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# Performance Evaluation of Cognitive Interference Channels Using a Spectrum Overlay Strategy

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# Performance Evaluation of Cognitive Interference Channels Using a Spectrum Overlay Strategy

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## Abstract

The use of cognitive radios (CR) and cooperative communications techniques may assist in interference mitigation via sensing of the environment and dynamically altering communications parameters through the use of various mechanisms - one of which is the overlay technique. This report provides a performance analysis of an interference channel with a cognitive transceiver operating in an overlay configuration to evaluate the gains from using cognition. As shown in this report, a cognitive transceiver can simultaneously share spectrum while enhancing performance of noncognitive nodes via knowledge of the communications channel as well as knowledge of neighboring users' modulation and coding schemes.

## 1.0 Introduction

As NASA future mission plans continue to evolve, new technologies and capabilities will be introduced into the space communications architecture to accommodate the anticipated mission needs. The envisioned future architecture will include new technologies such as optical communications, and will be more inter-networked in nature with user missions communicating over various architectural elements, including relay and surface assets. The implementation of cognitive communications systems within the architecture offers the potential for improved automation and efficiency. These potential advantages as well as the risks and complexities are currently under study and evaluation using test platforms such as the SCaN Testbed (Ref. 1).

Additionally, frequency spectrum allocations for users have become increasingly crowded with studies indicating that spectrum is not used efficiently. Regulatory bodies have traditionally used an approach of simply dividing the spectrum into distinct bands and allocating to users based on specific needs, rather than issuing spectrum allocations in a more dynamic and resource-efficient manner. Further, the Federal Communications Commission (FCC) initiated a Spectrum Efficiency Working Group (SEWG) in 2002 to evaluate the usage of radio spectrum and issued recommendations for improved efficiency. One result of this recommendation was the use of cognitive radio, which can intelligently sense the spectrum usage within its operational environment, and utilize the spectrum in a manner that is effective for its own purposes while minimizing interference with other licensed and nonlicensed users (Refs. 2 and 3).

The determination of achievable rate regions for cognitive radio channels using an information-theoretical approach has been thoroughly researched within the literature. These studies investigated various overlay mechanisms, such as rate splitting, cooperative relaying, and coding techniques such as Gel'fand-Pinkser and Dirty Paper Coding to evaluate theoretical rate limits. In some cases, noncausal message passing, referred to as the genie-aided cognitive radio channel, is included as a manner to evaluate the upper bound of the capacity region (Refs. 2 to 8).

The intent of this report is to investigate the advantages, in terms of enhanced bit error rate performance and spectrum utilization, of using a cooperative relaying mechanism for interference mitigation while also including the practical constraint of message passing that occurs over physical channels with nonnegligible attenuation and delay effects. As a preliminary effort, this analysis considers a two-transmitter and two-receiver interference channel configuration to evaluate the benefits of cognition. This preliminary study may be extrapolated to multiple transmitter and multiple receiver configurations to evaluate various mission use cases, such as multinode operations near the International Space Station or on a planetary surface. Custom MATLAB (The Mathworks, Inc., Natick, MA) scripts were used to perform the necessary computations for evaluating the attributes of the communication environment.

Follow-on efforts of this research may expand beyond physical-layer optimization strategies to encompass a broader range of optimization areas spanning multiple layers of the Open Systems Interconnection (OSI) protocol model. These areas include intelligent networking and routing, system-level intelligence, intelligent radio platforms, and others. Efforts to enhance cognitive communications capabilities is envisioned to benefit many user applications, including satellite communications systems, as well as terrestrial wireless systems. This can result in increased data return, new science observation capabilities, improved asset and resource efficiencies, and enhanced overall user experience.

Section 2 of this report provides a brief overview of cognitive radios in terms of functionality, operational paradigms, and intended benefits. Section 3 provides a description of the cognitive communication scenario under study and describes the assumptions, relationships, and analysis methods. Section 4 provides a description of the analysis results, and Section 5 provides concluding remarks.

## 2.0 Cognitive Radios and Operational Paradigms

At the physical and link layers of the OSI protocol model, various optimization mechanisms are used to enhance performance of communications conditions by altering parameters such as coding and modulation schemes. Additionally, the implementation of spectrum sensing and interference avoidance mechanisms are used to exploit use of unused portions of the radio spectrum. These physical-layer optimization methods and their general functionality are briefly summarized in this section.

A cognitive radio exploits information observed about its environment to improve spectrum utilization. This information may include knowledge concerning the activity of other nodes (cognitive and noncognitive) that share radio spectrum with the cognitive device. This allows the sharing of radio spectrum with concurrent users in a manner that strives to minimize or eliminate interference. Based on the information sensed about its environment, cognitive radio systems may use the underlay, overlay or interweave approach to share the spectrum with other cognitive and noncognitive users (Ref. 2).

### 2.1 Underlay Paradigm

The underlay paradigm requires transmissions from the cognitive device to occur only if the interference level observed by the primary (noncognitive) users is below a specified threshold. Meeting this minimum interference requirement may be achieved by focusing transmissions away from primary users (via directional antennas), or by using spreading techniques that reduce the signal level to below the required interference threshold. Spreading techniques may include spread-spectrum (e.g., Code Division Multiple Access) or ultra wideband (UWB) transmission, for example. The signal may then be de-spread at the receiving node.

### 2.2 Interweave Paradigm

In the interweave mode of operation, the cognitive radio periodically monitors the radio channel to find unused portions (or “white spaces”) of the radio spectrum and makes a decision on whether or not to exploit that unused spectrum for its own communications needs. If exploited, the cognitive system may transmit without power constraints since the portion of the spectrum is currently unused and will likely not cause any interference to primary (i.e., licensed) users. The interweave mode of operation was conceived after the FCC conducted studies and discovered that significant portions of the radio

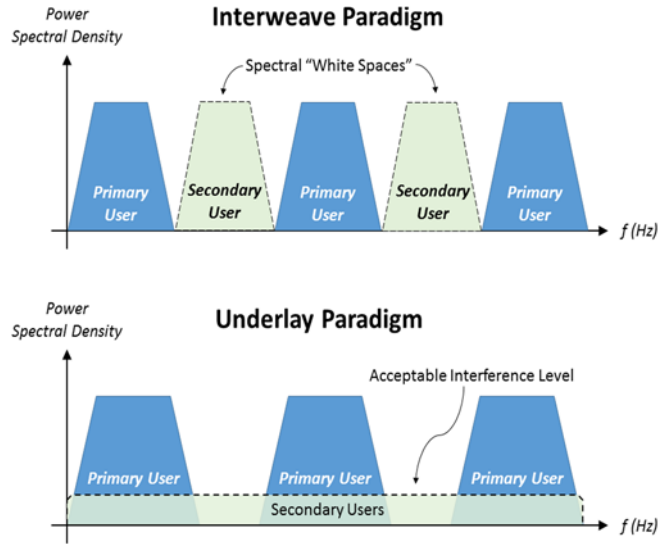


Figure 1.—Overview of interweave and underlay spectrum usage.

spectrum were not used most of the time. This allows cognitive users to sense and utilize these spectrum holes. Figure 1 provides an illustration of the underlay and interweave paradigms.

### 2.3 Overlay Paradigm

Overlay paradigm operates in a manner such that a cognitive system has knowledge of noncognitive system’s messaging and/or encoding schemes. From this knowledge, the cognitive system can assist the noncognitive user in relaying its transmissions in instances of interference or fading, while also using the communications medium for its own purposes. The cognitive system could also potentially cancel the effect of interference by receiving the noncognitive user’s transmission and using signal processing and/or encoding techniques to retransmit the information to the receiver. The overlay paradigm is applicable to both licensed and unlicensed spectrum bands since its operation does not incur interference with other users and may even improve performance during instances of interference or fading (Refs. 2 and 3).

In any of the aforementioned interference mitigation schemes, a cognitive radio must sense its environment to determine its most appropriate course of action. The number of antennas and the respective configuration depends on the interference scheme. For this study, a simple two transmitter receiver pair network using the overlay paradigm is evaluated in terms of benefits of cognition. The following sections describe the scenario and provide a description of the analysis results.

### 3.0 Procedures and Analyses

Channel capacity is defined as the supremum over all rates (expressed in bits/channel use) for which reliable communication may take place. The Shannon-Hartley Capacity Theorem shows that system capacity of a channel with additive white Gaussian noise (AWGN) is related to the average received signal power,  $P$ , average noise power,  $N$ , and system bandwidth,  $B$  (Ref. 8). Shannon proved from this theorem that it is theoretically possible to transmit information over the channel at any rate,  $R$ , with an arbitrarily small error probability given that  $R \leq C$ . The general capacity relationship for a bandwidth-limited channel is stated as:

$$C = B \log_2 \left( 1 + \frac{P}{N_0 B} \right) \quad (1)$$

Clearly, channel capacity is related to system bandwidth and power. Additionally, the statistics and dynamics of the channel (i.e., AWGN versus fading channel), availability of Channel Side Information (CSI) at the receiver and/or transmitter also play a part in determining channel capacity (Ref. 3).

Capacity is often challenging to determine, and in many cases the evaluation of inner and outer bounds of the capacity region may be more easily calculated. This is particularly true even in simple cases. An example may include a channel consisting of two independent transmitters communicating independent messages to two independent receivers. While the channel capacity region is known in certain cases, the general capacity region, despite promising recent advances remains unsolved (Ref. 7).

Extensive analysis has been described in the literature to determine the capacity region of cognitive communication networks. Oftentimes impractical assumptions, such as noncausal message passing from primary to secondary users (i.e., the genie assumption) is considered while evaluating theoretical data rate limits. Some studies have suggested that the benefits of cognition disappear if the genie assumption is factored into the analysis (Ref. 4). Therefore, the evaluation of message sharing occurring through actual physical channels is a worthwhile consideration.

The intent of this analysis is to determine the gains from including cognition at one of the transmitting nodes within the communication network while also including practical considerations such as causal message passing between noncognitive and cognitive nodes. This study evaluates the benefits of cognition for a simple two-transmitter and two-receiver interference channel.

In general, a channel output  $Y$  is related to the input  $X$  according to the equation  $Y = hX + N$  where  $h$  is a fading coefficient (often modeled as a Gaussian random variable), and  $N$  is the noise component which is typically modeled as Gaussian-distributed with zero mean and unity variance, i.e.,  $N \sim N(0, 1)$ . For all channel considerations, an average input power constraint  $E[|X|^2] \leq P$  is assumed. For an AWGN channel,  $h$  is considered a fixed and known constant. For fading

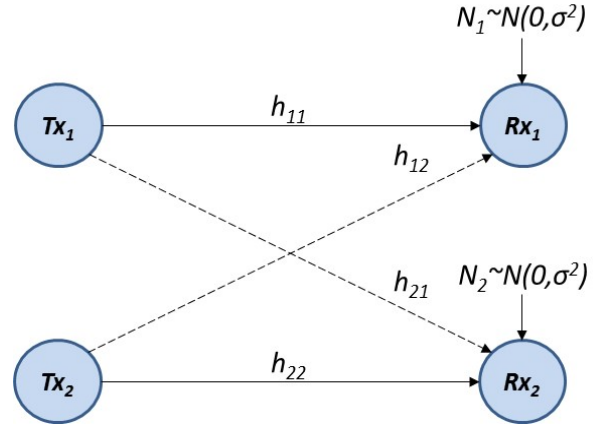


Figure 2.—Interference channel.

channels,  $h$  varies over time, and capacity is determined based on the rate at which the channel gain changes over time, i.e., fast-fading or slow-fading (Ref. 7).

An interference channel is described as containing two transmitters ( $Tx$ ) and two receivers ( $Rx$ ). The first transmitter,  $Tx_1$ , wishes to send information to the first receiver,  $Rx_1$ , without concern for what the second receiver,  $Rx_2$ , receives or is able to detect; this is similar for  $Tx_2$  and  $Rx_2$ . Consequently, the transmission from one transmitter will inevitably provide interference to the unintended receiver. As mentioned, this channel configuration still has yet to be solved in general even in the Gaussian case (Ref. 9). The interference channel is illustrated in Figure 2.

In this scenario, the signals transmitted by  $Tx_1$  and  $Tx_2$  are denoted as  $X_1$  and  $X_2$ , respectively, and the received signals at  $Rx_1$  and  $Rx_2$  are denoted as  $Y_1$  and  $Y_2$  respectively. This relationship can be described as follows:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} \quad (2)$$

This can be equivalently described as:

$$Y_1 = h_{11}X_1 + h_{12}X_2 + N_1 \quad (3)$$

$$Y_2 = h_{21}X_1 + h_{22}X_2 + N_2 \quad (4)$$

For this study, the interference channel was augmented to include cognition at the first transmitter,  $Tx_1$ , which allows it to function as a transceiver in an overlay configuration. In this scenario, the cognitive node may have knowledge of the second transmitter's modulation and coding schemes as well as Channel Side Information. Therefore,  $Tx_1$  can demodulate, detect, and relay  $Tx_2$ 's messages to  $Rx_2$ , as well as adjust a factor,  $\alpha$ , to control the allocation of its total power budget for transmitting  $X_1$  to  $Rx_1$ . This leaves  $(1-\alpha)$  of its power budget available to relaying  $X_2$  to  $Rx_2$  based on the observed channel conditions. During times of fading,  $Tx_1$  can adjust its gain factor



to provide enhanced performance to  $Rx_2$  while simultaneously suffering a performance degradation at  $Rx_1$ . Each transmit-receive pair (i.e.,  $Tx_1$ - $Rx_1$  and  $Tx_2$ - $Rx_2$ ) in this scenario is using a unique carrier frequency for its communication. To provide causality (i.e., no genie assumption), message passing from  $Tx_2$  to  $Tx_1$  results in an amplitude adjustment,  $\beta$ , and a time delay,  $\tau$ . The overlay channel model is illustrated in Figure 3.

In this case, the equations relating the transmitted signals,  $X_1$  and  $X_2$ , to the received signals,  $Y_1$  and  $Y_2$  are as follows:

$$Y_1 = \sqrt{\alpha}h_{11}X_1 + h_{12}X_2 + N_1 \quad (5)$$

$$Y_2 = \sqrt{\alpha}h_{21}X_1 + h_{22}X_2 + \beta\sqrt{1-\alpha}X_2(\tau) + N_2 \quad (6)$$

Clearly, setting  $\alpha = 1$  and  $\beta = 0$  reduces this overlay model to the general interference channel as described previously.

In all of the analysis done in this report, a simple binary phase shift keying (BPSK) modulation was used, for which a notional diagram for the transmitter and receiver models is shown in Figure 4.

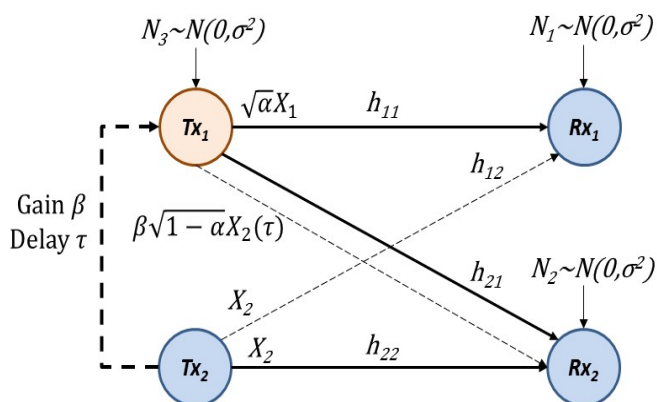


Figure 3.—Overlay model with causal message passing.

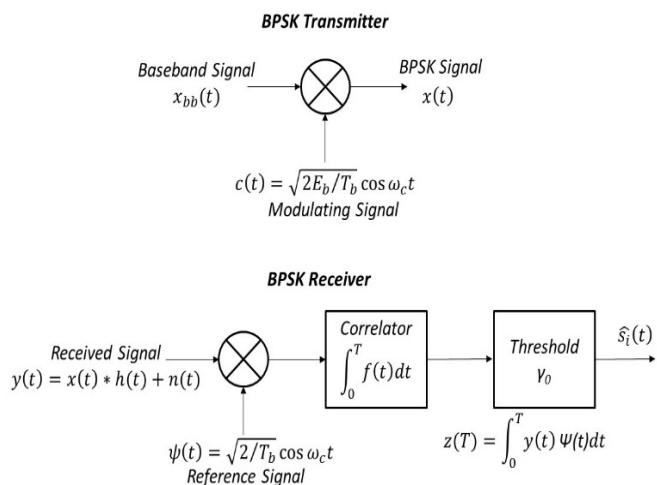


Figure 4.—BPSK transmitter and receiver models.

Optimal detection of BPSK signaling in the presence of AWGN uses a receiving filter that maximizes the output signal-to-noise ratio. The output of this filter is a test statistic  $z(T)$  that is compared to a threshold value  $\gamma_0$  to determine the estimated output signal,  $\hat{s}_i(t)$ . The receiving filter was implemented using a correlator where the noisy received signal was multiplied by a reference signal and then integrating over the bit duration,  $T_b$ . Assuming equally-likely bipolar signaling at the transmitter, the decision threshold,  $\gamma_0$ , is calculated as the average of the two possible transmitted message signals; which in this case results in a value of zero (Ref. 8).

## 4.0 Results and Interpretation

This section illustrates the performance (in terms of bit error rate) of the overlay model for various levels of interference, fading, and cognition. The simplest model, consisting of a static channel with no cognition, is described first; the most complex model with a fading channel and cognition at  $Tx_1$  is described last. In each case, key observations are indicated.

Figure 5 illustrates an analysis of the bit error rate of data received at receiver  $Rx_2$  with no cognition at  $Tx_1$  and a static channel matrix,  $H$ . For this analysis,  $\alpha = 1$  and  $\beta = 0$ , which reduces the model to the general interference channel. To provide varying levels of interference, the off-diagonal elements of the channel matrix  $H$  were varied from 0 (i.e., no interference) to 1 (i.e., strong interference).

Intuitively, the greater the interference between transmit-receive pairs, the greater the impact on bit-error rate performance. With no interference, the performance approaches that of the theoretical single-user channel with BPSK modulation. With strong interference, the error rate approaches 0.5, indicating the capacity of the channel in this case approaches zero.

Figure 6 illustrates the bit error performance for a fading channel (i.e., a dynamic channel matrix). The matrix elements of  $H$  were modeled as Gaussian random variables with a mean of 1 for diagonal elements, and a mean of 0.3 for off-diagonal

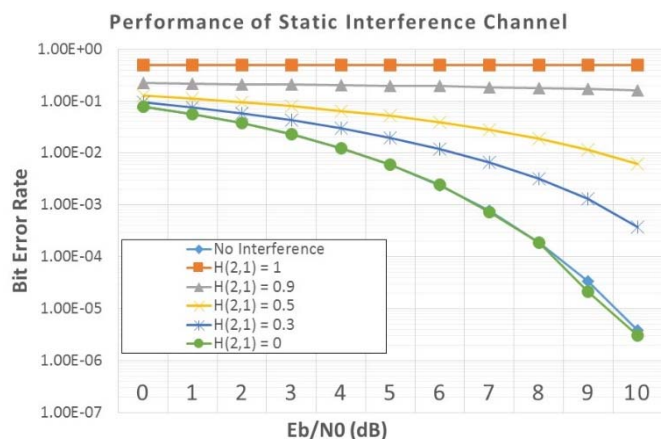


Figure 5.—Performance of static interference channel with varying off-diagonal channel gains.



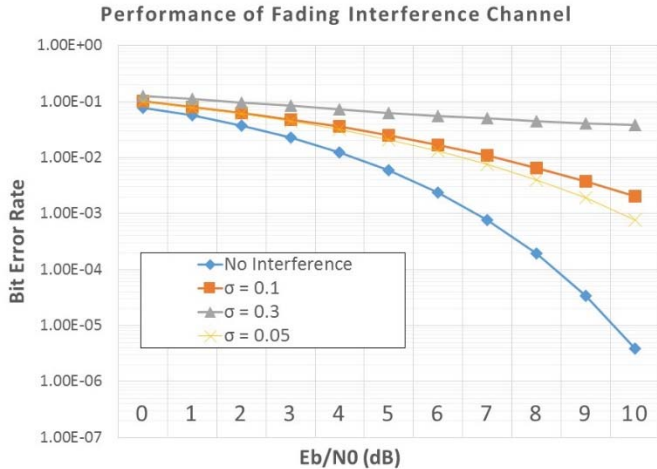


Figure 6.—Performance of fading interference channel with varying standard deviation for channel matrix elements.

elements. The standard deviation for the matrix elements was varied from 0.05 to 0.1. As expected, increasing the variation in channel matrix elements adversely affects the bit error rate performance.

Figure 7 illustrates the performance of a static channel using the overlay configuration with  $Tx_1$  having knowledge of  $Tx_2$ 's modulation scheme. Therefore,  $Tx_1$  can demodulate, detect, and relay  $Tx_2$ 's transmission while simultaneously using the spectrum to transmit to its intended receiver,  $Rx_1$ . As mentioned, the causality constraint results in an amplitude adjustment,  $\beta$ , and a time delay,  $\tau$ . For this scenario  $\beta$  is assumed to be 1, and the bit error rate performance at the relay node  $Tx_1$  is relatively error free (i.e.,  $E_b/N_0$  is greater than 10 dB). This configuration also assumes that  $Tx_1$  does *not* have CSI, and therefore uses a uniform power split ( $\alpha = 0.5$ ) for transmission to both  $Rx_1$  and  $Rx_2$ .

Intuitively, the amount of phase delay has an effect on the received signal at  $Rx_2$ , and can be considered similar to a multipath effect. For small values of delay (on the order of 30 percent of a symbol period  $T$ ), the resulting effect on performance is enhanced. In fact, for small values of  $\tau$ , the indicated bit error rate performance exceeds that of the performance of the channel with no relaying whatsoever. For values of  $\tau > 0.7$ , the performance begins to degrade to the point of being worse than the no-relaying case. Increasing  $\tau$  to beyond the symbol period results in inter-symbol interference (ISI) and further performance degradation.

For data rates of 1 kbps, an RF signal can propagate approximately 300 km during 1 symbol period. For data rates of 1 Mbps and 1 Gbps, a signal can propagate approximately 300 and 0.3 m, respectively. Consequently, for data rates in the Mbps range, propagation delays would not be detrimental for operations in which the proximity between neighboring nodes is on the order of 100 to 300 m.

Figure 8 illustrates the effect of varying the relaying gain  $\beta$  from 0 to 1. This assumes no CSI at the cognitive node and therefore a uniform power split ( $\alpha = 0.5$ ); also, the time delay  $\tau$

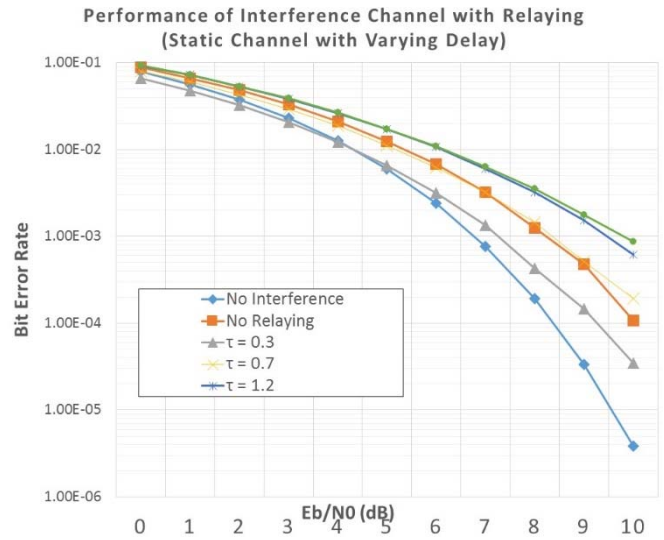


Figure 7.—Performance of static channel with varying message passing delay.

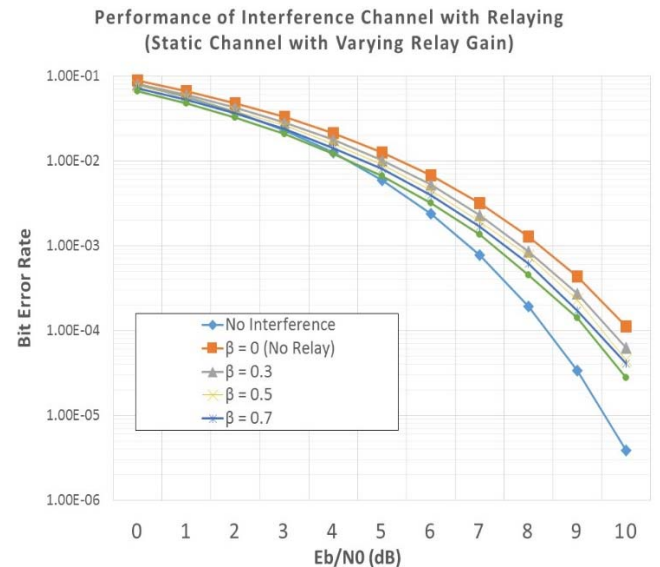


Figure 8.—Performance of static channel with varying message passing gain.

was assumed to be small such that ISI was not a contributing factor to the performance analysis. Clearly, performance improves as  $\beta$  increases.

Figure 9 illustrates the performance of a fading channel where  $Tx_1$  has both CSI and knowledge of  $Tx_2$ 's modulation scheme. Since the cognitive transmitter now has CSI, it is able to dynamically adapt its power allocation to enhance the noncognitive transmitter's messages during times of fading. The figure shows how performance degrades as the variance of the channel matrix elements increases; however, performance can be enhanced using a power adaptation algorithm. By allocating more power to relaying  $Tx_2$ 's transmission, the performance at  $Rx_2$  improves, but the performance at  $Rx_1$  degrades resulting in a need to decrease transmission rate in order to achieve the same signal-to-noise ratio at the receiver.

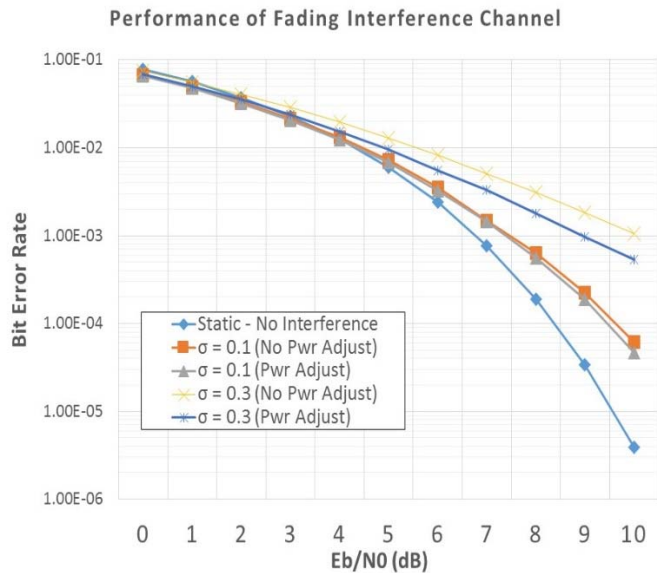


Figure 9.—Performance of a fading interference channel with and without adaptive power control.

## 5.0 Conclusions

This report has provided a performance analysis, in terms of bit error rate, of using the cooperative relaying mechanism for interference mitigation by using a more practical approach of constraining message passing to occur over physical channels with attenuation and delay effects. This analysis has shown that for small values of delay, the resulting effect on performance is enhanced over that of the case of no relaying. However, for values of greater than about 70 percent of the symbol period, the performance begins to degrade to the point of being worse than the no-relaying case. Increasing delay to beyond the symbol period results in ISI and further performance degradation.

Additionally, results of this study have shown that having CSI at the cognitive transmitter allows for implementation of a power adaptation mechanism to enhance performance at the intended receiver, especially during periods of fading. The results show a slight increase in performance; however, this analysis used a very simple power adaptation scheme, of which a more sophisticated implementation would certainly provide further performance improvement.

Follow-on efforts would expand the model to include multiple transmitters and multiple receivers with cognition on both the transmit and receive side of the channel. This could help determine whether cognition is more beneficial at the transmitter or the receiver. Also, a determination of the best cooperative paradigm for various channel considerations would be worthwhile as well.

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