over a portion of subcarriers where the PUs' signal does not exist.

One of the major obstacles to successful implementation of the OFDM-based overlay technique is the problem of signal acquisition by the OFDM receivers of SUs in the presence of narrowband interference (NBI) due to the PUs. Signal acquisition is required to reliably detect the presence of a data frame, and to estimate the transmission signal parameters, e.g., timing and frequency offsets between the transmitter and the receiver, necessary for reliable detection of the frame data. We have proposed a frequency-domain algorithm for timing-offset estimation [9], which partly solves the signal acquisition problem as it presumes that timing offset estimation is performed after presence of a data frame is declared by a hypothetical frame detector. For OFDM frame detection problem, it has been shown in [10,9] that state-of-the-art time-domain correlation-based frame detection schemes such as [11] are severely vulnerable to NBI. In [12], OFDM frame detection in the discrete Fourier transform (DFT) domain is investigated. Despite its strong performance at low SIR, its performance deteriorates at high SIR due to its reliance on retrieving over-estimated sets of parameters such as NBI variances as suggested by [12]. We are interested in a frame detection algorithm based on energy detection of signal in DFT domain. Our algorithm has a very interesting feature that it can exploit uncooperative sensing results obtained by the receiver itself during the sensing period. With NBI information, the algorithm can mitigate the contribution of NBI on particular frequency bins through a set of weighting coefficients constituting a window of contiguous passband and stop-band. In this paper, the algorithm is proposed and its performance is analyzed for quasi-static frequency-selective Rayleigh fading channels with Gaussian NBI assuming an environment of a wireless local area network (WLAN). Through appropriate parameter settings

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1 All research data presented in this manuscript is available at https://www.dropbox.com/sh/5f79e81ue1pe07n/AAApR0gSAxwMBI_3Ee_guldAa?dl=0.

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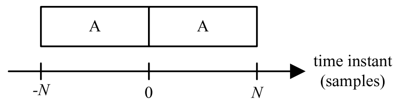

Fig. 1. Preamble content for frame detection.

considering practical CR use-cases in WLAN, the proposed algorithm exhibits strong performance without implementing coarse frequency estimate. We investigate the impact of several parameters such as NBI bandwidth, SIR, signal-to-noise ratio per active subcarrier (SNRPC) and weighting coefficients on the performance of our proposed system. In addition, the performance of our system outperforms other existing frequency-domain OFDM frame detection systems even at low SIR. Simulations results are confirmed using the numerical ones presented as a linear combination of the incomplete gamma function. The weight of each component is a function of the eigenvalues of the matrix associated with the detection metric and the number of summation is proportional to the number of non-zero eigenvalues of the matrix associated with the detection metric.

2. The frame detection algorithm

The algorithm computes a detection metric from N-point DFT of the input signal, compares the metric with a threshold, and declares presence of a frame if the metric is greater than the threshold. To keep the computational complexity at acceptable level, the metric computation is performed only once for every new window of N input samples, assuming the sampling rate is $N\Delta f$ where Δf is the OFDM subcarrier spacing. Suppose X_k's, $0 \le k \le N-1$, are the N-point DFT associated with the detection metric of a window. Then the detection metric is computed by

$$Y = \sum_{k=0}^{N-1} w_k |X_k|^2, \tag{1}$$

where w_k's are non-negative weighting numbers introduced for controlling the contribution of involved subcarriers that would be useful in combating NBI. In this paper, w_k will be set to zero if k corresponds to a subcarrier that is known from the design of preamble to be null or known from the spectrum sensing results to be corrupted by NBI, otherwise it will be set to one. Because the detection metric is computed only once for every new window of N input samples, the preamble of the OFDM frame is assumed to contain at least two identical N-sample symbols as shown in Fig. 1 to ensure that a detection window will capture the signal provided by the preamble.

3. Performance evaluation

3.1. Analysis

Note that, when the detection window could capture the signal provided by the preamble, X_k would be composed of three statistically independent terms contributed by the preamble, NBI, and additive white Gaussian noise (AWGN),

$$X_k = S_k + I_k + Z_k, \tag{2}$$

where S_k, I_k, and Z_k are the contributions of respectively the preamble, NBI, and AWGN. Hence, we will first discuss the model of each contribution in subsequent. We justify our model through simulation as presented in Section 3.2. Finally, based on the model we show how the detection performance in terms of the probability of missed detection and the probability of false alarm may be computed.

In modeling S_k, according to Fig. 1, the preamble for frame detection is provided by two identical copies of a symbol denoted as symbol A which are set over the time instants from $-N$ to $N-1$. Then, depending on the timing offset t_o between the transmitter and receiver ($t_o \in \mathbb{R}, 0 \le t_o \le N-1$), S_k would be obtained from N samples of the received signal from time instants $-t_o$ to $N-1-t_o$, and it may be expressed by

$$S_k = \hat{S}_k e^{-j2\pi k t_o/N}, \tag{3}$$

where

$$\hat{S}_k = \sum_{l=0}^{N-1} H_l A_l \frac{\sin(\pi\epsilon)}{N \cdot \sin(\pi(l-k+\epsilon)/N)} \cdot e^{j\pi\epsilon(N-1)/N} e^{-j\pi(l-k)/N}. \tag{4}$$

A_l's and H_l's, $0 \le l \le N-1$, are the N-point DFTs of respectively the symbol A and the channel impulse response where $|A_l| = 1$. ϵ is the carrier frequency offset (CFO) normalized to the subcarrier spacing. It may be noted that (3) is only exactly correct for $0 \le t_o \le N-L$, where L is the length of the channel impulse response which is generally much less than N. Hence, as actually $0 \le t_o \le N-1$, (3) could only be considered as an approximation for simplicity. H_l can be written as

$$H_l = \sum_{n=0}^{L-1} h_n e^{-j2\pi ln/N}, \tag{5}$$

where h_n is the nth sample of the channel impulse response. For a quasi-static frequency-selective Rayleigh fading channel, h_n's are independent zero-mean complex Gaussian random variables (ZMCG-RVs), i.e. H_k is a weighted sum of independent ZMCG-RVs.

The NBI is modeled as generated by passing a complex white Gaussian noise process (each sample has unit variance for both real and imaginary parts, i.e., the mean square of the complex sample equals two) through a fixed narrowband filter. Hence, I_k is also a weighted sum of independent ZMCG-RVs. Noting that Z_k's are independent ZMCG-RVs, we can then express (2) as a weighted sum of independent ZMCG-RVs. However, more conveniently, X_k's can be accordingly expressed in matrix form as

$$\mathbf{X} = [\mathbf{g}_{S\epsilon}\ \mathbf{g}_I\ \mathbf{g}_Z]\mathbf{V}, \tag{6}$$

where $\mathbf{X} = [X_0\, X_1\, ..\, X_{N-1}]^T$ with $(\cdot)^T$ denoting the matrix transpose, $\mathbf{V} = [V_0\, V_1\, ..\, V_{L+M+2N-2}]^T$ with M being the length of the impulse response of the narrowband filter generating the NBI and V_n's being independent ZMCG-RVs with $E[|V_n|^2] = 2$. Given ϵ, $\mathbf{g}_{S\epsilon}$ is a $N \times L$ constant matrix

$$\mathbf{g}_{S\epsilon} = \text{diag}(\mathbf{FPF}^H\mathbf{A})\mathbf{g}_S \tag{7}$$

where $\mathbf{A} = [A_0, A_1, \ldots, A_{N-1}]^T$. $\mathbf{F}$ is an $N \times N$ DFT matrix where $\mathbf{FF}^H = \mathbf{I}_N$ and $\mathbf{I}_N$ is the $N \times N$ identity matrix. $\mathbf{P} = \text{diag}([1, \exp(j2\pi\epsilon/N), \ldots, \exp(j2\pi\epsilon(N-1)/N)]^T)$. diag($\mathbf{x}$) is a diagonal matrix with the column vector $\mathbf{x}$ on its diagonal and $(\cdot)^H$ denotes the matrix conjugate and transpose. $\mathbf{g}_S$ is an $N \times L$ constant matrix representing the weights associated with contribution of H_l's. $\mathbf{g}_I$ is a $N \times M + N - 1$ constant matrix representing the weights associated with contribution of I_k's, and $\mathbf{g}_Z$ is a $N \times N$ diagonal matrix with all the diagonal elements having the same value representing the weights associated with contribution of Z_k's. The values of $\mathbf{g}_S$, $\mathbf{g}_I$, and $\mathbf{g}_Z$ may be summarized as follows. Firstly, the element at pth row $(1 \le p \le N)$ and qth column $(1 \le q \le L)$ of $\mathbf{g}_S$ is expressed as

$$\mathbf{g}_S(p, q) = \sqrt{E[|h_{q-1}|^2]/2}\, e^{-j2\pi(p-1)(q-1)/N}. \tag{8}$$

Secondly, the pth row of $\mathbf{g}_I$ may be expressed by

$$\mathbf{g}_I(p, :) = [h^i_{M-1}\ h^i_{M-2}\ ..\ h^i_0] * [1\ e^{\frac{-j2\pi(p-1)}{N}}\ ..\ e^{\frac{-j2\pi(p-1)(N-1)}{N}}] \tag{9}$$