SPECTRUM SHAPING FOR INTERFERENCE MANAGEMENT IN COGNITIVE RADIO NETWORKS

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ABSTRACT

Most dynamic spectrum access research centers on determining the set of frequencies being used by spectrum license holders, taking its converse, and from what remains selecting the optimal subset of spectrum. This, however, assumes unlicensed transmissions have a square power spectrum

By shaping our unlicensed power spectra, we can do much more. This paper investigates applications of spectrum shaping, and how they can be implemented using OFDM and DSSS. The first application involves creating notched power spectra that can take advantage of noncontiguous spectrum segments, increasing our signal bandwidth. The second is to create spectra inversely shaped to the current interference environment, allowing us to take advantage of gaps in the noise floor.

By modulating the power in each sub-carrier, OFDM can be easily shaped. For DSSS, spreading codes with particular spectral characteristics can be devised that give the desired shape.

1. INTRODUCTION

Many dynamic spectrum access protocols [1,2,6] assume frequency use is binary and seek to operate around licensed signals. This is perhaps an optimal strategy if unlicensed signals must have a square power spectrum. However, when a cognitive radio network is operating in a licensed band, its general goal is to constrain the interference perceived by licensed devices while maximizing his own capacity, and in these scenarios square power spectra are typically not optimal.

This paper details two main applications for spectrum shaping in cognitive radio networks. The first is called interference fitting, where a radio senses the shape of the interference power spectrum and designs a waveform whose shape is its converse, allowing us to constrain absolute interference. The second application is licensed signal avoidance, where a notched spectrum is engineered that allows us to easily use noncontiguous segments of spectra to avoid licensed signals. When the two applications are used together, we achieve a powerful tool to maximize achievable capacity in the FCC-proposed interference temperature model [4].

Additionally, we describe how spectrum shaping can be accomplished with both OFDM/OFDMA and DSSS/CDMA waveforms. For OFDM, we extend the common practice of discretely enabling and disabling different sub-carriers to a system that uses arbitrary power control on each sub-carrier. For DSSS, we describe techniques for computing spreading codes that result in arbitrarily shaped waveforms, in addition to a mechanism for transmitting the spreading code to cognitive receivers.

Each scheme offers interesting challenges. For example, in OFDM, we need to adjust the coding rate on each sub-carrier to account for the varying SINR experienced by each. By fitting our coding scheme precisely to our interference environment, we can actually increase our overall capacity. In DSSS, we analyze the tradeoff between the complexity of the derived spreading code, and its ability to form the proper spectral shape. Overall, spectrum shaping can boost achievable capacity in cognitive radio networks, especially when paired with the interference temperature model that allows for spectral coexistence with licensed signals.

Section 2 introduces the interference temperature model, which we use to quantify and restrict interference levels between licensed and unlicensed signals. Section 3 further introduces the applications of spectrum shaping within the context of the interference temperature model. Section 4 describes spectrum shaping with OFDM, and section 5 details DSSS. Section 6 presents power spectra of shaped signals generated in MATLAB. Section 7 concludes.

2. INTERFERENCE TEMPERATURE MODEL

In this paper we consider the primary/secondary user model for dynamic spectrum access. Primary users own various subsets of the frequency band in question, and use them according to some access methodology. For example, television stations transmit continuously on particular channels, while wireless MAN technologies are bursty and multiplex different users in time.

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Secondary users do not hold a license for the spectrum, but are authorized to use it on a non-interference basis. Generally this requires radios with some level of intelligence, which can detect primary users and determine which spectrum segments are available.

There are two basic dynamic spectrum access approaches, one based on hard constraints, and one based on soft. In the hard-constraints approach, if a licensed signal is detected in band $[B_1, B_2]$ then the unlicensed users' power *must* be zero in that frequency band.

The second approach, proposed by the FCC Spectrum Policy Task Force in 2003 [4], is the Interference Temperature Model. Here we enforce an interference maximum perceived by receivers. Rather than being 0, we can allow interference up to a preexisting interference floor. Softening the constraints allows more flexibility in dynamic spectrum access, and provides the opportunity for increased overall capacity.

To implement the Interference Temperature Model, a regulatory body would set an interference temperature limit T_L for a particular frequency band. Unlicensed transmitters would have to keep the average interference perceived by primary receivers below BkT_L, where k is Boltzman's constant and B is the primary transmitter's bandwidth. Various algorithms have been devised to compute the necessary bandwidth and transmission power to achieve a particular capacity subject to a particular interference environment [3].

One possible shortcoming of the Interference Temperature Model is that it only regulates *average* interference, and not *absolute* interference. Narrowband interference to a wideband primary spectrum user could severely interfere with signal reception, while the average interference over the licensed signal could be under the threshold. Another advantage of spectrum shaping is that we can regulate absolute interference, which is explored further in the following sections.

3. PROBLEM FORMULATION

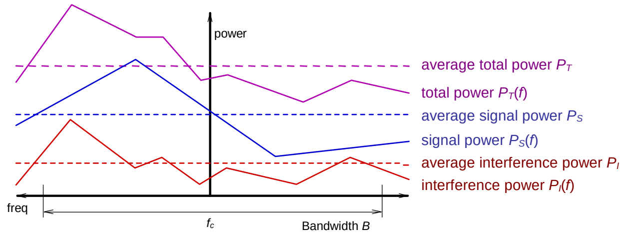

Figure 1 Figure showing that approximating $P_T(f)$ over the interval [f_c-B/2, f_c+B/2] by the average power $\bar{P}_I$ could yield unexpected interference exceeding regulatory allowances.

To better understand the problem, let's examine the differences between maximum power and average power. Figure 1 depicts three power curves, interference $P_I(f)$, signal $P_S(f)$, and total $P_T(f)$, where

$$P_T(f) = P_I(f) + P_S(f) \qquad \forall f \in [f_c - B/2, f_c + B/2]$$

Each signal has mean over bandwidth B of $\bar{P}_I$, $\bar{P}_S$, and $\bar{P}_T$, respectively.

Assuming a fixed licensed signal bandwidth, then the interference temperature model stipulates that

$$\bar{P}_T \le BkT_L$$

As Figure 1 indicates, even with equality we have no real guarantee on absolute maximum interference. A stronger requirement would be

$$P_T(f) \le BkT_L \qquad \forall f \in [f_c - B/2, f_c + B/2]$$

Note that this requirement wholly implies the first. That is,

$$\max P_T(f) \ge \bar{P}_T \to (P_T(f) \le BkT_L \to \bar{P}_T \le BkT_L)$$

Thus, in order to maximize both capacity and spectral efficiency while minimizing absolute interference, we must find some $P_S(f)$ such that $P_T(f) = BkT_L$.

We can actually build off the algorithms already developed for the interference temperature model [3]. These algorithms give us $\bar{P}_S$ and B that reach our target capacity while satisfying the interference temperature constraints. Knowledge of B is sufficient, and we compute

$$P_S(f) = BkT_L - P_I(f) \qquad \forall f \in [f_c - B/2, f_c + B/2]$$

This characterization describes the interference fitting application. We engineer $P_S(f)$ such that the signal plus interference equals some constant maximum threshold. However, for licensed signal avoidance, we have different constraints depending on whether or not we are overlapping a licensed signal. Here T_L is no longer a constant, but rather a function of frequency.

$$T_L(f) = \begin{cases} T_{\min} & f \in \text{licensed signal} \\ T_{\max} & f \notin \text{licensed signal} \end{cases}$$

For shaping with hard constraints, use $T_{\min} = 0$.

The next sections describe two ways of accomplishing our shaping goal. The first technique uses power control across OFDM sub-carriers. The second approach creates spreading codes with certain spectral characteristics that shape the signal.

4. SPECTRUM SHAPING WITH OFDM

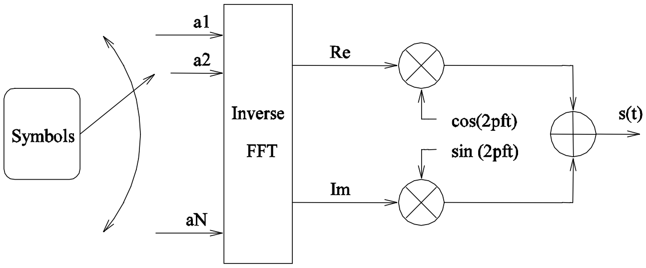

Figure 2 Simplified OFDM transmitter.

In Orthogonal Frequency-Division Multiplexing (OFDM), waveforms are constructed in the frequency domain and converted into the time domain before being transmitted. Figure 2 illustrates such a transmitter. Symbols are complex numbers representing modulated bit streams. For example, if QPSK is the underlying modulation technique, bit streams of length two would be modulated as $1+j$, $1-j$, $-1+j$, $-1-j$. The complete block of N symbols $\{a_1,\ldots,a_N\}$ are then sent into the inverse Fourier Transform to produce a time-domain waveform. The real and imaginary components of the complex-baseband signal are multiplied by sine and cosine to create the passband signal $s(t)$. Mathematically, the complex-baseband signal $v(t)$ can be expressed as

$$v(t)=\sum_{k=1}^{N} a_k e^{j2\pi kt/T} \quad \forall 0 \le t \le T$$

Assuming a uniform distribution over the input symbols, the average power spectrum is flat as a function of frequency. Our goal is to affect this average power. In particular, assume our bandwidth B is broken up into N sub-carriers, as described. The desired average power for subcarrier k is

$$p_k = BkT_N(f_c - B(N-2k)/2N) - i_k$$

where

$$i_k = \frac{N}{B}\int_{f_c-B(N-2k)/2N}^{f_c-B(N-2k-2)/2N} P_I(f)\,df$$

Let α be the average symbol power for the underlying modulation scheme. We can then reformulate our complex-baseband OFDM signal as

$$v(t)=\frac{1}{\alpha\sqrt{2}}\sum_{k=1}^{N} a_k\, p_k e^{j2\pi kt/T} \quad \forall 0 \le t \le T$$

This will convert the average power on sub-carrier k from α to p_k. The $\sqrt{2}$ is necessary to normalize since multiplication by p_k will affect both the real and complex portions of the waveform.

Alternatively, symbols could all be multiplied by some relative scaling value such as $p_k/(BkT_N - \overline{P_I})$ and then the final signal $s(t)$ could adjusted such that its average power was $\overline{P_S}$. This approach would likely make more sense in a real-world transmitter where amplification happens in the RF front end.

Regardless, we can now shape our power spectrum. However, we must be able to effectively utilize our spectral resources if we hope to achieve channel capacity. In particular, the capacity on each sub-carrier varies, as each has a different SIR. This means different coding is necessary on each sub-carrier to maximize capacity.

The capacity on sub-carrier k is

$$C_k = \frac{B}{N}\log_2\left(\frac{BkT_L\left(f_c - \frac{B(N-2k)}{2N}\right)}{i_k}\right)$$

For the interference fitting application with fixed interference temperature, the total capacity is

$$\begin{aligned} C &= \sum_{k=1}^{N} C_k \\ &= B\log_2\left(BkT_L - \frac{B}{N}\sum_{k=1}^{N}\log_2 i_k\right) \end{aligned}$$

If we have uniform interference, i.e. $i_k = \overline{P_I}$, then this equals the capacities derived earlier for the interference temperature model. However, variances in i_k will actually help us achieve higher capacities, since

$$\frac{1}{N}\sum_{k=1}^{N}\log_2 i_k \le \log_2 \overline{P_I}$$

For the licensed signal avoidance application, assume z sub-carriers overlap licensed signals The total capacity is then:

$$\begin{aligned} C &= \sum_{k=1}^{N} C \\ &= B\log_2\left(BkT_L - \frac{B}{N}\sum_{k=1}^{N}\log_2 i_k\right) \end{aligned}$$

Thus, with proper channel coding, we can outperform the standard interference temperature model by performing spectral shaping with OFDM. Not only can we decrease the maximum interference experienced by others, but we can also increase our capacity while using the same average transmission power and meeting regulatory requirements.

5. SPECTRUM SHAPING WITH DSSS

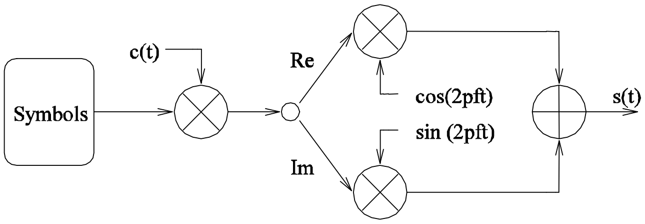

Figure 3 Simplified DSSS transmitter.

Direct Sequence Spread Spectrum (DSSS) is another technique commonly employed for creating wide-band signals. Here we start with a narrow-band complex-baseband signal and “spread” it using a spreading code.

In Figure 3 we can see the basic operation of a DSSS transmitter. Modulated symbols $a(t)$ are multiplied by a high-frequency signal $c(t)$ before being up-converted to passband.

Our goal is to specify $c(t)$ such that $s(t)$ has the spectral properties we desire. Note that in this section we focus on the interference fitting application, thus we use a constant interference temperature limit T_L. Mathematically, we have can define our complex baseband signal $v(t)$ as

$$v(t) = c(t)\,a(t)$$

Thus we have

$$c(t) = v(t)/a(t)$$

Let's look at $v(t)$, the desired signal. In the frequency domain, we have

$$\begin{aligned} V(f) &= P_S(f - f_c) \\ &= \Pi_B(f - f_c)(BkT_L(f) - P_I(f - f_c)) \\ &= \Pi_B(f - f_c)(BkT_L(f) - \mathbf{F}(i(t))) \end{aligned}$$

Here Π_B is the width-B rectangular function, and $i(t)$ is the current interference environment, downsampled to baseband.

Returning to the time domain, we have

$$\begin{aligned} v(t) &= \mathbf{F}^{-1}(V(f)) \\ &= \mathbf{F}^{-1}(\Pi_B(f - f_c)(BkT_L\mathbf{F}(i(t)))) \\ &= w(t) * (BkT_L\delta(t) - i(t)) \\ &= w(t) * (BkT_L\delta(t)) - w(t) * i(t) \\ &= w(t)BkT_L - w(t) * i(t) \end{aligned}$$

where $*$ is convolution and

$$w(t) = \frac{\sin(Bt/2)}{\pi t} e^{if_c t}$$

Thus combining everything, we have

$$c(t) = \frac{w(t)BkT_L - w(t) * i(t)}{a(t)}$$

This approach has some major realization drawbacks. Notice that $H(c(t)) \geq H(a(t))$, thus our spreading sequence actually contains *more* information than our information sequence. When we multiply $c(t)$ by $a(t)$, we cancel out our data symbols and transmit a signal with exactly the spectral characteristics we want. No actual data flows over the main channel, and everything passes through the side channel in which we convey the spreading code. Thus, this *ideal* approach is not realistic.

As a result, we must assume $i(t)$ and $a(t)$ are stationary, and sample them over a short period of time. From them, we compute $c(t)$ and quantize it into something we can represent in a finite number of bits to be communicated via our side channel. Such sampling will obviously degrade our performance, but is necessary to make the scheme practical.

Let τ_c be our spreading code's chip time and τ_s be our symbol time. If B_N is our narrow-band bandwidth, we must have

$$\tau_c > B_N \tau_s / B$$

in order to provide enough bandwidth expansion.

Thus, we must sample $c(t)$ every τ_c units of time, and we need at least τ_s / τ_c samples. More samples will provide a more accurate estimate and decrease interference. Any fewer and we won't get the necessary bandwidth expansion.

Assume we sample both the real and complex values of $c(t)$ with M-bit resolution. Our entire spreading code can be represented in a minimum of $MB/2B_N$ bytes. While this is not insignificant, it could be easily conveyed by a side channel, or the ITMA PHY header. For example, with 16 bytes of data we could accommodate 4-bit quantization for spreading a 2 MHz narrow-band signal to a 32 MHz wide-band signal.

Unlike OFDM, our capacity will remain unchanged. Each symbol is multiplied by a spreading code which may amplify some portions of the symbol and attenuate others. However, the average symbol power will remain unchanged, as compared to a traditional spreading code.

6. IMPLEMENTATION

To demonstrate the described spectrum shaping techniques, a MATLAB implementation was constructed. For OFDM, we implemented the subcarrier scaling techniques on a 64-subcarrier waveform.

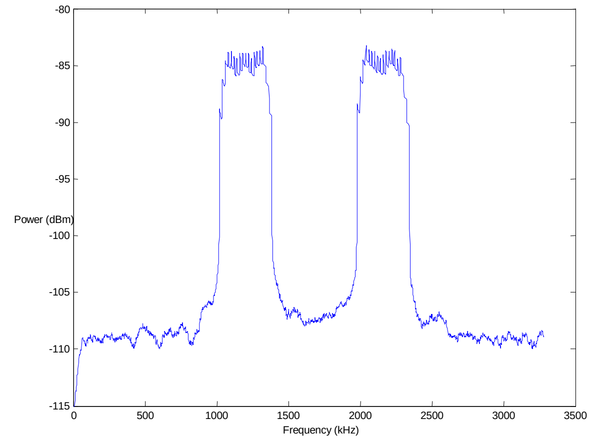

Figure 4 Shaped OFDM spectrum illustrating notch

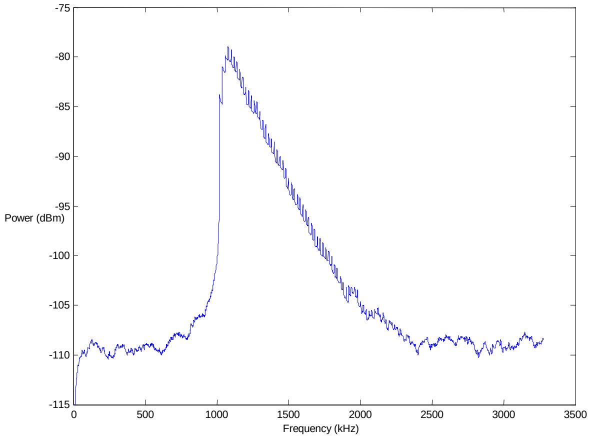

Figure 5 Shaped OFDM spectrum illustrating triangular shaping

Figures 4 and 5 depict two OFDM shaped waveforms. The first waveform zeros out subcarriers 17 through 48 of the 64 subcarriers, nulling the center half of the waveform. This type of waveform would be well suited for an environment where we wish to shape our signal around another to take advantage of noncontiguous free spectrum. The second shows some of the versatility of the technique, creating a triangular shape with the waveform.

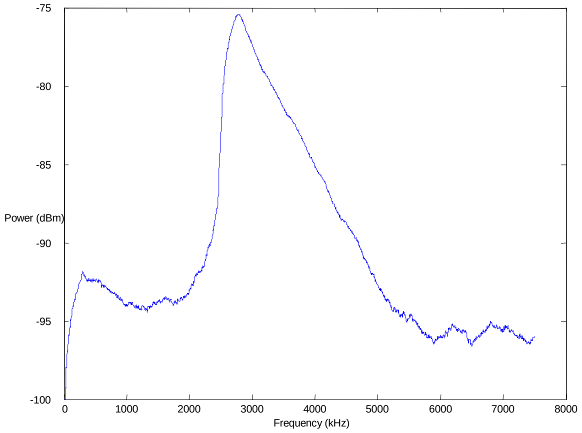

Figure 6 Shaped DSSS spectrum illustrating triangular shaping

Figure 6 performs the same triangular shaping using DSSS. Here we use spreading code $c(t) = \mathrm{F}^{-1}(10^{2-x})$ where x varied from 0 to 2, and a 256-bit inverse FFT was computed. The result was an 8-byte spreading code resulting in a power spectra triangular on a dBm scale. Certainly other shapes can also be created by specifying your spreading code in terms of your interference environment, rather than something constant.

7. CONCLUSION

Overall, these spectrum shaping techniques can help us "fill the regulatory gaps" in a particular interference environment. While the proposed FCC regulations only stipulate average interference over the transmission bandwidth, we can actually achieve the same or greater capacity by shaping our spectra.

This paper presented an initial analysis of applying spectrum shaping to OFDM and DSSS. Much research still needs to be done on implementing these ideas. In particular, a complete analysis of how quantization of our spreading codes affects the eventual waveform will yield important results on the viability of this approach. Additionally, the development of space-time codes appropriate to the OFDM scheme will be important if we hope to achieve anywhere near the theoretical channel capacity.

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