Out-of-Band Sensing Scheme for Dynamic Frequency Hopping in Satellite Communications

Mohammad J. Abdel Rahman[§], Marwan Krunz[§], and Richard Erwin[§§]

[§]Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721, USA

[§]E-mail:{mjabdelrahman, krunz}@email.arizona.edu

[§§]Air Force Research Laboratory, Kirtland Air Force Base, Kirtland, NM 87117, USA

***Abstract*—This paper makes preliminary steps at exploring a novel application of cognitive radios (CRs) for reliable satellite communications. We propose the use of dynamically adjusted frequency hopping (FH) sequences for satellite transmissions. Such sequences are more robust against smart eavesdropping and targeted interference than fixed FH sequences. In our approach, FH sequence is adjusted according to the outcome of out-of-band sensing, carried out by a CR module that resides in the satellite itself or at the receiving ground station. Our protocol, called OSDFH, relies on exploiting the spectrum sensing capabilities of CRs for proactive detection of channel quality. We analyze the characteristics of the proposed OSDFH using a finite state Markov chain (FSMC) framework. Level crossing rate (LCR) analysis is used to determine the transition probabilities of the Markov chain. These probabilities are then used to measure the "channel stability," a metric that reflects the freshness of sensed channel interference. We use simulations to study the effects of different system parameters on the performance of our proposed protocol.**

***Index Terms*—Out-of-band sensing, dynamic frequency hopping, cognitive radio, satellite communications.**

I. Introduction

Recently, there has been significant interest in spectrum-agile software-defined radios (a.k.a. cognitive radios or CRs) to be used in a variety of military and commercial applications. On the commercial side, such systems provide a much needed solution for improving the spectral efficiency of under-utilized portions of the licensed spectrum. On the military side, these systems can facilitate inter-operability between different radio platforms and also enable prolonged RF communications in the presence of dynamic fluctuations in channel quality.

In this paper, we make preliminary steps at exploring a novel application of the CR technology for reliable satellite communications. As a first "line of defense," satellite transmissions often rely on spread spectrum techniques, including frequency hopping (FH) and direct sequence. In this paper, we focus on FH. Traditional application of FH involves hopping according to a fixed, pseudorandom noise (PN) sequence, known only to the communicating parties. Although this approach tends to work well in random interference scenarios, it has a number of drawbacks. First, in networked satellite systems (e.g., systems involving satellite-to-satellite links, with satellites acting as routers in the sky), broadcasting control messages implies that the "secret" PN code is a network-wide (shared) code, which is prone to compromise by rogue users. Second, even if this code is not comprised, a smart eavesdropper may (eventually) figure out portions of the FH sequence and may attempt to persistently target certain frequencies in certain time slots.

One way to address the above limitations is to modify/replace the FH sequence according to channel quality and interference conditions. However, the overhead of doing that on the fly is high, and may not be feasible for real-time implementation. Instead, the approach we advocate in this paper relies on exploiting the spectrum sensing capabilities of CRs for *proactive detection of channel quality* . According to this approach, a CR module is placed within the satellite system (for uplink transmissions) or at the receiving ground station (for downlink transmissions). This module monitors frequencies that will be used in the near future for transmission according to the given FH sequence. Depending on the quality/stability of the channel, the CR decides which, if any, of the monitored frequencies exhibit high interference, and hence need to be swapped with better quality and/or more stable frequencies (channel stability will be defined later in Section IV-A). The CR module may also recommend boosting the transmission power over certain frequencies to combat relatively mild forms of noise. The CR may also recommend that the transmitter stays silent in certain time slots. The spectrum sensing results are reported to the satellite transmitter, possibly via a ground-based feedback channel (or a reverse satellite-to-transmitter link, if this exists). By focusing on "future" frequencies in the FH sequence, our approach prevents (rather than reacts to) disruptions to ongoing communications.

The remainder of this paper is organized as follows. Section II introduces our proposed proactive sensing approach. The finite state Markov chain (FSMC) model is discussed in Section III. In Section IV we discuss the proposed OSDFH protocol. We evaluate this protocol in Section V. Section VI gives an overview of related work. Finally, Section VII provides concluding remarks.

II. Proposed Proactive Sensing Approach

A. Overview

In this paper, we consider a bent-pipe satellite link, as shown in Figure 1. Frequency division duplexing (FDD) is used to operate the uplink (ground-to-satellite) and downlink (satellite-to-ground) links. The transmitting ground station uses FH to communicate with a receiving station via satellite. For the uplink (also, downlink), hopping is done according to a given PN sequence that exhibits a sufficiently large period m. Let T be the duration of one slot (time spent transmitting at a given frequency). We assume that T equals to the duration of one packet. Let f_i denote the ith frequency (channel), $i = 1, \ldots, F$. For any given slot j, let d_j denote the frequency selected for transmission according to the given PN code. For example, if f_3 is used for transmission during slot 1, then $d_1 = f_3$. The satellite and/or receiving ground station are augmented with a CR module that is capable of measuring the quality of any channel. To maintain low hardware complexity, we assume that the CR module cannot measure the noise over the *operating channel* (one currently used for transmission).

This research was supported in part by NSF (under grants CNS-1016943, CNS-0904681, IIP-0832238), Raytheon, AFRL, and the Connection One center (an I/UCRC NSF/industry/university consortium). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of NSF and AFRL.

Noise measurement is performed using an energy-based detector. Let τ_s be the time spent sensing a given channel in the FH sequence (a.k.a. *the sensing time*). Typically, $\tau_s \ll T$; τ_s is usually in the order of tens to hundreds of milliseconds, whereas T can be in seconds. Because we rely on energy-based detectors, the longer the sensing time, the higher is the sensing accuracy. Without loss of generality, we assume $T = l\tau_s$ for some integer l.

Consider the uplink transmission at an arbitrary time slot n (similar treatment applies to the downlink). The transmitting ground station and the receiving satellite will be tuned to frequency d_n. At the same time, the CR module will be sensing channel d_{n+K}, where K (in slots) is called the "lag parameter." If channel d_{n+K} does not satisfy the channel quality requirements described later, the CR module will start sequentially monitoring frequencies d_{n+K+1}, d_{n+K+2}, ..., $d_{n+K+l-1}$ until it can find a suitable channel to be used for transmission during slot $n+K$ (see the example in Figure 2). Note that the CR module can sense l channels sequentially in a period T. If the CR module cannot find a channel with the desired quality, it recommends the transmitter to stay silent during slot $n + K$ (so as not to waste energy). The lag parameter allows for adequate time to report back the outcome of the sensing process. This time is called *the feedback time*, and is denoted by τ_f. It enables the transmitter to adjust its hopping sequence and transmission power accordingly. For typical satellite systems, $\tau_f \sim$ 100s of milliseconds.

Depending on the outcome of the sensing process at time n, the CR may recommend that the transmitter stays silent in slot $n + K$, or to transmit using a recommended channel, denoted by h_{n+K}. This channel h_{n+K} may be the same as d_{n+K} (the channel that was supposed to be used according to the original FH sequence) or it may be a different channel. The transmission is done using a predefined nominal power P_{nominal}, or a power boost may be required. The transmitter criterion will be explained in detail in Section II-C.

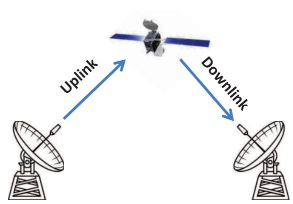

Fig. 1: Bent-pipe satellite link.

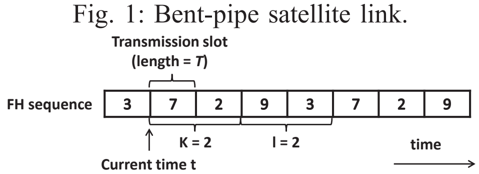

Fig. 2: Sensing of "future" frequencies (K = 2, l = 2).

B. Decision Criterion at the CR Module

To measure the quality of the sensed channel, the CR uses two metrics: "channel quality" and "channel stability." This section introduces the first metric. The second metric will be discussed in Section IV-A. The CR module uses the received noise power to decide whether the channel is usable or not based on a predefined threshold. For energy detectors, the received noise power during time slot i (Y_i) is approximately given by [2]:

$$Y_i = \frac{1}{2u} \sum_{j=1}^{2u} n_j^2$$

where $u = \tau_s B$ is the time-bandwidth product, B is the one-sided bandwidth of the low-pass signal, and n_j is a Gaussian noise signal with zero mean and unit variance. It is known that Y_i follows a central Chi-Square distribution of $2u$ degrees of freedom, mean one, and variance $1/u$ [2]. Hence, for a given B as τ_s increases the variance of the received noise power decreases. The probability density function (pdf) of Y_i can then be written as:

$$f_{Y_i}(y) = \frac{u^u}{\Gamma(u)} y^{u-1} \exp(-uy), \quad \forall y \geqslant 0$$

where $\Gamma(\cdot)$ is the gamma function.

Based on Y_i, the CR decision criterion can be expressed as follows:

$$\begin{cases} d_i \text{ is clean (usable)}, & \text{if } Y_i < \lambda_1 \\ d_i \text{ requires power boost (usable)}, & \text{if } \lambda_1 < Y_i < \lambda_2 \\ d_i \text{ cannot be used in slot } i \text{ (unusable)}, & \text{if } Y_i > \lambda_2 \end{cases}$$

where λ_1 and λ_2 are thresholds to be determined.

C. Decision Criterion at the Transmitter

During time slot i, the transmitter may communicate over channel d_i or it may swap this channel with one of the channels $d_{i+1}, d_{i+2}, ..., d_{i+l-1}$. In either case, the transmitter will either use power level P_{nominal} or it may boost its transmission power, up to a maximum value $P_{\max}$. If the CR module cannot find a channel that satisfies the channel quality requirements, described in Section IV, then it will recommend that the transmitter stays silent during slot i. Y_i (equivalently, the corresponding channel state) and h_i are fed back to the transmitter. Recall that $h_i \in \{d_i, \ldots, d_{i+l-1}\}$ is the channel that will actually be used for transmission during slot i. In the subsequent analysis, we say that channel h_i is in state 1 if $Y_i < \lambda_1$, in state 2 if $\lambda_1 < Y_i < \lambda_2$, and in state 3 otherwise.

III. FSMC Channel Model

We use FSMC to characterize channel dynamics. Using this model, we later assess the stability of the monitored channel. In our model, the noise power Y_i is approximated by a discrete-time Markov process with time slot equals to T. FSMCs have been used to approximate the dynamics of wireless channels, including satellite channels. In our FSMC model, the range of Y_i is divided into three regions: $R_j \overset{\text{def}}{=} \{Y_i : \lambda_{j-1} \leq Y_i \leq \lambda_j\}$, $j = 1, 2, 3$. In here, $\lambda_0 \triangleq 0$ and $\lambda_3 \triangleq \infty$. The boundaries of the three regions are parameters to be computed. In the literature, researchers have used FSMC models to characterize the channel, but without allowing for transitions between non-adjacent states. Therefore, they assume that once Y_i is in a given state, it stays in it for at least T seconds, and can only transition to the same state or adjacent states in the next T seconds. Let us denote the transition probability from state k to state j by $p_{k,j}$, $k, j = 1, 2, 3$. Then, $p_{k,j}$ can be expressed as.

$$p_{k,j} = \begin{cases} \frac{N_{\lambda_k} T}{\pi_k}, & \text{if } |j-k| \leq 1 \text{ and } j > k \\ \frac{N_{\lambda_j} T}{\pi_k}, & \text{if } |j-k| \leq 1 \text{ and } j < k \\ 1 - \sum_{i \neq k} p_{k,i}, & \text{if } j = k \\ 0, & \text{if } |j-k| > 1 \end{cases} \tag{1}$$

where $N_{\lambda_j}, j = 1, 2$, is the *level crossing rate* (LCR) of Y_i at λ_j (the rate at which Y_i crosses level λ_j in the upward/downward direction) and π_j, $j = 1, 2, 3$, is the steady-state probability of being in state j. Note that $p_{k,j}$ can be expressed as $N_{\lambda_{\min\{k,j\}}} T/\pi_k$ if $|j - k| \leq 1$, and the first two cases of (1) can be combined into one case. Denote the time derivative of Y_i by $\dot{Y}_i$. Then, N_{λ_j} is given by [1].

$$N_{\lambda_j} = \int_0^{\infty} \dot{y} f_{Y_i, \dot{Y}_i}(\lambda_j, \dot{y}) d\dot{y} = \frac{u}{\Gamma(u)} (\lambda_j u)^{u-1} \exp(-\lambda_j u) \tag{2}$$

where $f_{Y_i,\dot{Y}_i}(\lambda_j,\dot{y})$ is the joint pdf of Y_i and $\dot{Y}_i$. Note that $\pi_j = \Pr\{Y_i \in R_j\} = \Pr\{\lambda_{j-1} \le Y_i < \lambda_j\}$ can be expressed as:

$$\pi_j = \int_{\lambda_{j-1}}^{\lambda_j} f_{Y_i}(y)dy = e^{-\lambda_{j-1}u} \sum_{k=0}^{u-1} \frac{1}{k!}\left(\lambda_{j-1}u\right)^k - e^{-\lambda_j u} \sum_{k=0}^{u-1} \frac{1}{k!}\left(\lambda_j u\right)^k, \quad j = 1,2,3. \tag{3}$$

We here generalize the FSMC model in [8] to allow transitions between non-adjacent states to be able to capture fast varying channels. In [8], the authors require $p_{k,j} = 0$ for $|j-k| > 1$. In order to remove such a constraint, assume that $j > k$. Then, we aggregate states $k, k+1, \ldots, j-1$ as a new state k'. Thereby, the transition probability between those two neighboring states is

$$p_{k',j} = \frac{N_{\lambda_{j-1}}T}{\pi_{k'}}, \quad \pi_{k'} = \textstyle\sum_{i=k}^{j-1} \pi_i.$$

On the other hand, given the initial aggregate state k', the probability that the refined initial state to be k is $\pi_k/\pi_{k'}$. Combining the above results, we have

$$p_{k,j} = p_{k',j}\frac{\pi_k}{\pi_{k'}} = \frac{N_{\lambda_{j-1}}T}{\sum_{i=k}^{j-1}\pi_i}\frac{\pi_k}{\sum_{i=k}^{j-1}\pi_i}. \tag{4}$$

Similarly, if $j < k$, then

$$p_{k,j} = \frac{N_{\lambda_j}T}{\sum_{i=j+1}^{k}\pi_i}\frac{\pi_k}{\sum_{i=j+1}^{k}\pi_i}. \tag{5}$$

Combining (1), (4), and (5), $p_{k,j},\ k,j = 1,2,3$ can be expressed as:

$$p_{k,j} = \begin{cases} \frac{N_{\lambda_{j-1}}T}{\sum_{i=k}^{j-1}\pi_i}\frac{\pi_k}{\sum_{i=k}^{j-1}\pi_i}, & \text{if } j \ge k+1 \\ \frac{N_{\lambda_j}T}{\sum_{i=j+1}^{k}\pi_i}\frac{\pi_k}{\sum_{i=j+1}^{k}\pi_i}, & \text{if } j \le k-1 \\ 1 - \sum_{i \ne k} p_{k,i}, & \text{if } j = k. \end{cases} \tag{6}$$

The state diagram of the resulting FSMC model is shown in Figure 3.

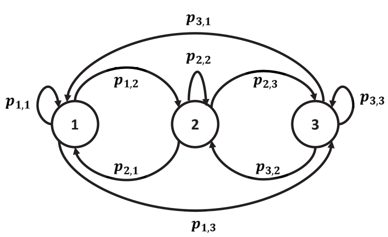

Fig. 3: FSMC state diagram.

Let $P = [p_{i,j}]$ be the transition probability matrix, and let P^k be the k-step transition probability matrix. The (i,j) entry of P^k is denoted by $p^k_{i,j}$. Let $\pi = (\pi_1 \ \ \pi_2 \ \ \pi_3)$ be the steady-state distribution.

Apparently, the range of each state should be large enough to cover the variations in Y_i during a packet time, so that for most of the time a received packet completely falls in one state. On the other hand, the range of each state cannot be made too large. The reason is that if this range is too large, then the time spent in a state is too large compared with the packet duration. Therefore, the variation in Y_i during a packet time is much smaller than the variation in Y_i during the state interval, and different packets falling in the same state may have quite different qualities. Based on the above considerations, the average time duration of each state is a critical parameter in our FSMC model. We define $\bar{\tau}_j$ as the average time spent in state j. It is the ratio of the total time the received signal remains between λ_{j-1} and λ_j and the total number of such signal segments, both measured during some long time interval τ. Let τ_i be the duration of each signal segment. Then, $\bar{\tau}_j$ can be expressed as [9]:

$$\bar{\tau}_j = \frac{\sum \tau_i}{(N_{\lambda_{j-1}} + N_{\lambda_j})\tau} = \frac{\pi_j}{N_{\lambda_{j-1}} + N_{\lambda_j}}. \tag{7}$$

We require that

$$\bar{\tau}_j = c_j T, \quad j = 1,2,3, \tag{8}$$

where c_j is a constant greater than 1. As discussed earlier, c_j should be made large enough so that for most of the time a received packet completely falls in one state. On the other hand, c_j should not be made too large, so that all packets falling in the same state experience approximately the same quality. From (2), (3), (7), and (8), $c_j, j = 1,2,3$, can be expressed as:

$$c_j = \frac{\Gamma(u)}{uT}\frac{e^{-\lambda_{j-1}u}\sum_{k=0}^{u-1}\frac{(\lambda_{j-1}u)^k}{k!} - e^{-\lambda_j u}\sum_{k=0}^{u-1}\frac{(\lambda_j u)^k}{k!}}{(\lambda_{j-1}u)^{u-1}e^{-\lambda_{j-1}u} + (\lambda_j u)^{u-1}e^{-\lambda_j u}}. \tag{9}$$

For given values of λ_1 and λ_2, we can obtain the corresponding c_j values. Our purpose is to find λ_1 and λ_2 with the requirement that the time durations c_j (in number of packets) are within a reasonable range. If we set the values of $c_j, j = 1,2,3$ in (9), there will be 3 equations with only 2 variables λ_1 and λ_2. Our procedure is to constrain the c_j to all be equal, i.e., $c_1 = c_2 = c_3 = c$. Thus, each state has the same average time duration. The equations in (9) now contain three unknowns: λ_1, λ_2, and c.

IV. OSDFH Protocol

In this section, we first introduce the channel stability criterion that the CR module uses to determine if a sensed channel is to be kept or not. We then explain the OSDFH protocol. The specification of various parameters used in this protocol will be discussed in Sections IV-C, IV-D, and IV-E.

A. Stability Condition

We say that a channel is stable if with a given probability p_{th}, its quality is not expected to deteriorate before completing the scheduled data transmission on that channel. More specifically, assume that we are currently in slot n and we want to select a channel to be used after K time slots. Then, the stability condition for channel d_{n+K} is

$$p^v_{i,i} + p^v_{i,i-1} > p_{th}$$

where $v \overset{\text{def}}{=} \lceil \frac{KT + T_{data} - x\tau_s}{T} \rceil$; T_{data} is the duration of the data transmission, $x\tau_s$ is the total time spent in sensing before finding channel d_{n+K}, and i is the current state of channel d_{n+K}. In the above condition, the values of interest for i are 1 and 2, because if the channel is in state 3, then it is unusable and there is no need to check its stability (as we will explain later in Section IV-B).

B. Proactive Sensing and Channel Selection Algorithm

In this section, we propose an algorithm for searching for a usable and stable channel, and for adjusting the FH sequence based on channel quality and stability. Our sensing and reporting algorithm can be executed in two steps. First, we search for a usable channel (i.e., channel in states 1 or 2). Second, we test the stability of this usable channel. If the channel is stable, the receiver feeds the channel (frequency) index along with its state back to the transmitter. Otherwise, the CR module at the receiver searches for another usable channel. The details of these two steps are explained next.

Step 1: Suppose that we are currently in slot n. Then, the CR module will be sensing channel d_{n+K}. If this channel is usable, then step 2 is executed to test its stability. Otherwise, the CR module starts sequentially sensing channels d_{n+K+1}, d_{n+K+2}, ..., $d_{n+K+l-1}$ until a usable channel is found. If the CR module can find a usable channel from the $l-1$ channels that follow channel d_{n+K}, then step 2 is executed to test the stability of the selected channel. Otherwise, the CR module informs the transmitter that no usable channel is available, and accordingly the transmitter stays silent during slot $n+K$.

Step 2: If the selected usable channel satisfies the stability condition defined in Section IV-A, then the receiver feeds the index of this channel (frequency) along with its state back to the transmitter. A pseudo-code of the sensing and reporting algorithm is shown in Algorithm 1.

Algorithm 1 Out-of-band sensing based DFH

Input: l, T, T_{data}, τ_f, τ_s, λ_1, λ_2, K, and p_{th}
For every time slot T**:**
Step 1: Search for a usable channel
Sense channel d_{n+K}
if state (d_{n+K}) == 3 **then**
    for $x = 1 : l-1$ **do**
        if state $(d_{n+K+x}) < 3$ **then**
            Go to **Step 2** with x and d_{n+K+x}
        end if
    end for
    if no useful usable channel is found **then**
        Inform the transmitter to stay silent
    end if
else
    Go to **Step 2** with d_{n+K}
end if
Step 2: Search for a stable channel
if the usable channel is unstable **then**
    if $x < l-1$ **then**
        Go to **Step 1** to find a usable channel
        if $\exists$ a usable channel d_{n+K+x} for some $x < l-1$ **then**
            Go to **Step 2** with d_{n+K+x}
        else
            Inform the transmitter to stay silent
        end if
    else
        Inform the transmitter to stay silent
    end if
else
    Send the channel index along with its state to the transmitter
end if

C. Determining the Sensing Period τ_s

Increasing τ_s decreases the variance of Y_i, thus reducing the uncertainty in the sensing outcome. Let x_r be the rth percentile of Y_i. We select τ_s such that x_r is less than or equal to a predefined value μ. The relation between x_r and τ_s can be expressed as:

$$F_{Y_i}(x_r) = 1 - \exp\left(-x_r u\right) \sum_{k=0}^{u-1} \frac{1}{k!} \left(x_r u\right)^k = r.$$

Recall from Section II-B that $u = \tau_s B$.

D. Computing $P_{\max}$ and P_{nominal}

To compute $P_{\max}$ and P_{nominal}, we need to consider the signal-to-noise ratio (SNR), which in the context of satellite communications is referred to as the carrier-to-noise ratio $\left[\frac{C}{N}\right]$. This $\left[\frac{C}{N}\right]$ is expressed in dB as [6, Section 12.6]:

$$\left[\frac{C}{N}\right] = [P_T] + [G_T] + [G_R] - [\text{Losses}] - [P_N],$$

where $[P_T]$ and $[P_N]$ are the transmitted power and the noise power, respectively; $[G_T]$ and $[G_R]$ are the transmitter and the receiver antenna gains, respectively; and [Losses] are the losses experienced by the signal while propagating in the wireless channel. $P_{\max}$ is computed by setting $\left[\frac{C}{N}\right]$ to SNR_{th} (the minimum required SNR for the receiver to correctly receive the transmitted signal) and $[P_N]$ to λ_2 in dB. Then, the corresponding $[P_T]$ is the value of $P_{\max}$. Similarly, P_{nominal} is computed by setting $\left[\frac{C}{N}\right]$ to SNR_{th} and $[P_N]$ to λ_1 in dB. The corresponding $[P_T]$ is the value of P_{nominal}.

E. Selecting the Lag Parameter K

We select K to be the smallest possible value that allows the CR module to sense and send its report back to the transmitter in a timely manner. Note that increasing K will decrease the freshness of the sensing information (recall that the maximum sensing duration $l\tau_s = T$ is independent of K). Accordingly,

$$K = \left\lceil \frac{T+\tau_f}{T} \right\rceil = 1 + \left\lceil \frac{\tau_f}{T} \right\rceil.$$

V. Performance Evaluation

In this section, we evaluate the performance of OSDFH via simulations. Our Matlab-based simulations are conducted for the FSMC channel model discussed in Section III. Our performance measures are the number of *black holes* (BHs), the number of transmission errors (TEs), and the number of unnecessary power boosts (UPBs). A BH occurs when the CR module cannot find a stable and usable channel for a given time slot. A TE occurs when the estimated channel state by the CR module is better than the actual state of that channel, encountered at the time of transmission. An UPB occurs when the CR module estimates the channel to be in state 2 (medium noise), but the channel is actually in state 1 (low noise). Unless stated otherwise, we use the following default values: $K = 3$, $l = 4$, $p_{th} = 0.7$, $P = \begin{pmatrix} 0.5 & 0.3 & 0.2; & 0.2 & 0.5 & 0.3; & 0.2 & 0.3 & 0.5 \end{pmatrix}$, and $\pi = \begin{pmatrix} 0.25 & 0.375 & 0.375 \end{pmatrix}$. We run our simulations over a FH sequence of length 1000 slots. The matrix P is taken as an input to our simulations, instead of deriving it from the LCR, as discussed in Section III. This makes our results independent of our assumption about the channel noise model (in Section III, P was computed assuming normal noise, and hence Y_i is Chi-Square distributed).

A. Numerical Example

We first consider a simple numerical example, with the goal of explaining the operation of OSDFH. Consider the FH sequence in Figure 2, where K = 2 and l = 2. The transition matrix P is given above.

TABLE I: Example explaining the operation of OSDFH

Time ($x\tau_s$)	Tx slot	Sensing slot	State of sensed Ch. (i)	$p^K_{i,i}$ + $p^K_{i,i-1}$	Actual Ch. state
1	1	3	1	0.914	2
2	1	4	–	–	–
3	2	4	2	0.628	2
4	2	5	1	0.914	1
5	3	5	2	0.628	3
6	3	6	2	0.628	2
7	4	6	1	0.914	1
8	4	7	–	–	–
9	5	7	1	0.914	1
10	5	8	–	–	–

In the first transmission (Tx) slot and the first sensing duration ($x = 1$ in Table I), the CR module senses channel d_3. Because d_3 is usable (in state 1) and also stable ($p^K_{i,i} + p^K_{i,i-1} = 2p^2_{1,1} = 0.914 > p_{th}$), the CR module assigns channel d_3 to slot 3. The actual channel state after $K = 2$ slots is 2, so a TE will occur because P_{nominal} is not enough to meet the required SNR at the receiver. (Recall from Section IV-D that P_{nominal} meets the required SNR at the receiver when the channel is in state 1. In other words, when the received noise power is less than λ_1 dB). The same applies to the remaining slots. The resulting FH sequence after executing Algorithm 1 is as follows: $h_3 = d_3$ (TE), $h_4 = d_5$, $h_5 = \emptyset$ (BH), $h_6 = d_6$, and $h_7 = d_7$. In this example, the number of BHs equals 1, the number of TEs equals 1, and the number of UPBs equals 0. In our numerical example, we ignored T_{data} and x in the stability definition of Section IV-A.

B. Number of Black Holes

Figures 4 (a) and 4 (b) show the number of BHs as a function of p_{th} and l, respectively. The number of BHs increases significantly when p_{th} exceeds 0.5, reaching its maximum value of 1000 when $p_{th} = 0.7$. As can be observed in Figure 4 (b), increasing l beyond 3 does not affect the number of BHs when $p_{th} = 0.7$. When $p_{th} = 0.5$, increasing l beyond 2 reduces the number of BHs significantly, as the CR module has a higher chance of finding a channel when the number of sensing periods increases (as long as p_{th} is not too large).

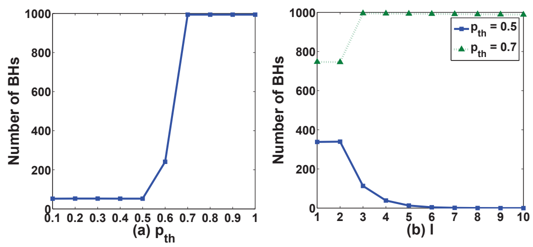

Fig. 4: Number of BHs versus (a) p_{th}, and (b) l.

C. Number of Transmission Errors

Figures 5 (a) and 5 (b) depict the number of TEs as a function of p_{th} and l, respectively. The number of TEs decreases significantly when p_{th} exceeds 0.5, and reaches its minimum value of 0 at $p_{th} = 0.7$. As Figure 5 (b) shows, for reasonably large values of l, the number of TEs becomes insensitive to l. Hence, as long as l is large enough, the number of TEs mainly depends on p_{th}. For $p_{th} = 0.5$ in Figure 5 (b), the number of TEs is large because the probability that the channel state will not change is small, and for $p_{th} = 0.7$, the number of TEs is small because the probability that the channel state will not change is high.

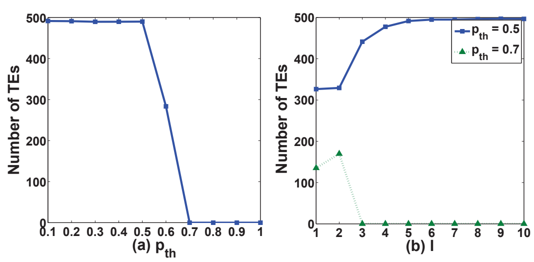

Fig. 5: Number of TEs versus (a) p_{th}, and (b) l.

D. Number of Unnecessary Power Boosts

Figures 6 (a) and 6 (b) depict the number of UPBs as a function of p_{th} and l, respectively. Both, a TE and an UPB occur when the estimated channel state is different from the actual channel state. Hence, the behavior of the number of UPBs is the same as that of the number of TEs, as Figure 6 (b) shows.

VI. Related Work

Our work is related to four main research areas, namely, out-of-band sensing, dynamic frequency hopping, cognitive radios, and satellite communications. In this section, we give

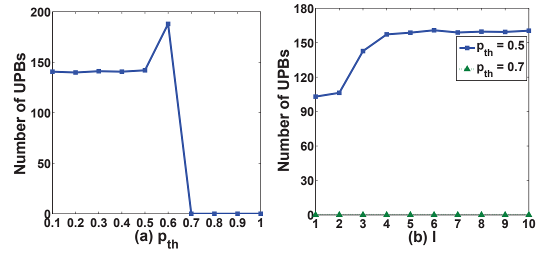

Fig. 6: Number of UPBs versus (a) p_{th}, and (b) l.

an overview of some of the important contributions in out-of-band sensing and DFH. In [3], DFH communities were proposed for efficient frequency usage and reliable channel sensing in IEEE 802.22 systems. The key idea in a DFH community is that neighboring WRAN cells form cooperating communities that coordinate their DFH operations. In [7] the hopping mode of the 802.22 standard was compared with its non-hopping mode. The results show that hopping reduces collisions with primary users and achieves higher throughput, thus providing enhanced QoS for secondary users. In [4], the use of out-of-band sensing was investigated. Sensing consumes part of the MAC frame that would otherwise be used for data transmission. In [5], a cooperative out-of-band sensing was investigated. The authors used the ATSC TV signal as an incumbent signal, and derived the mis-detection and false-alarm probabilities under a frequency-selective Rayleigh fading channel. To the best of our knowledge, OSDFH is the first protocol that employs out-of-band sensing of CRs for proactive adjustment of the FH sequence used over a satellite link.

VII. Conclusions

In this paper, we explored a novel application of the CR technology for reliable satellite communications. DFH sequences that mitigate the deficiencies of fixed FH sequences were studied. Our proposed OSDFH protocol exploits the sensing capabilities of a CR for proactive detection of channel quality. We analyzed the design parameters of our protocol using a FSMC model, where the transition probabilities were expressed in terms of the LCR of the received noise power at two predefined levels. We proposed an algorithm for searching for a usable and stable channel, and for adjusting the FH sequence based on channel quality and stability. Using simulations, we studied the effects of different system parameters on performance.

References

[1] N. Beaulieu and X. Dong. Level crossing rate and average fade duration of MRC and EGC diversity in Ricean fading. *IEEE Transactions on Communications*, 51(5):722–726, May 2003.

[2] F. Digham, M.-S. Alouini, and M. Simon. On the energy detection of unknown signals over fading channels. In *Proceedings of the IEEE ICC Conference*, pages 3575–3579, May 2003.

[3] W. Hu, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz. Cognitive radios for dynamic spectrum access - dynamic frequency hopping communities for efficient IEEE 802.22 operation. *IEEE Communications Magazine*, 45(5):80–87, May 2007.

[4] Y. Jembre, Y.-J. Choi, and W. Pak. Out-of-band sensing for seamless communication in cognitive radio systems. In *Proceedings of the CUTE Conference*, pages 1–4, 2010.

[5] B.-J. Kang, H.-S. Park, Y.-S. Kim, S.-M. Woo, and S.-W. Ban. Out-of-band cooperative spectrum sensing in cognitive radio system of multiple spectrum bands. In *Proceedings of the WSEAS Conference*, pages 31–34, 2009.

[6] D. Roddy. *Satellite communications*. McGraw-Hill, 2006.

[7] J. Tong, H. Wu, C. Yin, Y. Ma, and J. Li. Dynamic frequency hopping vs. non-hopping in IEEE 802.22 systems. In *Proceedings of the IEEE IC-NIDC Conference*, pages 95–99, November 2009.

[8] H. S. Wang and N. Moayeri. Finite-state Markov channel-a useful model for radio communication channels. *IEEE Transactions on Vehicular Technology*, 44(1):163–171, Feb. 1995.

[9] Q. Zhang and S. Kassam. Finite-state Markov model for Rayleigh fading channels. *IEEE Transactions on Communications*, 47(11):1688–1692, November 1999.