Towards a Video-Capable Wireless Underwater Modem: Doppler Tolerant Broadband Acoustic Communication

Thomas Riedl and Andrew Singer
University of Illinois at Urbana-Champaign
Urbana, IL 61801, USA
Email: triedl2@illinois.edu

***Abstract*—Current wireless underwater modems are advertised with data rates of only a few $kbps$ and the oil and gas industry has found them incapable of handling video and real-time control. Today, such communication underwater is almost entirely done through wired links. Using broadband acoustic signals with a bandwidth of $200kHz$ and more, we demonstrate the feasibility of wireless underwater communication at data rates greater than $1Mbps$. Such data rates are capable of streaming video in real-time. As broadband acoustic signals propagate through water, they suffer extreme Doppler effects. Different propagation paths experience different Doppler and the level of Doppler on each path is highly time-variant. In our work, time-varying Doppler is explicitly modeled, tracked and compensated. In this paper, we provide the results from our acoustic communication experiments conducted in a $50m$ long wave tank. Our resampling equalizer reliably achieved $1.2Mbps$ over a distance of $12m$.**

***Index Terms*—Doppler effect, Doppler compensation, Underwater acoustic communication, Video**

I. Introduction

There are two types of waves that can be used to carry information wirelessly subsea: Electromagnetic (EM) waves and acoustic waves. We argue that acoustic waves are the superior carrier and have the potential to meet the wireless communication needs of the subsea industry.

Salt water has a significantly higher electrical conductivity than air and attenuates EM waves substantially as they propagate. The level of attenuation depends on frequency. Only at frequencies below about $100Hz$ and in the visible spectrum is the attenuation low enough to allow useful penetration into the water column [1]. Note that attenuation is about$10dB/m$ at $100kHz$ and greater than $30dB/m$ for all radio frequencies above $1MHz$. At a distance of $50m$, data rates of only about $300bps$ have been reached [2]. The company WFS sells RF underwater modems with an advertised data rate of $156kbps$ at $4m$ distance using 19 watts of power [3].

This work was supported in part by the National Science Foundation under grant 1101338 and in part by Systems on Nanoscale Information fabriCs (SONIC), one of the six SRC STARnet Centers, sponsored by MARCO and DARPA.

978-1-4799-7578-5/14/$31.00 ©2014 IEEE

Inside the visible spectrum, blue-green light, around $480nm$ in wavelength, propagates with the least attenuation [4]. Free-space optical communication underwater has received renewed interest from researchers due to recent improvement in laser and LED technology [5], [6]. LEDs are low-cost and power-efficient light sources and their light intensity and switching speed have been shown to accommodate wireless underwater communication at $1Mbps$ over $100m$[5]. The authors of this work report that transmissions were error free for ranges up to $100m$, but their data also shows that the error rate increases sharply at ranges beyond $100m$. The error rate reaches 0.5 at about $140m$ making reliable communication impossible. This is still a significant step up from RF communication. Several serious issues, however, limit the applicability of free-space optical communication in practice: First and perhaps most importantly, communication range is highly dependent upon water turbidity. The above values for light attenuation in water only hold for operation in pristine and transparent water. But near-shore and estuarine waters are typically highly turbid because of inorganic particles or dissolved organic matter from land drainage [7]. Light attenuation is exponential in distance. If, for a given wavelength λ, $I_0(\lambda)$ is the light intensity at the source, the light intensity $I(\lambda, z)$ at distance z from the source is described by the Beer-Lambert law [8]

$$I(\lambda, z) = I_0 e^{-c(\lambda)z} \tag{1}$$

The wavelength-dependent factor $c(\lambda)$ is the extinction coefficient of the water through which the optical system operates. For the type of light best suited for optical communication, blue-green light with a wavelength of $480nm$, the extinction factor is about $0.16m^{-1}$ for pristine ocean water and about $2.8m^{-1}$ for typical coastal waters [7]. The above mentioned experiment that proved the feasibility of error free optical underwater communication at $1Mbps$ over $100m$ was conducted in the clearest water - near the seafloor in the deep ocean [5], for which the authors measured the extinction coefficient to be $0.05m^{-1}$. According to Equation 1, the attenuation would have been $21.7dB$ at $100m$ distance in this clear-water environment. This suggests that in typical coastal water with an extinction coefficient of about $2.8m^{-1}$, this system would likely only manage a range of about $1.8m$. Note that the waters of most commercial interest for the oil and gas industry, such as in the Gulf of Mexico or in the Irish sea, are highly turbid. Measurements in the Gulf of Mexico indicate that the extinction factor exceeds $3m^{-1}$ at many sites and can be as high as $5.1m^{-1}$ [9]. Another major issue of underwater optical communication is the tight alignment requirement. LEDs and lasers are highly directional and require the transmitter and receiver to be aligned with each other. In mobile applications the emitter would hence constantly need to be realigned as the mobile platform moves through the water.

The only practical method of carrying information wirelessly undersea over distances greater than a couple of meters is through acoustic wave propagation. In seawater, acoustic waves are significantly less attenuated than radio waves. At a frequency of $1MHz$, the absorption loss is only about $0.3dB/m$. A $1MHz$ acoustic wave hence travels more than $200m$ until $100dB$ of attenuation is observed. These lower levels of attenuation allow acoustic communication systems to achieve much higher data rates than would be possible with underwater radio communication. Figure 1 shows the

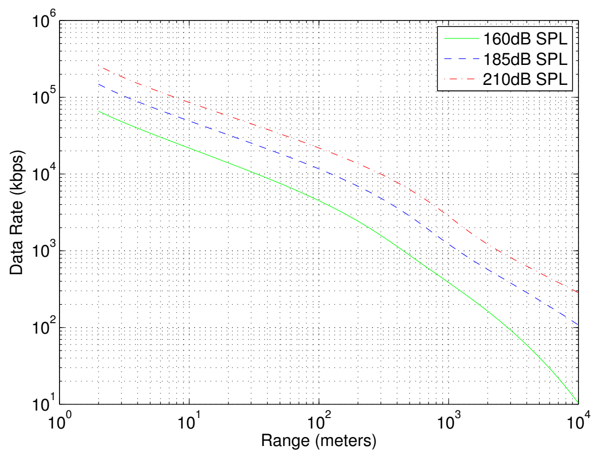

Figure 1. Information theoretic channel capacity of the underwater acoustic channel as a function of distance and source power.

information theoretic capacity of the underwater acoustic channel for different levels of transmit power. The transmit power is given as sound pressure level (SPL) at one meter distance from the sound source. At an SPL of $160dB$, a data rate greater than $4Mbps$ can be achieved at a range of $100m$. At an SPL of $210dB$ the data rate increases to more than $20Mbps$ for the same range. If the characteristics of available acoustic sources and sensors are taken into account data rates will drop, but they remain above $1Mbps$ at a range of $100m$. If an off-the-shelf transducer such as the ITC-1089D is used to emit and sense the acoustic signal, the channel capacity is about $1.75Mbps$ at $100m$ distance [10]. These data rates are significantly higher than the data rates achievable with EM waves as mentioned above.

The above capacity calculations ignored multi-path effects and assumed line-of-sight communication between stationary platforms. In this case, the underwater acoustic channel is well understood and can be modeled as a linear time-invariant (LTI) system with additive white Gaussian noise (AWGN) [11]. A line-of-sight between transmitter and receiver is often available underwater, but in a mobile communication scenario the assumption of stationary communication platforms is clearly invalid. Acoustic signals suffer severe Doppler effects even at moderate speeds of only around $1m/s$. Different propagation paths may experience different Doppler and the level of Doppler on each path is often highly time-variant.

In our work, we have developed a recursive sample-by-sample resampling equalizer [12], [13]. Time-varying Doppler is explicitly modeled, tracked and compensated. This novel equalizer has demonstrated strong communication performance in US Navy sponsored field tests and simulations [14]. In this paper, we focus on communication over shorter distances while scaling up bandwidth and data rate. We have conducted extensive laboratory experiments and verified that our wireless communication system reliably achieves $1.2Mbps$ over a distance of $12m$ and $120Mbps$ over distances of less than $1m$. These are, to the best of our knowledge, the highest data rates recorded for underwater acoustic communication.

II. Related Work

In the 1990s, it was shown that acoustic wave propagation allows phase-coherent digital communication underwater [15]. The authors combined an adaptive linear decision feedback equalizer (DFE) and a phase locked loop (PLL) to combat the channel distortion due to reverberation and Doppler effects. This system was then evaluated on data from at-sea experiments and the authors demonstrated a data rate of $10kbps$ in shallow water over $3.7km$ distance using $5kHz$ of acoustic bandwidth, a stationary $183dB$ SPL source and a stationary directional receiving element (hydrophone). This work indicated that coherent communication had the potential to significantly improve data rate and bandwidth efficiency. Note, however, that the directional hydrophone required alignment with the source and that no platform mobility was present. The directional hydrophone helped reject the noise generated at the surface due to wind and wave motion and also limited reverberation since the multi-path components with most delay generally impinge on the hydrophone at the widest angle. In practice, neither hydrophone alignment nor platform stability can be guaranteed. In a later follow-up paper, researchers recognize that the communication system devised in [15] cannot handle the level of Doppler introduced by standard mobile platforms such as autonomous underwater vehicles (AUVs) and that "its performance has been unsatisfactory under realistic field conditions" [16]. They extended the original approach and proposed a two-step detection algorithm. For each received data block, the detector first obtains an estimate of the average Doppler factor over the entire transmission and then resamples (interpolates) and phase corrects the demodulated base-band signal based on this factor. In the second step, the original method from [15] is used to estimate the sent data symbols. A digital phase-locked loop (PLL) is employed to remove any residual Doppler distortion from the demodulated signal and the adaptive equalizer estimates the transmitted symbols from the Doppler compensated signal. They reported a data rate of $2.5kbps$ on data from moving platforms at relative speeds up to 6 knots over an unspecified distance. Even this extended approach, however, only works if the Doppler variation is sufficiently small and roughly constant for the duration of a block. In a more recent paper [17], the authors report that for communication with AUVs the WHOI micromodem relies on its "robust FH-FSK modulation and error correction coding (ECC) scheme to communicate at long ranges ($2-4$ kilometers), in the very shallow water zone" at a data rate of $80bps$ using $4kHz$ of bandwidth and a powerful 190dB SPL source, corresponding to a bandwidth efficiency of only $0.02bps/Hz$.

III. Channel Model

For simplicity of exposition, we consider the acoustic signal path starting at the projector and ending at the hydrophone as our communication channel. The position of the projector and hydrophone are $\boldsymbol{x}_1(t)$ and $\boldsymbol{x}_2(t)$, respectively, and they depend on the time t. The projector emits the acoustic signal $\tilde{s}(t)$ and the hydrophone senses the acoustic signal $\tilde{r}(t)$. If these elements were operating in an ideal fluid, where energy was conserved and there was no absorption loss and no ambient noise, the acoustic wave equation completely describes the channel:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \triangle p = 4\pi \frac{\partial}{\partial t}\left\{\delta(\boldsymbol{x}-\boldsymbol{x}_1(t))\int_{-\infty}^{t}\tilde{s}(\tau)d\tau\right\} \quad (2)$$

where $p(\boldsymbol{x},t)$ is the sound pressure at position $\boldsymbol{x}$ and time t, c is speed of sound and $\triangle$ denotes the Laplace operator[18], [19]. Assuming there are no reflective boundaries and both transmitter and receiver move subsonically, the far field solution to this equation at position $\boldsymbol{x}_2(t)$ is

$$p^{FF}(\boldsymbol{x}_2(t),t) = \frac{\left(\frac{\partial t_e}{\partial t}\right)^2}{||\boldsymbol{x}_2(t)-\boldsymbol{x}_1(t_e)||}\tilde{s}(t_e) \quad (3)$$

where t_e is the unique solution to the implicit equation

$$t - t_e - \frac{||\boldsymbol{x}_2(t)-\boldsymbol{x}_1(t_e)||}{c} = 0 \quad (4)$$

[19]. The time t_e is often called the emission time or retarded time. Neglecting the near field component of the solution, we set $\tilde{r}(t) = p^{FF}(\boldsymbol{x}_2(t),t)$. This relationship completely describes the communication channel under the mentioned assumptions. We can write

$$\tilde{r}(t) = h(t)\tilde{s}(t_e) \quad (5)$$

and consider $h(t)$ a time dependent channel gain factor. Taking a close look at Equation 3, we notice that the gain $h(t)$ is inversely proportional to the communication distance. Further the "Doppler factor" $\frac{\partial t_e}{\partial t}$ is always positive, equal to unity when there is no motion, greater than unity when the source and receiver are moving towards each other and smaller than unity otherwise. This channel model can be extended to include multi-path effects, ambient noise and absorption. One such extension is given in [13].

IV. Resampling and Equalization

Reliable communication over the underwater acoustic channel introduced above can be facilitated by resampling and equalizing the received signals dynamically.

We transmit the symbol sequence $s[n] : [0:N] \rightarrow \mathrm{A}$. The set A is finite and $\mathrm{A} \subset \mathbb{C}$. The sequence $s[n]$ t is mapped to a waveform $s(t) : \mathbb{R} \rightarrow \mathbb{C}$,

$$s(t) = \sum_{l\in[0:N]} s[l]g(t-lT) \quad (6)$$

by use of a basic pulse $g(t)$ with bandwidth of no more than $1/T$. This signal is then modulated to passband

$$\tilde{s}(t) = 2\Re\{s(t)e^{2\pi\sqrt{-1}f_C t}\} \quad (7)$$

at carrier frequency f_C.

The demodulated received waveform reads

$$r(t) = h(t)e^{2\pi\sqrt{-1}f_C(t_e(t)-t)}s(t_e(t)) \quad (8)$$

We propose to sample $r(t)$ non-uniformly and adapt the sampling rate on-the-fly. We would like to sample $r(t)$ at $t_e^{-1}[n] \equiv t_e^{-1}(nT)$

$$r(t_e^{-1}[n]) = \underbrace{h(t_e^{-1}[n])}_{\text{channel gain}}\underbrace{e^{2\pi\sqrt{-1}f_C(nT-t_e^{-1}[n])}}_{\text{phase term}}s[n] \quad (9)$$

and then phase compensate and weight $r(t_e^{-1}[n])$, to recover $s[n]$

$$s[n] = w[n]r(t_e^{-1}[n])e^{-2\pi\sqrt{-1}f_C(nT-t_e^{-1}[n])} \quad (10)$$

The precise values of the weights $w[n]$ and times $t_e^{-1}[n]$ are unknown but they can be estimated from the given channel observations and interspersed training data. In [13], we introduced an algorithm that can estimate these parameters as well as the symbols $s[n]$.

V. Experimental Results

Our turbo resampling equalizer (TRE) has demonstrated competitive communication performance in US Navy sponsored field tests and simulations. We have reported on our results from the Mobile Acoustic Communications Experiment (MACE), in an earlier publication [14]. The depth at the site is approximately 100 m. A mobile V-fin with the transmit projector attached was towed along a "race track" course approximately 3.8 km long and 600m wide. The maximum tow speed was 3 knots (1.5 m/s) and the tow depth varied between 30 and 60 m. The receive hydrophone array was moored at a depth of 50 m. The projector was a ITC-1007 transducer and produced a SPL of $185dB$. Our transmissions had a carrier frequency of $13kHz$ and a bandwidth of only $9.76kHz$. For the entire duration of this three-day experiment our algorithms sustained error-free communication under challenging conditions (harsh multi-path, SNRs down to 2 dB and wind speeds up to 20.6 knots). They achieved a net data rate of $39kbps$

at $2.7km$ distance and a net data rate of $23.4kbps$ at $7.2km$ distance. These rates correspond to bandwidth efficiencies of $3.99bps/Hz$ and $2.40bps/Hz$, respectively.

Over shorter distances, the bandwidth available for acoustic communication is significantly greater and data rates can be scaled up. We built a short-range high-frequency acoustic communication testbed and installed it in a flume on our campus. Figure 2 shows the $1.22m \times 1.83m \times 49m$ flume. The walls can be lined with sound absorbers to simulate infinite horizontal extension. We use ITC-1089D high-frequency transducers among others [10]. These transducers have around $200kHz$ of bandwidth at a center frequency of around $300kHz$. The transmitter was about $12m$ apart from the receiver. Figure 3 shows the LMS estimate of the channel impulse response.

Figure 2. Our short-range high-frequency acoustic communication testbed: A $1.22m \times 1.83m \times 49m$ flume.

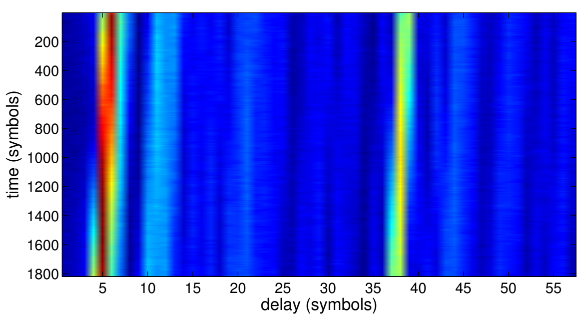

Figure 3. Heat map of channel impulse response magnitude.

Platform mobility of about $1m/s$ caused the impulse response to slip by one symbol after only about 1800 symbols. We recently achieved $1.2Mbps$ using this experimental setup. A 64-QAM constellation was employed. The raw equalizer output BER was about 10^{-3} and can be made error-free in a single turbo iteration with less than 1% FEC overhead. In a smaller tank, we reached rates of $120Mbps$ over distances of less than $1m$. For this experiment, we repurposed high frequency ultrasound transducers with a bandwidth of $20MHz$ and a center frequency of $20MHz$ and again transmitted 64-QAM symbols. The raw equalizer output BER was about 2×10^{-2} and can be made error-free with about 15% FEC overhead.

Table I compares the performance of our TRE method with competing reported approaches. The data rates are maximum payload data rates with BER $< 10^{-9}$. The LinkQuest modem is representative of commercially available acoustic modems. The LinkQuest modem uses a proprietary spread spectrum (SS) method for communication. The WHOI modem uses frequency shift keying (FSK) for its robust $80bps$ mode [17]. Both of these methods handle motion well but only provide low data rates. In [16], the authors use a combination of a phase-locked loop and linear decision feedback equalization (DFE) as devised in [15]. This method yields higher data rates than the FSK method but requires both transmitter and receiver to be near stationary. The at-sea experiments in [15] show that at a carrier frequency of $15kHz$ this method tolerates phase variations up to about $2rad/s$ which corresponds to a speed of $0.0318m/s$. Our TRE method has proven robust to all levels of Doppler that we were able to generate in laboratory experiments and at-sea tests to date ($> 1.5m/s$) while achieving data rates not previously reported, to our knowledge. The ultrasound equipment used for the $120Mbps$ experiment did not allow transmitter or receiver motion so only the stationary case has been tested at this data rate.

Table I
PERFORMANCE OF DIFFERENT UNDERWATER COMMUNICATION METHODS.

Reference	Data Rate	Range	Speed	Method
[20]	$80bps$	$4km$	$> 1.5m/s$	SS
[17]	$80bps$	$4km$	$> 1.5m/s$	FH-FSK
[16], [15]	$2.5kbps$	$1km$	$< 0.05m/s$	DFE
[21]	$150kbps$	$9m$	$0m/s$	DFE
[14]	$23.4kbps$	$> 7.2km$	$> 1.5m/s$	TRE
[14]	$39kbps$	$2.7km$	$> 1.5m/s$	TRE
here	$1.2Mbps$	$12m$	$> 1.5m/s$	TRE
here	$100Mbps$	$< 1m$	$0m/s$	TRE

VI. CONCLUSIONS

Current wireless underwater modems suffer significant performance degradation when communication platforms are mobile and Doppler effects corrupt the transmitted signals. FSK can be made to be robust to Doppler effects but then uses the available time and frequency resources rather inefficiently and typically only obtains a data rate on the order of $80bps$. Coherent communication has the potential to significantly improve data rate and bandwidth efficiency. Existing approaches, however, only work if the Doppler variation is sufficiently small and roughly constant for the duration of a block. In our work, time-varying Doppler is explicitly modeled, tracked and compensated. We propose to resample the received waveforms non-uniformly and adapt the sampling rate on-the-fly. The resulting signals are then filtered to remove any intersymbol interference caused by time dispersion and multi-path effects. This novel resampling equalizer has demonstrated unprecedented communication performance and achieved a data rate of $1.2Mbps$ at a distance of $12m$, with mobile platforms. This link is capable of streaming video in real-time at a fidelity that has not previously been reported, to our knowledge.

REFERENCES

[1] M. Burrows, *Elf Communications Antennas (IEE Electromagnetic Waves)*. Institution of Engineering and Technology, 6 1978. [Online]. Available: http://amazon.com/o/ASIN/0906048001/

[2] X. Che, I. Wells, G. Dickers, P. Kear, and X. Gong, “Re-evaluation of rf electromagnetic communication in underwater sensor networks,” *Communications Magazine, IEEE*, vol. 48, no. 12, pp. 143–151, 2010.

[3] WFS Technologies Ltd, “Seatooth Video Specifications,” June 2012. [Online]. Available: http://www.wfs-tech.com/index.php/products/viewtooth/

[4] J. Levine and E. J. MacNichol, “Color vision in fishes,” *Scie. Am.*, vol. 246, pp. 108–117, 1982.

[5] N. Farr, A. Bowen, J. Ware, C. Pontbriand, and M. Tivey, “An integrated, underwater optical/acoustic communications system,” in *OCEANS 2010 IEEE-Sydney*. IEEE, 2010, pp. 1–6.

[6] B. Cochenour, L. Mullen, and A. Laux, “Spatial and temporal dispersion in high bandwidth underwater laser communication links,” in *Military Communications Conference, 2008. MILCOM 2008. IEEE*. IEEE, 2008, pp. 1–7.

[7] C. D. Mobley, *Radiative transfer in the ocean*, ser. Encyclopedia of ocean sciences. Academic Press: Oxford, UK, 2001, vol. 4.

[8] A. Beer, “Bestimmung der Absorption des rothen Lichts in farbigen Flüssigkeiten,” *Annalen der Physik*, vol. 162, no. 5, pp. 78–88, 1852.

[9] C. T. Roman, N. Jaworski, F. T. Short, S. Findlay, and R. S. Warren, “Estuaries of the northeastern united states: habitat and land use signatures,” *Estuaries*, vol. 23, no. 6, pp. 743–764, 2000.

[10] International Transducer Corporation, “Model ITC-1089D Spherical Hydrophone Specifications,” 2013. [Online]. Available: http://www.channeltechgroup.com/publication/view/model-itc-1089d-spherical-hydrophone/

[11] M. Stojanovic and J. Preisig, “Underwater acoustic communication channels: Propagation models and statistical characterization,” *Communications Magazine, IEEE*, vol. 47, no. 1, pp. 84–89, 2009.

[12] J. W. Choi, T. Riedl, K. Kim, A. Singer, and J. Preisig, “Adaptive linear turbo equalization over doubly selective channels,” *Oceanic Engineering, IEEE Journal of*, vol. 36, no. 4, pp. 473 –489, oct. 2011.

[13] T. J. Riedl and A. C. Singer, “Broadband doppler compensation: Principles and new results,” *Proceedings of the Forty-Fifth Asilomar Conference on Signals, Systems and Computers*, November 2011.

[14] T. Riedl and A. Singer, “Must-read: Multichannel sample-by-sample turbo resampling equalization and decoding,” in *OCEANS - Bergen, 2013 MTS/IEEE*, June 2013, pp. 1–5.

[15] M. Stojanovic, J. A. Catipovic, and J. G. Proakis, “Phase-coherent digital communications for underwater acoustic channels,” *Oceanic Engineering, IEEE Journal of*, vol. 19, no. 1, pp. 100–111, 1994.

[16] M. Johnson, L. Freitag, and M. Stojanovic, “Improved doppler tracking and correction for underwater acoustic communications,” in *Proceedings of the 1997 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP ’97)*, vol. 1, 1997, pp. 575–.

[17] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, “The whoi micro-modem: an acoustic communications and navigation system for multiple platforms,” in *OCEANS, 2005. Proceedings of MTS/IEEE*. IEEE, 2005, pp. 1086–1092.

[18] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics, boxed set: The New Millennium Edition*, slp ed. Basic Books, 1 2011. [Online]. Available: http://amazon.com/o/ASIN/0465023827/

[19] S. Rienstra and A. Hirschberg, “An introduction to acoustics,” *Report IWDE*, pp. 92–06, 2001.

[20] LinkQuest, Inc., “UWM3000H Specifications,” April 2006. [Online]. Available: http://www.link-quest.com/html/uwm3000h.htm

[21] C. Pelekanakis, M. Stojanovic, and L. Freitag, “High rate acoustic link for underwater video transmission,” in *OCEANS 2003. Proceedings*, vol. 2. IEEE, 2003, pp. 1091–1097.