ON THE DYNAMIC RE-USE OF SATELLITE LINK SPECTRUM WITH AN ACTIVE SENSING COGNITIVE RADIO NETWORK

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Abstract. This report considers the use of external transceivers to actively sense and detect the operational status of Demand Assigned Multiple Access (DAMA) satellite communication (SATCOM) terminals. The main idea is to attach a small sensor (or network of sensors) directly to the DAMA terminal, with the use of control channel(s) for communicating its status. The goal is to enable dynamic re-use of SATCOM bandwidth with cognitive radio technology while maintaining full compatibility with legacy equipment.

1. Introduction

Radio frequency (RF) bandwidth has long been considered the most precious of resources for wireless communication networks. In the current fixed spectrum allocation paradigm, however, a significant fraction of the spectrum suitable for wireless transmissions goes unused at any given time and location. Two key examples of primary networks whose geotemporal spectrum allocations are vastly underutilized are broadcast television (TV) and SATCOM networks. Figure 1 shows the first- and second-order statistics of over-the-air power measurements made continuously over a period of 24 hours in 12 minute cycles. The Figure illustrates significant gaps in spectrum utilization in both time and frequency.

Advances in the performance and flexibility of RF hardware, along with improved techniques of communications signal processing, have spurred a flurry of recent research activity on wireless networks that sense and adapt to idle frequency bands, see for example [1, 2, 3, 4]. Such networks, often referred to as cognitive radio (or secondary) networks, hold the potential to drastically improve the capacity of wireless communication systems by more efficiently utilizing finite bandwidth resources. In order to maintain full compatibility with existing (or primary) networks with fixed bandwidth allocations, strict adherence to interference avoidance constraints is required. Since the cognitive radio must adapt its communications to available frequency bands, RF detectors, such as energy detectors or cyclostationary feature

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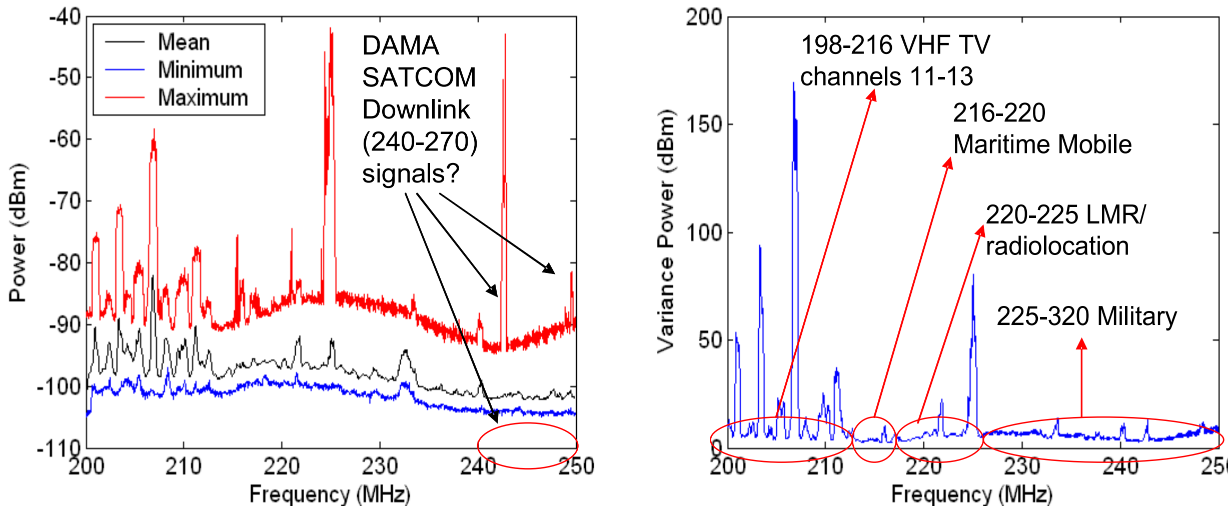

(a) Over-the-air power measurements

(b) Corresponding second order statistics

FIGURE 1. Measured spectrum utilization in Santa Barbara, CA.

detectors, are required to monitor the RF activity within the interference range of the secondary radio. A major hurdle in meeting interference requirements arises from shadowing phenomena in wireless networks [1].

Shadowing occurs when a potentially weak primary signal is sufficiently attenuated at the spectrum sensor, for example when there is no line-of-sight to the primary transmitter, causing a monitored channel to be incorrectly declared as idle. In general, shadowing can be moderated with diversity techniques such as collaborative sensing protocols [3]. Another very effective approach, if feasible, consists of primary receiver Local Oscillator (LO) leakage detection [5]. For example, in SATCOM terminals and broadcast TV receivers, the receiver radio front-end emits RF energy at the LO mixing frequency corresponding to the tuned channel. By augmenting any heterodyne receiver, such as the one depicted in Figure 2, with a spectrum sensor/transceiver that detects LO leakage energy, as in Figure 3, fast and reliable channel utilization information can be obtained even at low Signal-to-Noise Ratio (SNR). This approach, referred to as "active sensing," is assumed to be employed throughout the rest of this document.

The deployment of cognitive radio networks in TV bands [4] is considered an important first step towards realizing dynamic spectrum systems. In this work, we consider the dynamic re-use of SATCOM channels for cognitive radio applications. In particular, we focus on spectrum sensing for DAMA SATCOM channels and their associated bandwidth allocation, with emphasis on digital signal processing techniques for a single sensor architecture. The spectrum sensor consists of a heterodyning receiver employing LO leakage detection [5] with the use of the Maximum Likelihood (ML) criterion for channel usage estimation [6, 7].

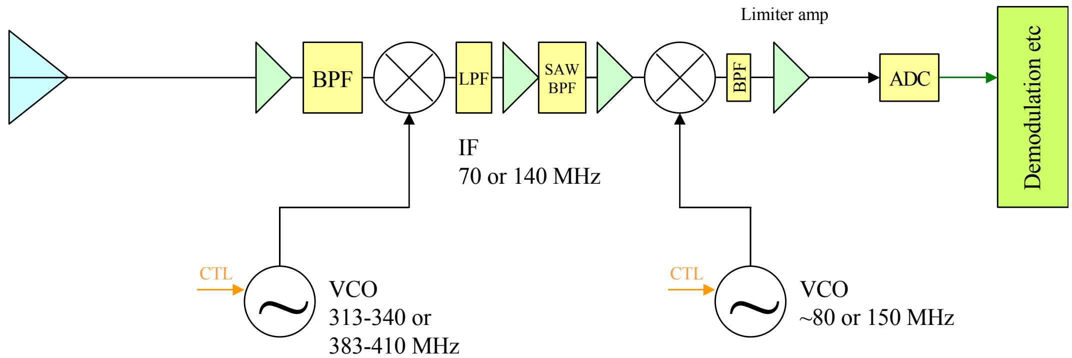

FIGURE 2. Possible DAMA Terminal Receiver.

When the SATCOM terminal is active, the LOs are assumed to be continuously running. The frame length of DAMA messages, which employ Time Division Multiple Access (TDMA), is 1.386 seconds, each including a synchronization preamble. Thus, the latency of a cognitive radio spectrum sensor should be a small fraction of a second. Section 2 outlines the system model, Section 3 describes the detection algorithm, and Section 4 presents the performance of a simulated detector. Simulation results show that roughly 45 milli-seconds of detector latency is required at an SNR of -50 dB.

2. SYSTEM MODEL

The DAMA receive frequencies are in the 243 MHz to 270 MHz range, spanning a bandwidth of 27 MHz. The bandwidth of an individual DAMA channel can be either 5 kHz or 25 kHz. Figure 2 illustrates a possible receiver architecture of the DAMA terminal. The first stage consists of down-converting a block of channels to an intermediate frequency (IF). We assume a fixed IF between 70 MHz (preferable for cheaper narrowband filters) and 140 MHz (preferable for better phase noise characteristics). The actual down-conversion in the DAMA terminal could be two (depicted) or three stages, in which case multiple tunable LOs will have to be detected in order to generate per-channel usage information. In this document, only the leakage energy corresponding to the first mixing stage is considered. Such a detector will indicate only which sub-group of channels is being demodulated at any given time, resulting in less efficient bandwidth re-use but providing a much simpler model. Note that for one stage heterodyning receivers, full channel usage information is obtained via LO energy detection.

The LO power level, P, at an external receiver/detector attached to the DAMA terminal is expected to be in the -70 to -110 dBm region. The sampling rate of the detector, f_s, must be large enough to differentiate the N monitored channels. We assume ideal Nyquist sampling of the baseband DAMA channels, so that $f_s = 2W = 2NB$ for a DAMA channel sub-group bandwidth B. Subsampling techniques, employing sub-Nyquist sampling rates,

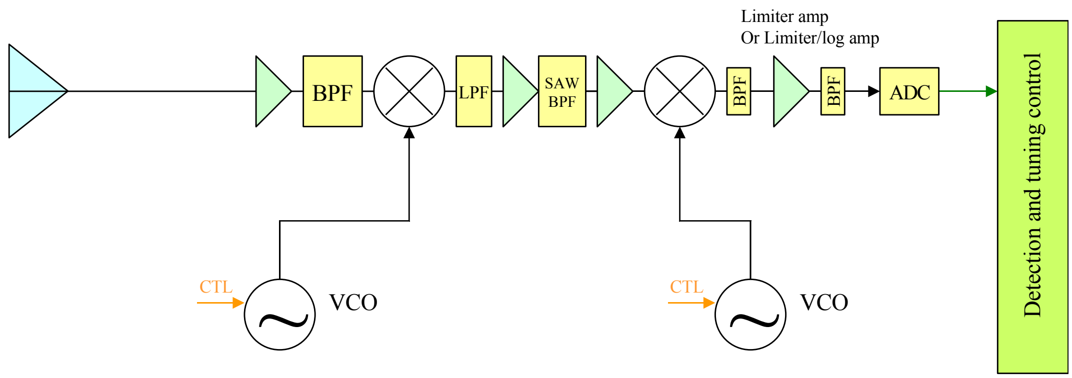

FIGURE 3. Possible Leakage Receiver.

as proposed in [7], can be used to relax sampling requirements for large N systems. The Signal-to-Noise ratio (SNR) is defined as E_s/N_0, where E_s is the received signal energy and N_0 is the noise power. With the receiver bandwidth $W = NB$, and $T = 1/f_s$, we have

$$E_s = PT = P/(2W),$$

and, assuming ideal, Additive White Gaussian Noise (AWGN) reception,

$$N_0 = k_B t W f,$$

where k_B denotes Boltzmann's Constant, t denotes the temperature, and the noise factor f for a decent receiver is assumed to be 2. The SNR is thus given by

$$SNR = \frac{P}{4 k_B t W^2}. \quad (1)$$

Thus, based on an assumed LO received power of -70 dBm, $N = 27$ channels of $B = 1$ MHz, and a temperature of 290° Kelvin, the detector SNR is approximated as -50 dB.

Signal model: Conditional on the DAMA terminal utilizing channel n, the baseband received signal is modeled as a tone at LO frequency f_n,

$$y(m) = e^{j2\pi f_n mT + j\phi} + w(m), \quad (2)$$

with AWGN, $w(m)$, of variance σ^2 per dimension. The unknown carrier phase ϕ is uniformly distributed, $U[0, 2\pi]$.

3. Detection algorithm

The goal is to quickly minimize the probability of false detection (in order to minimize interference) given that the DAMA terminal is employing one of N channels. We assume that the detector has been trained to LO frequencies that represent the DAMA channels (or channel sub-groups). Due to the unknown carrier phase, a noncoherent detector, that estimates the power spectrum density of the received signal, is used to generate channel state information. The decision rule is based on Maximum Likelihood (ML) criterion.

The channels are assumed to be equi-spaced by B MHz. So that for N channels, the detector is required to monitor a passband bandwidth of NB MHz. Note that our assumptions enable the use aliasing techniques for reducing the sample rate and improving SNR. However, for the SATCOM model considered here, typical values of B and N are tractable for most receivers employing Nyquist sampling rates.

This hypothesis testing problem may be formulated in discrete baseband as follows:

$$\begin{aligned} H_0 :\ & y(m) = w(m), \\ H_n :\ & y(m) = e^{j2\pi f_n mT + j\phi} + w(m), \\ & m = 0, \ldots, K-1,\ n = 1, \ldots, N, \end{aligned}$$

where the unknown carrier phase ϕ is uniformly distributed, $U[0, 2\pi]$, and $w(m)$ denotes AWGN of variance σ^2 per dimension.

The Discrete Fourier Transform (DFT) is employed to measure the energy content of the received signal at any given frequency, as described next. The emitted signal corresponding to LO frequency f_n is given by $x(m) = \exp(j2\pi f_n mT)$. The length K DFT of the LO signal corresponding to frequency f_n is given by

$$X_n(k) = e^{j\omega_{nk}(K-1)} \frac{\sin(\omega_{nk} K)}{\sin \omega_{nk}},$$

with $\omega_{nk} = \pi(f_n T - k/K)$, $k = 0, \ldots, K-1$. Thus, the DFT of the received signal is

$$Y(k) = e^{j\phi} X_n(k) + W(k),$$

where $W(k)$ denotes AWGN with variance σ^2 per dimension. The notation $\mathbf{Y} = [Y(0) \cdots Y(K-1)]$ denotes a vector of K symbols, and $\langle \mathbf{y}, \mathbf{x} \rangle = \mathbf{x}^H \mathbf{y}$ is the inner product of vectors $\mathbf{x}$ and $\mathbf{y}$.

The decision rule is based on the Maximum Likelihood criterion,

$$\hat{n}_{ML} = \arg\max_n \frac{P(\mathbf{Y}|H_n)}{P(\mathbf{Y}|H_0)} = \arg\max_n z(n), \tag{3}$$

where

$$z(n) = |\langle \mathbf{Y}, \mathbf{X}_n \rangle|^2, \tag{4}$$

and $\mathbf{X}_n = [X_n(0) \cdots X_n(K-1)]$.

When the LO frequencies correspond to DFT samples, the ML detector can be implemented directly by summing the appropriate DFT sample over multiple DFT blocks and taking the squared-magnitude. However, this implies the use of a very long DFT in order to achieve sufficient quantization granularity in frequency. In practice, it is more efficient to use a moderate value for the DFT length, K, and to aggregate statistics (over many DFT blocks) from logical quantizers with a resolution much finer then f_s/K. This is accomplished with a matched filter to the DFT of the leakage signal corresponding to a given LO frequency. In particular, as a measure of the relative energy at frequency f_n, the detector computes the squared-magnitude of the output of a filter matched to $\mathbf{X}_n$, whose input is the DFT of the received symbol sequence.

Since

$$x(m + lK) = e^{j2\pi fTlK} x(m),$$

a frequency dependent phase correction must be applied when combining filter outputs from multiple DFT blocks. Accordingly, the ML statistic, (4), at frequency f_n, is given by

$$z(n) = |\sum_{l=0}^{L-1} e^{-j2\pi f_n TlK} \langle \mathbf{Y}^{(l)}, \mathbf{X}_n \rangle|^2,$$

where $\mathbf{Y}^{(l)}$ denotes the DFT of the lth block of K received symbols and L the total number of such blocks.

4. Results

We consider the case of known presence of LO leakage signal. Training techniques should be used enable efficient detection of DAMA terminal inactivity. The detectors are further assumed to be trained to the LO frequencies of monitored DAMA channel sub-groups. We assume that the LO signal strength measured at the detector is -70 dBm. Note that several techniques may be employed to boost SNR, such as subsampling signal processing techniques, cooperative detection techniques, inline coupling of the detector antenna with the DAMA antenna, or even the use of high-end radio hardware. For example, it can be shown with calculations similar to those leading up to Equation (1) that subsampling by a factor of 10 improves the SNR by 10 dB.

Figure 4 shows the performance of ML detection with $N = 27$ channel groups of bandwidth of $B = 1$ MHz. The FFT length is 32. When the SNR is -50 dB, as in (1), the spectrum detector has a latency of 45 milli-seconds at an error rate of 1 in 10,000. SNR enhancement techniques are able to drastically reduce the latency. A 10 dB increase in SNR improves the latency by 40 milliseconds at the same error rate.

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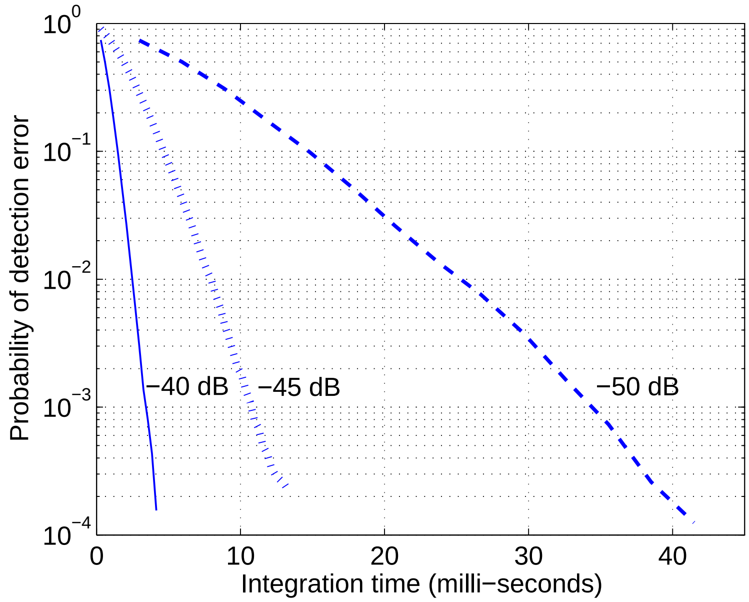

Figure 4. ML signal detection at anticipated SNRs.

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