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14. ABSTRACT Our research focuses on the horizontal underwater acoustic communications. Towards the high rate objective, we address two key issues, namely channel estimation and symbol detection. To enhance channel estimation, we propose a cyclic approach (CA) for designing training sequences and an iterative adaptive approach (IAA) for estimating the channel. We also present a minimum mean-squared error (MMSE) based symbol detector, RELAX-BLAST, which combines vertical Bell Labs Layered Space-Time (V-BLAST) algorithm and the cyclic principle of RELAX. Towards the high reliability objective, we design robust MIMO transceivers that allow for very low-complexity receiver processing while achieving superb error performance even in turbulent sea. Our unique study on the correlation between the error performance and environmental data further confirms the robustness of our designs. We also performed theoretical capacity analysis as well as practical system designs of relay-aided (RA-)UAC to augment both the reliability and transmission range.					
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FY09 Year End Report

“MIMO-UAC for Rate Enhancement and Range Extension”

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LONG-TERM GOALS

Our proposed research will focus on the horizontal underwater acoustic communications (UAC). One important metric for evaluating UAC systems is the maximum achievable range-rate product. Building on co-located and/or distributed multiple transducers and hydrophones, we plan to develop rate-oriented and range-oriented multiple-input multiple-output (MIMO) UAC systems, as well as additional range/rate enhancement via the deployment of distributed transceiver units which operate in a cooperative manner.

OBJECTIVES

The need for achieving higher data rates with higher reliability in UAC leverages the use of MIMO schemes. Towards the high rate objective, we address two key issues, namely channel estimation and symbol detection. To enhance channel estimation, we propose a cyclic approach (CA) for designing training sequences and an iterative adaptive approach (IAA) for estimating the channel. We also present a minimum mean-squared error (MMSE) based symbol detector, RELAX-BLAST, which combines vertical Bell Labs Layered Space-Time (V-BLAST) algorithm and the cyclic principle of RELAX. Towards the high reliability objective, we design robust MIMO transceivers that allow for very low-complexity receiver processing while achieving superb error performance even in turbulent sea. Our unique study on the correlation between the error performance and environmental data further confirms the robustness of our designs. We also performed theoretical capacity analysis as well as practical system designs of relay-aided (RA-)UAC to augment both the reliability and transmission range.

APPROACH

1. Enhanced Channel Estimation and Symbol Detection For High Speed MIMO-UAC

Training Sequence Design: Consider phase coherent communications over $N \times M$ MIMO-UAC multipath channels. For multipath channels, training sequences with good auto- and cross-correlation properties are needed. Training symbols have a generic form of $x_n(t) = e^{j\phi_n(t)}$, where $\phi_n(t) \in [0, 2\pi)$ is the

phase of $x_n(t)$ at the n^{th} transmitter and $t = 1, 2, \dots, P$, with P being the training sequence length. Let $\mathbf{X} \in \mathbb{C}^{(P+R-1) \times NR}$ contain N training sequences and their delayed versions, where R is the number of channel taps. Our goal is to make the Frobenius norm $\varepsilon = \|\mathbf{X}^* \mathbf{X} - P\mathbf{I}\|_F^2$ small, where $\mathbf{I}$ is an identity matrix. Let $\mathbf{U}$ be an arbitrary semi-unitary matrix. Then minimizing ε can be formulated as:

$$\{\phi_n(t)\} = \arg \min_{\{\phi_n(t)\}, \mathbf{U}^*} \|\mathbf{X} - \sqrt{P}\mathbf{U}^*\|_F^2, \text{ subject to } \mathbf{U}\mathbf{U}^* = \mathbf{I}. \quad (1)$$

This optimization problem can be solved by a cyclic algorithm (CA) as follows:

- Step 0: $\mathbf{U}$ is initialized to be $[(\mathbf{I} + j\mathbf{I})/\sqrt{2}, 0]$.
- Step 1: With the most recent $\mathbf{U}^*$, the solution to (1) is $\phi = \arg(\sum_{r=1}^R Z_r)$, where $\{z_r\}_{r=1}^R$ are given.
- Step 2: With the most recent $\phi_n(t)$, the solution to (1) is given by $\mathbf{U}^* = \bar{\mathbf{U}}\tilde{\mathbf{U}}^*$, where $\sqrt{P}\mathbf{X} = \bar{\mathbf{U}}\tilde{\mathbf{U}}^*$ is the singular value decomposition (SVD) of $\sqrt{P}\mathbf{X}$. Iterate Steps 1 and 2 until the difference of the cost function in (1) between two successive iterations becomes lower than a predefined threshold.

The Channel Estimation Algorithm (IAA): The second phase of channel estimation involves the design of the algorithm estimating the channel impulse response (CIR), denoted as $\mathbf{h}$, using known (training or detected) symbols $\mathbf{S}$, and highly contaminated measurements $\mathbf{y}$. The channel estimation problem at each receiver has the form: $\mathbf{y} = \mathbf{S}\mathbf{h} + \mathbf{e}$, where $\mathbf{e}$ is the additive noise. We use IAA to estimate $\mathbf{h}$, and make no assumption on the statistics of $\mathbf{e}$. Let $\mathbf{P}$ be a diagonal matrix with diagonal elements $P_r = |h_r|^2$, where h_r is the r^{th} element of $\mathbf{h}$. If the r^{th} column of $\mathbf{S}$ is $\mathbf{s}_r$, then the IAA can be implemented as:

- Step 0: Initialize $P_r = |\mathbf{s}_r^* \mathbf{y}|^2 / (\mathbf{s}_r^* \mathbf{s}_r)^2$.
- Step 1: With the most recent $\mathbf{P}$, calculate $\mathbf{R} = \mathbf{S}\mathbf{P}\mathbf{S}^*$.
- Step 2: With the most recent $\mathbf{R}$, update $\hat{\mathbf{h}}_r = \mathbf{s}_r^* \mathbf{R}^{-1} \mathbf{y} / \mathbf{s}_r^* \mathbf{R}^{-1} \mathbf{s}_r$, $P_r = |\hat{\mathbf{h}}_r|^2$.
- Iterate Steps 1 and 2 until convergence.

Sparse channel estimates can be obtained by combining IAA with the Bayesian information criterion (BIC). Moreover, the RELAX algorithm can be used to improve the IAA with BIC estimates further.

Symbol Detection: Following the CIR estimation, our focus is on the detection of the payload symbols. We use an MMSE based filter and propose the RELAX-BLAST algorithm. This algorithm first detects the symbol with the dominant channel taps and subtracts it from the measurements. It then estimates the next dominant symbol from the residue signal. The two already detected symbols are updated iteratively until the difference of two successive estimates becomes less than a threshold. Once these two symbols are subtracted from the measurements and the third strongest symbol is estimated, the three symbols are again updated iteratively as before. This process is repeated for all symbols.

2. Robust MIMO-UAC with Low-Complexity Receivers

Under this research thrust, we study basis expansion model (BEM) based coherent and differential schemes and a high reliability (HR-) direct-sequence spread spectrum (DSSS) scheme tailored for low-complexity receivers. We also compare different BEMs in both coherent and differential schemes.

BEM Based Schemes: In [1], [2], [3], [4], we presented a differential scheme and a coherent scheme with a windowed least squares (WLS) channel estimator, both based on discrete Fourier transform (DFT-) BEM. We generalize the schemes to accommodate general BEMs, e.g., discrete prolate spheroidal sequence (DPSS-) BEM. The performance difference of different BEMs in both coherent

and differential schemes is studied. DFT-BEM has a nice property that the equally-spaced decimated basis matrix is scaled unitary while DPSS-BEM does not. We prove the following lemma:

Lemma 1: Let $\mathbf{A}$ be a $K \times K$ full-ranked matrix with eigenvalues $\lambda_i, i = 0, \dots, K - 1$ satisfying $\sum_{i=0}^{K-1} |\lambda_i|^2 = K$. Let $\mathbf{x}$ be a $K \times 1$ random vector, in which the elements are i.i.d. with finite mean and variance. Then, $E\{\|\mathbf{A}^{-1}\mathbf{x}\|^2\} \geq E\{\|\mathbf{x}\|^2\}$, where the equality holds if and only if $\mathbf{A}$ is a unitary matrix.

According to Lemma 1, we know that although DPSS-BEM approximates the real UAC channel more accurately, the performance is degraded by the amplified model fitting bias and noise during the channel-BEM transform process. Therefore, there is a tradeoff between the modeling accuracy and the processing effect, in both BEM-based coherent and differential cases.

HR-DSSS: In [5], we presented an HR-DSSS scheme with multiple symbols riding on circularly shifted versions of an m-sequence during a single sequence block. At the receiver, only simple matched filters are required. The system diagram is shown as Figs. 1—3 with the following details:

- **Transmitted Signals:** Multiple symbols ride on shifted versions of an m-sequence. With $s(j)$ the j th symbol during a sequence block, $\mathbf{T}$ the shift matrix, $L + 1$ the channel delay taps, and $\mathbf{c}$ the m-sequence, the transmitted signal block is $\mathbf{x} = \sum_{j=0}^{J-1} s(j) \mathbf{T}^{j(L+1)} \mathbf{c}$, where J is number of superimposed sequences, at most $J_{max} = \lfloor M/(L + 1) \rfloor$.
- **UAC channel Propagation:** Use cyclic prefix (CP) to remove inter-block interference (IBI). After adding CP at the transmitter and removing CP at the receiver, the equivalent channel is $\tilde{\mathbf{H}} = \sum_{l=0}^L h(l) \mathbf{T}^l$.
- **Receiver Processing:** Separate each channel tap for each symbol using simple matched filters. With the noise vector $\mathbf{z}$, the received block is

$$\mathbf{y} = \sum_{j=0}^{J-1} s(j) \sum_{l=0}^L h(l) \mathbf{T}^{j(L+1)+l} \mathbf{c} + \mathbf{z}.$$

Then, multiplying $\mathbf{y}$ by a matched filter $[\mathbf{T}^{j(L+1)} \mathbf{c}]^T$, we obtain

$$v(j; l) = M h(l) s(j) - v_l(j; l) + \eta(j; l),$$

where $\eta(j; l)$ is the noise and $v_l(j; l)$ is the self- and co-channel interference that is proved to be negligible in [5]. Notice here each channel tap for every symbol is readily separated for channel estimation and symbol demodulation. Our HR-DSSS performs coherent detection without any phase ambiguity, which enables arbitrary modulations (QPSK used in sea trials).

3. Relay Aided (RA-)UAC

We analyze the capacity of RA-UAC. Consider a two-hop relay system with one relay and amplify-and-forward (AF) relaying protocol, the end-to-end capacity can be approximated at high signal-to-noise (SNR) as:

$$C(D, \alpha_p, \alpha_D) = \int_B \log_2 \left(1 + \frac{P}{B N_f} \frac{1}{A(\alpha_D D, f)/(1 - \alpha_p) + A((1 - \alpha_D) D, f)/\alpha_p} \right) df, \quad (2)$$

where α_p and α_D are the power allocation ratio and relay location ratio. P is the total transmit power of the system and B is the signal bandwidth. $A(D, f)$ is the empirical acoustic signal attenuation formula and N_f is the noise power spectrum density (PSD).

WORK COMPLETED

In terms of high rate MIMO-UAC, we have continued to focus on the channel estimation and symbol detection problems. We have developed both aperiodic and periodic cyclic algorithms for designing training sequences with good auto- and cross-correlation properties. The aperiodic training sequences are needed when a guard interval is placed between the training and payload sequences. The periodic training sequences are useful when a cyclic prefix is used instead of the guard interval. IAA coupled with BIC has been used to estimate the CIR. For channel tracking, we have considered how to use a better initial condition for IAA to improve the computational efficiency. We have continued to use the MMSE based RELAX-BLAST algorithm for symbol detection and extended it to deal with coded payload sequences. To improve the computational efficiency, we have proposed to implement the RELAX-BLAST algorithm via a conjugate gradient method together with DFT.

In terms of robust UAC with low-complexity receivers, we have established BEM-based coherent and differential schemes and compared different BEMs in both. We also developed an HR-DSSS scheme to transmit multiple symbols during a single sequence block. We have evaluated the system capacity of RA-UAC to reveal its benefits. Asynchronous Amplify-and-forward relaying with Precoded OFDM (AsAP) system is also uniquely designed for RA-UAC.

Our proposed schemes have been tested via both simulations and field data from experiments, including RACE'08 and GLINT'08 conducted by the Woods Hole Oceanographic Institution (WHOI) and GOMEX carried out by Naval Research Lab (NRL),.

RESULTS

1. High Speed MIMO-UAC

The transmitted data packages used CA sequences with 512 symbols for training followed by QPSK payload symbols. The payload was divided into blocks, each of length 250 encoded with a 1/2 convolutional encoder with constraint length of 5. Using 4 transducers and QPSK modulation, the resulting uncoded payload data rate is 62.5 kbps.

The SPACE'08 data encountered rich channel conditions over the course of the experiments, which is evident in Fig. 4, where the dynamic variations of the average wind direction and speed are shown. Using the average wind speed as a reference, the channel conditions have been roughly divided into the "good", "bad", and "ugly" categories, with each category containing approximately one third of the measured data. Fig. 5 shows how the normalized CIR between a given transmitter and receiver pair evolves over time in an ugly channel, at the 60 m receiver on Julian date 294 and 1 km receiver on Julian date 300. In these plots, a single transducer continually transmits an m-sequence, while the other transducers are inactive. It is observed that the channel taps experience significant variations over time.

To demonstrate the importance of optimal training for channel estimation, we consider the most challenging channel conditions (including those encountered by the 60 m receiver under the ugly channel conditions). Table I shows an example of the coded BER for the first 4 payload data blocks when random QPSK and CA optimized sequences of length 512 are used for training for the 60 m receiver. When the CA optimized sequences are used, the first payload data block gives zero BER. The channels used for the subsequent blocks are estimated in the decision-directed mode (partly training symbols, partly detected symbols from previous block(s)). Note that even the second payload data

block has zero BER. Note also that channel tracking beyond the second payload data block is difficult under the challenging channel conditions. In contrast, with the random QPSK sequences used for training, the initial channel estimates are poor, resulting in high BER even for the first payload data block, making subsequent channel tracking impossible.

Consequently, we suggest the data structure shown in Fig. 6 under the challenging channel conditions. For this case, the data rate is 20.7 kbps due to the frequent use of the training sequences. For benign channel conditions, channel tracking is possible and the number of payload data blocks following training can be infinite as long as the channel conditions remain the same. If coding is used, then the data rate is 31.25 kbps; otherwise, the data rate is 62.5 kbps. Channel tracking without coding, however, is only possible for 200 m receiver under good channel conditions. Table II summarizes the achievable data rates using our MIMO UAC designs and algorithms for the SPACE'08 experiment.

2. Robust MIMO-UAC with Low-Complexity Receivers

BEM-Based Schemes: We tested the robustness of our BEM-based schemes in RACE'08 at a 1000m distance. Our BEM-based coherent scheme achieves a remarkable 0.24% uncoded BER, shown in Table III, when the regular least squares estimator fails (~50% BER) during the roughest periods. The uncoded BER for differential schemes is shown in Table IV. Our BEM-based differential schemes outperform the non-BEM plain OFDM remarkably. The robustness of our scheme is further verified by the correlation between the BER and the sea environmental data that are shown in Figs. 7—8. Our BEM-based differential scheme has much smaller correlations shown in Table V, meaning more reliable against different sea conditions. We also observe in the tables that for the differential case, DFT-BEM is better than DPSS-BEM, while for the coherent case, DPSS-BEM is more preferable.

HR-DSSS: We tested our HR-DSSS scheme in both GLINT'08 and GOMEX sea experiments. As shown in Table VI, the uncoded BER is very good with a single hydrophone in GLINT'08. When 4 hydrophones are used, we get 0 bit error. In GOMEX sea experiment, our HR-DSSS achieves 2 bits error out of all 64800 bits with a single hydrophone at a nautical mile distance.

3. RA-UAC system

Capacity Analysis: We compare the capacity of RA-UAC system with direct-link system in Fig. 9. The result reveals a prominent capacity gain of over 40%.

AsAP System: Under underwater channel models, we simulate the performance of our AsAP relay systems in terms of BER, displayed in Fig. 10. The results show that our AsAP systems provide more reliable communication than the direct-link systems with better BER performance. Prominent diversity is collected through OFDM precoding.

IMPACT/APPLICATIONS

The natural bandwidth limitations of coherent underwater acoustic channel suggest a technical breakthrough. MIMO signal processing is a promising bandwidth efficient method to high data rate and high quality services. Building on both BEM-based and DSSS approaches, and considering both direct link and relay transmissions, our promising results are expected to favorably impact high-rate long-range MIMO-UAC designs.

RELATED PROJECTS

National Science Foundation (NSF) project "CAREER: Acoustic Underwater Sensor Network - Multi-Level Adaptations." This project focuses on the data storage and retrieval issues in underwater sensor networks. It is informed by the results obtained through the current ONR project.

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PATENTS

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	QPSK				CA			
	Tx 1	Tx 2	Tx 3	Tx 4	Tx1	Tx 2	Tx 3	Tx 4
1 st block	0.256	0.424	0.428	0.408	0	0	0	0
2 nd block	0.412	0.320	0.476	0.380	0	0	0	0
3 rd block	0.304	0.400	0.508	0.464	0.048	0.204	0.488	0.236
4 th block	0.384	0.444	0.500	0.444	0.316	0.364	0.460	0.412

Table I: The BERs of four payload blocks, each containing 250 symbols, when random QPSK and CA optimized sequences are used for training, for the 60 m receiver under ugly channel condition. [graph: using the optimized sequences for training gives much lower BERs for the first two payload blocks than using random QPSK sequences.]

	Good	Bad	Ugly
60 m	31.25 kbps	20.7 kbps	20.7 kbps
200 m	62.5 kbps	31.25 kbps	31.25 kbps
1 km	31.25 kbps	31.25 kbps	20.7 kbps

Table II: SPACE'08 in a nutshell. [graph: achievable data rates under good, bad, and ugly channel conditions for receivers at 60 m, 200 m, and 1 km for the SPACE'08 experiment.]

BER	Square window	Blackman window
DPSS-BEM	0.36%	0.24%
DFT-BEM	0.71%	0.58%

Table III: Uncoded BERs of our BEM-based coherent schemes with windowed least squares (WLS) channel estimator using 12 hydrophones in RACE'08 at a 1000m distance [graph: 1. For the coherent case, DPSS-BEM outperforms DFT-BEM; 2. the coherent scheme using our WLS channel estimator with a Blackman window achieves 0.24% BER]

BER	Number of hydrophones		
	1	2	12
DFT-BEM	0.78%	0.20%	0.12%
DPSS-BEM	0.79%	0.22%	0.13%

Plain OFDM	6.30%	3.30%	1.91%
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Table IV: Uncoded BERs of the differential schemes using 1—12 hydrophones in RACE'08 at a 1000m distance

[graph: 1. For the differential case, DFT-BEM outperforms DPSS-BEM; 2. Our BEM-based differential scheme is much better the plain OFDM one.]

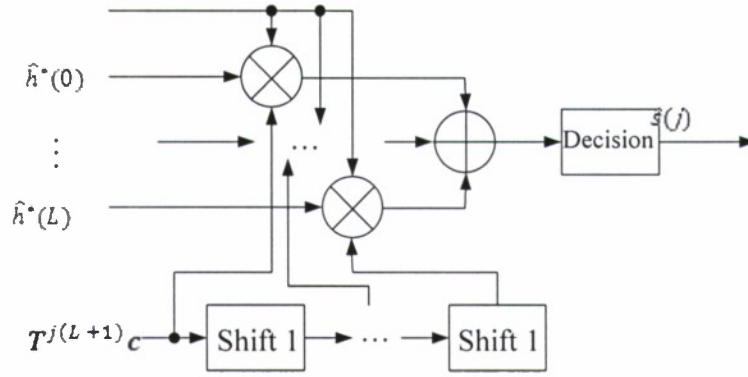
Correlation	DFT-BEM	DPSS-BEM	Plain OFDM
Surface height	0.0611	-0.0570	-0.4262
Wind speed	0.0270	0.0846	0.3295

Table IV: Correlations between the environmental data and the uncoded BERs for the differential schemes using 12 hydrophones in RACE'08 at a 1000m distance

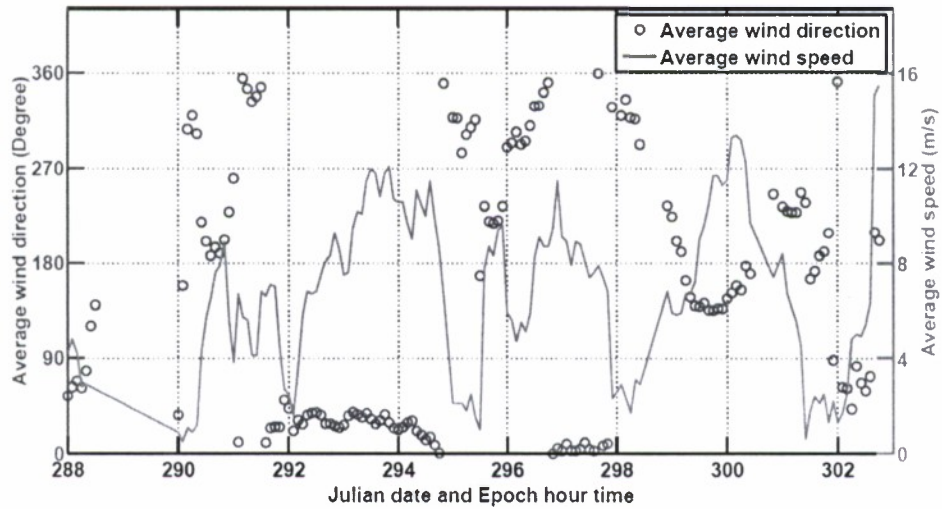
[graph: The BEM-based differential scheme has much smaller absolute values of the correlation than the plain OFDM one, meaning more robustness against various sea conditions.]

Date	Range	Moving speed	Demodulated packets	All bits	Error bits	Failed packets
July 25	500—1500m	Anchored	7	13440	0	0
July 26	1203—1667m	0—0.9knots	16	30720	7	0
July 27	300—2000m	0.4—0.6knots	15	28800	226	2
July 28	500—1000m	Anchored	4	7680	0	0
July 29	500—1000m	Anchored	7	13440	0	0

Table VI: Uncoded BER for our HR-DSSS with a single hydrophone in GLINT'08
[graph: Our HR-DSSS has very good error performance in GLINT08 sea experiment]



*Figure 3: The j th demodulation block in Fig. 1.
[graph: Only matched filters are required for demodulation.]*



*Figure 4: SPACE'08 meteorological data.
[graph: The average wind speed (m/s) and average wind direction (degrees) are shown over the course of the experiments.]*

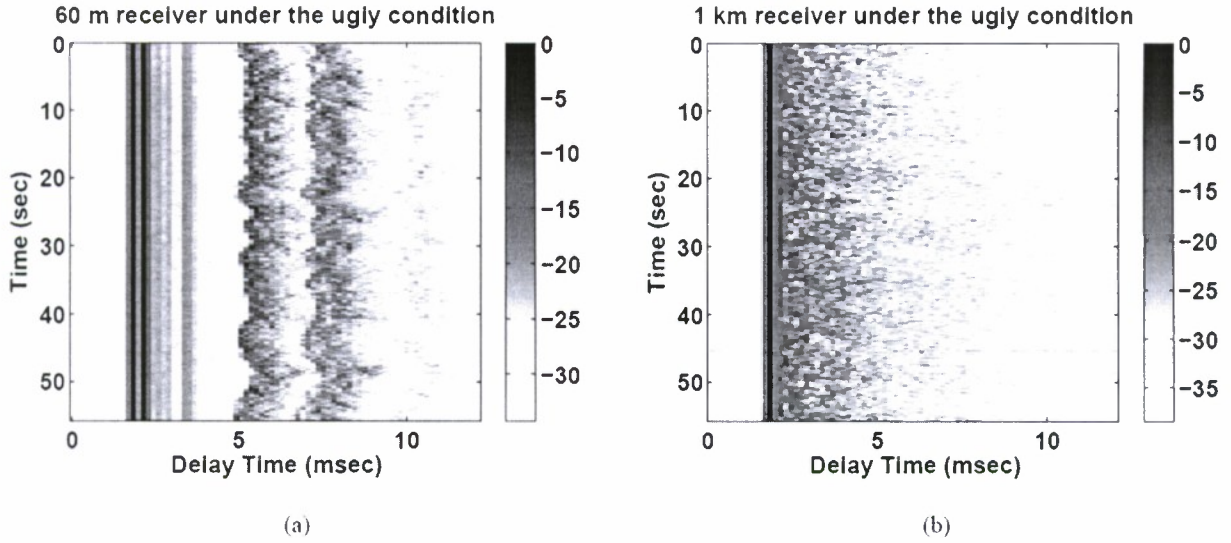


Figure 5: Normalized CIR evolution over approximately a 1 minute period. The CIRs are estimated using m-sequences as training sequences. The modulus of the channel taps in dB are shown. (a) 60 m receiver under the ugly channel condition on Julian date 294, and (b) 1 km receiver under the ugly channel condition on Julian date 300.
[graph: under challenging channel conditions, the channels vary significantly over the 1 minute period, making channel tracking difficult.]



Figure 6: Suggested data package structure under challenging channel conditions.
[graph: the channel estimates obtained by each training sequence are used for 2 payload data blocks preceding and succeeding it.]

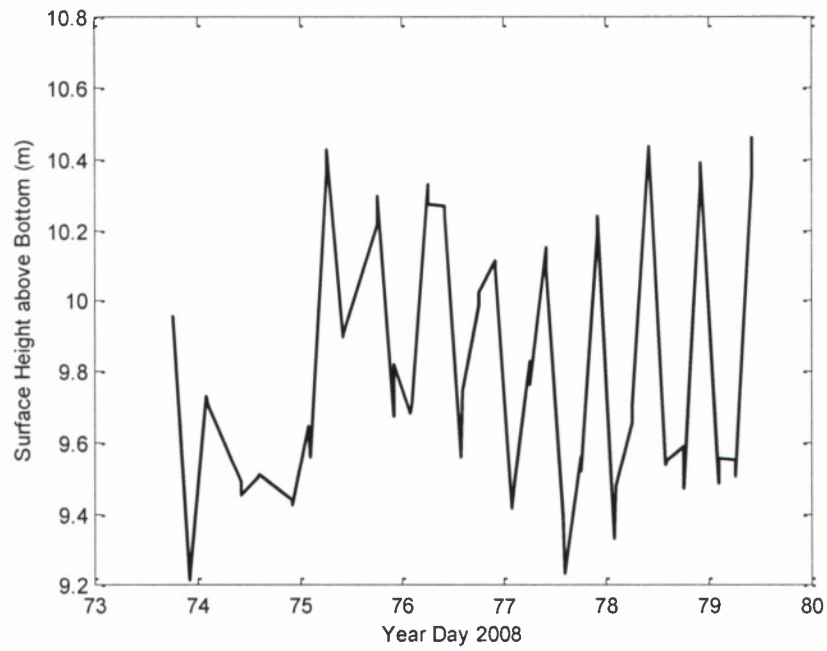


Figure 7: Surface height above bottom in RACE'08.
[graph: The surface height fluctuates during the experiment indicating various sea conditions.]

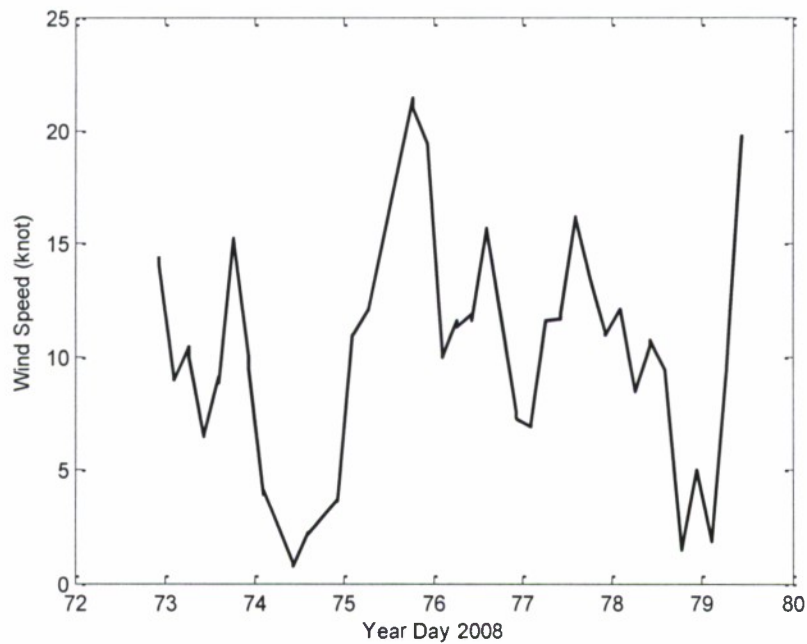


Figure 8: Wind speed in RACE'08
[graph: The wind speed covers a large range indicating various sea conditions.]

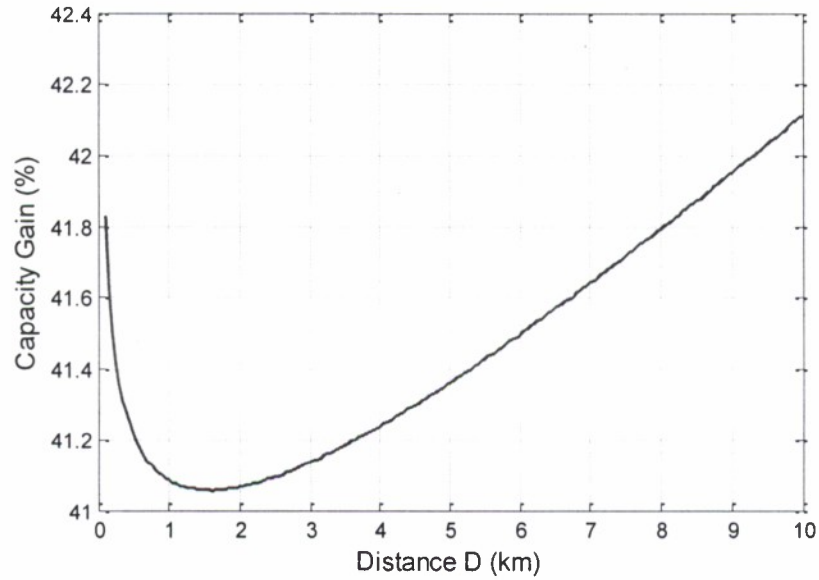


Figure 9: Capacity gain of the RA-UAC system over the direct-link system with different source-destination distance D .

[graph: A prominent capacity gain of over 40% is achieved for RA-UAC compared with direct-link system.]

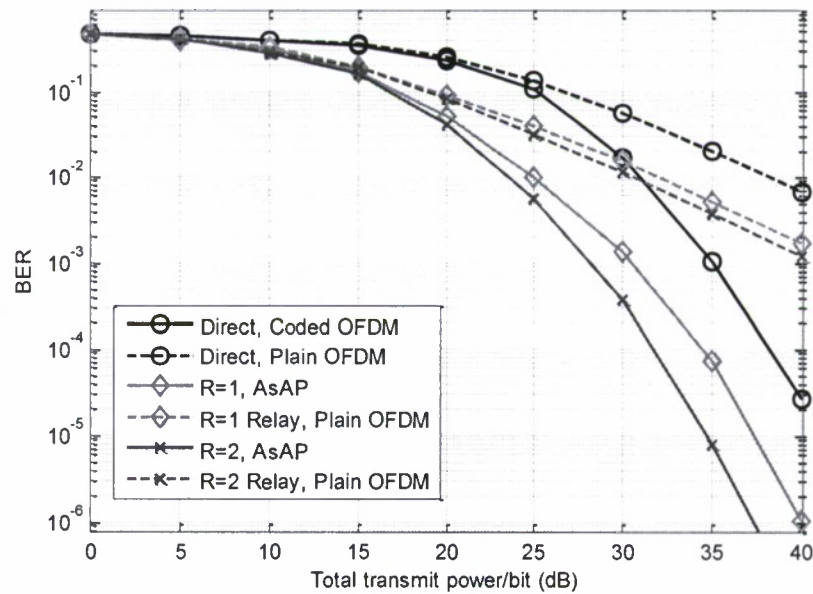


Figure 10: BER performance of the AsAP RA-UAC system with different number of relays compared with the direct-link system.

[graph: Our AsAP systems outperform the direct-link systems, and OFDM precoding collects prominent multipath diversity.]