Cognitive Radio - An Adaptive Waveform with Spectral Sharing Capability

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Abstract— **The growth of wireless applications and spectral limitations are serious concerns for both the military and civilian communities. Cognitive Radio (CR) technologies expand spectrum efficiency using elements of space, time and frequency diversity that up to now have not been exploited. An Adaptive Waveform (AW) generation technique is presented which adapts to the changing electromagnetic environment and synthesizes waveform features in the frequency domain. Spectral coexistence with other applications is also addressed and can be accomplished in both static and dynamic environments. Bit Error Rate (BER) serves as the primary performance metric for evaluating and comparing AW processing with other waveforms and systems.**

I. INTRODUCTION

With the introduction of every new communication application, military or civilian, the spectrum becomes more and more congested. Even though the Federal Communications Commission (FCC) has expanded some unlicensed spectral bands, the present system uses the procedure formulated in 1920 where different frequency bands are assigned to different users or service providers and licenses are required to operate within those bands. Although spectrum may be allocated to specific users, this does not necessarily ensure it is being used most efficiently at all times. A recent survey showed that “on average” only two percent of allocated spectrum in the United States is actually in use at any given moment [1] and this percentage may be even lower in other countries. To exploit unused spectrum more efficiently in dynamically changing environments, we desire a communication system that adapts to rapidly changing environmental conditions while ensuring minimal, or at least manageable, interference is added to the existing users. Such a technology is termed the Cognitive Radio (CR). The CR idea was initially introduced by Joseph Mitola in his doctoral thesis entitled, “Cognitive Radio an Integrated Agent Architecture for Software Defined Radio”. A CR is defined as a communication system which has the ability to detect other users in the electromagnetic environment and then dynamically alter its power, frequency, modulation, coding and other parameters to efficiently utilize vacant spectrum while at the same time avoiding interference to existing systems [2, 3]. Even though the CR is a relatively new concept, the Defense Advanced Research Project Agency (DARPA) and the FCC have already embraced it. DARPA has funded the XG program, i.e., the next generation communication program, which has a primary goal to develop technologies that allow multiple users to share the spectrum and spectrally coexist while keeping mutual interference at a manageable level. Furthermore, the FCC has sponsored a CR technology workshop and in December 2003 issued a Notice of Proposed Rule Making (NPRM) requesting inputs on how CR systems can be realized. We present one adaptive waveform technique which shows promise as a viable candidate for enabling the CR concept.

Traditionally, communication waveforms are synthesized in time domain using preset frequency allocation(s) to the user(s). The fundamental idea behind the Adaptive Waveform Communication System (AWCS) is to avoid preset frequency use and operate dynamically over a chosen spectral region. Since AWCS waveforms are synthesized in the Transform Domain (TD) it is also referred to as “Transform Domain Communication Systems (TDCS)”. TDCS concepts were initially proposed by German [4] in a technical report completed for Rome Laboratory in 1988. Andren at Harris Corporation subsequently patented a Low Probability of Intercept (LPI) communication system in 1991 using transform domain signal processing [5]. The Air Force Research Laboratory (AFRL) and Air Force Institute of Technology (AFIT) adopted Andren’s framework for environmental sampling and waveform generation and German’s transmit signal processing method at the transmitter. Conventional time-domain matched filtering and Maximum Likelihood (ML) detection are used at the receiver. In the basic TDCS implementation, spectral interference or “other” signal presence is estimated using Fourier-based or other spectral estimation techniques. Once frequency bands containing strong interference or “other” signals are identified, typically through some form of threshold detection, those frequency bands (components) are selectively removed by “notching” prior to creating a time-domain Basis Function (BF) using the appropriate inverse transform (e.g., inverse DFT). Previous research has effectively applied this technique to avoid interference at the transmitter [6–8], versus more conventional methods which place the burden of interference suppression on receiver processing. In this paper we explore TDCS as a possible CR candidate

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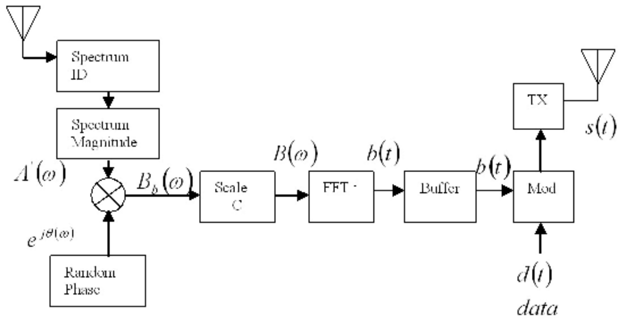

Fig. 1. TDCS Transmitter

II. TDCS BACKGROUND

Interference mitigation and the ability to reliably communicate in the presence of interference are important in all communication applications. In general, interference is mitigated at the receiver using some type of filtering and/or spectral spreading techniques. The fundamental idea behind TDCS is to "avoid" interference at the transmitter by not putting waveform energy at corrupted spectral locations. Assuming the receiver can then be designed to only "look" in the locations containing energy, desired signal energy loss due to filtering and receiver complexity can be reduced. This assumes that the transmitter and receiver are observing the same electromagnetic environment and thus produce similar spectral estimates and notches (identical in the ideal case). A brief overview of TDCS processing follows with more detailed implementation issues available in [6–8]

Figure 1 illustrates the fundamental building blocks involved in a TDCS transmitter. The process starts with environmental sampling over the system bandwidth. The spectral content of the environmental snapshot is then estimated using any existing techniques, e.g. periodogram, autoregressive linear predictive filtering, etc. To avoid interfering frequency bands, a hard limiting threshold is applied. Applying a threshold to the estimated spectrum generates a "clean" or interference free spectrum $A'(\omega)$. Amplitudes of interfering frequency components exceeding the threshold are set to zero ("nulled") and the remainder of the spectral components are assigned a value of one.

Following spectral estimation and notching, a multi-valued complex pseudorandom (PN) phase vector is generated of length equal to that of $A'(\omega)$. The phase vector is multiplied element-by-element with $A'(\omega)$ to produce the spectral vector $B(\omega)$. Application of the PN phase vector plays a key role in TDCS implementation because it ensures that the time domain signal has correlation properties similar to that of a noise signal. Linear Feedback Shift Registers (LFSR) can be configured to generate a maximum length, binary PN sequence. As shown in Figure 2, the maximum length sequence, or m-sequence, is generated using a LFSR. This in combination with an r-bit phase mapper is a uniform random number generator. Each snapshot of the m-sequence is mapped to one of 2^r complex phase points which are evenly spaced around the unit circle. In TDCS processing, the m sequence generated by LFSR has two important functions, 1) the PN phase generated using this m sequence is critical in the development of TDCS modulation schemes, as discussed in the next section, and 2) multiple access is implemented by assigning each user a unique primitive polynomial which results in a different m-sequence for each user.

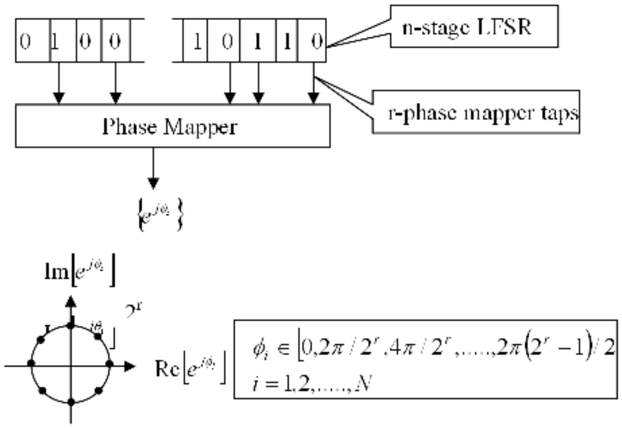

Fig. 2. TDCS Phase Mapping Process

$$s_1(t) = BF$$

$$s_2 = s_1\left(t - \frac{T_s}{2}\right)_T \tag{1}$$

Finally the spectral vector $B_b(\omega)$ is inverse Fourier transformed to produce the time-domain BF $b(t)$ which is subsequently stored and modulated by the data. The BF may be modulated using Binary antipodal or Cyclic Shift Keying (CSK). In antipodal signaling, a binary one is represented by the BF itself and a binary zero is represented by the negative of the BF. CSK modulation is a form of orthogonal modulation where cyclically time shifted versions of the BF are transmitted for each symbol as shown in (1). The BER for binary antipodal signaling is given by (2) and the BER for binary CSK is given by (3). Assuming perfect synchronization, TDCS receivers perform correlation of the received signal with M possible reference waveforms. The M correlator outputs are then compared and a symbol estimate produced based on relative weighting. Since TDCS waveforms are synthesized in transform domain it is often confused with other transform domain techniques such as Orthogonal Frequency Division Multiplexing and Multi-Carrier CDMA [9].

BPSK-Coherent Detection

$$P_B = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \tag{2}$$

BFSK-Coherent Detection

$$P_B = Q\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{3}$$

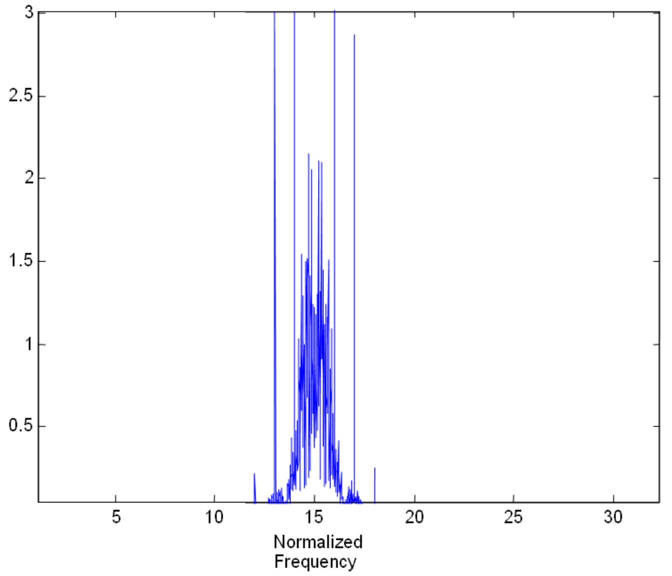

Fig. 3. TDCS Environmental snapshot of BFSK system operating at $f_c = 5.0Hz$

III. ANALYSIS AND SIMULATION OF SPECTRAL COEXISTENCE EFFECTS

Spectrum sharing or coexistence is defined as multiple systems or service providers (e.g., AT&T, Cingular, FM radio stations, etc.) sharing a spectral region while operating in the same geographic location. It is desirable that competing providers cause no (or manageable) interference to each other. This should not be confused with multiple users specifically designed to share communication resources. Multi-user or multiple access system analysis is beyond the scope of this paper and will be addressed in future work. Two cases of spectrum sharing are considered here, static and dynamic. Although both static and dynamic environments actually change over time, the dynamic environment is characterized as having changes which occur much faster than the static environment. Static systems in the environment are modeled as using Binary Phase Shift Keying (BFSK) and Binary Frequency Shift Keying (BPSK) using coherent detection. Their respective theoretical Bit Error Rates (BER) are given by (2) and (3) [10].

Figure 3 shows an environmental snapshot containing one BFSK user operating at a center frequency at 15.0 Hz. Figure 4 shows how the TDCS processing adaptively identifies usable spectrum by notching out the FSK spectrum. The resultant notch width and location are a function of both the spectral estimation technique employed and the threshold value used in the spectrum magnitude block in Figure 1.

Spectral estimation and adaptive notching is one of the important building blocks in minimizing TDCS interference to other users in the environment. Previous work has considered the periodogram, autoregressive (AR) filtering, and wavelet transform for spectral estimation in TDCS processing with both the AR and wavelet techniques proving quite effective for interference avoidance [7, 11].

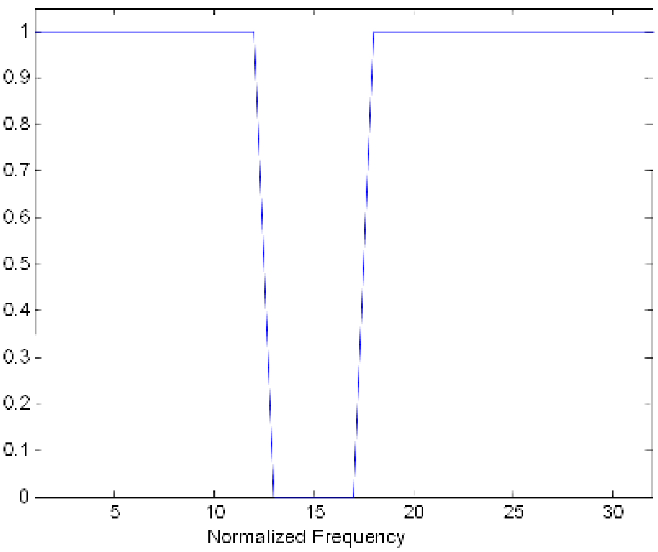

Fig. 4. TDCS usable spectrum avoiding BFSK system

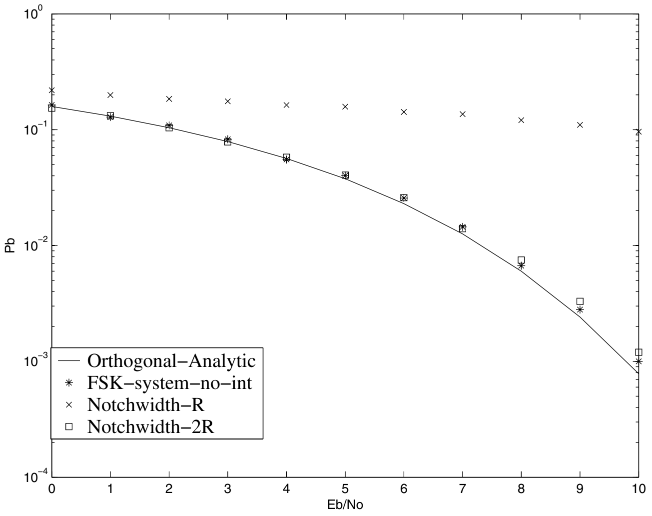

Fig. 5. TDCS notch filter selection

Results in this paper are generated using a 10th-order AR model to show the significance of TDCS spectral estimation and notching in spectral coexistence. Figure 5 shows BFSK BER performance when coexisting with a TDCS operating at different power levels $\left(\frac{E_b}{N_o}\right)$ and different notch widths. The legend in the figure is as follows: 1) 'Orthogonal-Analytic' represents theoretical BER for BFSK system, 2) 'FSK-system-no-int' represent a BFSK system without TDCS 3) 'Notchwidth-R' and 'Notchwidth-2R' represents BFSK system with TDCS applying differnt notch filters. To show the effectiveness of TDCS spectral shaping and filtering two notching filters $f_c \pm R$ and $f_c \pm 2R$ where f_c and R are the center frequency and data rate of BFSK system. It is obvious from Figure 5 that TDCS interference to BFSK system is much greater when the filter size is R and by using filter size of $2R$ BFSK performance improves at the cost of TDCS usable

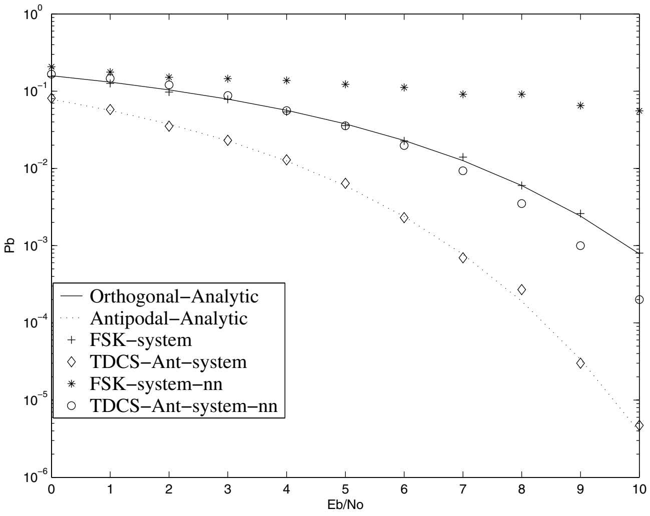

Fig. 6. Spectrum Sharing of TDCS Antipodal and BFSK systems

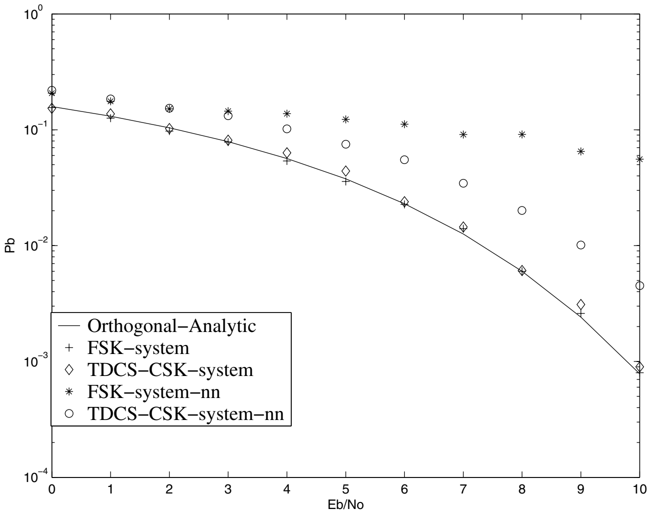

Fig. 7. Spectrum Sharing of TDCS CSK and BFSK systems

bandwidth. The simulation results presented in the remainder of this paper uses notch filter size of $f_c \pm 2R$.

A. Static Single System Environment

Figure 3 shows the environment consisting of one system with the resultant spectral notch and usable spectrum from the TDCS process shown in Figure 4. Results for the addition of a TDCS are shown in Figures 6 and 7. The TDCS is modeled as using each of the binary modulation techniques described earlier (CSK and antipodal signaling). The conventional system in the environment is again modeled as BFSK modulation. The power levels of the BFSK and TDCS signals were set to establish an $\frac{E_b}{N_o} = 15dB$ when acting as interference. The legend in figure 6 is explained as follows: 1) 'Orthogonal-Analytic' represents theoretical BFSK BER, 2) 'Antipodal-Analytic' represent theoretical TDCS BER using antipodal signaling, 3) 'FSK-system' and 'TDCS-Ant-system' represent simulated BFSK and TDCS antipodal BER with spectral notching applied, and 4) 'FSK-system-nn' and 'TDCS-system-nn' are results with no notching applied.

Similarly, the legend in figure 7 is explained as follows: 1) 'Orthogonal-Analytic' represents theoretical BER for BFSK and TDCS CSK modulations, 2) 'FSK-system' and 'TDCS-CSK-system' represents BFSK and TDCS CSK BER with spectral notching applied, and 3) 'FSK-system-nn', and 'TDCS-CSK-system-nn' are simulated results with no notching applied. As indicated in figures 6 and 7, the performance of all three waveforms, BFSK, TDCS with antipodal signaling, and TDCS with CSK modulation, degrades as expected when TDCS does not employ notching. With notching applied using a notch width of $2R$, interference avoidance and spectral sharing improve such that simulated BERs are consistent with the theoretical results.

B. Static Multiple System Environments

Thus far, TDCS performance has been demonstrated with a single system in the environment. Multiple systems are now introduced to further demonstrate TDCS potential as a spectrum scavenger. Figure 8 shows a spectrum consisting of two systems, one modeled as BPSK and the other as BFSK operating at a center frequency f_c of 5.0 Hz and 15.0 Hz, respectively. Figure 9 shows the resultant TDCS spectral notch generated by the TDCS. Analytic BERs for BPSK and BFSK are given by (2) and (3), respectively (note that the analytic BER expression for TDCS antipodal signaling is the same as BPSK and TDCS with binary CSK modulation is same as BFSK). The BER results in Figure 10 show how the TDCS was able to coexist with other BFSK and BPSK systems without inducing performance degradation.

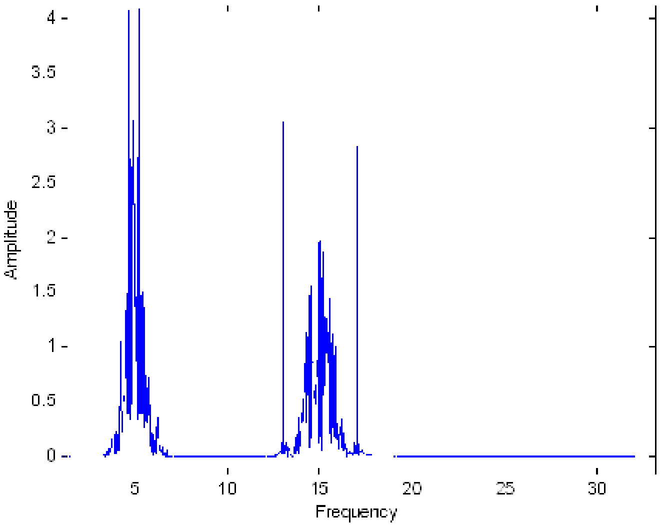

Fig. 8. Environmental snapshot with multiple BFSK and BPSK systems

C. Dynamic Environment

The dynamic environment is modeled as containing two systems, the TDCS and a Frequency Hopper using BFSK data modulation (FH-BFSK). The spectrum was divided into eight

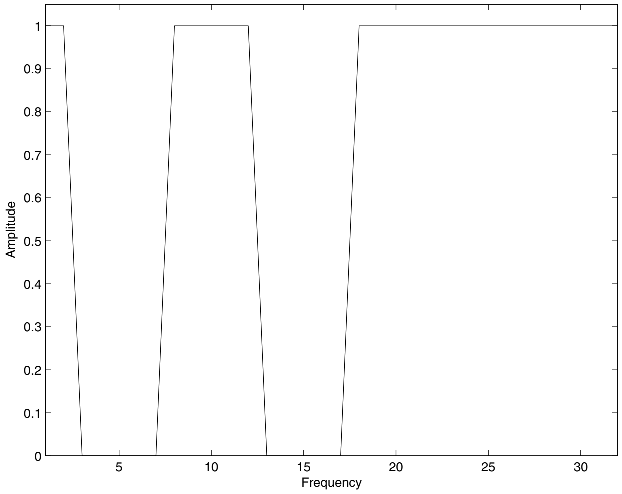

Fig. 9. Resultant TDCS usable spectrum avoiding BFSK and BPSK

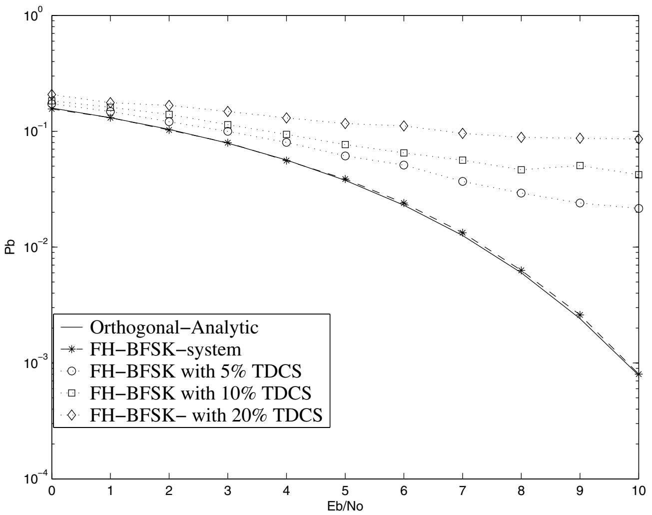

Fig. 11. Performance of FH-BFSK in a dynamic environment

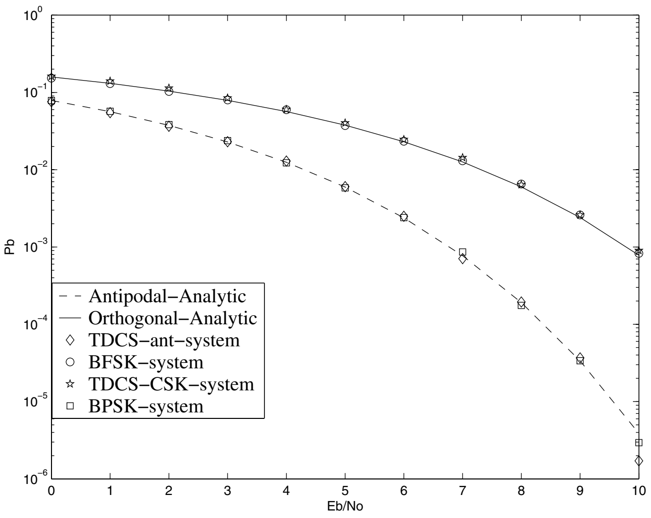

Fig. 10. Spectrum Sharing TDCS, BFSK and BPSK systems

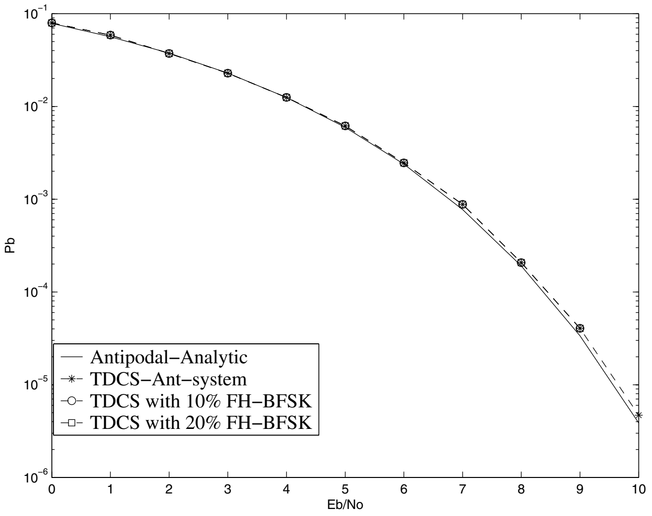

Fig. 12. Performance of TDCS in a dynamic environment

frequency bins with the FH-BFSK system randomly hopping in accordance with a pseudorandom code. The hop rate is 100 bits/hop (sometimes referred to as slow hopping) and thus for a data rate of 3K bits/sec the hop rate is 30 hops/sec.

Two dynamic environment cases were considered. In both cases, the TDCS is assumed to have *a priori* knowledge of the FH-BFSK hopping pattern (sequence and ordering of hop frequencies). However, in the first case the TDCS is perfectly time synchronized with the FH-BFSK system and in the second case it is not. In the first case, perfect synchronization implies that when the FH-BFSK system hops to a new center frequency, the TDCS adapts in a timely fashion such that a new BF is generated which perfectly matches FH-BFSK characteristics and ideal spectrum sharing is achieved. For the second asynchronous scenario, the TDCS again has *a priori* knowledge yet it is not perfectly synchronized, i.e., as the FH-BFSK system hops to a new center frequency, the TDCS system experiences a delay in BF generation and thus uses a previous BF for current environmental conditions. This delay results in mutual TDCS/FH-BFSK interference for a duration equaling the time it takes the TDCS to generate a current BF. Thus, the delayed TDCS response has resulted in 1) unused spectral regions and 2) increased mutual interference regions.

Performance of FH-BFSK in the presence of a TDCS system is shown in figure 11. When both systems are perfectly synchronized the BER of 'FH-BFSK-system' follows the analytic results. When TDCS experiences some delay (represented as a percentage of hop rate) in adapting to the new spectral environment, the TDCS induces more interference into the FH-BFSK system for the duration of the delay. The resultant FH-BFSK performance degradation is shown in figure 11 as 'FH-BFSK with 5% TDCS', 'FH-BFSK with 10% TDCS' and 'FH-BFSK with 20% TDCS', corresponding to delay values of 5%, 10% and 20% of the hop rate, respectively. The figure clearly shows that FH-BFSK performance is severely impacted with as little as 5% delay in BF estimation and utilization. Corresponding TDCS performance in the presence of the FH-BFSK system under these same conditions is shown in figure 12. From figure 12 results it is evident that TDCS performance is minimally affected by FH-BFSK interference resulting from delayed BF generation. The reason behind the performance degradation differences can be linked to fundamental system operation. For the FH-BFSK system, the TDCS acts as broadband interference during interfering time intervals and spans the entire FH-BFSK spectrum. Whereas, the FH-BFSK system acts as partial band interference and only a portion of the TDCS spectrum is affected. One potential solution for mitigating TDCS interference to FH-BFSK systems under these conditions might involve the introduction of guard time during FMW generation.

IV. CONCLUSION

In this paper we discuss the cognitive radio as a possible solution to address the spectral congestion problem. An adaptive waveform processing technique called TDCS is introduced as a possible candidate for achieving cognitive radio goals. Several simulation scenarios are considered to demonstrate the spectral coexistence concept. Given results presented, future research needs to address: 1) TDCS coexistence in a more realistic environment containing perhaps both licensed and unlicensed users 2) TDCS and other users in multiple access environments, and 3) TDCS and other users in a multipath-fading environment.

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