A FREQUENCY HOPPING SPREAD SPECTRUM TRANSMISSION SCHEME FOR UNCOORDINATED COGNITIVE RADIOS

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ABSTRACT

One of the major challenges to cognitive radios is the synchronization of distributed radios onto the same spectrum white spaces which vary in time and space. In this paper, we propose a frequency-hopping spread spectrum transmission scheme which works reliably without any a priori handshaking assumption. Each cognitive radio independently detects white spaces, and then selects one of them to transmit or receive signals according to a pre-defined frequency hopping pattern. While exploiting the reliability of the white space detection capability of cognitive radios, the new scheme is robust to even large detection errors. According to the accuracy of the spectrum sensing, both the secondary data rate and the interference to primary users can be optimized by adjusting the spreading gain. Its performance is analyzed and demonstrated by simulations.

***Index Terms*—** cognitive radio, dynamic spectrum access, frequency hopping, frequency shift keying, synchronization

1. INTRODUCTION

Cognitive radios have attracted great interests recently. A major application of cognitive radios is to support dynamic spectrum access, i.e., secondary access to spectrum white spaces that the primary users to whom the spectrum is assigned to are currently not using. This would provide a fundamental way to enhance spectrum efficiency so as to mitigate the spectrum scarcity problem. Cognitive radio based dynamic spectrum access has been in extensive investigation in both industry and military. Such activities include the reassignment of a portion of the conventional analog TV spectrum for secondary spectrum access, and the well known DARPA XG program. Much progress has been achieved in spectrum sensing (looking for usable spectrum white spaces) [1], synchronization between a pair of secondary users [2], testbed implementation [3], theoretical performance analysis [4], etc.

In this paper, we address one of the major challenges to cognitive radios, i.e., the coordination between a secondary transmitter and a secondary receiver in order for them to use the same spectrum white space. This problem is also called the transmitter-receiver synchronization in some publications [2]. Because of the distributed nature of cognitive radios and the uncertainty of the availability of spectrum white spaces, it is difficult to pre-design such synchronization into the hardware devices.

This "chicken-and-egg" challenge is simplified in some publications by using a special handshaking channel not occupied by primary users [1], [3]. Unfortunately, such a special channel may not be easy to find in practice due to the overly crowded spectrum. It is a waste of precious spectrum resource and brings many security concerns, especially for military applications.

As an alternative approach, some special MAC (medium access control) layer protocols are developed for secondary spectrum access [2]. They rely on the successful data packet transmission acknowledgement (or feedback from receivers) for handshaking and white space knowledge sharing, which is different from our approach that does not require any feedback.

In this paper, we attack this coordination challenge by developing a new transmission scheme that can work reliably without any initial coordination assumption between the secondary users. Even in case of large white space detection errors, it can still work reliably with low interference to primary users. When the spectrum sensing becomes more reliable, the transmission data rate can be increased without increasing the interference to primary users. We do not require any special coordination channel, nor the feedback-based negotiation.

We build such a new transmission scheme within a framework of frequency-hopping spread spectrum (FHSS) transmission with M-ary frequency-shift keying (M-FSK) modulation. Because no receiver feedback is required, we consider only the transmission from a secondary transmitter to a secondary receiver. By adjusting the spreading gain, we can conveniently adjust the tradeoff between the interference to primary users and the data rate of the secondary transmissions. Such adjustment can be optimized according to the accuracy of spectrum sensing. More specifically, when the white space detection error is large, which happens more often during the initial stage of the secondary transmissions, we can increase the spreading gain so as to reduce the interference. Then, when the white space detection is reliable enough, which happens more often after the initial stage of the secondary transmission, we can reduce the spreading gain in order to increase the secondary transmission data rate without increasing the interference to primary users.

The use of FHSS naturally meets the requirements of avoiding interference to primary users and of guaranteeing security for military applications. We can use a smaller spreading gain for high rate commercial applications. With respect to transmission security, this scheme in fact becomes a full spectrum frequency hopping, which is extremely difficult for listening or jamming.

The rest of this paper is organized as follows. In Section 2, the model of cognitive radio and secondary spectrum access is setup. Then FHSS-FSK transmission is developed and analyzed in Section 3. Simulations are conducted in Section 4 and conclusions are given in Section 5.

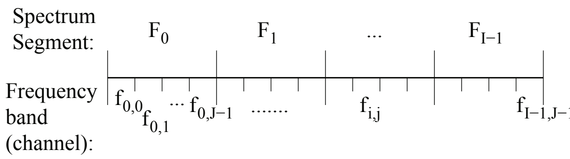

Fig. 1. A wireless spectrum is segmented into I spectrum segments, each of which is further subdivided into J frequency bands. Each frequency band is a basic channel for white space detection and secondary spectrum access.

2. SYSTEM MODEL

Consider a wireless spectrum, some portion of which may be occupied by primary users during some time and in some places. We subdivide this spectrum into I spectrum segments which are denoted as F_i, where $i = 0, 1, \cdots, I-1$. Each spectrum segment is further subdivided into J frequency bands. Each frequency band is a basic channel for spectrum sensing and secondary access. As shown in Fig. 1, we denote the channel by $f_{i,j}$, which stands for the j^{th} channel in the i^{th} spectrum segment, where $j = 0, 1, \cdots, J-1$. Altogether we have IJ channels which are licensed to primary users but some of them may be available for secondary spectrum access.

In this paper, we do not explicitly assume any primary user activity models. In contrast, we ask the secondary users to detect the availability of channels before accessing. Specifically, before a secondary user selects a channel $f_{i,j}$ in the spectrum segment F_i, it should have already detected the availability of all the J channels in this segment F_i. From [1] we know that white space detection requires sufficiently long data record, which in our case can be collected when the secondary user is using other spectrum segments. Therefore, we do not have to assume full spectrum sensing capability, nor simultaneous reception and transmission in the same channel. Note that knowledge about the white spaces obtained previously may be used to improve the detection accuracy so as to further enhance performance.

We consider a pair of secondary users, one transmitter and one receiver, who want to conduct secondary spectrum access by hopping among spectrum segments. We consider the extreme case that in each spectrum segment, they just use one channel to conduct the transmission of one chip. Therefore, the frequency segments and channels should be reused according to certain predefined hopping patterns. Because the hopping among spectrum segments is predefined, each user can collect data and conduct spectrum sensing well before using a channel. We do not assume any coordination or handshaking protocol between the two users, except some predefined pseudo-noise (or specially designed) sequences that are shared, just as a conventional spread spectrum system.

We assume that each of the secondary users has a certain white space detection error probability. As a matter of fact, besides detection errors, there is also possibility that a channel is a white space for one of the users, but is occupied near the other user. We include both cases into the mismatch between the transmitter and the receiver, and the probability of mismatch is denoted as p_d. Note that for the majority of the spectrum, detection error is the dominating factor because the un-symmetric channel exists only in some special spectrums, such as when the primary system is the cellular system and the secondary transmission distance is larger than the cell size.

To indicate whether a channel is spectrum white space, we use

$$a_{i,j} = \begin{cases} 1, & \text{if } f_{i,j} \text{ available for secondary access} \\ 0, & \text{else} \end{cases} \quad (1)$$

Considering the mismatch, the secondary transmitter may have detection results

$$t_{i,j} = \begin{cases} 1, & \text{if } f_{i,j} \text{ is detected available} \\ 0, & \text{else} \end{cases} \quad (2)$$

whereas the secondary receiver may have some different results

$$r_{i,j} = \begin{cases} 1, & \text{if } f_{i,j} \text{ is detected available} \\ 0, & \text{else} \end{cases} \quad (3)$$

Because of the lack of coordination between the second transmitter and receiver, any mismatch may potentially make them out of synchronization. As a result, our objective is to design a transmission scheme so that the secondary users can perform reliably under mismatch probability p_d.

The basic procedure of the secondary spectrum access is that the secondary transmitter and secondary receiver first select a spectrum segment according to certain pre-defined common hopping pattern, and then conduct white space detection in this segment independently. From the detection results, each of them picks a channel to access according to another pre-defined hopping pattern and a common rule. This procedure is repeated until all data are transmitted. Considering the mismatch in white space detection, we only ask them to occupy a channel for a short time period before hopping to another channel.

3. FHSS-FSK TRANSMISSIONS

3.1. Frequency-hopping protocol

Let the secondary transmitter have a symbol sequence $\mathbf{s}_k$, $k = 0, \cdots, K-1$, to transmit to the secondary receiver. Note that the FSK symbol $\mathbf{s}_k$ is in fact a vector. For spread spectrum, each symbol is simply spreaded into M chips. Because frequency hopping can guarantee security, we simply model the spreading as a repeated transmission of each symbol by M times, each in a different channel. Therefore, the symbol $\mathbf{s}_k$ is transmitted as a sequence of M chips

$$\mathbf{s}_{k,m} = \mathbf{s}_k, \quad m = 0, \cdots, M-1. \quad (4)$$

The chip $\mathbf{s}_{k,m}$ is transmitted in a channel in the spectrum segment F_i, where we have modular operation

$$i = (kM + m)|I. \quad (5)$$

In other words, the symbol $\mathbf{s}_k$ is transmitted in the frequency segment sequence F_i, for $i = (kM)|I, \cdots, (kM + M - 1)|I$.

Note that we can also use other more complex spreading protocols, such as the direct-sequence spreading based on some spreading codes. Note also that the frequency segments F_i are used sequentially in a cyclic shifting manner. We may in fact randomize the segments as well by some predefined hopping pattern.

In each frequency segment F_i, the transmitter and receiver each needs to pick one of the available channels $f_{i,j}$ to transmit a chip. To minimize the impact of mismatch, both of them utilize a common binary sequence $\{c_n\}$, where $c_n = 1$ or 0, to determine the selectability of each white space (channel). Specifically, the secondary transmitter calculates the sequence

$$u_{i,j} = t_{i,j} c_{(kM+m)J+j}, \quad (6)$$

where

$$u_{i,j} = \begin{cases} 1, & \text{if } f_{i,j} \text{ is selectable} \\ 0, & \text{else} \end{cases} \tag{7}$$

Similarly, the secondary receiver calculates the sequence

$$w_{i,j} = r_{i,j} c_{(kM+m)J+j}, \tag{8}$$

where

$$w_{i,j} = \begin{cases} 1, & \text{if } f_{i,j} \text{ is selectable} \\ 0, & \text{else} \end{cases} \tag{9}$$

Note that the index i satisfies the constraint (5).

Based on the channel selectability results (6)-(9), the secondary transmitter and receiver use the following simple rule to select a channel to use:

Channel Selection Rule: Use the first selectable channel in each spectrum segment.

Specifically, the secondary transmitter uses the channel u_{i,j_1} to transmit a chip if

$$u_{i,j_1} = 1, \text{ and } u_{i,\ell} = 0 \text{ for } 0 \le \ell < j_1. \tag{10}$$

The secondary receiver uses the channel w_{i,j_2} to collect signal for demodulation if

$$w_{i,j_2} = 1, \text{ and } w_{i,\ell} = 0 \text{ for } 0 \le \ell < j_2. \tag{11}$$

To summarize the transmission procedure, the secondary transmitter transmits a chip $\mathbf{s}_{k,m}$ in the channel f_{i,j_1} if $u_{i,j_1} = 1$. Otherwise, it simply stops transmission in this chip interval. In order to demodulate the chip $\mathbf{s}_{k,m}$, the secondary receiver picks up signals from the channel f_{i,j_2} if $w_{i,j_2} = 1$. Otherwise, it stops receiving during this chip interval. Obviously, if $j_1 = j_2$, then both the transmitter and the receiver have used the same channel, and the transmission becomes identical to the conventional frequency-hopping system except the extremely large spectrum to hop. On the other hand, if $j_1 \neq j_2$, then there is a mismatch (or loss of synchronization) between the transmitter and the receiver. In this case, the receiver in fact takes extra noise/interference which further decreases spreading gain.

3.2. FHSS-FSK demodulation

For the M-FSK modulation, we assume to have L different baseband symbols which we denote as $\tilde{s}_\ell$, $\ell = 0, \cdots, L-1$. Each chip $\mathbf{s}_{k,m}$ now becomes an L-dimensional vector

$$\mathbf{s}_{k,m} = [s_{k,m,0}, \cdots, s_{k,m,L-1}]^T, \tag{12}$$

where all the coefficients $s_{k,m,\ell} = 0$ except that $s_{k,m,\ell} = 1$ if the symbol $\mathbf{s}_{k,m} = \tilde{s}_\ell$.

Because the secondary transmitter may transmit $\mathbf{s}_{k,m}$ or 0 in each chip interval, the received baseband discrete signal is

$$\mathbf{x}_{k,m} = I_{j_1=j_2} \mathbf{G}_{i,j_2} \mathbf{s}_{k,m} + \mathbf{v}_{i,j_2}, \tag{13}$$

or in details

$$\begin{bmatrix} x_{k,m,0} \\ \vdots \\ x_{k,m,L-1} \end{bmatrix} = I_{j_1=j_2} \begin{bmatrix} g_{i,j_2,0} & & \\ & \ddots & \\ & & g_{i,j_2,L-1} \end{bmatrix} \times \begin{bmatrix} s_{k,m,0} \\ \vdots \\ s_{k,m,L-1} \end{bmatrix} + \begin{bmatrix} v_{k,m,0} \\ \vdots \\ v_{k,m,L-1} \end{bmatrix}. \tag{14}$$

Note that $\mathbf{v}_{i,j_2}$ includes both noise and primary user's signal, and

$$I_{j_1=j_2} = \begin{cases} 1, & \text{if } j_1 = j_2 \\ 0 & \text{if } j_1 \neq j_2 \end{cases} \tag{15}$$

is an indicator function unknown to both the secondary transmitter and the secondary receiver.

From the received FSK samples $\mathbf{x}_{k,m}$, the receiver can either use coherent demodulation or noncoherent demodulation. The former means phase coherent, so channel knowledge can be used during demodulation. The latter does not need phase coherence, nor channel knowledge, so only energy of the received samples is used.

For the coherent demodulation, the receiver coherently combines the received M chip samples in order to estimate a symbol, i.e.,

$$\begin{aligned} \mathbf{y}_k &= \sum_{m=0}^{M-1} \mathbf{G}_{i,j_2}^H \mathbf{x}_{k,m} \\ &= \sum_{m=0}^{M-1} \mathbf{G}_{i,j_2}^H \mathbf{G}_{i,j_2} I_{j_1=j_2} \mathbf{s}_{k,m} + \sum_{m=0}^{M-1} \mathbf{G}_{i,j_2}^H \mathbf{v}_{i,j_2}. \end{aligned} \tag{16}$$

The above equation can be decomposed into element-wise representation as

$$y_{k,\ell} = \sum_{m=0}^{M-1} |g_{i,j_2,\ell}|^2 I_{j_1=j_2} s_{k,m,\ell} + \sum_{m=0}^{M-1} g_{i,j_2,\ell}^* v_{i,j_2,\ell}. \tag{17}$$

Based on the results in (16) or (17), FSK symbols can be detected in the maximum likelihood manner as

$$\arg \max_{\ell=0,\cdots,L-1} |y_{k,\ell}|^2. \tag{18}$$

Note that this procedure does not require $I_{j_1=j_2}$ to be known.

For the noncoherent demodulation, the receiver can only use energy detector

$$\begin{aligned} y_{k,\ell} &= \sum_{m=0}^{M-1} |x_{k,m,\ell}|^2 \\ &= \sum_{m=0}^{M-1} \left| I_{j_1=j_2} g_{i,j_2,\ell} s_{k,m,\ell} + v_{i,j_2,\ell} \right|^2. \end{aligned} \tag{19}$$

Then the symbol detection procedure (18) can be similarly applied.

3.3. Performance analysis

For the FHSS-FSK with coherent demodulation, if $j_1 = j_2$ is always true, then

$$y_{k,\ell} = \begin{cases} \sum_{m=0}^{M-1} g_{i,j_2,\ell}^* v_{i,j_2,\ell}, & \text{if } s_{k,m,\ell} = 0 \\ \sum_{m=0}^{M-1} |g_{i,j_2,\ell}|^2 + g_{i,j_2,\ell}^* v_{i,j_2,\ell}, & \text{if } s_{k,m,\ell} \neq 0. \end{cases} \tag{20}$$

From the above equation, we can easily find that the symbol level SNR of the received signal is

$$\gamma_{\text{coherent}} = M \frac{\sigma_s^2}{\sigma_v^2}, \tag{21}$$

where σ_s^2 and σ_v^2 are variances of symbol and noise/interference, respectively. Note that the channels are assumed flat fading with unit gain. This equation shows that we can have the full spreading gain M.

Unfortunately, such full spreading gain is not available in case of $j_1 \neq j_2$. In this case, from (17), we can derive the SNR as

$$\gamma_{\text{coherent}} = \frac{\hat{M}^2}{M} \frac{\sigma_s^2}{\sigma_v^2}, \tag{22}$$

where

$$\hat{M} = \sum_{m=0}^{M-1} I_{j_1=j_2} \tag{23}$$

is the average number of correct white space detections for both the secondary transmitter and the secondary receiver. The equation (22) clearly shows that the mismatch of white space detection not only reduces the spreading gain, but also introduces extra noise and interference.

For the noncoherent demodulation, the analysis becomes more difficult. From (19), if $j_1 = j_2$, we can derive

$$y_{k,\ell} = \begin{cases} \sum_{m=0}^{M-1} |v_{i,j_2,\ell}|^2, & \text{if } s_{k,m,\ell} = 0 \\ \sum_{m=0}^{M-1} |g_{i,j_2,\ell} + v_{i,j_2,\ell}|^2, & \text{if } s_{k,m,\ell} \neq 0. \end{cases} \tag{24}$$

The above equation indicates the reliability of symbol detection if there is no white space detection errors.

Another important issue is the probability of $j_1 \neq j_2$. We give an upper bound of such a probability as follows. For the channels $j = 0, \cdots, J-1$ in a spectrum segment, the probability that there is mismatch in the first j channels (i.e., channels $0, \cdots, j-1$) is

$$P_j \leq 1 - (1-p_d)^j. \tag{25}$$

Therefore, the average channel mismatch probability for this segment is

$$P_J \leq \frac{1}{J} \sum_{j=0}^{J-1} \left[1 - (1-p_d)^j\right]. \tag{26}$$

For M repeated transmissions of a symbol, on average, we may have

$$\hat{M} = M(1-P_J) \geq M \left[1 - \frac{1}{J} \sum_{j=0}^{J-1} [1-(1-p_d)^j]\right] \tag{27}$$

transmissions that are error free. This can be used to determine the SNR (22).

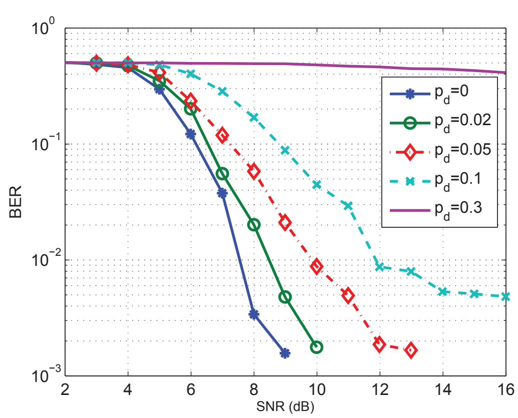

Fig. 2. BER as functions of SNR under various mismatch probability p_d.

4. SIMULATIONS

In this section, we use Monte-Carlo simulations to verify the proposed method. In each run of the experiment, we transmitted $K = 100$ symbols, with various spreading gain $M \leq 40$. We used $I = 20$ spectrum segments, with $J = 100$ channels each segment.

Fig. 2 shows that even with relatively large mismatch rate $p_d \approx 0.1$, our method can still work reliably. Higher white space detection accuracy makes our method converge rapidly to conventional error-free frequency hopping. Fig. 3 shows that we can increase the spreading gain M to combat the higher mismatch probability p_d.

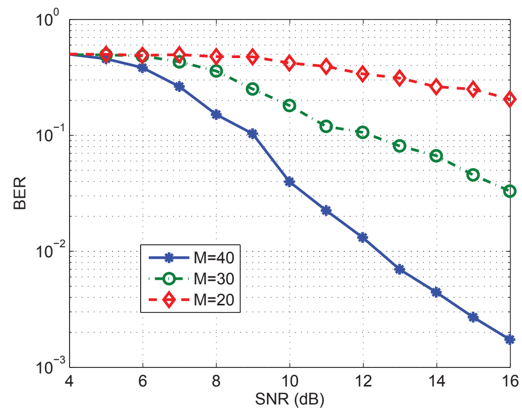

Fig. 3. BER as functions of SNR under various spreading gain M. Mismatch probability $p_d = 0.1$.

5. CONCLUSIONS

In this paper, we propose an FHSS-FSK transmission scheme for uncoordinated cognitive radios in case the spectrum sensing error is unavoidable. The new transmission scheme exploits the spreading gain to combat spectrum sensing errors while needs no extra coordination between the transmitter and the receiver.

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