2014

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Citation/Publisher Attribution
McGee, James, Peter Swaszek and Josko Catipovic. "Leveraging Spatial Diversity to Mitigate Interference un Underwater Acoustic Communication Networks." *The Journal of the Acoustic Society of America*, 135, (2014), pp. 2430-2431. doi: 10.1109/OCEANS.2014.7003066
Available at: http://dx.doi.org/10.1121/1.4878091

Leveraging Spatial Diversity to Mitigate Interference in Underwater Acoustic Communication Networks

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Abstract

Many acoustic channels suffer from interference which is neither narrowband nor impulsive. This relatively long duration partial band interference can be particularly detrimental to system performance. We survey recent work in interference mitigation as background motivation to develop a spatial diversity receiver for use in underwater networks. The network consists of multiple distributed cabled hydrophones that receive data transmitted over a time-varying multipath channel in the presence of partial band interference produced by interfering active sonar signals as well as marine mammal vocalizations. In operational networks, many "dropped" messages are lost due to partial band interference which corrupts different portions of the received signal depending on the relative position of the interferers, information source and receivers due to the slow speed of propagation. Our algorithm has been tested on simulated data.

I. Introduction

To date the only long term undersea cellular network is operated by the U. S. Navy in the Tongue of the Ocean [1]. Known as the Atlantic Undersea Test and Evaluation Center (AUTEC), it consists of 96 acoustic sensors placed over a 60 by 30 kilometer square area and is shown in Fig. 1. As currently configured, approximately 97 percent of transmitted messages are successfully decoded; of the remaining three percent, many are corrupted by acoustic interference arising from active acoustic emissions. For example, Fig. 2 shows the impact of interference on a received data packet. In pane (a), the data packet was received without interference and successfully decoded in contrast to pane (b) where interfering signals are clearly evident and the message was lost. Years of extensive observations of activities in the vicinity of the network demonstrate that the widely separated hydrophones suffer from partial-band interference emanating from multiple spatially separated sources. The nature of this interference is different from the impulsive or narrowband interference typically encountered in other applications. Furthermore, unlike RF communications and acoustic array processing applications where interference is highly correlated in time among the various receivers, in the acoustic network, interference affects different portions of the received signals due to the wide separation of the receivers and the low speed of propagation. The degradation in the received signal is highly variable, depending on the relative position of the interfering signals, information source and receivers as well as the channel conditions. While successful steps to mitigate interference have recently been reported [2], utilizing the spatial diversity implicit in the undersea network to mitigate interference has not yet been attempted. The motivation behind this work is to examine the potential benefits that leveraging spatial diversity in underwater acoustic networks might provide.

Interference mitigation has a long history in RF communications, but the interference is typically impulsive or narrowband [3]. Partial band interference is not addressed [2]. The interference mitigation techniques typically exploit the short time or limited frequency span of the interfering signal. Examples of impulsive noise suppression techniques for multi-carrier modulation may be found in [4]–[10], while [11]–[20] address narrowband interference mitigation. Early approaches tended to separate channel estimation and interference detection, while more recent work has focused on jointly estimating the channel and mitigating interference. Joint approaches may work iteratively such as in [5] or by expanding the states of the decoding algorithm as in [15] and [17]. A message-passing approach to jointly estimating the channel and mitigating strong co-channel interference of similar form as the desired signal was proposed in [21]. Two blind algorithms to mitigate multiple interferers were proposed in [22]. Joint approaches provide better performance at the cost of additional computational complexity. Limitations on system performance may be found in [23] for Orthogonal Frequency Division Multiplexing (OFDM) systems subject to impulsive noise and for multicarrier and single carrier quadrature amplitude modulation (QAM) systems in [24]. The capability of low density parity check (LDPC) and turbo coding to mitigate burst errors is discussed in [25].

Observations from past field experiments indicate that significant improvement in the reliability of message reception can be realized by mitigating interference. Discussion of the interference typical in the underwater environment is available in [26] and [27].

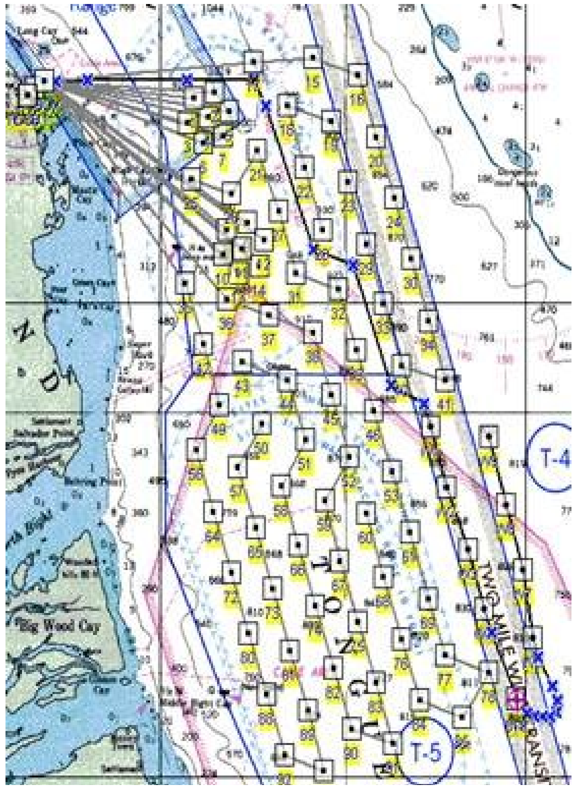

Figure 1: The AUTEC acoustic network.

The work in [2] developed a single receiver algorithm to mitigate partial band interference. Building upon this work, we seek to develop a spatial receiver for underwater networks which takes advantage of the geographical separation of the hydrophones resulting in the interference arriving at different times and lasting for different durations in the received signal.

II. A Spatial Diversity Receiver

The reconstruction process, illustrated in Fig. 3, identifies the portions of the received waveforms suffering from interference and then optimally combines the remaining clean portions of the signals. The interference is time and band limited, and as in [2], we assume these parameters are known. The reconstruction process must occur in the time domain since the interference occupies the same frequency band on all receivers but arrives at different times on different receivers. Furthermore, it is essential that the reconstruction process operate on equalized waveforms. All of the information for channel estimation and residual Doppler compensation is present in the frequency (or OFDM symbol) domain. Consequently, after signal detection and gross Doppler compensation, the reconstruction process begins with interference detection/suppression in the frequency domain followed by channel equalization. The algorithms developed in [2] and the references therein can be used for these tasks. The equalized received signals must then be transferred back to the time domain to remove the residual time orthogonal interference. The time domain interference detector may take advantage of information gained from the frequency domain interference detector. Portions of the received signals where interference is declared are excised, provided a clean copy of the same portion of the waveform exists on another receiver. The synthesized signal is then transferred back to the frequency domain for data detection.

To demonstrate the concept of waveform reconstruction, we implemented a simple frequency domain interference detector based on comparing the energy in the null subcarriers in the interference band to the energy in the null subcarriers in the noise only band. If the frequency domain interference detector declared interference present, the time domain interference detector selected an appropriately sized contiguous window with the highest signal energy for potential excision.

The zero-padded OFDM signal consists of K subcarriers which are divided into non-overlapping sets of active subcarriers $\mathcal{S}_A$ and null subcarriers $\mathcal{S}_N$ satisfying $\mathcal{S}_A \cup \mathcal{S}_N = \{-K/2 \dots K/2-1\}$. The transmitted time domain symbol $s[n]$ is related to the OFDM data symbol through the inverse Fourier transform. Specifically,

$$s[n] = \sum_{k=-K/2}^{K/2-1} d[k] e^{j2\pi \frac{kn}{K}} \tag{1}$$

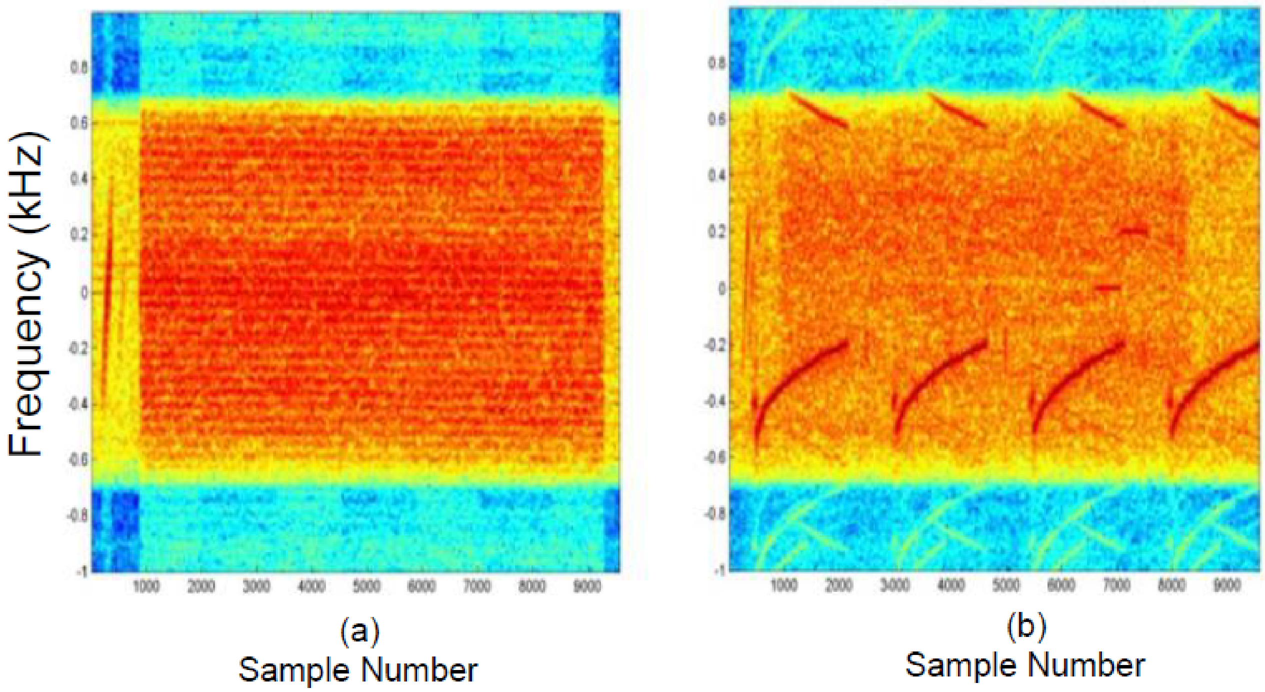

Figure 2: Clean packet reception (a) and packet corrupted by acoustic interference (b).

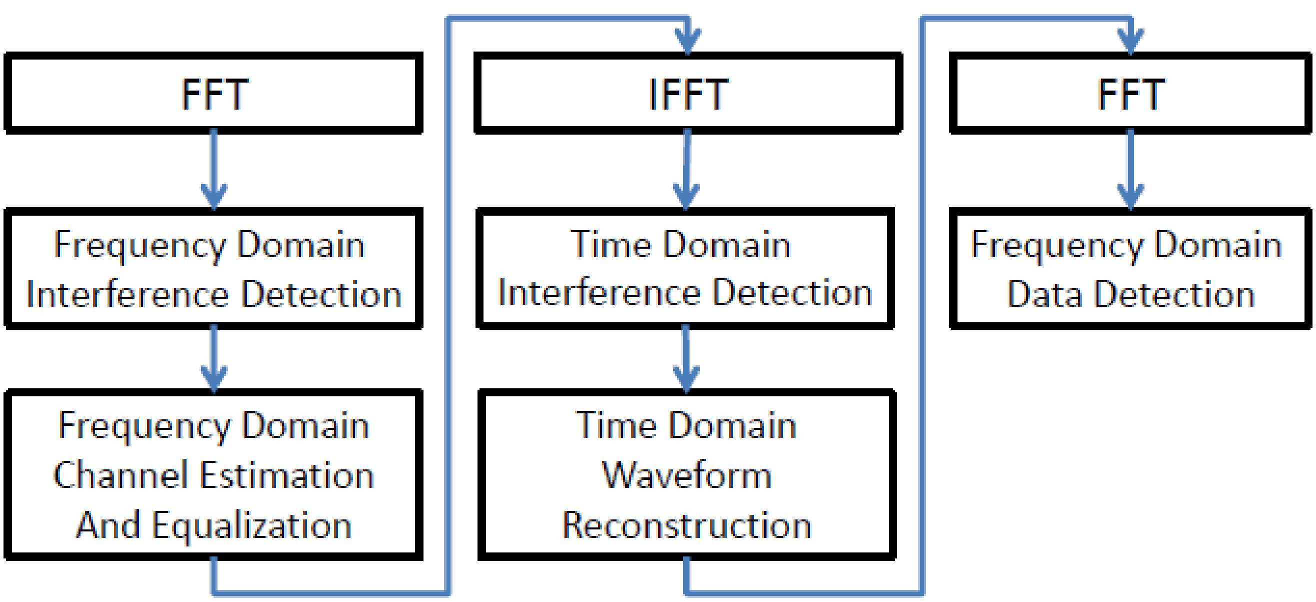

Figure 3: OFDM waveform reconstruction process.

OFDM Parameter		Value
Center frequency	f_c	13 kHz
Bandwidth	B	9.77KHz
# of subcarriers	K	1024
# data subcarriers	$\lvert\mathcal{S}_D\rvert$	672
# pilot subcarriers	$\lvert\mathcal{S}_P\rvert$	256
# null subcarriers	$\lvert\mathcal{S}_N\rvert$	96
Symbol Duration	T	104.68 ms
Symbol Constellation		BPSK
Subcarrier spacing	Δf=1/T	9.54 Hz
Guard interval	T_g	24.6 ms
Number of Guard Samples	N_g	240
Interference Parameter		**Value**
Center Frequency	$f_{c,I}$	15 kHz
Bandwidth	B_I	2.4 kHz
Duration	T_I	26.2 ms
Channel 1 Start time	$T_{s,1}$	$\mathcal{U}(.1T_I, T/2 - 1.1T_I)$
Channel 2 Start time	$T_{s,2}$	$\mathcal{U}(T/2 + .1T_I, T - 1.1T_I)$

Table I: Simulation parameters.

so that $\mathbf{s} = \text{IFFT}(\mathbf{d}, K)$. The input-output relationship between the transmitted symbols, $d[m]$, and the discrete frequency sample $z[k]$ may be written as

$$z[k] = \sum_{m=-K/2}^{K/2-1} \mathbf{H}[k,m]d[m] + w[k] + v[k], \tag{2}$$

where $\mathbf{H}$ describes the frequency response of the channel, w is additive noise assumed to be white Gaussian noise and v is the interference.

Let $\mathcal{S}_w$ denote the subcarriers in the noise only band, and $\mathcal{S}_v$ denote the subcarriers in the band which potentially suffers from interference. The frequency domain interference detector declares interference if

$$\frac{1}{|\mathcal{S}_v|} \sum_{k\epsilon\mathcal{S}_v} |z[k]|^2 > \frac{1}{|\mathcal{S}_w|} \sum_{k\epsilon\mathcal{S}_w} |z[k]|^2 \tag{3}$$

and the Komogorov-Smirnov hypothesis test determines the samples $z[k\epsilon\mathcal{S}_v]$ and $z[k\epsilon\mathcal{S}_w]$ to be from different distributions with significance level of greater than five percent. The MATLAB® function kstest2 may be used to perform the hypothesis test.

Provided interference is detected, the received frequency samples are transformed to the time domain, $\mathbf{x} = \text{IFFT}(\mathbf{z}, K)$. A rolling window of size L sums the energy in the time domain signals. For this work, we chose L so that the window was $1.05T_I$. Because the frequency domain samples in ZP-OFDM are formed from overlapping and adding samples from the guard period with samples in the symbol period, the window "wraps" around $\mathbf{x}$, that is

$$y[k] = \sum_{n=0}^{L-1} |x[\text{mod}(k+n, K)]|^2 \tag{4}$$

Time domain interference is declared in the window $i = \text{mod}(k_{\text{max}} : k_{\text{max}+L-1}, K)$ where k_{max} denotes the index where y achieves its maximum. Let $I_{k,r}$ denote the indicator function of interference in the kth band on the rth receiver, and similarly concatenate the received signals into a matrix $\mathbf{Z}_{k,r}$. The signal reconstruction operation on the R receivers is then defined by

$$\bar{\mathbf{z}}_k = \begin{cases} \frac{\sum_r \mathbf{Z}_{k,r} \circ \mathbf{I}_{k,r}}{\sum_r \mathbf{I}_{k,r}} & \text{where } \sum_r \mathbf{I}_k > 0 \\ \\ \frac{\sum_r \mathbf{Z}_{k,r}}{R} & \text{where } \sum_r \mathbf{I}_k = 0 \end{cases} \tag{5}$$

where $\circ$ denotes the Hadamard (element-wise) matrix product. Thus, non-contemporaneous interference is excised from the reconstructed signal while averaging is performed across all portions of the signals where the interference occurs concurrently on all receivers resulting in a clean portion of the signal being unavailable.

III. SIMULATION

The waveform reconstruction algorithm was tested using simulated data which assumed the source is equidistant from the receivers and the interfering source is closer to receiver 1 than receiver 2. We tested the algorithm assuming both channels are known and equalize the receptions by inverting the channel response; that is, we employ a zero-forcing equalizer as well as employing a minimum mean square error equalizer that estimated the channel response based on pilot tones. On channel 1, the interference arrives in the first half of the OFDM symbol period whereas the interference corrupts the second half of the received signal on channel 2. Table **??** lists the simulation parameters and Fig. 5 shows the channels.

The interference is generated by passing white Gaussian noise of time duration $T_I = T/4$ ms through a bandpass filter with a center frequency of 15 kHz and bandwidth of 2.4 kHz. The delay of the interference relative to the start of each block is

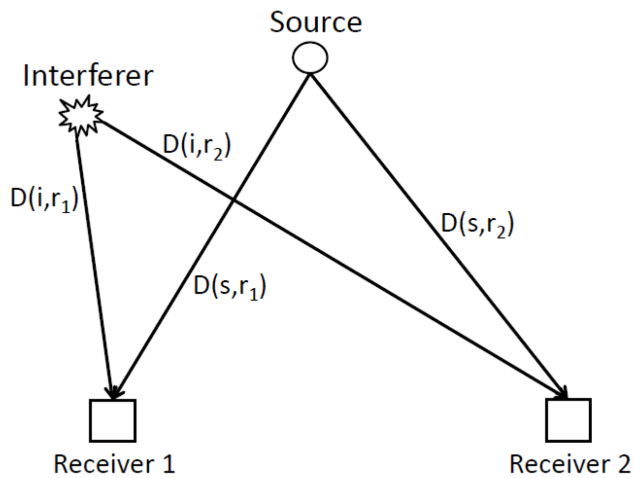

Figure 4: Simulation geometry. $D(s, r_1) = D(s, r_2)$ and $D(i, r_1) < D(i, r_2)$.

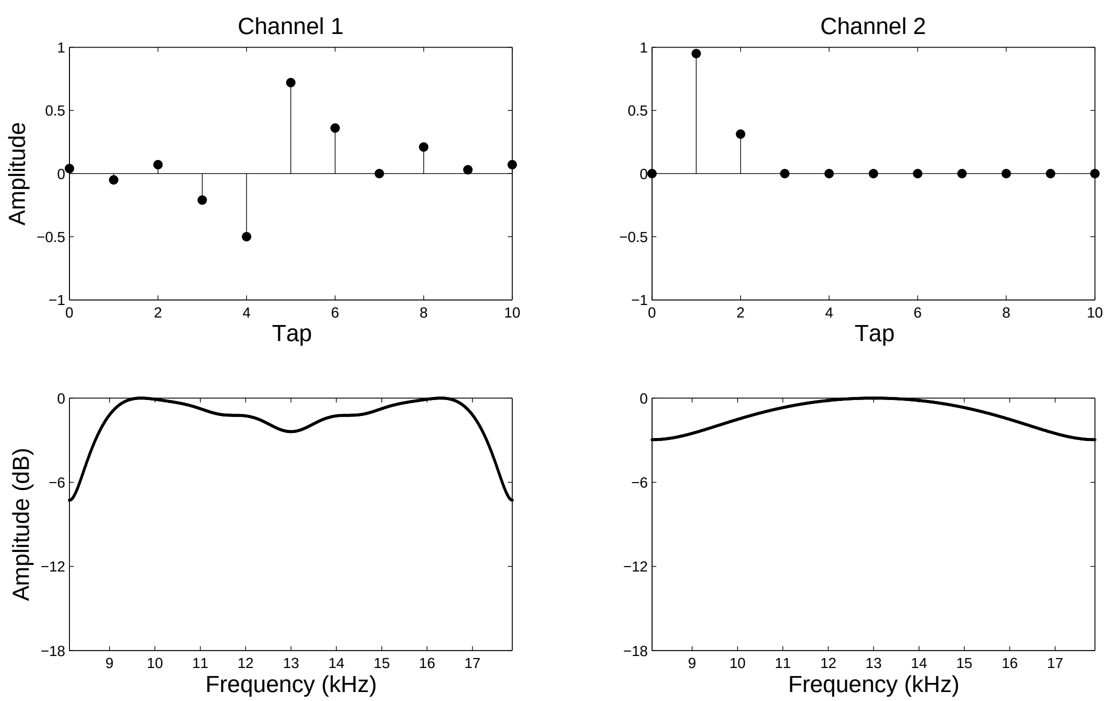

Figure 5: Simulated Channels.

uniformly distributed according to the start time parameter listed in table **??**. The interference is thus orthogonal in the time domain on the two receivers but overlaps in the frequency domain.

The simulated time domain interference is sampled, overlapped and added, and an FFT is taken to produce frequency domain interference which is then scaled to the appropriate signal-to-interference (SIR) level and added to the background noise, which is modeled as complex white Gaussian noise with signal-to-noise ratio (SNR) of 7.9 dB. After adding the simulated noise to an OFDM symbol vector, the waveform reconstruction algorithm was run at a SNR of 7.9 dB for SIRs varying from -10 to 2 dB. The Monte Carlo simulation was stopped when either 500,000 bits had been processed or 250 errors were made.

IV. Results

Fig. 6 clearly demonstrates the benefits of leveraging spatial diversity to reconstruct the transmitted waveform. The figure shows a comparison of the performance of the spatial diversity reconstruction (SDR) technique and the traditional maximum ratio

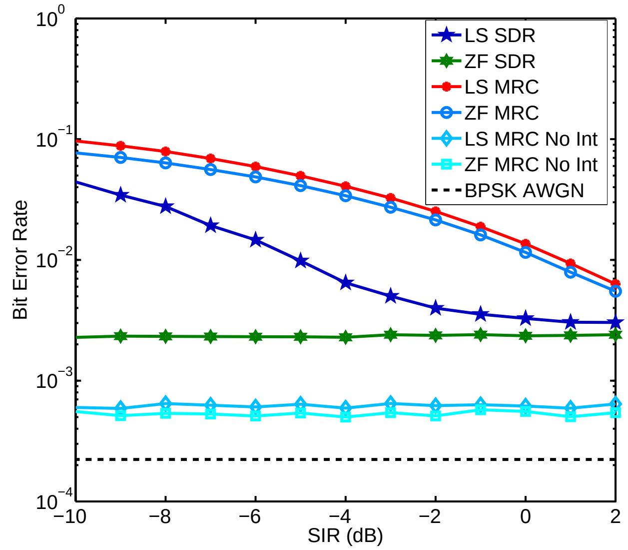

Figure 6: Bit Error Rate for different combining strategies and equalization methods at an SNR of 7.9 dB and various SIRs: SDR - Spatial Diversity Reconstruction, MRC - Maximum Ratio Combining, No Int - No interference present, LS - Least Squares Equalizer, ZF - Zero Forcing Equalizer, BPSK AWGN - binary phase shift keying on an impulse channel in additive white Gaussian noise.

combining (MRC) technique using a minimum mean square error (LS) equalizer which must estimate the channel and a zero forcing (ZF) equalizer which knows the channel *a priori*. The MRC performance on the same channels without interference and the single receiver performance on an additive white Gaussian noise channel with no interference are also shown for comparison. SDR consistently performs better than MRC and significantly so at low SIRs. The importance of accurate channel estimation and equalization is seen in noting the difference in the performance of the SDR algorithm with the LS and ZF equalizers at low SIRs. Channel equalization plays a critical role not only because better equalization improves the averaging operation in the time domain, but critically because any noise enhancement resulting from equalization is smeared across the time series through the subsequent Fourier transform operation.

V. Summary

Many acoustic channels suffer from interference which is neither narrowband nor impulsive. This relatively long duration partial band interference can be particularly detrimental to system performance. Due to the slow speed of sound propagation in water and the geographical extent of networks, the interference corrupts different portions of the received signal depending on the relative positions of the information source, receivers and interferers. Operating simple detectors on relatively benign simulated channels, we demonstrated that leveraging spatial diversity to reconstruct the transmitted waveform results in significant performance improvement over the classical maximum ratio combining strategy at high signal-to-interference ratios.

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