BLIND SIGNAL DETECTION AND IDENTIFICATION OVER THE 2.4GHz ISM BAND FOR COGNITIVE RADIO

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ABSTRACT

In this article, a novel spectrum awareness engine is proposed that can be integrated in cognitive radios. Since characterization of the interfering signal will help with overcoming their effects, blind signal detection is described in the proposed engine. The proposed engine is intended for the ISM band. A study of the major ISM band wireless standards is been performed, and the main key identifying features of each standard is marked. A feature detector for different wireless standards is proposed. Finally a decision making process is proposed to utilize all the detected features before making the decision of the detected signal identity.

1. INTRODUCTION

There is growing interest towards providing broadband communication with high bit rates and throughput, especially in the Industrial Scientific Medical (ISM) band, as it was an ignition of innovation triggered by the Federal Communications Commission (FCC) to provide, to some extent, a regulation-free band that anyone can use. But with such freedom comes the risk of interference and more responsibility to avoid causing it. Therefore, the need for accurate interference detection and identification, along with good blind detection capabilities are inevitable. Since cognitive radio (CR) is being adopted widely as more researchers consider it the ultimate solution for efficient spectrum sharing [1], it is reasonable to study the CR in the ISM band [2].

Due to the need of a peaceful coexistence between wireless users, the FCC began to encourage innovation and to enhance spectrum usage, which began with the ISM band. Cognitive radio has the ability to sense, adapt and learn to overcome environment changes and possible interference [3]. The biggest challenges with CR are the ability to identify the existence of the primary users and avoid interfering with them or with other CRs. To have this ability, CR needs to constantly sense the spectrum and identify possible wireless users, and based on the identification result, make the appropriate decision to overcome their effect as interference. Since signal identification and interference will be the core concerns [4], [5], we will describe a novel approach for a CR spectrum awareness engine, which will be essential to design more efficient ISM band transceivers.

2. COGNITIVE RADIO AND THE PROPOSED MODEL

From the early dawn of the wireless communications era, engineers realized the importance of utilizing the spectrum to increase the number of users and provide better quality of service. In the Spectrum Policy Task Force (SPTF) released report 2002 [6], the SPTF demonstrated that the current usage for the spectrum is not very efficient and recommended regulations for the efficient use of the spectrum. CR is being widely adapted, as many researchers look to it as the ultimate solution for efficient spectrum sharing [3], [7]-[12].

In 1999 Mitola described the CR's capabilities of interacting with the outside world through cognition cycle [7]. In 2005 a simplified cognitive cycle was proposed by Haykin [3], where the focus is on three basic units: Spectrum sensing unit, channel identification unit, and dynamic spectrum managements unit. In 2008 a novel CR model was proposed [13]. This model describes a CR transceiver that consists of four engines: Cognitive engine, spectrum awareness engine, location awareness engine, environment awareness engine to handle the frequency spectrum usage, and efficiency.

A brief literature scan shows that there are a number of proposed models to achieve the spectrum awareness in (CR). But these proposed models describe functionalities rather than applicable designs. In this research we propose a tangible model for spectrum awareness that consists of five main units: RF front ends, energy detector for initial stage channel sensing, features extraction unit(for detailed detection and identification), processing unit (for decision making and controlling the engine component), and adaptive waveform generator of the transmitter (included for consistency). The main three units that are described in this paper are the energy detection, the feature extractions unit, and central processing unit. Figure 1 describes the proposed spectrum awareness engine.

2.1 The Energy Detector

We propose an energy detector as first stage sensing to help detect the presence of the signals before we process the sampled data and extract its features. After successfully receiving and sampling the band of interest, the blind signal detection process will begin in a form of energy detection to initially decide if there is a signal or just noise. The energy detector will also help in the decision process of tuning the bandwidth of the band pass filter to capture the whole signal without losing any frequency domain information. Fine tuning to the correct central frequency and bandwidth of the signal will help in achieving some coherency in the reception and will help to sample the filtered band at Nyquist rate.

The energy detection is performed in the frequency domain. The magnitude square of the fast Fourier transforms (FFT) of the signal is calculated, and the output is compared to a predefined threshold γ to make the first judgment if a signal exists or not. The energy estimation in the frequency domain can be described as:

$$E(Y) = \sum_k |Y(k)|^2$$

where $Y(k)$ represents the FFT output of the sampled spectrum and

$$Y(k) = \begin{cases} W(k) & H_0 \\ S(k) + W(k) & H_1 \end{cases} \quad k = 1, \dots, N$$

Figure 2 demonstrates the proposed energy detector design.

2.2 The Feature Extraction

When detecting energy in the band of interest which may indicate the presence of a signal, the sampled signal will be passed to the features extractor to detect the main features that are present. This process will thoroughly be explained in Section 4 where we illustrate the features extraction methods.

2.3 The Central Processing Unit

This unit is responsible for the decision making process that is based on the parameters coming from the feature detection units. This stage will be explained in Section 5 where we describe the decision making algorithm.

3. 2.4 GHZ ISM BAND TECHNOLOGIES

In 1985 the FCC put in place a creative plan by opening an unlicensed band for wireless networks. This band was regulated by the FCC Part 15 rules [1]. These rules allow new and existing technologies to share the same frequency band and to try to coexist and operate together.

Although those bands are license-free, however, there are some regulations concerning these bands and these are outlined in [1]. Coexistence between various wireless devices in the ISM band was and still is the focus of much study and research. It is worth mentioning that our main concern will be the ISM 2.4GHz band; therefore, we will study the standards that are available in this band only.

We presume (as many other studies in the literature do) that the major players in the ISM band can be broken down to the following: WiFi, Bluetooth, Cordless phones, Zigbee networks, and microwave.

3.1 WiFi IEEE 802.11 Standards

The wireless local area networks (WLAN) technologies appeared in the markets began to quickly increase in the number of users. The WLAN types that are active in the ISM band are:

3.1.1 WiFi IEEE 802.11b
This standard operates in the 2.4GHz with 11 assigned channels; each has 22MHz bandwidth [14]. It employs Direct-Sequence Spectrum Spreading, with Bit rate modes are (1, 2, 5.5, and 11)Mbps.

3.1.2 WiFi IEEE 802.11g
This standard operates in the 2.4GHz with 11 assigned channels; each has 22MHz bandwidth [14]. To sum up the main features of the IEEE802.11g standard: It uses OFDM modulation. It has useful symbol duration of 3.2 μs, and whole symbol duration of 4μs. It has subcarriers numbering 64, and a subcarrier spacing of 312.5 KHz.

3.2 IEEE 801.15.1/2 Bluetooth

This standard operates on the 2.4GHz band. It is considered a short range (up to 10 meters) wireless personal area network (WPAN). Bluetooth standard uses a mixture of Time Division Duplex and FHSS transmission mode over 79 channels with 1MHz spacing [15]. The central frequencies are chosen from the following equation [15], and [16]:

$$Fc = 2402 + K \, MHz, k = 0, \dots, 78$$

The transmission time slot length is 625μs, and the transmission can use up to five time slots.

3.3 IEEE 802.15.4 Zigbee Networks

Zigbee is part of the WPAN family that operates in ISM band and has the features of being small, low maintenance, and low power. The main features of the Zigbee that are useful for our purposes are [17], [18]. And [19]: It has 16 channels with 1MHz separation, with bandwidth of 5MHz. Its bit rate is 250Kbps. It uses DSSS, with chip rate 2000Kcps. Its time slot length can be between $15.36ms$ up to 251.65824 seconds.

3.4 Microwave Ovens

Microwave ovens (MWO) are the perfect example of non-intentional interference of transmitters in the 2.4GHz ISM band. Although microwave ovens were not meant to transmit electromagnetic waves, they usually leak these waves during operation in scattered power all over the ISM band. This phenomenon causes a non-intentional interference. To sum up the main features of the microwave oven standard that is useful for our present study: It has no predefined channels or central frequencies [20], [21]. It has periodic transmission, with bandwidth of 20MHz. It transmits in bursts (transient parts) synchronized to electric power lines cycle. It has a distinguished power spectrum shape. Its signal is modeled as an AM and FM signal. Its transient part width $\sim 1ms$, the AM-FM part duration is 5-7ms.

3.5 FCC Regulations

The FCC regulates the usage of the ISM band, and these regulations should be followed by any wireless device operating in it. This is one of the best reference features, because they are mandatory regulations. Thus, it is important to understand them and use these regulations for the benefit of our blind identifications. In [1], [23], the FCC put up rules for the (FH) systems that operate in the ISM band, more precisely the 2.4G ISM band. We summarize the points that deal with the 2.4GHz band as:

1. FH systems should have hopping channels frequencies with a minimum separation of 25 KHz or the 20dB bandwidth of the hopping channel.
2. The system shall hop to channel frequencies that are selected at the system hopping rate from a pseudo-randomly ordered list of hopping frequencies.
3. Each frequency must be used equally on the average by each transmitter.
4. FH systems shall use at least 15 hopping frequencies.
5. The maximum 20dB bandwidth of the hopping channel is 1MHz.
6. The average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 30 second period.

We believe that the most important rules are the fifth and sixth, as they state that any hopping sequence should have a bandwidth of no more than 1MHz. This will be helpful to reduce the computational complexity in our algorithm, as will be explained later in Section 5.

4. FEATURES EXTRACTION

In this section we describe the features extractions stage and explain the algorithms used to extract each feature. A comprehensive list of features that can be used to detect the presence of the ISM band technologies is discussed and analyzed.

As we explained in Section 2, the CR should have the capability to blindly identify interference and try to mitigate its effects. This capability will be executed in the spectrum awareness engine. In Section 2, a design for the spectrum awareness engine was proposed. Energy detection alone is not sufficient to have an accurate idea about the available spectrum or the interference [24], [25]. Therefore we propose a feature detector stage to deeply explore the captured signal's features to identify them.

Studies examined the various features of the wireless signals. Some even proposed methods to extract these features. In [26], the bandwidth is estimated through the use of FFT operation. In [27], 4th order cumulants test is used to extract the used carrier systems. In [28], moments test is applied to reveal the carrier system. In [29], autocorrelation function is used to estimate the OFDM time parameters. In [30], cyclostationarity is deployed to estimate the OFDM frequency domain parameters. As it is shown, different approaches are proposed to extract different types of features. In this research we define the possible features that can be targeted and propose an algorithm to extract each one of these features with the appropriate approach.

We define the physical layer features and characteristics that can be used to identify signals and interferences as below:

1. Central frequency and bandwidth
2. Duty cycle
3. Statistical characteristics
4. Distinguishing between single carrier or multicarrier
5. Single carrier: DSSS, FHSS
6. Multi-carrier parameters: time (symbol duration, CP duration) and frequency (subcarrier spacing, number of subcarriers)
7. Chip rates
8. Symbol rates
9. Hopping sequence
10. FCC regulation

Comprehensive algorithms are proposed to extract each one these features.

4.1 Bandwidth and Central Frequency Estimation

Right after the energy detection stage, we need to check if there is one signal or more than one signal in the spectrum, and also to make sure that we captured all of the signals. For this purpose we calculate the power spectrum density of

the signal (PSD), and pass the PSD to an edge detector algorithm to check if we have more than one signal in the spectrum. To estimate the bandwidth and central frequency, we use the time frequency Heisenberg-Gabor inequality concept, where the central frequency f_m and the signal bandwidth B can be found through the following equations:

$$f_m = \frac{1}{Ex} \int_{-\infty}^{\infty} f \, |X(f)|^2 \, df$$

$$B = 2 \sqrt{\frac{\pi}{Ex} \int_{-\infty}^{\infty} (f - f_m)^2 \, |X(f)|^2 df}$$

where Ex is the energy of the signal, and assumed to be finite. Figure 3 illustrates the performance of the proposed bandwidth estimation algorithm against various SNR.

4.2 Single Carrier versus Multi-Carrier

Some standards adopt the multicarrier approach like the OFDM based WLAN, and some take the single carrier approach, like cordless phones. That being said, we identify the importance of detecting the signal's carrier system, for both detection purposes and to help reduce the computational complexity of the decision making. We choose to use the moments based test to blindly detect the carrier system of the signal.

In a nutshell, with the moments test based algorithm, we calculate the mixed moment's values of the received signal and compare the values to predefined typical values for each possible modulation scheme. Based on the least minimum mean square error (MMSE) judgment can be made about the modulation of the signal. The mixed moments of the received signal will be:

$$M_{p+q,q}(y) = E\{y(n)^p \times (y(n)^*)^q\}$$

And the the minimum mean squared error(MMSE) criterion is:

$$\theta = arg_\theta^{min} \left(E \left(\left| \widetilde{v_{30}^\theta} - v_{30} \right|^2 \right) \right)$$

Figure 4 illustrates the outcome of the algorithm for different modulation schemes.

4.3 Modulation Order and Type of Single Carrier Signals

The same algorithm that is described in Section 4.2 is used to identify the digital modulation order. The same (MMSE) argument will hold when the algorithm is applied with different modulations parameters and the values that reflect the least MMSE value will represent the modulation used in the received signal.

4.4 OFDM Signals Parameters Estimation

4.4.1 OFDM Time Parameters Estimation
To estimate the OFDM symbol time parameters, an autocorrelation based algorithm is used to estimate the useful symbol duration due to the Cyclic Prefix (CP). While a sliding correlation algorithm with fixed window is used to estimate the Total Symbol Duration. Figure 5 shows the success rate of our algorithm for different SNR values.

4.4.2 Frequency Parameters Estimation
As for the frequency domain parameters it can be calculated since the time domain parameters and the bandwidth are known. Assuming that the orthogonality is maintained in the detected OFDM symbol, the subcarrier spacing and the number of subcarrier will be:

$$\frac{1}{T_u} = \Delta f$$

$$N = \frac{W}{\Delta f}$$

Where Δf is the subcarrier spacing, W is the total bandwidth of the OFDM signal and N is the FFT size.

4.5 Symbol Rate Estimation of Single Carrier Signals

We use the nonlinearity test to create spectral lines in the frequency domain representation of the signal, which helps us detect the symbol rate. Knowing that in pulse-shaped signal cases, the filter bandwidth and roll-off factor impact the occupied bandwidth of the signal as follows:

$$BW \propto \frac{1}{2} R_s (1 + \alpha)$$

where α the roll-off factor of the pulse shaping filter is, R_s is the symbol rate, and BW is the signal bandwidth. And since $\alpha < 1$, it is safe to assume that the bandwidth of the signal is larger than the symbol rate.

We use the modified Welch periodogram method to estimate the symbol rate. By defining a search region using the pre estimated BW, we limit our search between $0.25BW - BW$ to detect the spectral line that corresponds to the symbol rate. Figure 6 illustrates the symbol estimation performance with respect to the SNR in 5 tabs AWGN channel.

4.6 DSSS and its Symbol Rate Estimation

Applying the same algorithm described in the previous section on the DSSS signals will result in revealing the original data symbol rate features. Where we will have distinguished spectral lines that can be used to indicate the DSSS based signals. Furthermore, this approach indicates the IEEE 802.11b from other DSSS based signals. A similar approach is used in [31] and those results matched our algorithm results.

4.7 Frequency Hopping Spread Spectrum and Hopping Sequence

In frequency hopping spread spectrum (FHSS), the data stream is divided and transmitted over different central frequencies after modulating each part with Gaussian frequency shift keying (GFSK). We propose a method to detect the hopping sequence as a unique feature of each FHSS standard. Using the Joint Time Frequency analysis; we detect the FH, and the hopping sequence. A spectrogram based algorithm is used to describe the signal in both frequency and time domain. Through it we have the signal information in both domains so we can identify the FH signals and the hopping sequence. The spectrogram is calculated through the short time frequency transform (STFT), where:

$$Spectrogram(t, w) = |STFT(t, w)|^2$$

A measurement of magnitude versus frequency for each time instant is performed, and the time plot is put side to side to construct the three dimensional image. Figure 7 illustrates the result of Bluetooth signal spectrogram.

5. CONTROL AND EXECUTE

Many algorithms were proposed for blind signal identification, but many of these studies target a specific type of signal or one wireless standard. For instance in [25], the proposed algorithm focuses only on the energy detection, bandwidth, and central frequency to make the judgment. In [32] a threshold for the short time Fourier transforms is set to identify the DSSS signals. In [33] bandwidth and energy level of the signal is used to identify the signal type. In [26] 4th order cumulants test is used to identify multicarrier systems, as well as many other algorithms that can be found where only a certain number of features are incorporated for the purpose of identification. This way may be sufficient enough to use for the bands where only certain licensed operators may be present. In the ISM band, on the other hand, there are many standards that operate at the same time. This makes signal detection and identification more complicated, and the uncertainties are larger. Furthermore by now we can safely say that wireless standards have overlapping features and techniques. This means that although each wireless standard is unique, there exist common physical layer features which can be found between different wireless standards. Therefore, making a decision about a detected signal is not as straightforward as it may appear. From this point of understanding, we propose an approach to utilize the detected features while making the final judgment with the help of the ISM band FCC regulations.

In Section 3 we investigated each possible technology that may appear in the ISM band, and we analyzed their main features. Using what we learned, an identification table is created, where we cross linked each standard with the features that may be used to identify it.

The process begins by first estimating the bandwidth and the central frequency of the signal. If the bandwidth is less than 2MHz, we can safely assume that the signal might be a FHSS. In this case the signal will be passed to the joint time frequency analysis unit to check if the signal is FHSS and to extract the hopping sequence. If the signal bandwidth is larger than 2MHz, we can safely assume that the signal is not FHSS; therefore, we can bypass the joint time frequency analysis.

Power related measurements are conducted, as well as the duty cycle information by passing the signal through a burst detector. The signal will be tested for single carrier or multicarrier schemes. If the carrier test indicates that the signal is multicarrier, the OFDM parameter estimation will be applied to extract the time and frequency parameters of the signal. Otherwise, the moments test and the nonlinearity based algorithm are executed to determine the modulation scheme. The outcome will be the modulation type and order identification or the confirmation that DSSS exists in the signal. In case of a DSSS signal, we extract the chip rate of the signal through the nonlinearity and cyclostationarity test. The symbol rate is estimated through the nonlinearity test for all the single carrier signals and is reported to the decision unit as well. At the end of this flow, we have the features parameters that we described in Section 4, and these are fed into our decision unit to make the decision about the signal identity. Figure 8 illustrates the proposed algorithm integration for the signal detection and identification.

The algorithm performance for different wireless standards is calculated. Table 1 illustrates the success rate of the algorithm blind detection in different SNR environments.

6. CONCLUSIONS

The ISM band is one of the most popular destinations for wireless standards for many reasons, one of which is the fact that it is a license-free band and opens to any wireless device. Peaceful coexistence between the wireless standards is important in the ISM band, and recently, an increasing concern has been given to this issue due to the fact that the number of users in the ISM band are increasing rapidly, which leads to many interference issues. A certainty is that characterizing the signals will help overcome their interference effects, with the CR as the ultimate solution.

Wireless standards have many features, some common and some different. A novel design has been proposed to utilize all these features to blindly identify the signals in order to evaluate how to overcome their effects. The decision making method will have a big impact on the spectrum awareness performance of the CR, especially in a band like the ISM. Fuzzy logic and a soft decision approach

should be considered in the CR functionalities since flexibility should be one of the CR's main characteristics.

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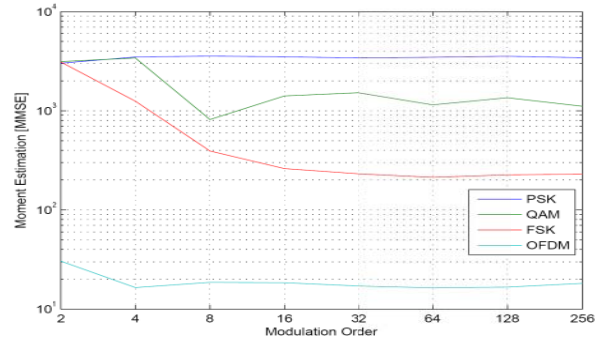
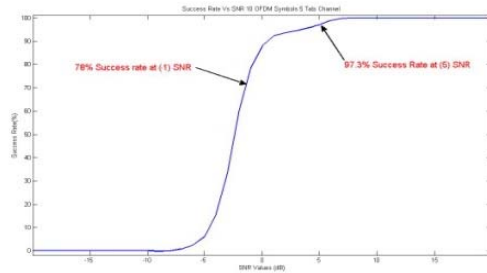Fig 4 Moments test for different modulation schemes

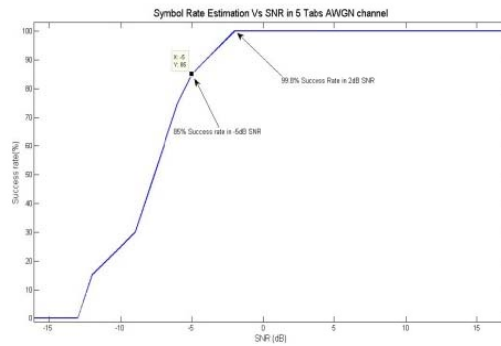Fig 5 The success rate of the time parameters estimation

Fig 6 Symbol rate estimation with respect to SNR
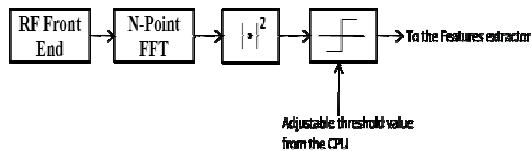
Fig 1 Spectrum awareness engine
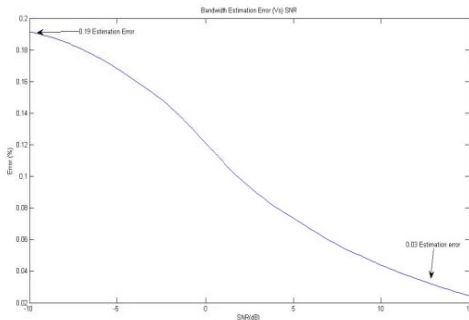

Fig 2 Frequency domain energy detector

Fig 7 Spectrogram representation of a Bluetooth signal
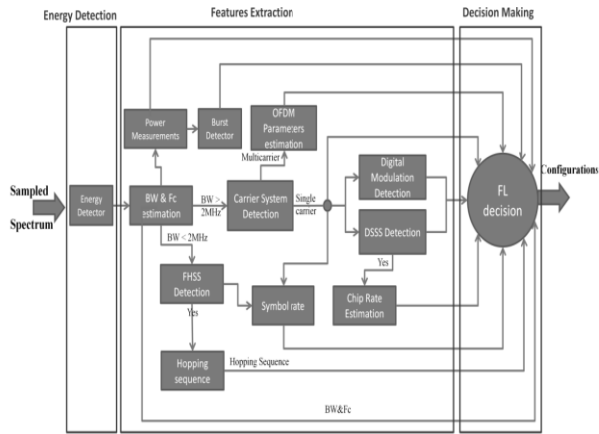

Fig 3 Bandwidth estimation error with SNR values

Fig 8 Feature detection and decision making flow chart

Standard SNR	Wlan 802.11g	Wlan 802.11b	Bluetooth	Cordless Phone	MWO
0	89%	87%	79%		
5	90%	88%	84%		
10	95%	93%	87%		
15	97%	96%	88%		
20	97%	96%	90%	93%	91%

Table 1 The proposed algorithm performance