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Broadband RF Communications in Underwater Environments Using Multi-carrier Modulation

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Abstract—**We describe new methods that solve well-known problems associated with high throughput, robust communication in underwater environments. By robust, we imply simultaneous increases in enabled underwater communication data rates, range, and reliability. Our methods borrow concepts from advanced multi-carrier modulation using Orthogonal Frequency Division Multiplexing (OFDM), multiple input multiple output (MIMO) space time codes (e.g. Alamouti diversity), and zero carrier frequency ultra wideband (UWB) wireless. In addition, we discuss system optimization involving the elimination of the phase synthesizer and analog mixer through direct sampling of the RF antenna port.**

Keywords—**component, underwater wireless communications, OFDM, EM-wave propagation, underwater broadband, zero-carrier underwater signalingcomponent**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been widely adopted and implemented in wireline and wireless communication systems. Relative to narrow band, single carrier modulation, multi-carrier OFDM is less sensitive to inter-symbol interference (ISI) caused by frequency selective multipath fading. This is due to the narrow band channel property associated with the fact that the delay spread of the channel is typically much larger than the inverses symbol rate for OFDM signaling. In addition, OFDM's high spectral efficiency supports high data rate communications.

Currently the majority of underwater communications relies upon acoustic signaling. There are different approaches to mitigating the effects of the underwater acoustic channel [15]. The traditional approach is to use of an adaptive delay equalizer to compensate the effect of delay-spread due to multipath propagation. Other methods have been used to mitigate the effect of delay-spread. The drawbacks of underwater acoustic communications include relatively slow propagation speeds, shadowing, and an inability to penetrate behind objects [1]. We pursue broadband RF-OFDM in the underwater environment due to the potential for significant increases in data throughput and fading amelioration. Furthermore, OFDM enables additional diversity gain through the application of smart antenna processing.

Historically, single-input, single-output (SISO) radios involving one transmitter and one receiver have been the dominant transceiver structure. However, a current trend in wireless communications is the deployment of multiple input multiple output (MIMO) antennas systems to enable improvements in reliability and capacity. Such systems can also integrate traditional beamforming with MIMO space time codes for additional antenna gain (e.g. spatial division multiple access (SDMA)). In beamforming methods, the data symbols across the antenna array are transmitted in a spatially coherent way towards in the desired spatial direction. In MIMO diversity systems, the space-time codes add information redundancy to a multiple layered data stream which is multiplexed across the antenna array. The redundant information content multiplexes each symbol across the transmit antenna array. These systems offer improved data rates and bit error performance. Our approach applies advanced over the air wireless concepts to the underwater channels using RF signaling. In doing so, we reveal potentially huge increases in underwater RF data rates relative to conventional underwater acoustics. In order to evaluate the RF underwater channel, we presented initial simulation models in Matlab.

II. MODEL FOR WATER INTERFACE COMMUNICATION

Ours underwater communication system model is based upon the wireless system shown in Figure 1. The system follows from Al-Shamma'a and Shaw's results in [1],[2]. They demonstrate that a loop antenna placed in water-impermeable casing, underwater (sea), after an initial 60 dB near-field attenuation, exhibit relatively minor 1dB to 3dB far-field attenuations losses from 60-1000 meters. This applies to EM waves with spectral content from approximately 0-20 MHz. As shown in Figure 1, the seawater should not be in direct contact with the antenna and the antenna requires impedance matching to the water. The results apply to both horizontal and vertical transmission.

Figure 2 illustrates an RF transceiver using OFDM that exploits the prior results in a way that can achieve huge throughput increase over acoustic methods. Current underwater communication using acoustics is known to suffer from latency, low bandwidth constraints, low throughput, distortion, and interference. EM-waves can be viewed as an alternative approach which avoids problems inherently native to acoustics. We note for example that underwater, electro-magnetic-waves nominally propagate 3000 [16] times faster than acoustic waves. Thus, advanced communication concepts involving closed loop methods such as MIMO, Hyrid-ARQ, and adaptive modulation [6],[7] that inherently require low-latency closed loop feedback fundamentally cannot be applied to the acoustics model of communication.

The system model shown in Figure 2 applies iterative turbo codes, QAM-OFDM, and MIMO transmit and received diversity. We apply Alamouti space-time coding [14] to increase link reliability. Since it is well known that underwater attenuation is a problem at high RF frequencies, we direct the RF signal through a zero-carrier frequency channel akin to the approach found in ultra-wideband wireless. By lowering the code rate and increasing signal coding gain, we can trade off high spectral efficiency in OFDM for improved signal reliability. Likewise, the application of 2x2 Alamouti space time codes to the physical data channel significantly increases the reliability (i.e. diversity gain).

Rather than derive entirely new OFDM parameters, we adapt as, necessary, communication system parameters from the 3rd Generation Partnership Project Long Term Evolution standard (3GPP-LTE protocol). As shown in Figure 3, the 3GPP-LTE standard adopts a 14 symbol subframe. Each symbol in the subframe spans 71.4 μ-Sec and every subframe spans 1msec. There are 10 subframes per 10 msec frame. This is shown in Figure 3 along the vertical axis of the time frequency plane. Along the horizontal axis, we illustrate the resource elements (REs) which are separated by 15KHz in frequency. This implies a cyclic prefix of length 4.76 μ-Sec (i.e. 71.4 μ-Sec – 66.67 μ-Sec) which we estimate to be more than sufficient for the underwater delay spreads.

We adopt a 10MHz (one sided) bandwidth model for the underwater channel. One can apply a narrow band fading model due to the fact that the delay spread of the channel is much smaller than the inverse of the symbol rate. For the undersea environments, we are accounting for possible signal reflection and diffraction for underwater scatterers. We presume a linear and time invariant (LTI) impulse response with negligible Doppler frequency shifts. When the line of site (LOS) component of is significant relative to the non-line of sight (NLOS) component, we apply a Ricean distribution. Otherwise we invoke a Rayleigh distribution.

$$\text{NLOS Rayleigh}: \; p_r(z) = \frac{z}{\sigma_n^2}\exp\left(-\frac{z^2}{2\sigma_n^2}\right) \tag{1}$$

$$\text{LOS-Ricean}: \; p_r(z) = \frac{z}{\sigma_{nlos}^2}\exp\left(-\frac{\left(z^2+\sigma_{los}^2\right)}{2\sigma_{nlos}^2}\right) I_0\left(\frac{z\sigma_{los}}{\sigma_{nlos}^2}\right) \tag{2}$$

Ricean distributions will predominate in certain deep ocean of underwater scenarios, whereas Raleigh distributions are more likely in costal inlets and sea bays. A significant advantage of the OFDM system is that we can invoke the flat fading model since the coherence bandwidth is greater than the system bandwidth.

The transceiver in Figure 1, including the antenna, is encapsulated inside of an air containment vessel with a water impermeable outer layer. Our path loss models and channel bandwidth selection follow from the work of Al-Shamma'a, Shaw, and Saman who experimentally report. When the EM-wave propagates, there is a large near field attenuation of 60dB and other diffraction losses create total attenuation on the order of 130dB. However, the fair field through water attenuation is more moderate well out past 60 meters [1],[2]. Based upon this we can derive an empirical path lost model similar to that shown in Figure 4. We note that the model does not currently differentiate between vertical and horizon spatial directivity of communications relative to the sea surface.

For very high SNR scenarios, MIMO spatial multiplexing can be applied. We view it a low likelihood scenario due to the large under water attenuation factors. As previously discussed, our transceiver based upon these results is illustrated in Figure 2. We note that the transceiver utilizes OFDM with adaptive modulation and coding. The modulation adapts between 2, 4 and 16-ary QAM modulation constellations. The code rate has a nominal value 1/3, but can be increased via puncturing. The information band is from 0MHz to 10MHz. Since we are using a zero carrier signal, the band from -10MHz to 0Hz is reserved for RE images as illustrated in Figure 4a. The negative image frequencies require Hermitian symmetry to preserve the "realness" property of the baseband signal. The zero-carrier frequency therefore constrains the information two half of the normal RF-band. Conversely, the combination of a zero-carrier frequency signal and high rate A/D that samples the antenna ports has side-benefit of completely "digitizing" the radio. This allows the system to avoid analog mixers and synthesizers. It also enables high degrees of flexibility due to the ability to apply digital signal to the entire chain of communication algorithms [3],[14]).

Underwater signals tend to be noise limited due to the relatively high attenuation levels (relative to the receiver noise figure). In order to evaluate the ability of the underwater channel to support broadband signal communication, we developed simulation models in Matlab to establish the minimum Eb/No. The Matlab simulation results for 10MHz OFDM bandwidths were run for 16QAM OFDM with Turbo codes [4],[5] and Alamouti space time codes [7],[11],[12]. We used an AWGN noise source and a Rayleigh Fading channel model. The results are shown in Figure 5. We utilized zero forcing OFDM equalization with perfect channel estimation and a rate 1/3 Turbo code, which uses a recursive systematic code with generator polynomial, [4-6]:

$$G(z) = \left[1, \frac{1+z^2+z^3}{1+z++z^3}\right] \tag{3}$$

The 1-Tx,1-Rx antenna scenario was run for both Rayleigh fading and AWGN and bit error results (BER) were plotted as a function of Eb/No. We anticipate that the MIMO 2x2 antenna configurations using 16-QAM OFDM modulation using Alamouti in the dashed line. By projecting a conservative 3dB gain over the 1x1 Turbo coded system, we currently estimate a 2 dB sensitivity for the joint 2x2 Alamouti-MIMO, turbo decoder transceiver. The estimated Eb/No of 2dB is sufficient to achieve a desired 10^{-4} BER for coded information packets. We view this as a conservative model with additional improvements available from Turbo equalization.

From the BER data in Figure 5, we derived a system level radio link budget for the underwater communication transceiver. The radio link model is shown in Table 1. For this model, a ratio of ~50% in regards to information sub-carriers relative to the overall number of RE training and control sub-carriers. For the coded simulation, we use of a rate 1/3 Turbo code with constituent recursive systematic code. We add one final control overheads of 15% in computing information data rates. In Table 1, we base the required Eb/No on the BER simulations from the illustrated Matlab simulation model is based upon a MIMO-Alamouti diversity scenario. The radio link simulation model presumes a 2dB antenna gain in both the transmit and receive antenna, 1 Watt transmit power, a receiver noise figure of 5dB, and 130dB path loss model from [1]. Based upon this, we conservatively calculate that a 1.14 Megabit RF data rate is possible out to 60 meters and data rates out to 1000 meters are possible at over 400Kbit rates (not shown). This represents an order of magnitude improvement beyond currently available acoustic equipment. Moreover, the throughput is for a single hop links. Improvements can occur by operating over 20MHz bands, employing underwater ad-hoc network configurations, and increasing the number of MIMO antennas.

III. COMMUNICATION SYSTEM OPTIMIZATION: PACKET LEVEL PERSPECTIVE

From a packet perspective, our ad-hoc system is separated into physical, transport, and logical channels, as shown in Figure 6 with symmetrical up-link and down link channels. Generally speaking, downlink transmission also implies uplink receiving functionality. The Physical Downlink Shared Channel (PDSCH), as illustrated in Figure 6, shows the structure of the time-frequency channel(s) which carry the physical data over a shared link. The hybrid ARQ channel communicates acknowledgements (ACKs), negative acknowledgements (NACKs), control information related to requests for repeated packets. The physical random access channel (PRACH) carries data related to association and re-association of nodes with the underwater network. When new nodes enter the underwater network region, the physical random access channel enables association request signaling. Once a node is associated with the network and a local sub-region, a quasi-synchronous behavior is initiated with nodes in the local region of the associated node. Nodes in the region multicast bandwidth information, coarse frame timing information, node identification, frequency information, and discontinuous operation parameter information. The nodes also broadcast a frequency-hopping channel pattern useful for minimizing multiple access interference in the underwater network. By the term broadcast, we imply data communicated across the entire networks. Multi-cast implies data communicated with a regional sphere. Uni-cast implies one-to-one data communications between two nodes.

IV. WANLAB REAL TIME PROTOTYPING

In Figure 7, we illustrate the laboratory configuration currently underway in the Wireless Advanced Next Generation Laboratory (WANLAB) at the University of Texas at San Antonio. We currently support 4x2 MIMO configuration is currently underway. The system has a signal generator with four antennas on the transmitter and two antennas on the receiver. To achieve real time RF experimentation in the underwater channel, the transmitter contains two Vector Signal Generators (VSG) visible on the front panel. Each VSG transmitter contains 3-boards that deliver RF signals from 250 kHz to 6.6. At the transport level we have logical channels optimized for data and control. The ARQ transport channel carriers all control information related to the retransmission and acknowledgements of ad-hoc packets. The BCH transport channel carries broadcast and multi-cast information necessary for coordinated communication that minimizes interference levels. The PCH transport channel contains short messages and information related to discontinuous operation for low power.

Finally, at the logical level, we have paging (PCCH) and broadcast (BCCH) common control channels. The common control channel (CCCH), dedicated traffic channel (DTCH), and dedicated control channel (DCCH) carry higher bandwidth information packets. Radio Prototyping

The initial prototype is being developed based upon the underwater transceiver describe in Figure 2. The communication algorithms are mapped to the National Instruments (NI) equipments and can support more than 100 MHz bandwidth. This SDR lab prototype is capable of achieving high bandwidth streaming data from a RAID disk at the rate of 100 MS/s. The VSG also has an arbitrary waveform generator and a 16-bit digital to analog converter that generates baseband I and Q channels at data rates of up to 200 MS/s. At this sample rate, the generator is capable of implementing radio functions up to than 100MHz in bandwidth. Each lab SDR receiver contains Vector Signal Analyzers (VSA) boards. The VSA is shown up close in Figure 7. The VSA supports 250KHz to 6.6 GHz RF carrier frequencies. Combined with high-performance PXI controllers and the high-speed PCI Express data bus, the VSA can perform common automated measurements significantly faster than traditional instruments.

Because of the vector signal analyzer's PCI Express data bus, one can also use multiple analyzers to stream data to a RAID disk. With more than 1 GB/s of total system bandwidth,

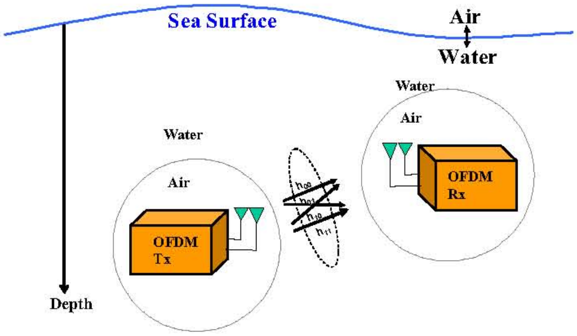

Figure 1: Model of Underwater Communication

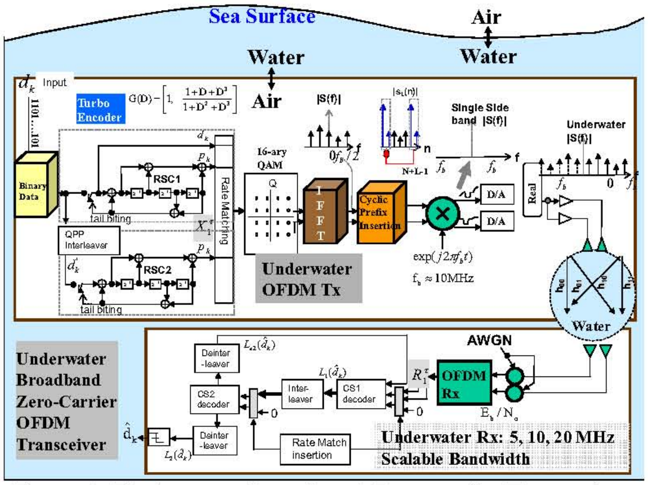

Figure 2: Underwater Broadband Zero-carrier Transceiver

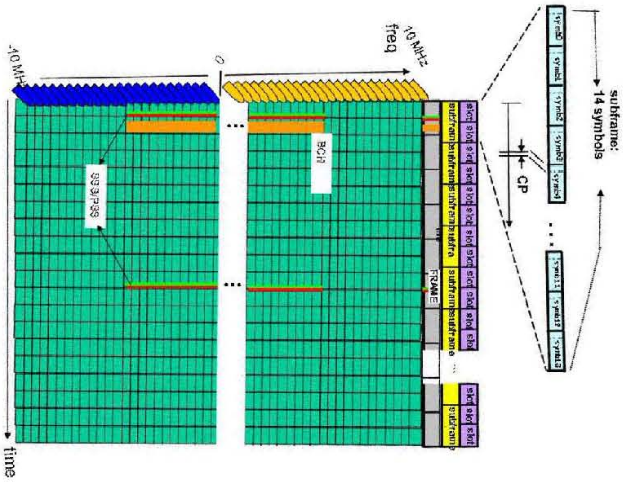

Figure 3: OFDM, Underwater Frame Structure

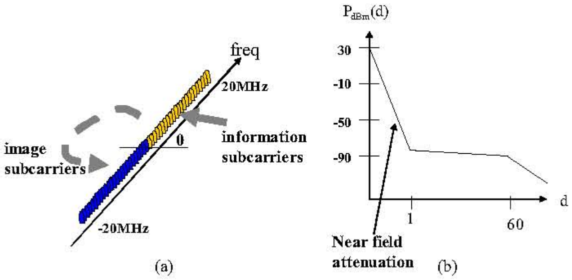

Figure 4: Underwater path loss model.

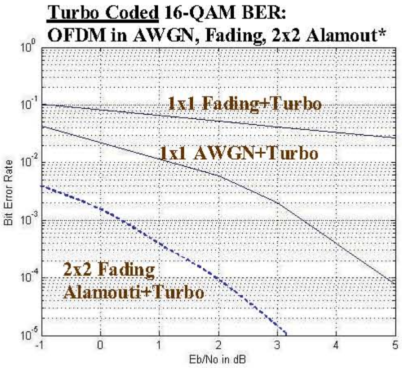

Figure 5: Turbo-Coded BER

10MHz Underwater Link Budget Parameters: 60 Meter

	Parameter	Value
Link Parameters	Ambient System Temp Ts	290.00 K
	Tx power: Pt	30.00 dBm
	Antenna Gain Tx: Gt	2.00 dB
	Antenna Gain Rx: Gr	2.00 dB
	Distance: d	60.00 meters
	frequency: v	1.00E+07 Hz
	Far Field Attenuation: Lo_P	8.00 dB
	Near Field Attenuation: Lo_A	60.00 dB
	Far Field Diffraction Losses: Lo_D	62.00 dB
	Alamouti+Turbo Required: Eb/No	2.00 dB
	Noise Figure: NF	5.00 dB
	Bit rate: R	1.14E+07 bits/sec
Constants	constant: PI	3.1415
	speed of light: c	3.00E+08 m/sec
	Botlzmann's k	1.38E-23 W/K-Hz
	Thermal noise: kTo	-173.98 dBm/Hz
	Traditional Over Air Path Loss*	28.00 dB
	Estimated Underwater Path Loss	130.00
	Receiver Antenna Power	-96.00 dBm
	Rx Margin	0.43 dB
	Actual Receiver Eb/No	2.43 dB
	Required Min Rx Power for Demod.	-96.43 dBm

Table 1: Link Budget

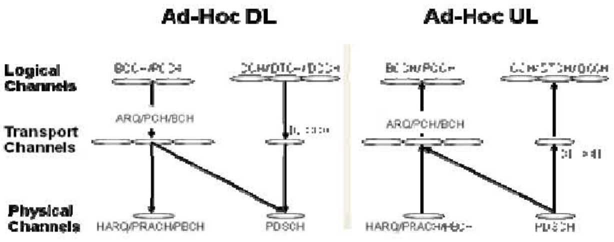

Figure 6: Packet Based Communication

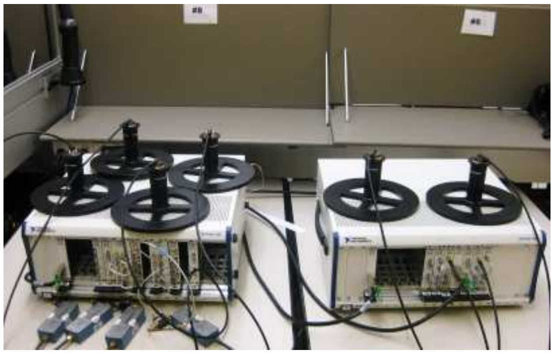

Figure 7: Software Radio Prototype in the WANLab at UTSA

one can stream more than 100MHz continuously to disk using multiple analyzers

V. CONCLUSIONS

We have estimated that underwater data rates in excess of 1MBs are possible using modern 4G transceivers properly configured for underwater communications. In essence, we use the spectral efficiency of modern communications to overcome the large near field and diffraction attenuations of 130dB. With the modular design of equipment we are capable of testing our RF underwater channel. Future research will focus upon new transceiver configurations with even high capacity and experimental modeling of underwater channels.

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Dr. Kelley received his BSEE from Cornell University's College of Electrical Engineering in Ithaca NY. He received his MSEE and PhDEE from Georgia Tech’s ECE Department where he was an Office of Naval Research Fellow and a Georgia Tech Presidential Fellow. Dr. Kelley spent 8 years with Motorola’s Advanced Cellular Research group and 4 years with Motorola-Freescale where he was a Distinguished Member of the Technical Staff. From 2000-2007, Dr. Kelley taught communications and Statistical DSP at the University of Texas at Austin's Department of Electrical Engineering. In 2007, Dr. Kelley joined the faculty of the University of Texas at San Antonio as an Assistant Professor in Communications. Dr. Kelley's current research interests include Software Define Radio, 3GPP-LTE Cellular, and ad-hoc networks. He is a Senior Member of the IEEE, Chair of the San Antonio IEEE Communication and Signal Processing Chapter, and Associate Editor of Computers & Electrical Engineering, Elsevier. Has numerous publications, is a holder of 13 US patents or patents pending, and is a member of Tau Beta Pi and Eta Kappa Nu.

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Mo Jamshidi (Fellow-IEEE, ASME, AAAS, NYAS, TWAS, Associate Fellow AIAA) received his Ph.D. Degree in Electrical Engineering from the University of Illinois at Urbana-Champaign in February 1971. He holds Honorary Doctorate Degrees from Azerbaijan National University, Baku, Azerbaijan (1999), the University of Waterloo, Canada (2004) and Technical University of Crete, Greece, (2004). Currently, he is the Lutcher Brown Endowed Chaired Professor at the University of Texas at the San Antonio Campus, San Antonio, Texas, USA. He was the founding Director of the Center for Autonomous Control Engineering (ACE) at the University of New Mexico (UNM), and moved to the University of Texas, San Antonio in early 2006. He has been the Director of the ICSoS – International Consortium on System of Systems Engineering (icsos.org) – since 2006. Mo is an Adjunct Professor of Engineering at Deakin University, Australia. He is also Regents Professor Emeritus of ECE at UNM. In 1999, he was a NATO Distinguished Professor in Portugal of Intelligent Systems and Control. Mo has written over 560 technical publications including 62 books and edited volumes. Six of his books have been translated into at least one foreign language other than English. He is the Founding Editor, Co-founding Editor or Editor-in-Chief of 5 journals. Mo is Editor-in-Chief of the new IEEE Systems Journal (to be inaugurated in 2007) and founding Editor-in-Chief of the IEEE Control Systems Magazine. Mo is a Member of Senior Member of the Russian Academy of Nonlinear Sciences, Hungarian Academy of Engineering and an associate fellow of the AIAA. He is a recipient of the IEEE Centennial Medal and IEEE CSS Distinguished Member Award. Mo is currently on the Board of Governors of the IEEE Society on Systems, Man and Cybernetics and the IEEE Systems Council. In 2005, he was awarded the IEEE SMC Society’s Norbert Weiner Research Achievement Award and in 2006 the IEEE SMC Distinguished Contribution Award. In 2006 he was awarded a “Distinguished Alumni in Engineering” at the Oregon State University (one of his Alama Matters), Corvallis, Oregon, USA.

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