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# Final Report: 03-LW-005 Space-Time Secure Communications for Hostile Environments

J. V. Candy, A. J. Poggio, D. H. Chambers, B. L. Guidry, C. L. Robbins, C. A. Hertzog, F. Dowla, G. Burke, R. Kane

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## Disclaimer

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## Space-Time Secure Communications for Hostile Environments

*James V. Candy, Andrew J. Poggio, David H. Chambers, Brian L. Guidry, Christopher L. Robbins, Claudia A. Hertzog, Farid Dowla, Gerry Burke, Ron Kane*

U.S. Department of Energy

Lawrence
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## October 21, 2005

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# Space-Time Secure Communications for Hostile Environments

**James V. Candy, Andrew J. Poggio, David H. Chambers, Brian L. Guidry, Christopher L. Robbins, Claudia A. Kent, Farid Dowla, Gerry Burke, Ron Kane**

University of California, Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551

## Executive Summary

The development of communications for highly reverberative environments is a major concern for both the private and military sectors whether the application is aimed at the securing a stock order or stalking hostile in a tunnel or cave. Other such environments can range from a hostile urban setting populated with a multitude of buildings and vehicles to the simple complexity of a large number of sound sources that are common in the stock exchange, or military operations in an environment with a topographic features hills, valleys, mountains or even a maze of buried water pipes attempting to transmit information about any chemical anomalies in the water system servicing a city or town. These inherent obstructions cause transmitted signals to reflect, refract and disperse in a multitude of directions distorting both their shape and arrival times at network receiver locations. Imagine troops attempting to communicate on missions in underground caves consisting of a maze of chambers causing multiple echoes with the platoon leader trying to issue timely commands to neutralize terrorists. This is the problem with transmitting information in a complex environment. Waves are susceptible to *multiple paths* and *distortions* created by a variety of possible obstructions, which may exist in the particular propagation medium. This is precisely the communications problem we solve using the physics of wave propagation to not only mitigate the noxious effects created by the hostile medium, but also to utilize it in a constructive manner enabling a huge benefit in communications. We employ *time-reversal* (T/R) communications to accomplish this task. This project is concerned with the development of secure communications techniques that can operate even in the most extreme conditions while maintaining a secure link between host and client stations.

We developed an approach based on the concept of time-reversal (T/R) signal processing. In fact, the development of T/R communication systems is a recent signal processing research area dominated by applying these techniques to communicate in hostile environments. The fundamental concept is based on time-reversing the impulse response or Green's function characterizing the uncertain communications channel to mitigate deleterious dispersion and multipath effects. In this project, we have performed proof-of-principle experiments to demonstrate point-to-point and array-to-point communications by first establishing the basic theory to define and solve the underlying multi-channel communications problem and then developing various realizations of the resulting T/R receivers. We showed that not only do these receivers perform well in a

hostile environment, but they also can be implemented with a “1-bit” analog-to-digital (A/D) converter design structure. We validated these results by performing the proof-of-principle acoustic communications simulations and experiments in air as well as electromagnetic (EM) simulation/experiments. It was shown that the resulting T/R receivers are capable of extracting the transmitted coded sequence from noisy microphone array measurements with zero (bit) error. We chose to perform the bulk of our work in the acoustics medium for simplicity in implementation and cost compared to the EM modality. However, we did perform some simple simulations and experiments using the LLNL micro-impulse transceiver system.

## INTRODUCTION

Communicating in a complex environment is a daunting problem. Think of cellular communications in a hostile urban setting populated with a multitude of buildings and vehicles, the complexity of a large number of shouting brokers common at the stock exchange, or military operations in an environment with topographic features such as hills, valleys, mountains, etc. These inherent obstructions cause transmitted sounds or signals to bounce, bend and spread in a multitude of directions distorting both their shape and arrival times at receiver locations. Imagine being lost in a maze of caves that cause multiple echoes. You shout for help but at the entrance all that can be heard is garbled noise. This is the problem with transmitting information in a complex environment. Sound in the form of waves is susceptible to *multiple paths* created by a variety of possible obstructions. We can observe this phenomenon by dropping a pebble into a puddle and observing the rings (waves) propagate outwardly while being distorted by the presence of a large rock or twig. This is precisely the type of communications problem we are attempting to solve. We utilize the physics of acoustic wave propagation to mitigate the noxious effects created by the hostile medium. Using this in a constructive manner also enables a huge benefit in communications. We employ a technique called *time-reversal* (T/R) communications to accomplish this feat.

Time-reversal is a simple notion that we have all observed. For instance, consider watching a movie of the demolition of a building. Merely running the movie *in-reverse* or equivalently *running it backwards in time* allows us to reconstruct the building, at least visually; even though it cannot be reconstructed physically. Using this same idea, time-reversal can be applied to “reconstruct” communication signals by *retracing* all of the multiple paths from the source that originally distorted the transmitted signals in the first place! That is, if we broadcast a sound into a hostile environment or medium, the sound waves bounce, bend and spread, yet eventually make their distorted way to the receiver. Unfortunately, they arrive at the receiver at various times and signal levels creating a completely jumbled message. In order to separate or decompose the individual components of the message, the T/R receiver must use its knowledge of the medium to not only separate each path, but also to add them together in some coherent manner to extract the message with little or no distortion and increase their signal levels.

The basic communications problem is to transmit coded sound information through the hostile environment or medium and receive it at desired receiver or client stations. These client stations can also broadcast back through the medium to create a two-way conversation as shown in Fig. 1a. The proposed solution to this problem is shown in Fig. 1b where the transmitted code is distorted by the medium, received and then processed by the T/R receiver to extract it at the output with minimal distortion.

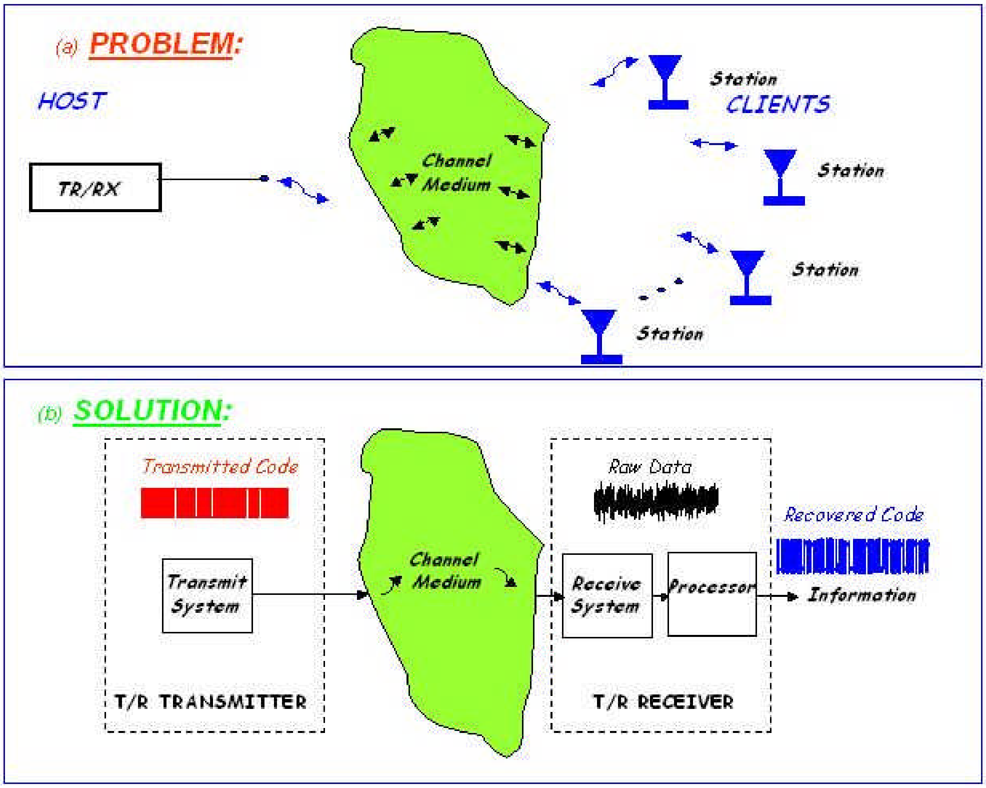


Fig. 1. Communications in a hostile environment: (a) The basic problem including the host transmitter/receiver, hostile medium and client receiver stations. (b) A T/R receiver solution showing the transmitter, medium and a particular T/R receiver structure extracting the coded information from the distorted received data.

In this introduction we briefly describe the development of techniques to construct a variety of receivers, sometimes called "software radios" based on the theory of T/R communications. The particular T/R receiver designs developed (e.g. see Fig. 1b above) are applied to controlled experimental data gathered from a hostile environment created by a one story, L-shaped, stairwell with three landings consisting of many acoustic obstructions such as protruding pipes, corrugated ceilings, rough walls and entry/exit doors deflecting and distorting the propagated sound waves. The stairwell along with the experimental setup is shown in Fig. 2 where we see the speaker sound source, microphone receiver and computer system used to capture and digitize the data.

The results of processing this data with the T/R system to recover transmitted information is accomplished by essentially retracing the sound waves from the speaker.

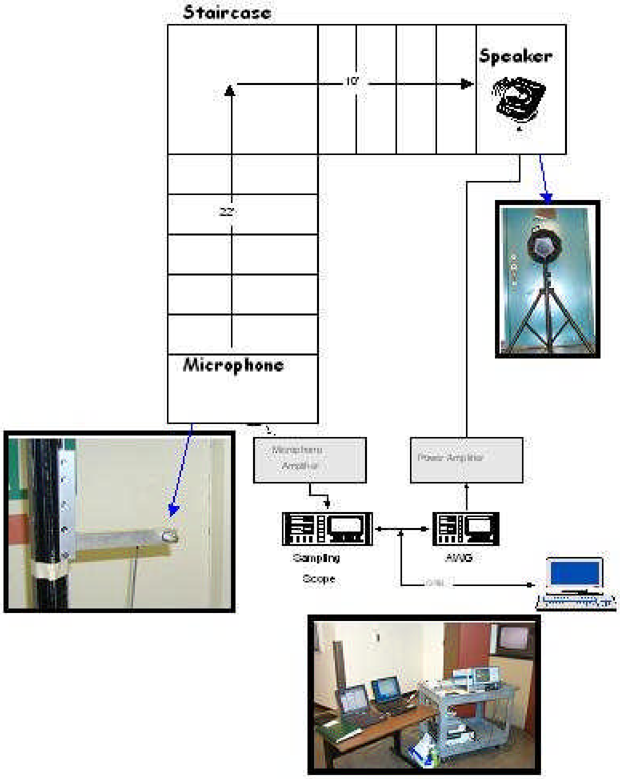


Fig. 2. Controlled experimental set-up for T/R receiver designs: sound source (loud speaker), hostile medium (stairwell with obstructions) and the microphone receiver with the T/R receiver implemented in software on the computer.

With this in mind we demonstrate the performance of a T/R receiver below in Fig. 3 where the upper traces show the T/R processed signal (dotted blue line) including the synchronized coded information sequence (solid cyan line) and the transmitted code (red line). The code is composed of symbols that have either a +0.75 or –0.75 amplitude. Zooming on the trace in the lower portion of Fig. 3, we see both the recovered code *prior* to quantization (dotted cyan line) and the quantized code which precisely overlays the true transmitted code (solid red line). There is no symbol error confirming that the T/R receiver has a flawless performance on this data. That is, the true symbol values depicted by the asterisks are recovered from the T/R receiver output as shown by the circles. If there were any errors, the recovered T/R receiver symbol (circle) would not overlay the true symbol (asterisk). Thus, we conclude that the T/R receiver is capable of performing in a hostile environment.

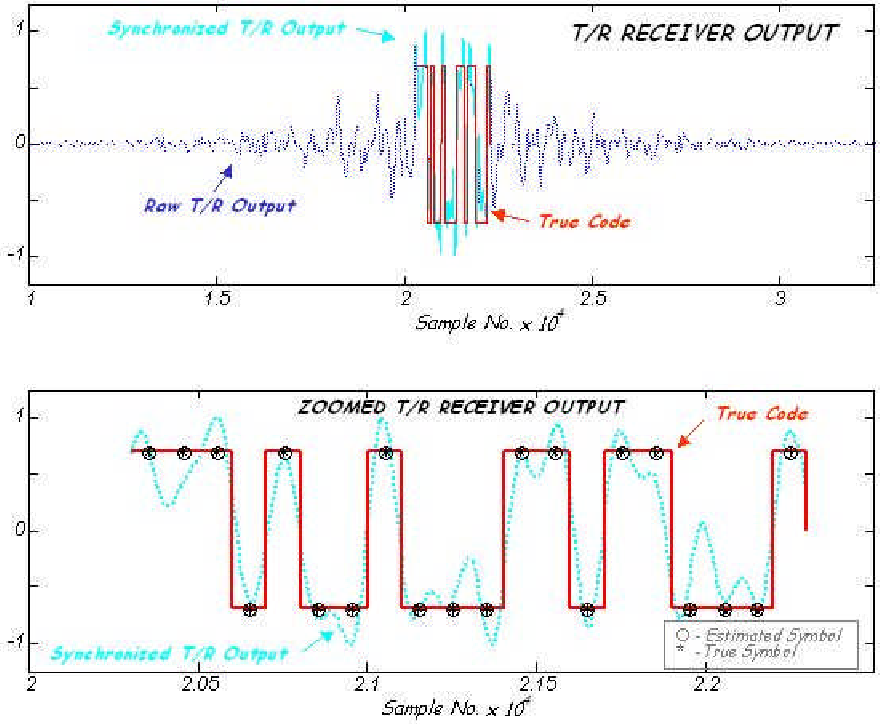


Fig. 3. Time-reversal receiver output for the controlled stairwell experiment: (a) Raw T/R receiver output (dotted blue line) with synchronized code (solid cyan line) with true code (red line) superimposed (upper trace). (b) Zoomed synchronized T/R output (dotted cyan line) with both quantized code information extracted and true code superimposed (red line) along with estimated symbol "O" and true symbol "*" overlaid demonstrating flawless T/R receiver operation.

## APPROACH

Time-reversal can be applied to "reconstruct" communication signals by *retracing* all of the multiple paths that originally distorted the transmitted signals, that is, if we transmit a signal into a hostile environment (medium), then the waves bounce, bend and spread, yet eventually make their distorted way to the desired receiver. Unfortunately, they arrive at the receiver at various times and signal levels creating a completely distorted message. In order to separate or decompose the individual components of the message, the T/R receiver must use its knowledge of the medium to not only separate each path, but also to superpose them together in some coherent manner to extract the message with little or no distortion while increasing their signal levels. The basic communications problem is to transmit coded information through the hostile environment or medium and receive it at desired receiver or client stations. These client stations can also broadcast through the medium characterized by unique Green's function paths to create a two-way communication link as depicted previously in Fig. 1.

Typical communications channels are subjected to a variety of noise and signal distortions corrupting the fidelity of the information being transmitted and reducing the effective capacity of the channel to reliably receive the information. Contrary to intuitive notions, multipath propagation in a communications channel residing in a hostile environment can be considered a potential advantage by increasing the overall signal-to-noise ratio (SNR) --- when utilized properly. T/R communications is based on taking advantage of the multipath arrivals and multiple scatterers to enhance SNR. Significant effort is continually directed towards developing new techniques for correcting or negating the effects of channel distortions. The ever-increasing demand for greater channel capacity continually necessitates better solutions for channel signal processing. This approach is based on utilizing T/R principles and theory to communicate in a hostile environment contaminated by multipath arrivals and multiple (random) scatterers. Here we investigate the performance of time-reversal based communications systems employing sensor arrays using multi-channel processors for client stations in a hostile multipath/multiple scatterer environment.

The basic idea in time-reversal signal processing for communications is to first estimate the set of Green's functions for transmitter-receiver pairs from pilot signal measurements. The communications problem, itself, can be decomposed into a suite of different scenarios to determine if the T/R approach is applicable and just how it may be applied. T/R communication receivers rely directly on their ability to utilize the underlying and unique propagation paths characterized by the set of Green's functions transmitter-receiver pairs from host-to-client or vice-versa (see Fig. 4). It is this knowledge that provides unique communication links even in hostile environments. In an *open* communications scenario, where every station is privy to all of the information to establish the link, then *both* host and clients know the pilot signals, Green's functions, synchronization times, carriers etc. In a *secure* communications environment then some of the information is known, while in a *covert* operation only one or the other station need know the critical information. For instance, if the host array knows the set of Green's functions to a particular client station receiver, then it can transmit directly to it through its unique paths or it can broadcast directly into the medium and the client receiver can extract (on reception) the particular information from knowledge of its own set of Green's functions. The latter is an example of covert reception by the client.

### *Time-Reversal Background*

In this subsection we briefly develop the simplest mathematical description of the time-reversal operation for a point-to-point communication systems comparing it to the classical optimal matched-filter receiver --- common to most communication systems. The more complex multichannel systems along with the full development of the point-to-point system are summarized in a subsequent section and the published references. The detection of a transmitted information sequence can be transformed to the problem of maximizing the output signal-to-noise ratio, $SNR_{\text{out}}$, at the receiver of a communications system. The underlying system model for the communications problem is given by

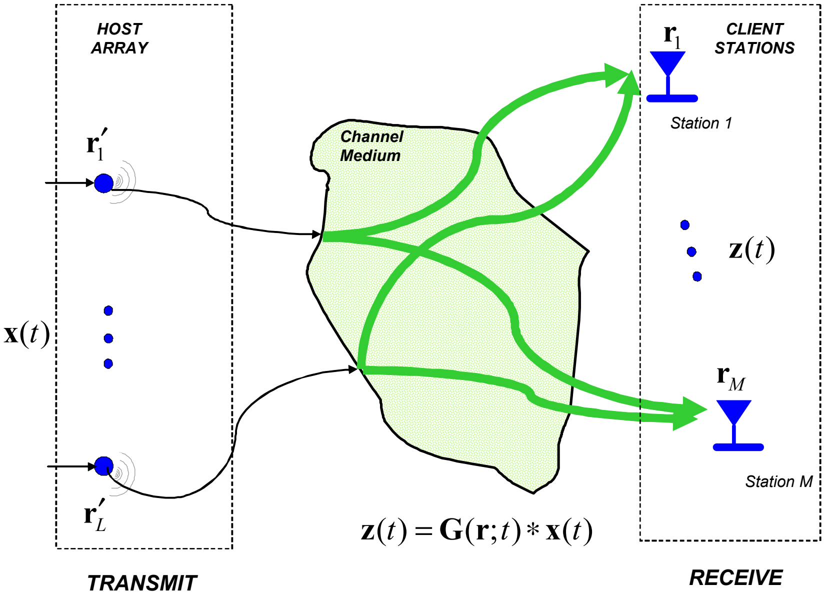


Fig. 4. The basic communications problem: Host array transmission to client receiver stations through propagation channel (medium). The basic environment including the host transmitter/receiver, hostile medium along with the corresponding sets of Green's functions transmitter-receiver pairs from host array to client receiver stations in the communications network array.

$$z(t) = s_{\text{out}}(t) + n_{\text{out}}(t) = g(r;t) * \left[ s(t) + n(t) \right], \tag{1}$$

for $z(t)$, the noisy measurement, $s_o(t)$, the output signal consisting of the convolution of $s(t)$, the transmitted signal (information) and $g(r;t)$, the spatio-temporal channel response. The output noise, $n_{\text{out}}(t)$, is also the convolution with the input noise, $n(t)$, an additive random (white) zero mean, noise of variance, $\sigma_n^2$. The matched-filter problem based on the model of Eq. 1 is *given* a "known" signal, $s(t)$, in additive white noise, *find* the filter response, $f(t)$, that maximizes the $SNR_{\text{out}}$ defined by

$$\max_f SNR_{\text{out}} \equiv \frac{\xi_{s_{\text{out}}}}{E\left\{ n_{\text{out}}^2(t) \right\}} = \frac{\left| f(t) * s(t) \right|^2}{\sigma_{n_{out}}^2}, \tag{2}$$

for $\xi_{s_{out}}$ defined as the output signal energy. The solution to this problem is classical and reduces to applying the Schwartz inequality[1,2] to the numerator, that is,

$$\left| f(t) * s(t) \right|^2 \leq \xi_f \times \xi_s, \tag{3}$$

for $\xi_\bullet$ the energy of $f(t)$ and $s(t)$. This relation is satisfied with equality at some time $T$ when $f(t)$ is related to $s(t)$ by a constant, say unity, then

$$f(t) = s(T-t), \tag{4}$$

the reversed, shifted signal or replicant. The matched-filtering operation, $mf(t)$, is then

$$mf(t) = E\{f(t) * z(t)\} = E\{s(T-t) * z(t)\} = C_{sz}(T-t), \tag{5}$$

where $C_{sz}$ is the cross-correlation function.

For time-reversal, the matched-filter in additive white noise is identical to that posed above with a "known" Green's function of the medium replacing the known signal. The Green's function, $g(r,r_o;t)$, is the result of a point-to-point communication link between a station (source) at $r_o$ to a master station (receiver) at $r$. In this case, the matched-filter solution is again found by maximizing, $SNR_{\text{out}}$, leading to the modified numerator

$$\left|f(t) * g(r,r_o;t)\right|^2 \le \xi_f \times \xi_g, \tag{6}$$

that is satisfied with equality at some time *T*, if

$$f(t) = g(r,r_o;T-t). \tag{7}$$

Thus, for T/R, the optimal matched-filter solution is the time-reversed Green's function from the link station-to-master station (source-to-receiver) or visa versa. Comparing these results with the usual matched-filter solution above, the Green's function of the channel is reversed rather than the transmitted replicant signal. Note that since T/R theory requires reciprocity[3,4], the result of Eq. 6 is valid for *both* transmission and reception, that is, $g(r,r_o;T-t) \leftrightarrow g(r_o,r;T-t)$. Note also that if an array is included to sample the spatial field or transmit a wave, then these results include the focus at link station (source) position, $r_o$, yielding the optimal, spatio-temporal matched-filter solution[2], $g\left(\mathbf{r}_\ell,\mathbf{r}_o;T-t\right)$ at sensor position, $\mathbf{r}_\ell$. The completes the simplistic description of the time-reversal approach to solving the complex communications problem.

## 1-BIT T/R RECEIVERS

T/R receivers are based on the underlying T/R principle that rather than eliminating the multipath information, it can be exploited to significantly increase SNR, even in highly reverberant environments. To accomplish this enhancement the unique paths between host and clients are retraced throughout the medium using the spatial and temporal information obtained by employing the channel estimator obtained in establishing the initial communications link. That is, the pilot signal is used to estimate the underlying set of Green's functions from transmitter array sensors to client receiver locations as illustrated in Fig. 1. The spatial information provided by the host array is not only used to establish the unique link between host sensor and client reciever, but also to increase SNR incorporating the inherent array gain (spatially) as well as the multipath arrivals (temporally). Both sets of spatial and temporal information enable the T/R receiver to perform as the optimal spatio-temporal matched-filter. Since the spatial information in the transmitted signal is essentially captured by the *phase* portion of the propagating wave ($g(\mathbf{r};t)$), the amplitude information is not as critical in utilizing the multipath; therefore, we developed a receiver that ignores or quantizes the amplitude and merely exploits the "phase-only" time reversed signals. This is accomplished, quite simply, by recording the corresponding zero-crossings of the time-reversed signals quantized between $\pm 1$ amplitudes establishing what we define as the 1-bit T/R receiver realization. This two-state system is commonly referred to as binary phase shift keying (BPSK) in the communications literature. The major advantage of such an implementation is that instead of requiring an expensive analog-to-digital (A/D) converter (e.g. 24-bits), a simple threshold switch can be used instead, since all that is required is to detect the zero-crossings. This is especially important in the electromagnetic case or for that matter any high frequency applications where digitization is expensive and prohibitive to consider. The disadvantage of this approach is increased quantization error and noise. That is, the noise will also be quantized to the $\pm 1$ amplitudes and its inherent high frequency zero-crossings as well. However, the high frequency noise is removed quite naturally by the usual bandpass filtering within the information bandwidth.

Although the 1-bit receiver design is simple in concept, it does introduce uncertainty into the processed data. First, 1-bit quantization is a *nonlinear* process identical to a switch or relay in a physical system. The crudeness of 1-bit sampling introduces large quantization errors relative to the amplitude sampling. In fact the lower bound on quantization error indicates that the 1-bit design introduces 8 orders of magnitude larger deviations (errors) than the 24-bit design[1]. This error translates into an equivalent measurement noise decreasing the "in-band" (signal frequency bandwidth) SNR. The 1-bit quantization also acts as a strong amplifier of low amplitude data (usually noise) thereby reducing the overall processing gain. However from the time-reversal perspective, it offers a cheap solution to phase sampling high frequency signals (EM, ultrasound) providing a mechanism to use T/R processing thereby increasing the overall spatial gain and coherence available at the receiver.

We illustrate the two generic realizations, reversal-on-transmit or reversal-on-receive, for the 1-bit design in Fig. 5. For T/R I and II (reverse-on-transmit), the realization is shown in *a* separating the analog and digital implementations required along with T/R III and IV (reverse-on-receive) in *b*. Here we annotate the 1-bit quantized functions by the overbar, "$\overline{\phantom{x}}$". For instance, if we were to quantize the estimated Green's function using a 1-bit A/D, we would obtain

$$\hat{\hat{g}}(\mathbf{r};t) = \begin{cases} 1 & \hat{g}(\mathbf{r};t) \geq \mathrm{T} \\ & \\ \text{-}1 & \hat{g}(\mathbf{r};t) < \mathrm{T} \end{cases}, \tag{8}$$

with T the selected quantization threshold. The underlying mathematics was actually developed using the quantized notation, but little insight was gained, since the quantization process is nonlinear and the operations could not be decomposed.

Suffice it to say that we simply describe the operation of the 1-bit designs in Fig. 5. In Fig. 5a we illustrate the design of a 1-bit T/R receiver for transmission. In both T/R I and II, the quantized signals are reversed and convolved (in software) with the information sequence, converted for transmission using a digital-to-analog (D/A) converter, bandpass filtered (BPF) and transmitted by the array into the medium. Even though these signals have been quantized as signified by the overbar notation, once a digital convolution operation occurs, new amplitude information other than a ±1 is superposed. On reception, two BPF are utilized prior to A/D conversion. Out of band interference as well as anti-alias filtering is provided by the first analog BPF, while the second digital BPF (after A/D) smoothes the quantized measurement reducing quantization error and eliminates the high frequency noise created by the 1-bit quantization process. This processed data is then input to the usual demodulation, synchronization and information extraction operations (see Fig. 6).

The 1-bit T/R designs for reception are shown in Fig. 5b. Here coded information is transmitted into the medium, analog BPF and digitized using the 1-bit A/D as before, while the second digital BPF performs the same basic role of filtering, smoothing and noise rejection. The processed measurement is then convolved (in software) with the reversed signals to extract the coded information using the T/R III and IV algorithms. Although not quite as good as the 24-bit designs, the results of the 1-bit T/R implementations are quite reasonable, while simultaneously providing a huge cost savings for high frequency communications in a reverberant medium.

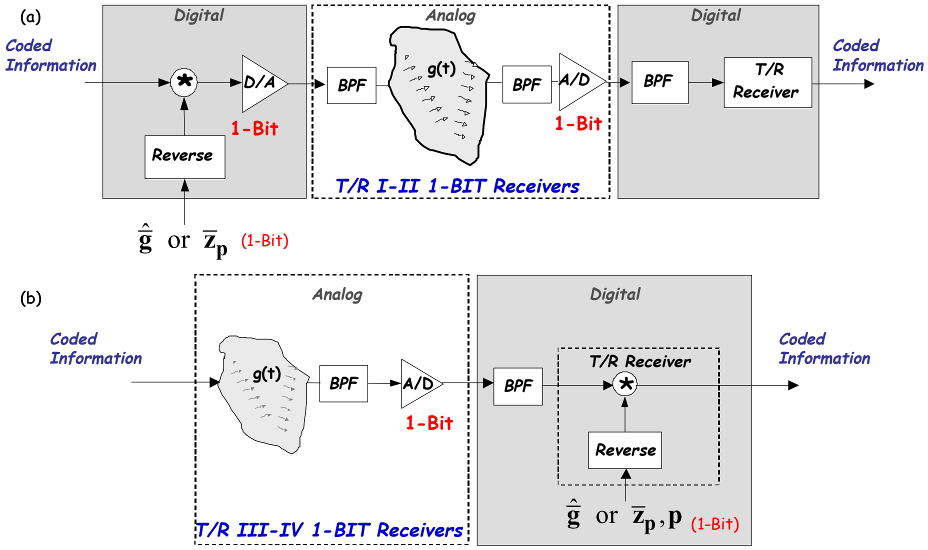


Fig. 6 1-bit T/R receiver realizations: (a) T/R I and II 1-bit designs on transmission. (b) T/R III and IV 1-bit designs on reception.

We summarize the operations performed on the received data to extract the desired coded information sequence from the noisy, reverberant data in Fig. 6. All of the T/R receiver realizations incorporate the common functions of demodulation, synchronization and quantization to extract the transmitted codes from the host station. In the figure, we see that the *raw* signal is received by the T/R receiver and processed to produce the *estimated* code sequence. The data are then *demodulated* to remove the carrier providing the processed data for synchronization. Note that this step usually incorporates a phase-locked loop to align the carrier phase of the receiver with the transmitted carrier, perform the demodulation (multiplication) and low-pass filtering. We found the loop an elegant solution to the problem but quite difficult to implement. Thus, we chose to search for the initial phase yielding the best performance by minimizing the symbol error. A standard matched filter is then used to synchronize the processed data and temporally locate the onset of the code which is then quantized, extracted and compared to the transmitted for performance analysis. This completes this section, Next we summarize our results and accomplishments and refer the interested reader to the published documents.

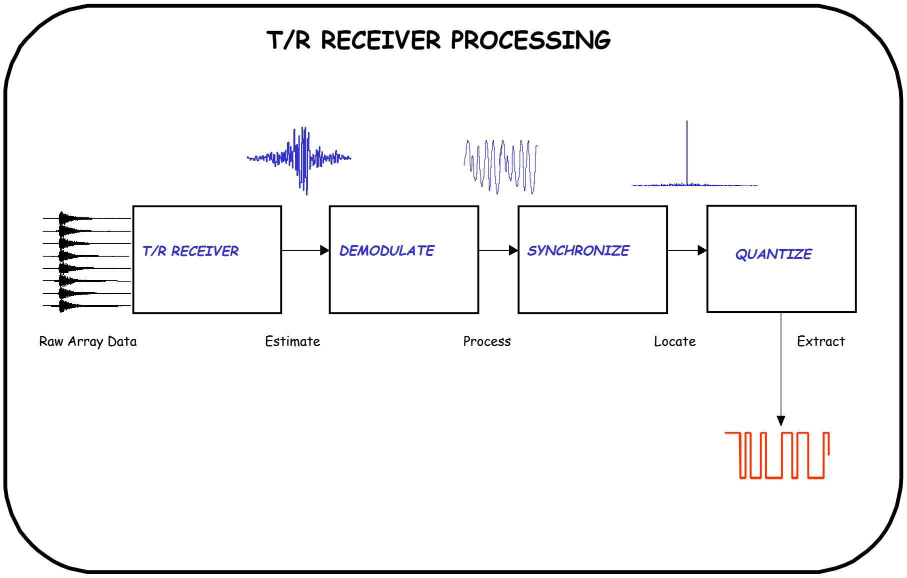


Fig. 7. Signal processing of experimental data: T/R reception (estimate code), demodulation (process), synchronization (locate code), quantization (extract code).

*Overall Performance Comparison:*

Next we compare the overall robustness performance of each design at the individual client stations for both 24-bit and 1-bit designs shown in Figs. 8 and 9. We illustrate the performance by bar charts with the height of the bar determined by the % threshold range occupied by zero-symbol error of the corresponding U-curve. In Fig. 16 the 24-bit design chart shows a significant performance improvement over previous point designs[5] with the average range over 40% of the total threshold interval for zero-symbol error compared to approximately 15%-20% performance of the point-to-point design. This significant increase is due to the improved SNR at the receiver afforded by the array (spatial gain) and improved focusing capability. By simultaneously superposing the two foci associated with the sets of corresponding reversed Green's functions, the receiver performance at both client stations improved. Channel isolation, that is, focus at one client receiver and checking for no focus at the other appears quite reasonable for T/R receivers I and II.

Observing the performance of the 1-bit T/R receivers in Fig. 8, we see that the performance is somewhat degraded, especially when superposing the foci, as the 24-bit design (as expected), but still much better than the previous point-to-point designs reported on earlier. However, for some applications, where cost is a major consideration, the 1-bit designs are satisfactory.

From the zero-symbol error and the % threshold range interval bar charts, it is clear that the T/R receivers can achieve zero-symbol errors over a reasonable range of the available thresholds for robust operations. The implementation advantages and simplicity of the T/R receivers offer an attractive alternative to the optimal. However, for a slowly time-varying channel, the T/R receivers may require more pilot signal transmissions to maintain the validity of the underlying set of Green's functions which is the key to T/R receiver design in a highly reverberant environment. In fact, our experience is to periodically transmit a pilot signal prior to the information codes to update the Green's functions using the reverse pilot signal approach. This scheme eliminates and changes in the environment or location changes of the clients and host array. Before we conclude our analysis, we performed one more test to evaluate the T/R receivers---long symbol length code transmissions.

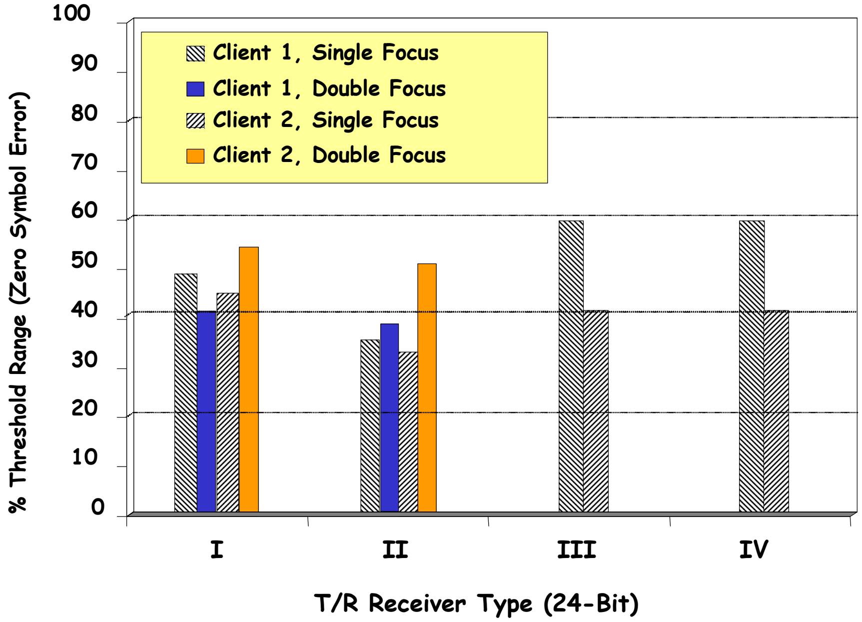


Fig. 8. T/R receiver performance based on the threshold range (% of total) for zero-symbol error performance at both client stations for 24-bit designs.

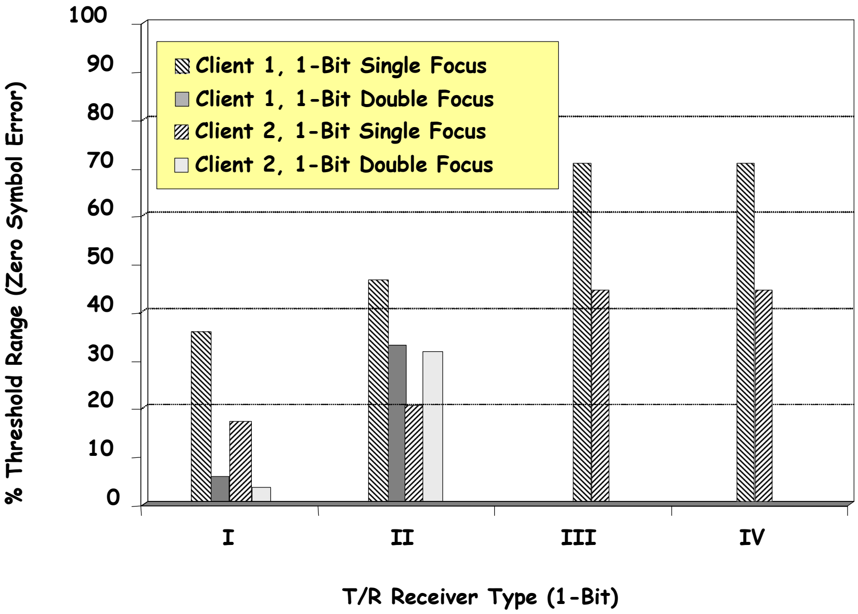


Fig. 9. T/R receiver performance based on the threshold range (% of total) for zero-symbol error performance at both client stations for 1-bit designs.

Next we summarize our results and accomplishments and refer the interested reader to the published documents.

## RESULTS

The detailed results of this project are best summarized through the following references which describe the various stages in the research and development of T/R receivers. This project evolved initially as a set of theoretical development and simulations which lead to the following conference papers presented at a variety of Acoustical Society of America conferences, that is,

### Effectiveness of using time reverse signal processing for mitigating multipath in communications channels.

*J. Acoust. Soc. Am.* Vol. 111, 2367 (2003) Paper 2aSPa1. (UCRL-ABS-147465)

Alan W. Meyer, James V. Candy, and Andrew J. Poggio

The use of time reverse signal processing (TRSP) to compensate for distortion in a communications channel is well established in recent literature. Our recent work quantifies the effectiveness of TRSP techniques *vis-a`-vis* traditional adaptive equalization techniques. These quantitative measurements are developed using simulations and laboratory experiments. A rigorous mathematical development of the communications problem is first necessary to establish a consistent model of the communications channel, and various approaches for implementing TRSP and adaptive equalization as well. These techniques are then simulated and performance measures developed for a large set of conditions spanning an increasing number of multipaths and increasing SNR. Acoustic laboratory experiments are also conducted in a highly reverberant environment to confirm both our techniques and results. In this paper we report on these measures of effectiveness comparing TRSP vis-a-vis traditional adaptive equalization techniques for compensating for multipath in a communications channel.

## Reversing Time: A Way to Unravel Distorted Communications.

*J. Acoust. Soc. Am.* Vol. 114, 2367 (2003) Paper 2pSPa. (UCRL-CONF-200292)

James V. Candy

This paper provides a discussion of time-reversal communications for a layman. It includes sounds and a variety of scenarios for the reader. It is a web-based paper that can be accessed from the Acoustical Society website directly (Newsroom).

## Time-reversal communications in a hostile, reverberative environment.

*J. Acoust. Soc. Am.* Vol. 114, 2367 (2003) Paper 2pSPa1. (UCRL-CONF-201023)

James V. Candy, Alan W. Meyer, Andrew J. Poggio, and Brian L. Guidry

Time-reversal _T/R_ communications is a new application area motivated by the recent advances in T/R theory. T/R receivers offer an interesting solution to the communications problem for a reverberant channel. This paper describes the performance of various realizations of the T/R receiver for an acoustic communications experiment in air. An experiment is developed to evaluate the performance of point-to-point T/R receivers designed to extract a transmitted information sequence propagating in a hostile, highly reverberant environment. It is demonstrated that T/R receivers are capable of extracting the transmitted coded sequence from noisy microphone sensor measurements with reasonable success. The processing required to validate these experimental results is discussed. These results are also compared with those produced by an equivalent linear equalizer or inverse filter, which provides the optimal solution when it incorporates all of the reverberations.

## Experimental design and processing for time-reversal communications in a highly reverberant environment.

*J. Acoust. Soc. Am.* Vol. 114, 2367 (2003) Paper 2pSPa2. (UCRL-CONF-200793)

Brian L. Guidry, James V. Candy, Andrew J. Poggio, and Alan W. Meyer

A suite of experiments has recently been conducted to validate the utility of using time-reversal (T/R) theory to solve a communications problem for highly reverberant environments. This paper discusses the design and layout of those experiments as well as experimental equipment criteria and selection. Solutions to problems arising from equipment limitations encountered during the experimental design process are examined. The signal processing used to extract information from gathered data is described and it is shown that communications receivers utilizing T/R theory can be used to accurately reproduce messages broadcast through hostile, reverberant communications channels.

## Simulation of time-reversal processing fro electromagnetic communications.

*LLNL Report* (UCRL-ID-154698)

Gerry Burke and Andrew Poggio

This report discuss the application of time-reversal techniques to simulated electromagnetic waves scattered from a plate.

## Acoustic propagation in a water-filled cylindrical pipe.

*LLNL Report* (UCRL-ID-153887)

Edmund J. Sullivan and James V. Candy

This report discuss the propagation of acoustic waves in a water-filled pipe which is used for the application of time-reversal techniques for eventual communication problems.

## Time-reversal processing for an acoustic communications experiment in a highly reverberant environment

*J. Acoust. Soc. Am.* Vol. 114, 1621-1631 (2004). (UCRL-JC-154219)

James V. Candy, Alan W. Meyer, Andrew J. Poggio, and Brian L. Guidry

Time-reversal (T/R) communications is a new application area motivated by the recent advances in T/R theory. Although perceived by many in signal processing as simply an application of matched-filter theory, a T/R receiver offers an interesting solution to the communications problem for a reverberant channel. In this paper, the performance of various realizations of the T/R receiver for an acoustic communications experiment in air is described along with its associated processing. The experiment is developed to evaluate the performance of point-to-point T/R receivers designed to extract a transmitted information sequence propagating in a highly reverberant environment. It is demonstrated that T/R receivers are capable of extracting the transmitted coded sequence from noisy microphone sensor measurements with zero-symbol error. The processing required to validate these experimental results is discussed. These results are also compared with those produced by an equivalent linear equalizer or inverse filter, which provides the optimal solution when it incorporates all of the reverberations.

PACS numbers: 43.60.Dh, 43.28.We, 43.28.Tc @JCB Pages: 1621–1631

## Multichannel time reversal communications in a highly reverberative environment.

*J. Acoust. Soc. Am.* Vol. 114, 1621 (2004) Paper 2aSPa4. (UCRL-CONF-207935)

James V. Candy, Brian Guidry, Andrew Poggio, and Claudia Kent

The development of point-to-point time-reversal _T/R_ communications in a highly reverberative environment was discussed previously _Candy *et al.*, J. Acoust. Soc. Am. Suppl. 1 **114**, 2367_. This paper focuses on the extension of that effort to the multichannel case. Here, we discuss the theoretical development of a suite of multichannel TR receiver realizations, similar to the point-to-point case, using an acoustic T/R array and a set of client stations. The performance of these processors on both simulated and experimental data is discussed in detail. The experiment is provided by a stairwell between two floors of a noisy building. The stairwell is populated with obstructions _pipes, rails, wall, etc._ and a 90-deg landing—clearly a highly reverberative environment. It is shown that the multichannel receivers perform quite well when compared to their point-to-point counterparts, and are able to reliably extract the ransmitted code from the noisy measurements.

## Time reversal and the spatio-temporal matched filter (L)

*J. Acoust. Soc. Am.* Vol. 116, 1348-1350 (2004). (UCRL-JRNL-202959)

D. H. Chambers,a) J. V. Candy, S. K. Lehman, J. S. Kallman, A. J. Poggio, and A. W. Meyer

It is known that focusing of an acoustic field by a time-reversal mirror ~TRM! is equivalent to a spatio-temporal matched filter under conditions where the Green's function of the field satisfies reciprocity and is time invariant, i.e., the Green's function is independent of the choice of time origin. In this letter, it is shown that both reciprocity and time invariance can be replaced by a more general constraint on the Green's function that allows a TRM to implement the spatio-temporal matched filter even when conditions are time varying.

PACS numbers: 43.60.Gk @EJS Pages: 1348–1350

## Performance of a multichannel time-reversal receiver design in a highly reverberative environment.

*J. Acoust. Soc. Am.* Vol. 116, 2574 (2004) Paper 3aSP1. (UCRL-ABS-201966)

James V. Candy, Brian Guidry, Christopher Robbins, Andrew Poggio, David Chambers, and Alan Meyer

The development of multichannel time-reversal (T/R) communications in a highly reverberative environment was discussed previously (Candy *et al.*, J. Acoust. Soc. Am. Suppl. **115**, 2467 (2004). This paper focuses on the development and performance of a 1-bit receiver in the multichannel case. Here, we discuss the performance of a suite of multichannel TR 1-bit receiver realizations, similar to the multichannel case, using an acoustic 8-element T/R array and a set of client stations. The performance of these processors on both simulated and experimental data is discussed in detail. The experiment is provided by a stairwell between two floors of a noisy building. The stairwell is populated with obstructions _pipes, rails, wall, etc. and a 90-deg landing—clearly a highly reverberative environment. It is shown that the 1-bit multichannel receivers perform quite well when compared to their full-dynamic-range 16-bit counterparts, and are able to reliably extract the transmitted code from the noisy measurements.

## Time-reversal communication through a highly scattering medium.

*J. Acoust. Soc. Am.* Vol. 116, 2574 (2004) Paper 3aSP2. (UCRL-CONF-201967)

David Chambers, Christopher Robbins, Brian Guidry, and Ahmad Elayat

An ultrasonic time-reversal array system is used to transmit communication signals across an aluminum slab with 195 holes drilled through it. Multiple scattering and mode conversion stretches a 0.4-microsecond transmitted pulse into a received signal that rings for over 75 microseconds with little attenuation. Communication through such a medium is subject to severe multipath distortion. Four variations of a time-reversal receiver are used to mitigate multipath distortion and allow error-free transmission of a variety of bit sequences (see Candy *et al.* J. Acoust. Soc. Am. Suppl. **115**, 2367, 2004). Performance of point-to-point receivers constructed from different segments of the Green's function (channel response) is compared.

## Wideband multichannel time-reversal communications in a tunnel-like structure.

*J. Acoust. Soc. Am.* Vol. 118, 2039 (2005) Paper 5aSP7.

James Candy, Christopher Robbins, Brian Guidry, David Chambers, Andrew Poggio, and Farid Dowla

The development of multichannel time-reversal _T/R_ processing continues to progress rapidly, especially when the need to communicate in a highly reverberant environment is critical. One such environment is a tunnel or cave, or even a pipe with many obstructions, multipath returns, severe background noise, disturbances, path disruptions (bends) as well as a long propagation path (~120 ft.). For this environment, multichannel T/R receiver designs have been extended to include a wideband processor and modulation scheme along with designs to communicate in the highly reverberative tunnel-like environment that includes high background noise levels and disturbances. The acoustic information signals are transmitted by an 8-element host or base station array and received some distance away with a significant loss in transmitted signal levels. In this paper the results of the new wideband processor and modulation scheme coupled with the underlying T/R theory are discussed to demonstrate the overall performance for both high and low bit-level designs in the tunnel.

## Eigenvalues of the time-reversal operator for a small ellipsoid.

*J. Acoust. Soc. Am.* Vol. 118, 2039 (2005) Paper 5aSP9.

David Chambers

Earlier analysis of the eigenvalues of the time-reversal operator for a small sphere showed there could be up to four eigenvalues for a planar array _Chambers and Gautesen, J. Acoust. Soc. Am. **109**, 2616_. In this talk, we generalize this result to a small ellipsoid and show how the relative values of the eigenvalues depend on orientation, as well as distance and material parameters. We show specific calculations for short rods and small discs.

## Multichannel time-reversal processing for acoustic communications in a highly reverberant environment

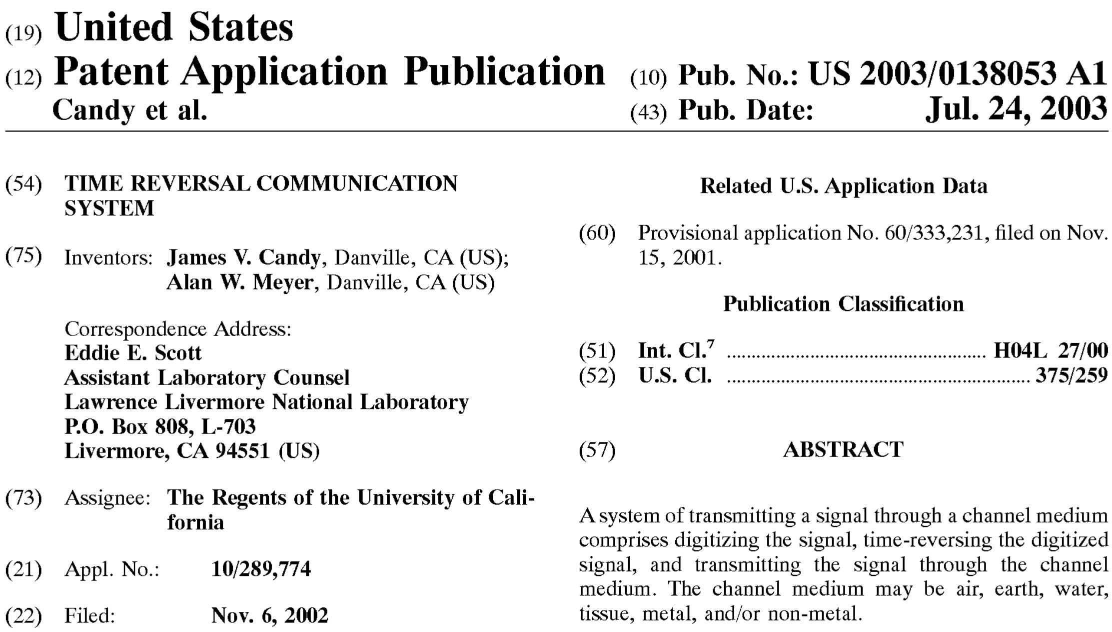
*J. Acoust. Soc. Am.* Vol. 118, 2339-2354 (2005). (UCRL-MI-215056)

James V. Candy,a_ Andrew J. Poggio, David H. Chambers, Brian L. Guidry, Christopher L. Robbins, and Claudia A. Kent

The development of time-reversal (T/R) communication systems is a recent signal processing research area dominated by applying T/R techniques to communicate in hostile environments. The fundamental concept is based on time-reversing the impulse response or Green's function characterizing the uncertain communications channel to mitigate deleterious dispersion and multipath effects. In this paper, we extend point-to-point to array-to-point communications by first establishing the basic theory to define and solve the underlying multichannel communications problem and then developing various realizations of the resulting T/R receivers. We show that not only do these receivers perform well in a hostile environment, but they also can be implemented with a "1 bit" analog-to-digital converter design structure. We validate these results by performing proof-of-principle acoustic communications experiments in air. It is shown that the resulting T/R receivers are capable of extracting the transmitted coded sequence from noisy microphone array measurements with zero-bit error.

PACS numbers: 43.60.Dh, 43.28.We, 43.28.Tc (EJS) Pages: 2339–2354

We also have two patents pending on this effort that resulted from this project:



(19) **United States**

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**Candy et al.** (43) **Pub. Date: Jul. 24, 2003**

(54) **TIME REVERSAL COMMUNICATION SYSTEM**

(75) Inventors: **James V. Candy**, Danville, CA (US); **Alan W. Meyer**, Danville, CA (US)

Correspondence Address:
**Eddie E. Scott**
**Assistant Laboratory Counsel**
**Lawrence Livermore National Laboratory**
**P.O. Box 808, L-703**
**Livermore, CA 94551 (US)**

(73) Assignee: **The Regents of the University of California**

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**Publication Classification**

(51) **Int. Cl.$^7$** .................................................... **H04L 27/00**
(52) **U.S. Cl.** ............................................................ **375/259**

(57) **ABSTRACT**

A system of transmitting a signal through a channel medium comprises digitizing the signal, time-reversing the digitized signal, and transmitting the signal through the channel medium. The channel medium may be air, earth, water, tissue, metal, and/or non-metal.

## *Multi-channel Time-Reversal Receivers for Multi and 1-Bit Implementations*

**[0001]** The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

### CROSS-REFERENCE TO RELATED APPLICATIONS

**[0002]** This application is a Continuation-in-Part of United States Patent Application Serial No. 10/289,774 filed November 6, 2002 titled, "Time Reversal Communication System." United States Patent Application Serial No. 10/289,774 filed November 6, 2002 and titled, "Time Reversal Communication System" is incorporated herein by reference.

**[0003]** *THIS APPLICATION CLAIMS THE BENEFIT OF UNITED STATES PROVISIONAL PATENT APPLICATION NO. 60/627397 FILED NOVEMBER 12, 2004 BY JAMES V. CANDY ET AL AND TITLED "MULTI-CHANNEL TIME-REVERSAL RECEIVERS FOR MULTI AND 1-BIT IMPLEMENTATIONS." UNITED STATES PROVISIONAL PATENT APPLICATION NO. 60/627397 FILED NOVEMBER 12, 2004 AND TITLED "MULTI-CHANNEL TIME-REVERSAL RECEIVERS FOR MULTI AND 1-BIT IMPLEMENTATIONS IS INCORPORATED HEREIN BY REFERENCE.*

## SUMMARY

We summarize the individual accomplishments of this project that can be considered as its deliverables:

- completed the theoretical development of T/R multichannel receivers;
- developed an eight-element T/R array capability;
- performed experimental designs validating multichannel T/R receiver designs;
- demonstrated a critical theoretical development for future electromagnetics (EM) experiments, using 1-bit A/D conversions for T/R receivers;
- conducted controlled experiments demonstrating T/R receiver performance;
- designed a highly scattering medium (on an aluminum plate);
- investigated the development (hardware) for an EM receiver design;
- initiated spin-off DARPA projects using related T/R concepts and team members;
- developed multichannel theory for T/R communications both patent application and papers;
- implemented new wideband T/R modulation scheme (with MIR personnel), executed design and analysis, demonstrated performance through simulation and experiments;
- performed controlled acoustic experiments using array in a stairwell of Bldg. 131, a tunnel-like hostile environment (Bldg 194) and electromagnetics in hallway of Bldg 181;
- demonstrated T/R performance using 1-bit A/D conversion validating performance in stairwell and tunnel-like structure;
- investigated experimental design for EM hardware including teaming with ultra wideband radar personnel;
- demonstrated T/R performance in Bldg 194 hallway for a variety of LLNL personnel and potential sponsors; and
- initiated hardware design for FPGA technology.

### *Final Experimental Results*

Our final results can be illustrated in Figures 10 and 11. We see the experimental set-up in the tunnel-like structure of Bldg. 194 with all of its bends, pipes, blind corners and multitude of reflectors creating an extremely hostile acoustic communication environment for T/R receiver performance analysis. The results of one receiver performance in this environment is shown in Figure 4 for both the 24-bit (left-most figure) and 1-bit receiver designs. After T/R processing the received wideband signal is shown along with the asterisk representing the "true" transmitted symbol and the circle (lollypop) representing the processed result for a given threshold. In both cases the receiver captures the information with no error (zero symbol error). The U-shaped curve (% symbol error vs. threshold) at the bottom of the figure is a measure of receiver performance demonstrating the extent of the zero (symbol error) interval relative to the entire interval, that is, the range of thresholds in which *no* symbol error has occurred. Of course, the larger the interval, the more robust the receiver performance obtained. Notice the degradation going from 24 to 1-bit A/D conversion.

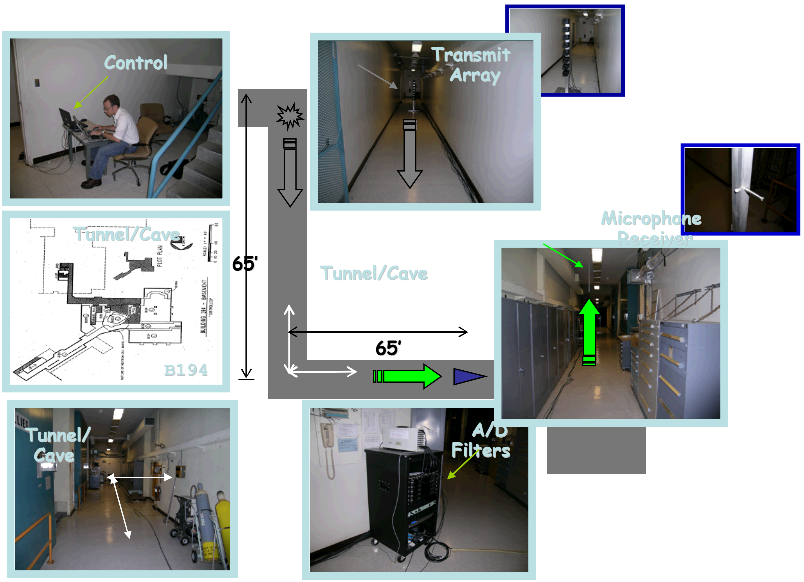

Fig. 10. Experimental environment and setup for T/R communications testing: tunnel (Bldg 194) layout with blind hallways and high corrugated steel ceilings (10-20′) along with the equipment set-up for array-to-point communications. Note that a schematic map demonstrates the tunnel communications path with the client receiver is approximately 180′ from host array.

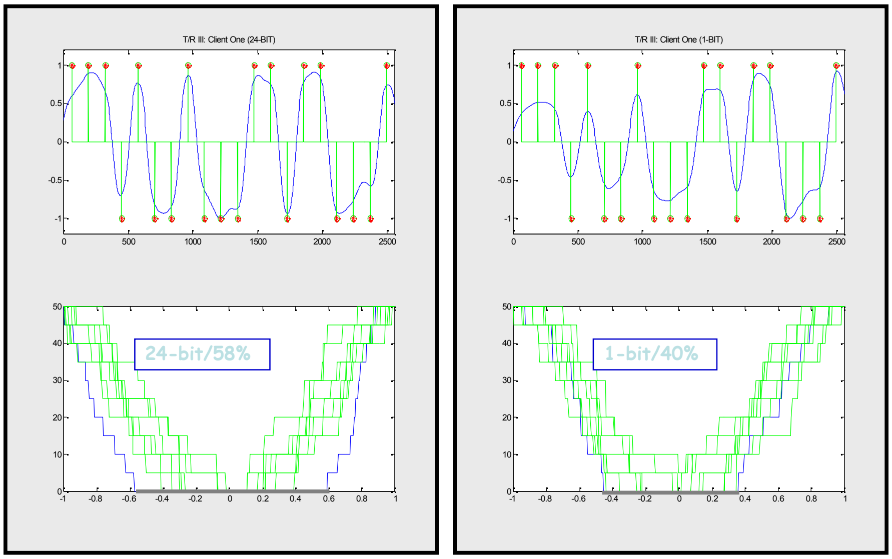

Figure 11. Time-reversal receiver designs (24/1-bit) for the controlled tunnel experiment: (a) raw T/R receiver output, with synchronized code and true code superimposed; (b) U-curve (% Symbol/bit-error vs. threshold) performance demonstrating zero-bit error (bottom of U-curve on zero). The wider the zero interval length, the better or more robust the receiver.

## *T/R Receiver Hardware Design*

Recently a study was conducted to examine the schedule and costs associated with developing a portable system capable of demonstrating Time Reversal Equalization. The study was conducted by Dan Bower, a senior hardware engineer with considerable experience in the design and production of commercial hardware/software systems of similar complexity. His findings, which I summarize below, give us a very clear estimate of the effort required to engineer, implement, and package a working Time Reversal demonstration system.

Several assumptions were made regarding system parameters:

- The system will operate at acoustic (audible) frequencies.
- The system will be capable of operating as a transmitter or receiver
- The message length will be > 100 seconds
- The channel response will be > 2 seconds
- The chassis will be less than 4” x 12” x 12”
- The weight will be less than 10 lbs

One encouraging find of the study is that current analog and digital technology is well-equipped to handle the processing requirements necessary for the proposed system. The specific processor selected in the study is a Xilinx FPGA (Field Programmable Gate Array) part optimized for signal processing applications (shown in Fig. 12), but other digital processing options are available. Also needed would be power amplifiers and some sort of custom filtering assembly, but these parts are also easy to find in the marketplace and quite inexpensive relative to their EM counterparts.

After examining a detailed list of tasks necessary to complete the system, it was found that the work necessary could readily be accomplished in the span of one fiscal year assuming that the people and dollars outlined in the study were made available. In terms of manpower, a full-time electrical engineer and 2 months of a mechanical designer are required. The summary of estimated costs is:

| | |
|---|---|
| Materials cost estimate | $29,000 |
| Manpower cost estimate | $165,400 |
| **Total** | $194,400 |

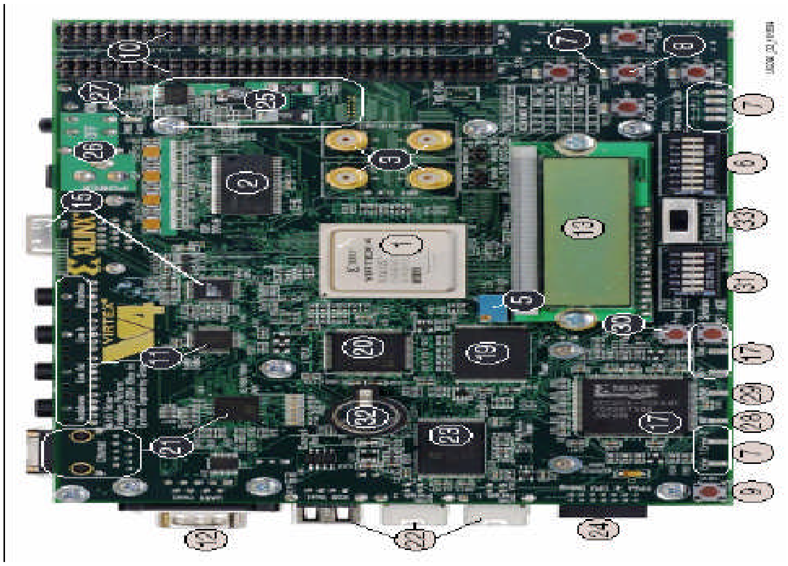

Fig. 12. Xilinx ML402 FPGA Board

This completes the final report.

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551