

WAVELET DOMAIN COMMUNICATION SYSTEM (WDCS) INTERFERENCE AVOIDANCE CAPABILITY: ANALYTIC, MODELING AND SIMULATION RESULTS

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ABSTRACT

A recently proposed wavelet domain communication system (WDCS) using transform domain processing is demonstrated as having enhanced interference avoidance capability under adverse environmental conditions. The proposed WDCS and its response to various interference scenarios are modeled and simulation results obtained using MATLAB®. Relative to a system without suppression capability and a developmental, Fourier-based transform domain communication system (TDCS), the WDCS provides improved/comparable bit error performance in several interference scenarios – single-tone, multiple-tone, swept-tone, and partial-band interference is considered. The system was evaluated using an E_b/N_o of 4.0 dB and interference energy-to-signal energy (I/E) ratios ranging from 0 dB to 16.0 dB. For antipodal data modulation cases, the average WDCS bit error performance improvement was 12.4 dB relative to a system without suppression capability, approximately equaling TDCS results. For orthogonal data modulation, average WDCS improvement was 5.7 dB versus 6.8 dB for the TDCS. Collectively, these results indicate the proposed WDCS is a viable option for interference avoidance communications.

INTRODUCTION

Reliable communication is a concern in both military and commercial sectors. With respect to digital communications, a system fails to be reliable when too many bits are received in error. Communication channel interference is a major contributor to increased bit error. Such interference can be broadly classified as either intentional or unintentional. With most military communication systems, the ability to operate in the presence of both unintentional and intentional (jamming) interference is a necessity; considerable research effort has been directed toward securing this capability. One developmental system has demonstrated improved interference avoidance capability, namely, the transform domain communication

system (TDCS) [3, 4, 6] – the WDCS architecture presented here is based on this previous TDCS work.

All systems must contend with unintentional channel interference, including additive white Gaussian noise (AWGN), generally defined as having a constant power spectral density (PSD) for all frequencies. Other sources of unintentional interference include other systems operating within, or producing harmonic energy within, the spectral region of interest, e.g., radio stations, television stations, cellular communications, navigational aids, airport radar, etc. Intentional interference is an energy source specifically directed at a communication system with the intent of disrupting (perhaps completely) effective operation; such interference is primarily associated with military applications. The focus of this work is such that the ‘nature’ of the interference (intentional or unintentional) is inconsequential.

Interference may be broadly classified as narrowband or wideband depending on the amount of bandwidth, with respect to the system's bandwidth, occupied by the interference. Within the narrowband classification, there are four subcategories considered: single-tone, multiple-tone, swept-tone, and partial-band. Single-tone interference has energy at one frequency (ideally). Multiple-tone interference consists of several, single frequency tones dispersed throughout the system bandwidth. Although multiple-tone interference covers more frequencies, given a finite amount of interference energy (power), each tone contains less energy per frequency. Swept-tone interference is manifest as a single-tone changing frequency over time, losing time-stationary characteristics. Partial-band interference contains energy over a continuous range of frequencies, typically a fraction of the system bandwidth. In cases where the interference energy is spread equally over a continuous range of frequencies exceeding the system's bandwidth, the system noise floor is effectively raised.

METHODOLOGY

The recently proposed WDCS architecture is based on previously demonstrated TDCS technology [3] that utilized a Fourier transform. The Fourier transform provides orthogonal signal decomposition with each coefficient representing energy at a particular frequency. The Wavelet transform is also orthogonal, but each coefficient ($d_{i,j}$) represents a time-frequency bin, as shown in Figure 1. As indicated, the wavelet coefficients are grouped into sub-bands, each reflecting a different level of scale or resolution detail. These properties (orthogonality, time-frequency localization, and multi-resolution) were exploited in previous WDCS research, which clearly demonstrated the potential of using wavelet techniques to improve transform domain performance [2].

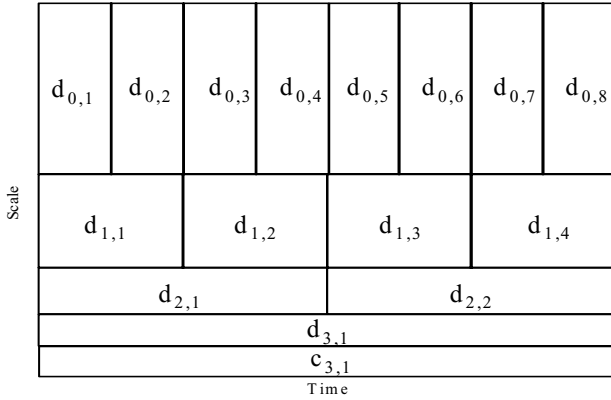


Figure 1. Time/Scale Representation of Wavelet Transform [1].

As indicated by the shaded regions in Figure 2, only relatively simple modifications to the basic TDCS architecture were required to implement the WDCS under consideration. Basic WDCS processing is as follows. Using the Wavelet transform, the WDCS transmitter estimates the electromagnetic spectrum and determines a spectral notching threshold based on estimated characteristics. The power in each wavelet detail sub-band is compared to the noise power of the environment. When the sub-band power exceeds that of the noise by a factor of 20% (a factor determined to provide acceptable results in previous work [2]), interference is declared present and the entire detail sub-band is nulled-out (spectral coefficient weights set equal to zero). Sub-bands with power not exceeding the threshold are retained (coefficients assigned a value of one). A pseudo-random (PR) phase weighting is then applied to each coefficient creating a “notched” vector of complex elements having uniform magnitude and PR phase. The elements are then

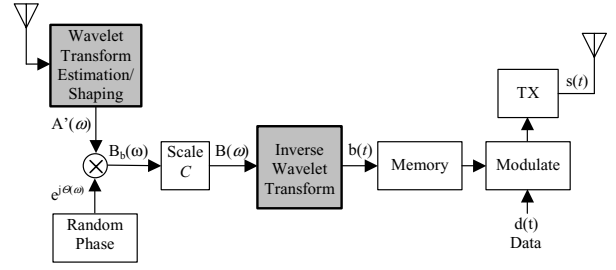


Figure 2. WDCS Transmitter Block Diagram [2].

scaled and inverse Wavelet transformed to create a time-domain waveform called a *Basis Function*. The stored basis function (BF) waveform is subsequently data modulated and transmitted. Assuming the WDCS receiver can remotely generate an identical (or nearly identical) basis function, the receiver uses the generated basis function to estimate communication symbols in the same fashion as a typical communication system, i.e., matched filtering or correlation.

Two forms of digital data modulation were considered for this research: antipodal and orthogonal. Antipodal modulation is a form of binary modulation that uses the BF as one symbol, $s_1(t)$, and the negated BF as the second symbol, $s_2(t)$, per (1).

$$\begin{aligned} s_1(t) &= \text{Basis Function (BF)} \\ s_2(t) &= -s_1(t) \end{aligned} \quad (1)$$

For orthogonal signaling, symbols are geometrically viewed as being separated by 90° , versus the 180° separation of antipodal signaling. Fundamentally, the smaller communication symbol separation produces larger bit error probabilities while allowing for M -Ary signaling. The *bit error probability*, P_b , for binary signaling over an AWGN channel is given by (2), where E_b is the average energy per bit, N_0 is the noise power density, and the Q -function is the Complementary Error Function [5].

$$P_b = Q\left(\sqrt{\frac{\alpha E_b}{N_0}}\right) \quad \begin{aligned} \alpha = 1 &\Rightarrow \text{Orthogonal} \\ \alpha = 2 &\Rightarrow \text{Antipodal} \end{aligned} \quad (2)$$

As introduced in preliminary WDCS research, Binary Cyclic Antipodal Shift Keying (BCASK) was the form of orthogonal modulation implemented here [2]. As reported, BCASK was identified as a special modified form of Cyclic Shift Keying (CSK) obtained by 1) dividing the basis function into two halves, 2) negating one-half of the basis function values, and then, 3) reversing the order of the basis function halves. In

conjunction with the proposed WDCS architecture, the BCASK data modulation proved to be very effective, producing bit error results consistent with orthogonal modulation performance characterized by (2).

RESULTS

For validation with previous WDCS work, simulations were run for all models in the absence of interference. In each simulation, the environment was observed for a length of time equaling 100 data bits. Following BF generation, data modulation, signal transmission, and reception, the communication symbols were demodulated and the total number of bit errors recorded. All simulations were terminated when the total number of bit errors exceeded 500 – an empirically chosen number shown sufficient in previous research [2]. Simulated communication performance for antipodal modulation nearly matched theoretical, antipodal signaling bit error performance, reflecting a mean absolute error of 8.9×10^{-4} and standard deviation of 1.1×10^{-3} .

WDCS performance was verified against theoretical performance for scenarios containing interference *without spectral shaping*, i.e., no wavelet detail thresholding or nulling. These results are important for establishing a comparative baseline for analyzing interference avoidance capability. Here, theoretical performance is estimated assuming constant interference power density over the system bandwidth, effectively adding to the system noise floor and impacting bit error performance of (2).

Figure 3 shows antipodal signaling results. The partial band-interference results (10% and 70%) closely approximate the theoretical antipodal performance for all I/E values considered. Tone interference results are less

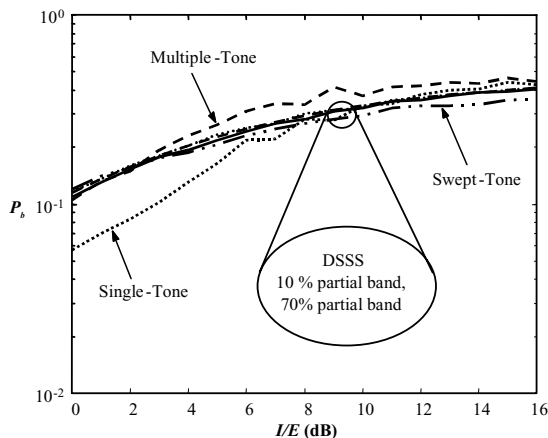


Figure 3. Antipodal Signaling Interference Results - No WDCS Spectral Shaping.

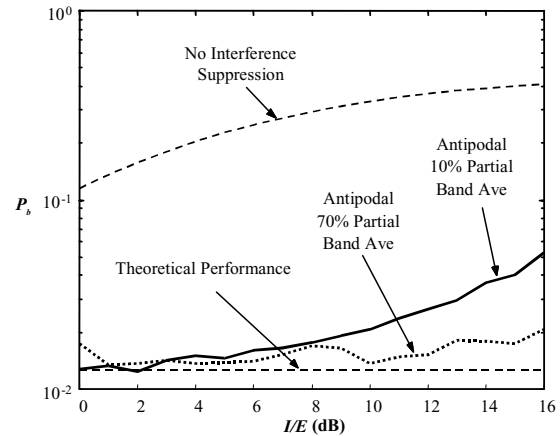


Figure 4. Partial-Band Interference: Antipodal Modulation with Spectral Shaping.

favorable, e.g., the single-tone case exhibits considerable deviation at lower I/E values – anticipated results given the tone energy is concentrated at a particular frequency which violates the constant interference power density assumption used to generate theoretical performance.

Given model performance was verified with and without interference present, a series of simulations were run to include WDCS spectral shaping – effectively a test to demonstrate WDCS “interference avoidance” capability. Here, effectiveness is manifest as bit error performance improvement relative to the data presented in Figure 3. Partial-band interference scenarios were first considered.

Interference scenarios for a WDCS using antipodal data modulation and spectral shaping (detail sub-band nulling) were first considered. The partial-band interference results are presented in Figure 4. By comparison with Figure 3, the results clearly indicate the achievable bit error improvement (interference avoidance capability) provided by the WDCS. Although improvement decreases as I/E increases, the WDCS is still effective by comparison with the case using no spectral shaping. The single-tone and multiple-tone interference results are shown in Figure 5. As in previous interference scenarios, simulation results closely approximate the theoretical performance of an interference-free environment.

The final interference scenario included the presence of swept-tone interference. In previous TDCS research, swept-tone interference could not be accurately estimated due to the specific spectral estimation algorithm used [3]. Thus, TDCS performance improvements resulting from spectral shaping could not be investigated for the swept-tone interference.

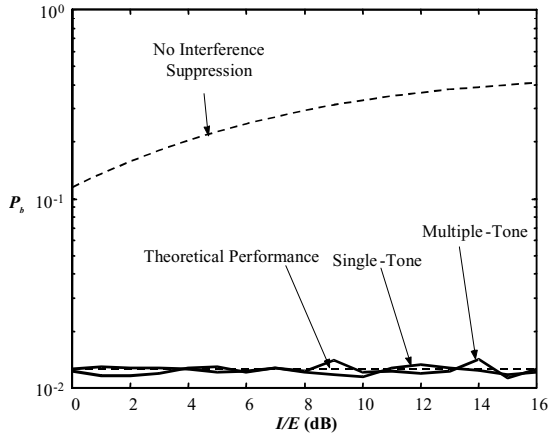


Figure 5. Single-Tone and Multiple-Tone Interference: Antipodal Modulation with Spectral Shaping.

Swept-tone interference results are shown in Figure 6. As indicated, the WDCS performs very well against swept-tone interference when using antipodal data modulation and spectral shaping. At first glance, the apparent discontinuity in the P_b curve for I/E values between 7.0 and 8.0 dB is perhaps disconcerting, potentially leading one to believe the WDCS model is malfunctioning. However, after several investigative simulation runs, it was discovered the data discontinuity actually results from the WDCS thresholding and detail nulling process, i.e., between I/E of 7.0 and 8.0 dB interference power increases sufficiently such that one additional wavelet detail sub-band is nulled-out. This causes a drastic reduction in interference effects and the sudden improvement in P_b as indicated in Figure 6.

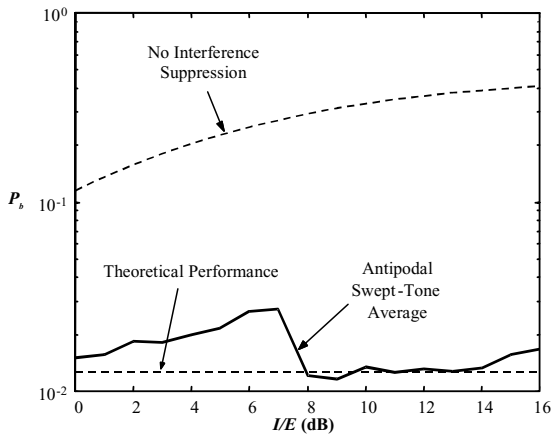


Figure 6. Swept-Tone Interference: Antipodal Modulation with Spectral Shaping.

The previous interference results demonstrate the WDCS can successfully mitigate the effects of multiple types of interference. However, to compare WDCS interference avoidance capability with other systems, a metric is introduced to quantify how much improvement the WDCS offers. As defined in previous research and adopted for this analysis [3], an *Improvement Factor*, $I(I_E)$, is used to represent a measure bit error performance improvement (decrease) provided by the WDCS relative to a another interference suppression/avoidance system. For this research, improvement was characterized relative to 1) a system with no interference suppression capability, and 2) a developmental Transform Domain Communication System (TDCS). All characterizations were performed under identical scenarios. The *Improvement Factor* ratio is defined per (3) where $I_E = I/E$, $(P_b)_{WDCS}$ is the WDCS probability of bit error for a given set of conditions, and $(P_b)_{Reference}$ is the reference system probability of bit error under identical conditions.

$$I(I_E) = \frac{(P_b)_{Reference}}{(P_b)_{WDCS}} \quad (3)$$

The WDCS bit error performance for antipodal modulation was averaged over all interference scenarios and compared to a non-suppressing system under similar conditions. The average WDCS bit error performance for the antipodal modulation is plotted in Figure 7. From Figure 7, the average WDCS P_b for all interference scenarios using *antipodal data modulation* was approximately 1.6×10^{-2} over the range of I/E values considered, averaging approximately 1.0 dB above the

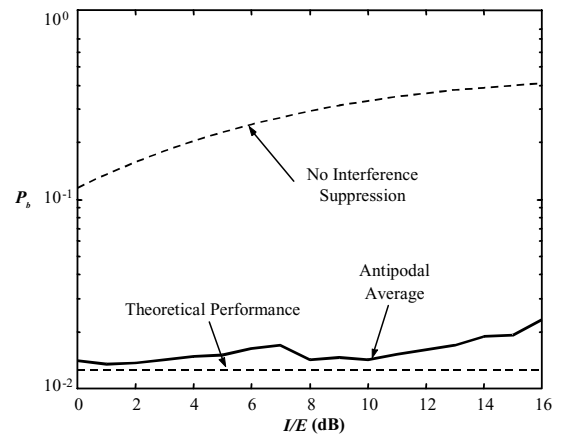


Figure 7. Average WDCS Bit Error Performance - Antipodal Data Modulation with Spectral Shaping

CONCLUSIONS

theoretical performance of 1.3×10^{-2} . In this case, the average WDCS improvement is 12.4 dB – approximately 0.4 dB poorer than the developmental TDCS [3].

Similar results were obtained for the WDCS using the orthogonal (BCASK) data modulation and identical interference scenarios. For brevity, orthogonal modulation results are not explicitly presented. Rather, a summary of results is presented for comparative analysis and completeness.

The average WDCS P_b for all interference scenarios using *orthogonal data modulation* was approximately 9.2×10^{-2} over the range of I/E values considered, averaging approximately 1.8 dB above the theoretical performance of 5.7×10^{-2} . The average WDCS improvement was 5.7 dB – approximately 1.1 dB poorer than the developmental TDCS improvement [3].

The overall difference in WDCS bit error performance for antipodal and orthogonal modulations was approximately 7.6 dB; the overall performance difference excluding the multiple-tone interference case was 6.5 dB. Theoretically, the difference in bit error performance between antipodal and orthogonal data modulations is approximately 6.6 dB as evident by considering (2) for fixed E_b/N_o .

Comparative analysis results are presented in Table 1, including a summary of average WDCS improvement for all interference scenarios considered.

Table 1. Summary of Average WDCS Improvement for $E_b/N_o = 4.0$ dB.

	Antipodal Modulation	Orthogonal Modulation	Orthogonal Minus Multiple-Tone
Ave P_b Above Theoretical Performance	1.0dB	1.8 dB	0.9 dB
Ave Imp. – No Suppress	12.4 dB	5.7 dB	6.8 dB
Ave Imp. – Dev. TDCS	-0.4 dB	-1.1 dB	0.0 dB

Simulation results indicate the recently proposed WDCS offers significant interference avoidance capability. Bit error performance analysis for several interference scenarios, including single-tone, multiple-tone, swept-tone, and partial-band interference, revealed the WDCS system is highly capable of estimating and mitigating interference effects. WDCS performance was simulated using MATLAB® at an average signal bit energy-to-noise power spectral density (PSD) level (E_b/N_o) of 4.0 dB and average interference-to-average signal energy (I/E) levels ranging from 0.0 dB to 16.0 dB. A bit error improvement metric, defined as the ratio of average bit error performances (reference system over WDCS), was introduced to provide a metric for comparing system performances over the range of I/E values considered. For antipodal data modulation, the average bit error improvement was 12.4 dB, similar to the TDCS. Using binary orthogonal (BCASK) data modulation, the average bit error improvement was 5.7 dB, slightly less than the TDCS.

BIBLIOGRAPHY

- [1] Burrus, C. Sidney, et. Al. *Introduction to Wavelets and Wavelet Transforms: A Primer*, New Jersey: Prentice Hall, 1998.
- [2] Klein, Randall W., et. al., "Performance Characterization of a Proposed Wavelet Domain Communication System (WDCS)," 5th World Multi-Conference on Systemics, Cybernetics and Informatics, *SCI '01*, July 2001.
- [3] Radcliffe, Rodney A. and Gerald C. Gerace, "Design and Simulation of a Transform Domain Communication System," *MILCOM '97*, October 1997.
- [4] Roberts, Marcus L., et. al., "Initial Acquisition Performance of a Transform Domain Communication System: Modeling and Simulation Results," *MILCOM '00*, Oct 2000.
- [5] Sklar, Bernard L. *Digital Communications: Fundamentals and Applications*, New Jersey: Prentice Hall, 1988.
- [6] Swackhammer, Patrick J., et. al., "Performance Simulation of a Transform Domain Communication System for Multiple Access Applications," *MILCOM '99*, Nov 1999.

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