COMPREHENSIVE MIMO TESTING IN THE 2005 MAKAI EXPERIMENT

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Abstract: *Dramatic improvement in data rate and/or power efficiency using multiple-input multiple-output (MIMO) wireless links may be one of the most significant technical breakthroughs in modern communications. Originally developed for the flat-fading, terrestrial, free-space channel, its application for improving communication performance in the severely bandwidth limited, frequency-selective fading, acoustic channel is gaining momentum. To capitalize on this interest, a multi-institution MIMO component within the Makai Experiment was conceived and executed in September of 2005 in 100-m water off the northwest coast of Kauai, Hawaii. This paper will summarizes transmit schemes, receiver structures, the experiment, a new, versatile, high-performance, multi-element transmit system, and discuss communication results.*

1. INTRODUCTION

Recent information theoretic studies [1, 2] have shown that communication performance gains are possible without increasing power or bandwidth in systems using multiple transmitters and receivers, in other words MIMO (multiple input / multiple output) configurations. MIMO system performance gains are possible in "rich" multipath propagation environments because of simultaneous information transmission on virtual channels that exist between transmitter and receiver pairs. Each transmitter transmits in the same frequency band and at the same time; and therefore the receiver must depend on the unique spatial signatures or statistically independent links that exist between transmit/receiver pairs to separate the data streams from each data source.

As an example, for a system using n_T transmit and n_R receive antennas over a flat, Rayleigh fading channel, the information theoretic capacity grows linearly with the minimum of n_T and n_R. This tremendous potential for increased capacity directly translates to a corresponding increase in achievable data rate. On the other hand with proper coding at the transmitter, $n_T\, n_R$ diversity order is attainable which leads to a corresponding decrease in error rates.

Research on this topic began earnestly in the late 1990s and focused on the inherently wideband, typically flat-fading, wireless, radio-frequency channel where spectral efficiencies of 40 bits per second per Hertz have been demonstrated in lab environments [3]. The extremely bandwidth limited, shallow, underwater channel, unlike the radio channel in many ways, poses significant impediments to successful communication due to its fast temporal variations, long multipath spreads causing significant ISI, and perhaps most importantly, severe frequency-dependent attenuation.

A research team consisting of personnel from SPAWAR Systems Center (San Diego), Arizona State University, and the University of California at San Diego was formed in fall 2004 to study the applicability of MIMO systems for shallow underwater channels with the potential of improving data and error rates. Since then, significant headway has been made towards successfully demonstrating the feasibility and payoff of this newly developed and applied technology through our theoretical research and two field experiments.

This paper, which covers the most recent experiment, is organized as follows: Section 2 and 3 briefly describe MIMO transmission methods and associated receivers. Section 4, 5, and 6 describe the 2005 Makai Experiment, the communication and probe signals generated, and the recently developed ten-element system that transmitted them. Finally, Section 7 will summarize results.

2. TRANSMISSIONS SCHEMES

Dictated by encoding method at the transmitters, MIMO systems provide flexibility in offering high throughput, low error rates, or a compromise of these two. In particular, we have concentrated on space-time trellis coding (STTC) for obtaining low error rates and layered space-time coding (LSTC) for high spectral efficiency, and their combinations.

Space-time trellis codes introduced by Tarokh *et al.* in 1998 [4] provides full spatial diversity of $n_T\, n_R$ for a flat fading channel with no reduction in the presence frequency selectivity [5]. In fact, with a properly designed code, a diversity order of $n_T n_R L$, where L is the multipath extent in number of symbols. This high diversity order is a “hedge” against channel-induced errors. As an example of a particular STTC scheme consider a 2 x 2 (2 transmitters and 2 receivers) system, whereby each information bit is encoded into two outgoing bits dictated by a trellis structure and distributed on the two transmitters. This design causes the error rate to decay as the fourth power (i.e. 2 x 2) of the SNR.

As early as 1996, Foschini *et al.* [3] [6] introduced layered space-time coding for rich scattering, flat Rayleigh-fading environments. These codes, unlike STTC, aim at achieving spectral efficiencies not attainable by single transmitter systems. Simply stated, the serial information bit stream is spatially multiplexed onto n_T transmitters whereby each substream, so formed, is independently encoded. Since independent streams are transmitted from each transmit antenna, the spectral efficiency of the system grows linearly with n_T.

Applications requiring a trade-off between diversity order and spectral efficiency can be satisfied by implementing groups of STTC [7].

3. MIMO RECEIVERS

The benefits of additional degrees of freedom afforded by multiple transmit and receive antennas are counterbalanced by the complexity of optimal signal detection methods (MLSE: [8], and MAP: [9]) for ISI channels. Therefore, suboptimal lower complexity, channel-tailored receivers are sought, have subsequently been developed, and will be briefly presented next.

Stojanovic *et. al* [10] demonstrated that phase-coherent communication, i.e. phase-shift keying, is possible in the dynamic underwater channel when channel equalization and carrier phase tracking is conducted jointly. A multi-element transmitter and receiver extension to that in [10] is the canonical DFE-PLL (decision feedback equalizer – phase-locked loop) receiver that we originally proposed in [11], whereby co-channel interference (CCI) in addition to ISI, must be mitigated.

To investigate the performance of STTC encoded data, we embedded a modified Viterbi decoder in the DFE-PLL receiver structure to facilitate the generation of instantaneous, but tentative, trellis-code-based symbol decisions that are more reliable than a symbol-by-symbol slicer and therefore reduce DFE error propagation.

It has been shown in [12] that for coded systems over frequency-selective channels, significant performance improvement can be obtained by performing iterative, i.e. turbo, equalization where the equalizer and channel decoder exchange soft information in an iterative fashion, thereby reducing bit errors gradually. Iterative equalization and decoding has been added to the STTC receiver, just discussed.

In addition to the standard iterative DFE-PLL receiver for decoding LSTC encoded data, we added a successive interference cancellation (SIC) component along with a symbol-by-symbol channel estimator for each MIMO link [13]. Unlike the MIMO DFE feedback portion which attempts to cancel ISI and CCI and therefore results in large feedback filters, the iterative SIC DFE attempts to only cancel ISI for a given transmitter. The SIC DFE initially decodes data from the strongest transmitter and then using the symbol-by-symbol SIC impulse response estimate, it subtracts the interference effects from this transmitter and submits a new time series to the next stage for decoding. This is done in a layer-by-layer fashion until all transmit streams have been decoded. Once all the layers are processed, the proposed receiver can return to the first layer and reprocess it using new information from the decoder, *i.e.* perform turbo equalization.

4. MAKAI 2005 EXPERIMENT

SPAWAR lead the MIMO Experiment component within the Makai Experiment which was conducted in 100-m water off the northwest coast of Kauai Hawaii in September 2005. The following institutions participated: Arizona State University (ASU), Heat Light & Sound Research Inc., Marine Physical Laboratory at the Scripps Institute of Oceanography (MPL), Naval Post Graduate School (NPS), Naval Research Lab (NRL), University of Delaware (UDEL), and the University of California at San Diego (UCSD). Participants provided communication waveforms and were provided a time slice for transmission.

The 10-element MIMO transmitter provided by SPAWAR and the 8-element receiver provided by NRL were deployed three separate times for a total of 11 hours of transmission. NRL’s autonomous, ACDS, vertical receive array was deployed by the research vessel Kilo Moana and set in a free drift mode, while the vertical transmitter array was set over the side with the deepest element at 40 meters with 2-m element spacing. Once deployed, the Kilo Moana maintained roughly a 2-km separation between these two systems.

5. TRANSMITTED COMMUNICATION AND PROBE SIGNALS

This section and the Experimental Results Section cover joint work by SPAWAR, ASU, UCSD, and HLS.

A comprehensive set of over 150 distinct phase-shift-keyed modulated communication signals were generated by varying constellation order, coding, transmitter mapping, and number of carriers. Data rates varied from 5 to 200 k bits/s. Generally speaking, we “walked before we ran” by transmitting a data packet, in sequence, from each of the ten transmitters using a rate ½ Turbo code plus interleaver. Next, a single group, two-transmitter STTC was sent followed by 2, 3, 4, and 5 groups of two-transmitter STTC signals. We then concentrated on LSTC signals with rate 1/3 outer turbo code plus interleaver and increased the number of transmitters involved from 4 to 10 in steps of 2.

The transmissions were organized into 12-second data packets comprised of a leading 4.2 second channel probe signal, 200-ms channel clearing time, 4.8-second data payload part of which is used for equalizer training, and lastly, 3 seconds for the transmit system to resynchronize and prepare for the next data packet. The composite channel probe consisted of LFMs (linear frequency modulation) for each transmitter and provided symbol synchronization and channel response estimates between each transmitter/receiver pairs.

6. TEN-ELEMENT TRANSMIT SYSTEM

A ten-element, wideband (25-50 kHz), flexible, and portable, MIMO transmit testbed was developed by SPAWAR in the spring of 2005 and debuted during the Makai Experiment. Its architecture is shown in Fig. 1. A custom interface to a hard disk drive via a microcontroller and field programmable gate array (FPGA) was implemented for high-rate playback at 200 k samples/s per channel, or 4 Mbytes/s in aggregate (note: 2 bytes per sample). Each digital data stream is routed to 5 custom programmable gain, 2-channel digital-to-analog converters. Pairs of analog signals are then routed to five, 2-channel, Boston Acoustics GT-28, 1000-watt car stereo amplifiers. The amplified communication and probe signals then pass through a 5-th order, matching network for controlling load impedance and broadening the transducer response. The 100-meter custom cable consisted of ten bundled RG-58 coaxial cable with non-compressible cores and allows adjustment of inter-element spacing up to 2 meters.

The transmit system's maximum source level is $193 \text{ dB re } 1\ \mu\text{Pa}$ at 1 meter simultaneously on all elements; and is 100 percent duty-cycle capable at 190 dB on all elements. The end-to-end frequency response is flat to ± 1 dB across the passband from 25-50 kHz, with channel-to-channel matching better than 1 dB.

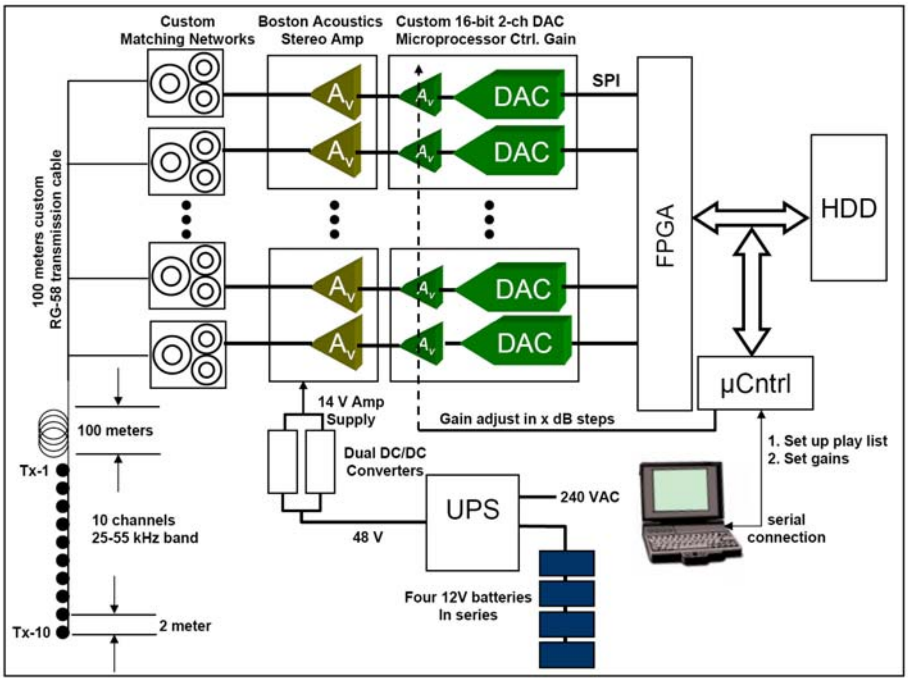

Fig. 1: Ten-element MIMO transmit system block diagram.

7. EXPERIMENTAL RESULTS

The full available bandwidth of 25 kHz was broken down into six 3 kHz bands with a 1 kHz guard band between each. This maximize the symbol duration as a percentage of the significant multipath extent, which also minimizes equalizer lengths. It also facilitate better phase tracking due to the channel remaining constant over as many symbols as possible. The end result is a slower symbol rate per each of 6 carriers than a comparable single carrier scenario.

The results can be broken down into three categories: 1) Single transmitter / single receiver scenario using iterative decoding, 2) turbo coded LSTC using MIMO DFE with and without successive interference cancellation (SIC), and 3) STTC encoded data sets.

Prior to processing each data packet, the time-averaged impulse response using the LFM probe signal was used to set equalizer lengths. The selection of other receiver parameters such as the RLS forgetting factor, λ, and the PLL tracking constants, K_1 and K_2, was guided by the dynamic nature of the impulse response as provided on a symbol-by-symbol basis from the RLS correlation vector during the receiver training period.

	Receiver 1	Receiver 2	Receiver 3	Receiver 4	Receiver 5	Receiver 6	Receiver 7	Receiver 8
Band 1	0	0	0	0	0	0	0	0
Band 2	0	0	0	0	0	0	0	0
Band 3	0	0	0	0	*F*	0	*F*	0
Band 4	0	*F*	0	*F*	0	0	0	0
Band 5	0	0	0	0	0	0	0	0
Band 6	0	*F*	0	*F*	0	0	*F*	*F*

Table 1: Results of decoding single transmitter, single receiver data packet using optimized receiver settings and without manual intervention. "0" indicates zero errors after a varying number of iterations. "F" signifies equalizer divergence.

Table 1 depicts results of BPSK (binary phase shift keying) modulated signal from transmitter 1 to each of the 8 receivers. Through iterative decoding, the errors were reduced to zero in most cases with increasing failures, *i.e.* divergence of equalizer, related to lower SNR due to greater absorption at higher frequencies.

7.2 LSTC decoding results

Table 2 compares decoding results for turbo encoded, BPSK modulated, 4 transmitter, LSTC data packets using the canonical MIMO DFE and the SIC DFE for the 39 – 42 kHz band. Notice that for transmitter number 4, the errors using the MIMO DFE do not converge; however, convergence is demonstrated for the SIC DFE receiver that has a shorter feedback section and is consequently less vulnerable to error propagation. Figure 2 shows the variability of the instantaneous impulse response estimates using the SIC algorithm output for two transmitter/receiver pairs. Figure 3 shows the powerful error correction capabilities of iterative decoding even in low-SNR (< 7 dB at the equalizer output) situations, with the distribution of the soft decoder output approaching a mixed Gaussian.

Band	**Transmitter**	**Symbol errors / 9600 (equalization only)**	**Information bit errors after decoding / 3200**	**SNR (dB)**
4	1	1735	293, **0**	-
	2	1402	0, **0**	-
	3	1089	0, **0**	-
	4	2905	*1192, 1062*	-
4	1	2078	805, 682, 0, , **0**	6.45
	2	1593	2, 0, 0, **0**	6.91
	3	728	0, 0, 0, **0**	6.93
	4	1997	733, 562, 3, **0**	6.17

Table 2: Decoding results for BPSK, turbo coded, 4 Tx, band 4, LSTC using MIMO DFE (top) and SICDFE (bottom). Multiple numbers in column 4 refer to multiple turbo iterations.

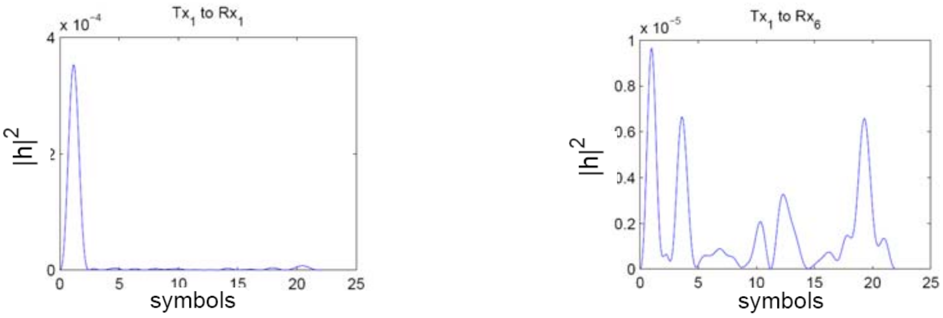

Fig. 2: Channel impulse response estimates using the SIC algorithm for a 4 transmitter LSTC QPSK data packet.

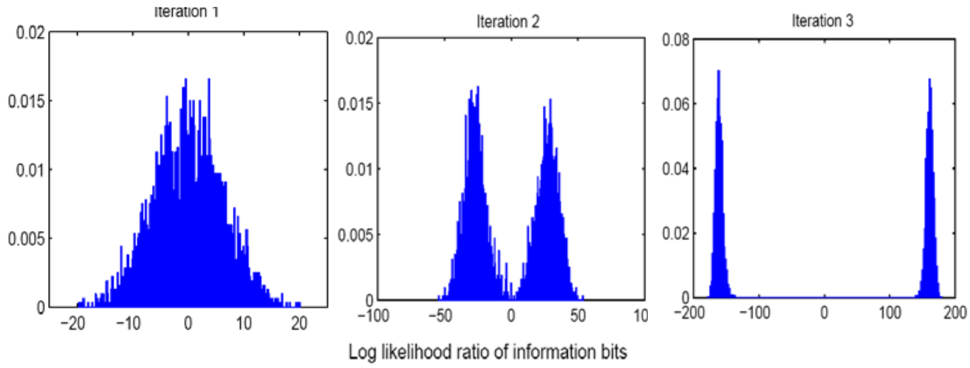

Fig. 3: Distribution of the log-likelihood ratios of input bits after iterations 1,3, and 4 for a 4 transmitter, LSTC, turbo coded BPSK data packet.

7.3 STTC decoding results

Table 3 shows the decoding results for a QPSK, 2 transmitter, STTC data packet. For STTC, coding across channels provides transmit diversity and results in significant improvement in number of errors in the first iteration, column 6, over the uncoded symbol errors shown in column 3. By preceding the STTC with a high-rate (9/10) turbo outer code followed by an interleaver, the residual error rates shown in the right most position of column 6 could be brought to zero with minimal rate loss. Although packets with information bit rates as high as 200 k bits/s were transmitted, at the time of this publication we have been able to decode a 4 transmitter, STTC, QPSK, 6 carrier data packet for a information throughput of 48 k bits/s.

Band	Transmitter	Symbol errors / 9600 (equalization only)	SNR (dB)	Group	Information bit errors after decoding / 19200
1	1 2	58 1592	11.74 8.67	1	96, 18, **11**
2	1 2	237 2245	10.25 8.16	1	416, 61 **39**
3	1 2	111 2808	11.43 8.23	1	220, 34, 21 **17**
4	1 2	107 2269	11.09 8.61	1	195, 30, 26 **21**
5	1 2	2711 2698	8.03 7.65	1	2587, 327, 205, **167**
6	1 2	4869 4018	7.27 6.52	1	4948, 1783, 546, **356**

Table 3: Decoding results for QPSK, 2 transmitters, STTC using MIMO DFE. Multiple numbers in column 4 refer to multiple turbo iterations

8. CONCLUSIONS

A comprehensive multi-institution MIMO communications experiment was conducted in the fall of 2005 off the coast of Kauai, Hawaii. During this test, a new, wideband, 10-element MIMO transmitter performed well during its first use and transmitted multi-element communication waveforms that fall into two basic camps -- high diversity order space-time trellis encoded data and high data rate, turbo encoded layered space-time signals. We showed the MIMO SIC DFE advantage over the canonical MIMO DFE and showed the benefits of transmit diversity inherent in coding spatially as with STTC. Table 5 provides highlights of data processed and successfully decoded so far. Table 4 taken from [14] provides a historical perspective and when compared to Table 5, points to the promise of MIMO configurations over traditional single transmitter systems and will motivate future research.

Year	Data rate (kbps)	Bandwidth (kHz)	Range (km)	Prob. of error
1989	500	125	0.06_D	$< 10^{-7}$
1985	$20 - 30$	10	3.5_D	$< 10^{-4}$
$1993 - 94$	$0.6 - 3$	$0.3 - 1.0$	$89 - 203_{S,D}$	$< 10^{-2}$
1994	6	3	0.04_S	N/A
1994	6	3	4.0_D	N/A
1994	20	20	0.09_S	$\sim 10^{-3}$
1995	$1.1 - 2.2$	$0.6 - 2.2$	$0.5 - 8.0_{S,D}$	$< 10^{-3}$
1996	0.2	0.2	50_D	$< 10^{-4}$
1997	$0.9 - 1.8$	N/A	$4.0_S - 8.0_D$	$< 10^{-4}$
1998	$1.67 - 6.7$	$2 - 10$	$4.0_S, 2.0_S$	N/A

Table 4: Historical data rates and implied spectral efficiencies. Reproduced from [14].

Year	Data rate (kbps)	Bandwidth (kHz)	Range (km)	Data type	Prob. of error
2005	6	23	2_S	1 tx, turbo coded BPSK	~ 0
2005	16	23	2_S	4 tx, turbo coded BPSK	~ 0
2005	24	23	2_S	2 tx, STTC QPSK	$\sim 5 \times 10^{-3}$
2005	48	23	2_S	4 tx, STTC QPSK	$\sim 10^{-2}$
2005	12	3	2_S	6 tx, STTC QPSK	$\sim 10^{-2}$

Table 5: Summary of MIMO data rates and implied spectral efficiencies obtained from the Makai Exp. Subscript ‘s’ indicates shallow water. The non-zero error rates for STTC were brought down to zero using an additional high-rate outer code with little rate loss. This table is excerpted from [13].

9. ACKNOWLEDGEMENTS

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