

Spectral Signatures and Interference of 802.11 Wi-Fi Signals with Barker Code Spreading

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Abstract—This paper characterizes interference in 802.11 Wireless Fidelity (Wi-Fi) systems that utilize Barker codes as spreading sequences. Particularly, detailed spectral analyses are performed. These studies result in exact power spectral densities (PSDs) for 1 Mbps and 2 Mbps signaling schemes that define their spectral signatures. Investigation of the leakage of interference power into adjacent 802.11 channels, which can be useful for the deployment of cognitive radios, is presented. The theoretical and computer simulation results for the Wi-Fi signal PSDs are verified through experimental measurements and emulation.

Keywords—802.11; PSD; Wi-Fi; spectral signature; Barker code.

I. INTRODUCTION

Wireless communication networks have become ubiquitous in the 21st century. Applications of audio, video, and multimedia have fueled the growth of high-speed Wireless Local Area Networks (WLANs). Such networks are regularly deployed in government, military, industrial, and educational settings. WLANs are now found in many urban and rural environments including residences. For example, Wireless Fidelity (Wi-Fi) networks are commonly found in coffee shops, libraries, and shopping malls.

Wi-Fi networks operate in the unlicensed Industrial, Scientific, and Medical (ISM) bands and are regulated by IEEE 802.11 Standards [1]. These standards were implemented to provide reliable and secure wireless connectivity at high data rates. However, the abundance of Wi-Fi networks in the ISM bands in geographical proximity creates a multitude of problems.

One of the ISM bands allocated by the Federal Communications Commission (FCC) is in the 2.4 GHz range. A host of Wi-Fi equipment such as access points, wireless laptops, Personal Digital Assistants (PDAs), and Bluetooth [2] devices intentionally operate in this band. In addition, commercial devices not intended for Wi-Fi communications, like microwaves ovens, cordless phones, and sulfur lamps, also operate in this band. The radiated electromagnetic Radio Frequency (RF) signals they produce act as interference to Wi-Fi users. The composite interference from intentional Wi-Fi transceivers and unintentional emitters results in reduced network performance, even to the extent of a loss of connectivity.

Currently, there exist a variety of techniques to mitigate the effects of interference. For example, to limit out-of-band power, which is a source of adjacent channel interference, the FCC has specified a spectral mask [1]. Additionally, selecting appropriately spaced ISM carrier frequencies for minimal spectral overlap also alleviates adjacent channel interference. In a user-rich environment, these methods are insufficient to provide reliable high-speed communications. Hence, it is important to explore other methods to reduce interference that requires characterization of the radiated signals, temporally, spectrally, and spatially. With the advent of inexpensive sensor networks, the use of cognitive radio [3] becomes a viable communication technique. Herein, the objective is to exploit the “white space” in a multidimensional communication channel.

This paper emphasizes the spectral signatures of the basic 1 Mbps and 2 Mbps 802.11 signals, providing an exact Power Spectral Density (PSD) analysis and computation of adjacent channel interference power. The 802.11 Standard [1] specifies Differential Binary Phase Shift Keying (DBPSK) for 1 Mbps data and Differential Quadrature Phase Shift Keying (DQPSK) for 2 Mbps transmission. Both use an 11-chip Barker code sequence to spread the main lobe RF bandwidth to 22 MHz. In this work, the theoretical PSDs of these 802.11 signals are derived and compared with both simulated and experimental spectra. Adjacent channel interference power for these two 802.11 signals is also investigated.

The paper is organized as follows. Section II contains the spectral analysis of the 1 Mbps 802.11 signal. The spectral analysis of the 2 Mbps 802.11 signal is developed in Section III. Experimental results are included in Section IV for both data rates. Interference power results are presented in Section V. Conclusions are detailed in Section VI.

II. SPECTRAL ANALYSIS OF A 1 MBPS 802.11 DBPSK SIGNAL

An exact analytic expression for the PSD of a DBPSK 802.11 signal with Barker code spreading can be obtained by starting with 1 Mbps random binary data, $x(n) \in \{-1, +1\}$, that is independent and identically distributed (i.i.d.). The data is differentially encoded to yield

$$y(n) = x(n) \oplus y(n-1) = x(n) \cdot y(n-1) \quad (1)$$

It is easy to show that $y(n) \in \{-1, +1\}$ is identically distributed (i.d.) and uncorrelated binary data. The continuous time signal, $y(t)$, can be represented as

$$y(t) = x(t) \cdot y(t-T) , \quad (2)$$

where $x(t)$ is the continuous time data signal and $T = 1/R$ is the duration of the data pulse.

The differential data is spread with an 11-chip Barker code sequence,

$$\underline{b}_T = [b_j] = [+1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1] . \quad (3)$$

The Barker symbol can be expressed as

$$b_T(t) = \sum_{j=-5}^5 b_j \cdot p(t - jT_c) , \quad (4)$$

where the chip interval $T_c = 1/R_c = T/11$, and $p(t)$ is a unit amplitude rectangular pulse over the interval $[-T_c/2, T_c/2)$. The baseband spread data signal can now be formulated as

$$v(t) = \sum_{n=-\infty}^{\infty} y(n) \cdot b_T(t - nT) . \quad (5)$$

Observe that $v(t)$ is a pulse amplitude modulated signal with amplitudes $+1$ and -1 and is a zero-mean cyclostationary random process. Consequently, its PSD is given as [4]

$$S_v(f) = \frac{\sigma_y^2}{T} |B_T(f)|^2 , \quad (6)$$

where σ_y^2 is the variance of $y(n)$ and $B_T(f)$ is the Fourier transform of the Barker symbol, $b_T(t)$. After some algebraic manipulation, one obtains

$$|B_T(f)|^2 = T_c^2 \left(\frac{\sin \pi f T_c}{\pi f T_c} \right)^2 \left[11 - 2 \sum_{i=1}^5 \cos(4\pi i f T_c) \right] , \quad (7)$$

and finds that σ_y^2 equals unity.

The transmitted RF signal carrying 1 Mbps data can be written as

$$\phi_1(t) = \sqrt{2} \cdot v(t) \cdot \cos(2\pi f_c t + \theta) , \quad (8)$$

where f_c is the carrier frequency of an 802.11 channel and θ is an independent uniform phase random variable in the range $[-\pi, \pi)$. Modulating a carrier with amplitudes $+1$ and -1 from the differential data, $y(n)$, results in the desired DBPSK signal. The power in $\phi_1(t)$ is 1 watt, conforming to the maximum allowed by the IEEE Standard. The PSD of the 1 Mbps Barker code spread DBPSK signal in (8) is given by [5]

$$S_1(f) = \frac{1}{2} [S_v(f - f_c) + S_v(f + f_c)] . \quad (9)$$

An exact analytic expression for the PSD of a 1 Mbps 802.11 signal results from (6), (7), and (9) with $\sigma_y^2 = 1$. The analytic PSD is plotted in Fig. 1, where a nominal carrier

frequency of 110 MHz is used. This value of the carrier frequency facilitates efficient computer simulation. Observe that the 1 Mbps 802.11 PSD is characterized by notches spaced by 5.5 MHz, allowing for easy spectral identification of this signal and the main lobe bandwidth is 11 MHz, as expected. Computer simulation of $\phi_1(t)$ was performed using MATLAB[®] and the Welch PSD [6] computed. The simulated PSD is plotted in Fig. 2, clearly confirming the analytic result. These spectral signatures are shown without the required 802.11 frequency mask. In Section IV, the simulated spectrum with the frequency mask is compared with the experimental measurements.

III. SPECTRAL ANALYSIS OF A 2 MBPS 802.11 DQPSK SIGNAL

The 802.11 Standard specifies DQPSK for transmission of 2 Mbps data, using the same 11-chip Barker code sequence specified in Section II to again spread the main lobe RF signal bandwidth to 22 MHz. The spectral signature of this DQPSK signal is developed in this section via an exact analysis and computer simulation. The 802.11 DQPSK signal can be expressed in compact form as

$$\phi_2(t) = \sum_{n=-\infty}^{\infty} \sqrt{2} \cdot \cos(2\pi f_c t + \alpha(n) + \theta) \cdot b_T(t - nT) , \quad (10)$$

where $\alpha(n)$ is the discrete-time quaternary phase signal at 1 M symbols/second and all other terms are detailed in Section II. The phase signal is defined as

$$\alpha(n) = \alpha(n-1) + \Delta\alpha(n) , \quad (11)$$

where two bits of data are encoded into the four valued differential phase, $\Delta\alpha(n)$, providing for 2 Mbps data transmission. In this development, $\alpha(n) \in \{\pm\pi/4, \pm3\pi/4\}$ and $\Delta\alpha(n) \in \{0, \pi/2, \pi, 3\pi/2\}$. As in DBPSK case, the power in $\phi_2(t)$ is again set to 1 watt.

The DQPSK signal in (10) can be written in quadrature transmission form as

$$\phi_2(t) = p(t) \cdot \cos(2\pi f_c t + \theta) + q(t) \cdot \sin(2\pi f_c t + \theta) , \quad (12)$$

where the in-phase and quadrature signals are given by

$$p(t) = \sum_{n=-\infty}^{\infty} \sqrt{2} \cdot \cos(\alpha(n)) \cdot b_T(t - nT) , \quad (13a)$$

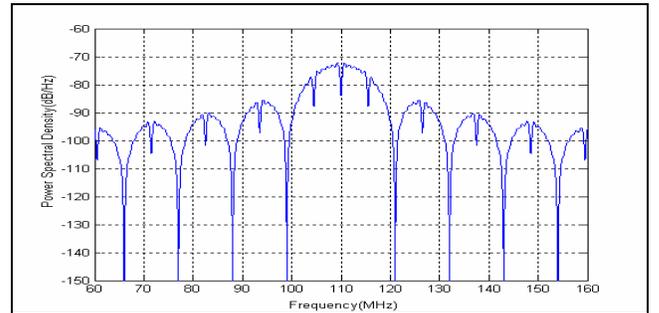


Figure 1. Analytical PSD of the Barker spread 802.11 signal without mask

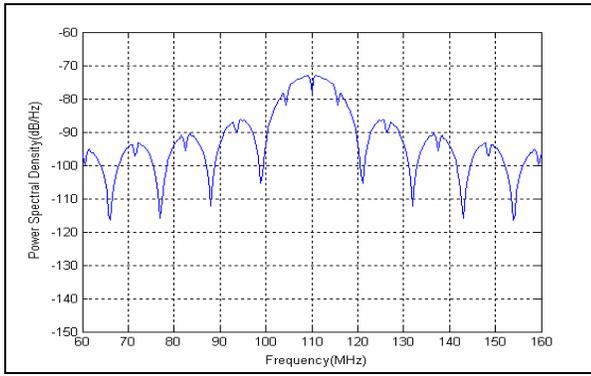


Figure 2. Simulated PSD of the Barker spread 802.11 signal without mask

and

$$q(t) = \sum_{n=-\infty}^{\infty} -\sqrt{2} \cdot \sin(\alpha(n)) \cdot b_r(t-nT), \quad (13b)$$

respectively. With the values of $\alpha(n)$ used in this development, $\sqrt{2} \cdot \cos(\alpha(n))$ and $-\sqrt{2} \cdot \sin(\alpha(n))$ evaluate to be +1 and -1, and both $p(t)$ and $q(t)$ are characterized exactly as $v(t)$ in (5). Thus, we can conclude that their PSDs are identical, i.e., $S_p(f) = S_q(f) = S_v(f)$, and given by (6) and (7) with $\sigma_p^2 = \sigma_q^2 = \sigma_v^2 = 1$.

The PSD of the DQPSK bandpass random process in (12) is obtained from its autocorrelation function, $R_2(\tau)$, given by

$$\begin{aligned} R_2(\tau) &= E[\phi_2(t)\phi_2(t+\tau)] \\ &= \frac{1}{2}[R_p(\tau) + R_q(\tau)]\cos(2\pi f_c \tau) \\ &\quad + \frac{1}{2}[R_{pq}(\tau) - R_{qp}(\tau)]\sin(2\pi f_c \tau), \end{aligned} \quad (14)$$

where $R_p(\tau)$ and $R_q(\tau)$ are the autocorrelation functions of $p(t)$ and $q(t)$, respectively, while $R_{pq}(\tau)$ and $R_{qp}(\tau)$ are crosscorrelation functions of $p(t)$ and $q(t)$. It is straightforward to show that the term $[R_{pq}(\tau) - R_{qp}(\tau)]$ is zero for the DQPSK data used in this discussion. In addition, $R_p(\tau)$ and $R_q(\tau)$ are identical since their PSDs are the same. Thus, the autocorrelation function of $\phi_2(t)$ reduces to

$$R_2(\tau) = R_p(\tau) \cdot \cos(2\pi f_c \tau), \quad (15)$$

and the PSD of the 2 Mbps 802.11 DQPSK signal is given by

$$S_2(f) = \frac{1}{2}[S_p(f - f_c) + S_p(f + f_c)]. \quad (16)$$

Analytically, it is found that the spectral signature of the 1 Mbps and the 2 Mbps 802.11 signals are identical, and plotted in Fig.1 with a carrier frequency of 110 MHz. An independent MATLAB[®] computer simulation of the DQPSK signal, $\phi_2(t)$, was performed with random data and the Welch PSD computed. The resulting spectrum is identical to that displayed in Fig. 2 corroborating the exact theoretical analysis.

IV. EXPERIMENTAL RESULTS WITH BARKER SPREAD 802.11 SIGNALS

The work described herein follows a three-pronged approach using theoretical analysis, computer simulation, and experimental measurements and emulation. The radiated 802.11 signal with Barker spreading must adhere to the PSD mask defined in the standard, that is, -30 dBc for frequencies 11 MHz to 22 MHz offset from f_c , and -50 dBc for frequencies greater than 22 MHz offset from f_c . The spectrum of the simulated 802.11 signal with Barker spreading is attenuated to satisfy the mask requirement and then a gain of 1.106 is applied to maintain the transmitted power at 1 watt. The resulting simulated PSD with the mask and the gain is shown in Fig. 3.

The transmission from a WLAN access point was received with a dipole antenna and applied to a down converter from 2.4 GHz to 144 MHz. The PSD was then measured with an HP8568B spectrum analyzer and plotted to reflect channel 6 of the 2.4 GHz 802.11 band. This is shown in Fig. 4. These experimental measurements were consistent for DBPSK (1 Mbps) and DQPSK (2 Mbps). They exhibit the notches, the main lobe bandwidth and the spectral shape found theoretically and via computer simulation.

The Barker spread 802.11 signals were also verified through experimental emulation using a Telecommunications Instructional Modeling System (TIMS) from Emona Technologies, LLC [5]. The emulation was performed at audio rates: 1 kHz for random binary data, 11 kHz for the Barker sequence, and 50 kHz for the carrier frequency. The emulated DBPSK and DQPSK PSDs were measured with a SR760 spectrum analyzer. The baseband Barker spread PSD is

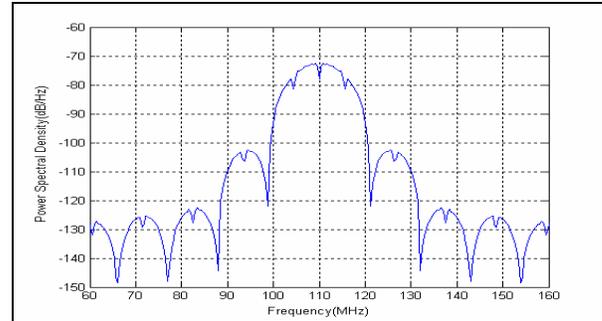


Figure3. Simulated PSD of the Barker spread 802.11 signal with mask and gain

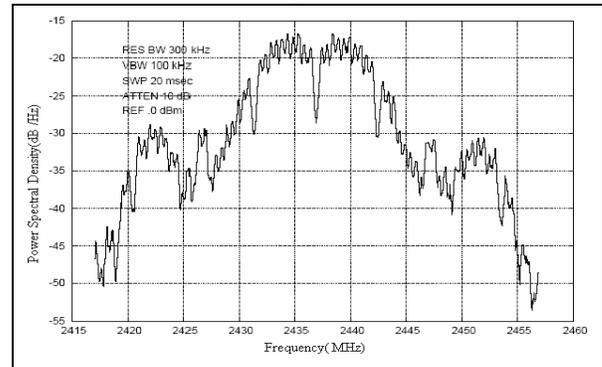


Figure 4. Experimental PSD of the Barker spread 802.11 signal

displayed in Fig. 5 and is compared to the simulated PSD before masking shown in Fig. 2 for frequencies above 110 MHz. The agreement is remarkable, comparing notch locations as well as their depth and the main lobe bandwidth.

V. INTERFERENCE FROM ADJACENT 802.11 CHANNELS

The basic 802.11 Standard dictates 5 MHz spacing between channels. In the 2.4 GHz ISM band, the first channel is at 2412 MHz. The channels are numbered sequentially from 1 up to 11 in North America and up to 13 in Europe. The main lobe of the Barker spread 802.11 signals do not overlap for channels 1, 6, and 11. However, an 802.11 transceiver is free to operate at any carrier frequency specified in the standard. Since the PSD has multiple sidelobes, there will always be some interference power in the 22 MHz main lobe RF signal bandwidth regardless of how far an adjacent channel is offset from the nominal RF data signal channel.

Let the nominal RF data signal channel be number 1 and assume that an interfering signal is in proximity to RF data receiver. The interference power from an 802.11 Barker spread signal in channels 1 to channel 11 is computed using the theoretical PSD and the results are shown in Fig. 6 with three curves. Note that the lower two curves overlap significantly. The upper curve is the interference power from the theoretical PSD in a 22 MHz bandwidth where the carrier frequency is varied from channel 1 through channel 11 with no spectral mask. The lower curves represent the interference power in a 22 MHz bandwidth from the theoretical PSD (1) with the 802.11 mask, and (2) with a gain of 1.106 to bring the radiated power back to 1 watt after the 802.11 mask.

Observe from Fig. 6 that the lower curves are virtually identical. This indicates that the interference power is the same after the mask with or without the gain that returns the transmitted power to 1 watt. This observed characteristic is important when applying power to spectral management and cognitive radio strategies. Also included in Fig. 6 is an interference temperature [8] scale, computed by dividing the interference power by $B \cdot k$, where $B = 22$ MHz is the bandwidth and k is the Boltzmann's constant. It has been suggested [8] that this metric can provide a measure of reliability of a WLAN if it is known over space, time, and frequency scales.

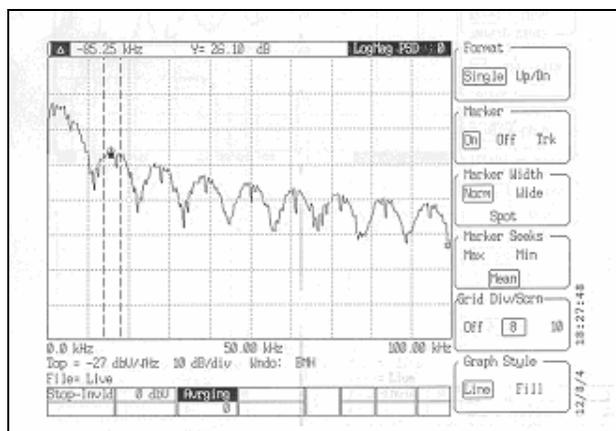


Figure 5. Emulated PSD of the Barker spread 802.11 signal at baseband

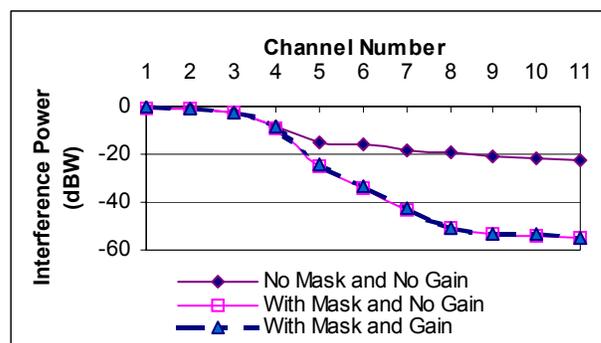


Figure 6. Interference power in adjacent 802.11 channels

One can also modify the interference power results shown in Fig. 6 to include loss over a distance, d , using the factor $(d_0/d)^\gamma$ [9] for distance longer than a reference distance d_0 , dictated by the antenna type. The path loss exponential γ ranges from 2 to 6 depending on the environment [9].

VI. CONCLUSIONS

An exact analytic expression has been derived for Barker spread 802.11 signals showing that the spectral signature is the same for the 1 Mbps DBPSK and the 2 Mbps DQPSK formats. This signature exhibits both the spectral notches spaced by 5.5 MHz and the expected 22 MHz main lobe bandwidth. Computer simulations, experimental measurements, and system emulation bear out these definitive characteristics that allow for confident identification of the basic 802.11 signals.

The interference power from adjacent 802.11 channels that are spaced by 5 MHz has been computed starting with the concurrent channel 1 and ending with channel 11. It was found that the interference power is virtually the same after the spectral mask, with and without the gain. This interference metric can be applied to spectral management and cognitive radio networks.

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