High Data Rates in the High Frequency Acoustic Channel

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***Abstract*—Underwater acoustic modems are normally considered to offer low data-rates over distances of a few kilometers. This paper reports on open water performance of a high-frequency acoustic modem with demonstrated data rates of 380 kbps. The modem is simple and runs on commodity hardware using well understood signaling techniques.**

Keywords—underwater; acoustic; communication; modem; high-frequency

I. INTRODUCTION

Water covers around 70% of the Earth's surface, yet the area under water remains poorly explored and utilized. A key reason for the under utilization is the difficulties that working on and underwater present. Water is prone to ingress through any opening in housings, is corrosive to many materials, and at depth transfers immense pressure onto any submerged objects. Furthermore water is far from homogeneous, in particular the turbidity and salinity vary dramatically, making optical and electromagnetic communication difficult or impossible in many circumstances.

Yet underwater environments, and in particular the oceans, are both critical to the well-being of the planet, and also a potential source of valuable resources. Methods of transferring data under water are therefore important. Yet the affordability of data transfer, and the rates at which data can be transferred are far behind the same characteristics of radio systems that operate above water.

II. THE RANGE DATA-RATE PRODUCT

Kilfoyle and Baggeroer [1] observed that data rate and range in underwater acoustic communication are inversely related, and that a useful measure of the achievable range•data-rate product is 40 km.kbps, or 40 Mbm/s.

Similar effects can also be seen in terrestrial radio communications, where the maximum operating frequency broadly scales with range, as a consequence of higher frequencies demanding line of sight and being more prone to atmospheric losses. Hence even in radio, range and operating frequency tend to have an inverse relationship. Signal bandwidth being related to operating frequency, there tends to be a trade between data-rate and link distance, although this effect is not as strong as that observed by Kilfoyle and Baggeroer [1].

The underlying driver of the relationship between frequency (and hence bandwidth) and range in underwater acoustic communication is absorption. The absorption rate of acoustic signals in water is a monotonically increasing function of frequency, as shown in Figure 1.

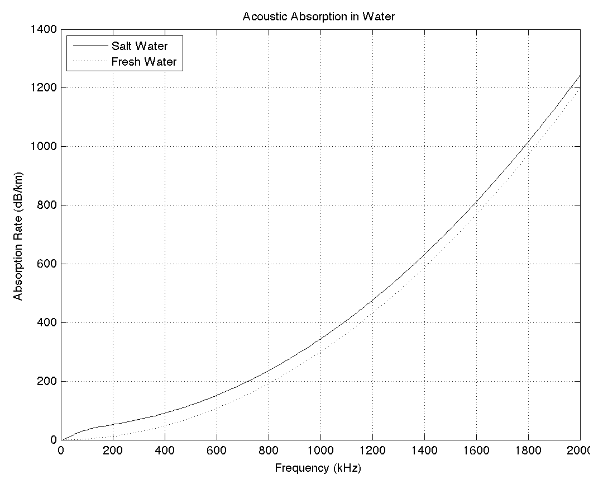

Fig. 1. Absorption rate of acoustic signals in water

Available signal bandwidth cannot exceed the highest frequency in the signal, and in practice approximates some proportion of the upper frequency. In underwater communication the bandwidth often approaches 50% of the upper frequency of the signal. Ergo, underwater acoustic signal bandwidth tends to be directly related to operating frequency. The modulation schemes used for underwater acoustic communication tend to provide a relatively low number if bits per hertz of efficiency, because the signal quality is relatively poor. As a result, the data rate achievable is closely aligned to the signal bandwidth, which is itself closely aligned to operating frequency. In this context, the use of a range•data-rate product as an indicator of the best performance achievable is reasonable. We re-emphasise that this measure is only a working guide, not a hard limit in any way.

This working guide to the likely achievable range•data-rate product then indicates that high data rates are only likely to be achieved over relatively short ranges as plotted in Figure 2. Whilst a 10 km link might only provide around 4 kbps data

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rate, a 1 km link could support ten times the data rate at 40 kbps. Reducing communication range to 100 m indicates that data rates around 400 kbps should be achievable. It is underwater acoustic modem performance in this region around 100 m link distance that we report in this work.

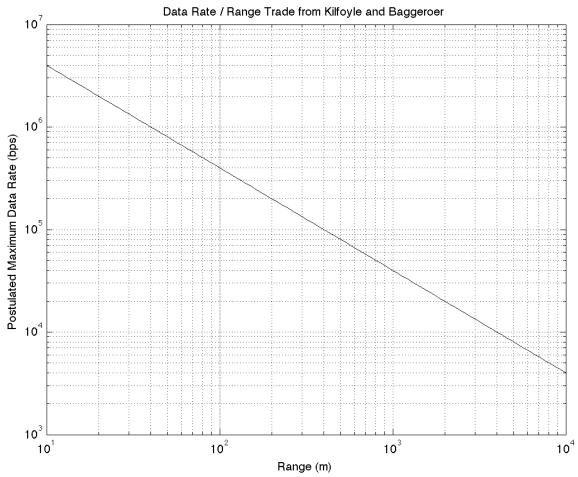

Fig. 2. Kilfoyle and Baggeroer's apparent range•data-rate product

III. The Utility of Short-Range Links

Most underwater modem products and research modems operate over ranges of a kilometer or more. However this is not to say that short-range links are not useful. Much of the world's population regularly use short-range wireless links in forms such as Wi-Fi and Bluetooth. A major benefit of these systems is that they are cable-free, simplifying set-up and allowing modest mobility. In the underwater environment, cables are orders of magnitude more problematic than in the office or coffee-shop.

Watertight cables are expensive, mating is difficult, water-proof cable receptacles are expensive, and the complexity and cost increases with increasing depth. Therefore short-range cable-free links are not only useful for communicating within closely spaced network nodes, but more crucially, they facilitate many applications, such as downloading data from a mooring to an AUV. The link range is almost unimportant – it is the absence of a cable and it's attendant problems that is the key feature.

IV. Modem Concept and Physical Implementation

In pursuit of high data rates, we have been developing short-range, high-frequency hydro-acoustic modem techniques. The hardware arrangement is designed to maximise flexibility for testing, and minimize cost and design time.

The modem is based on a Xilinx Spartan-3A/DSP FPGA built into a module. The module is integrated to a dual channel ADC/DAC that we operate at 4 Msps. For the purposes of testing, the transmitted signal is actually generated off-board and played by the modem boards from a micro-SD card. For open water testing we record the received signal using a high-speed digital oscilloscope at 4 Msps. The recordings are then processed in Matlab on a computer to confirm the processing technique used in the modem. Those same through-water recordings can also be played back into the modem hardware to confirm performance in repeatable, but entirely realistic, tests. Such signal injection can take place either at the digital input to the FPGA – allowing confirmation of bit-perfect performance between the Matlab computer model and the FPGA processing, and also as an acoustic waveform into the ADC analog front-end. For former provides verification of correct implementation, and the latter validates that the modem does indeed work. Results presented here are all from processing in Matlab on a computer, although we have since completed the demodulator FPGA coding to the point where the FPGA implementation produces a bit perfect with the Matlab code using digital signal injection, and equivalent results when fed with analog signal injection.

V. In Water Test Arrangement

The arrangement for the open water test was to package a transmitter unit as a free-floating unit, triggering the transmissions from a GPS receiver as reported in [2], with a similar GPS receiver triggering the signal collection. The advantage of this technique is that highly accurate propagation delay measurements can be taken, in turn allowing accurate estimation of the actual acoustic path length. Time delay produces much more accurate distance measurements than would be obtained from GPS positioning, even if carrier-phase differential corrections were used, since transfer of position from the GPS antenna to the location of the actual transducer in open water is difficult to achieve with high accuracy.

The transducers used for both transmission and reception are a version of the potted ring transducer described by Freeman et al [3]. The receiver transducer was weighted and suspended below a drifting small passenger ferry. The recording apparatus and personnel were also located on the ferry. The transducers used are operating in the thickness mode, and the ring height is 18 mm.

The transmitter unit was a watertight aluminium tube containing the electronic boards, amplifier and ballasted by sealed lead acid batteries in the lower section. The tubes are negatively buoyancy, and are suspended below Styrofoam floats. The ballast in the bottom of the transmitter makes the tubes very stable, and they hang vertically below the float. The ring transducer for the transmitter is arranged to protrude approximately vertically above the aluminium tube. Both the transmitter and receiver transducers were arranged to sit at a depth of approximately four meters. Depth error of each transducer is estimated to be in the vicinity of 30 cm.

The open water test was carried out during the late morning of 12 September 2013 on Lake Burley Griffin in Canberra, Australia.

VI. Transmitted Signal Structure

The transmitter was configured to transmit in the frequency range 525-825 kHz. We transmitted a synchronization header, plus 50 symbols each of 16.384 ms with 2 ms of zero padding in a total period of 952 ms. The structure is illustrated in Figure 3.

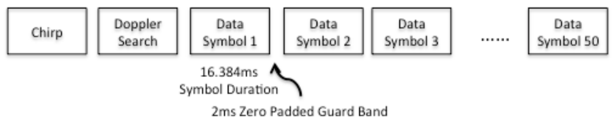

Fig. 3. Illustration of transmitted signal construction

The synchronization header consisted of a 16.384 ms chirp over the full 300 kHz bandwidth, followed by a 2 ms zero padded guard period and then a set of strong carriers which are used to estimate the initial carrier offset.

Each OFDM symbol consisted of 3800 QPSK data carriers, 139 null subcarriers and 985 pilots. Doppler is automatically detected from the null subcarriers, and Doppler correction is performed simply by padding or dropping samples from the oversampled (4 Msps) input stream. Each OFDM symbol is preceded by 2 ms of Zero-Padding.

The processing technique is simple enough to be carried out in real time on a Spartan-3A DSP/FPGA module. By real time we specifically mean that each 16.384 ms OFDM symbol is fully decoded during the time period that the subsequent OFDM symbol is being buffered in the FPGA module. Thus the entire data stream is decoded and exported by the modem in no more than 18.384 ms. The decoding has been demonstrated to work at this speed on the actual hardware with both digital and analog signal injection. The FPGA implementation is a synchronous, single pass operation, so processing time is unaffected by signal conditions and bit error rate. No Forward Error Correction has been included, as the modem is intended for demonstration of physical layer performance only.

The Bit Error Rate (BER) is shown plotted as a function of link range in figure 4. The lowest BER achievable is hindered by the presence of a nearby high-power AM radio transmitter (666 kHz), that is clearly evident in the plot of BER vs subcarrier of the serial 67 recording shown in figure 5. Naturally these few subcarriers could be removed from the processed data if desired, and likewise bit errors in the raw signal can be mitigated by channel coding.

Further we believe that the interference strength is due to the electrical configuration of the transducer assembly, leading to Electromagnetic Interference susceptibility on an unbalanced line so is not directly relevant to demonstration of the ability of underwater acoustic modems to deliver high data rates over short-range links.

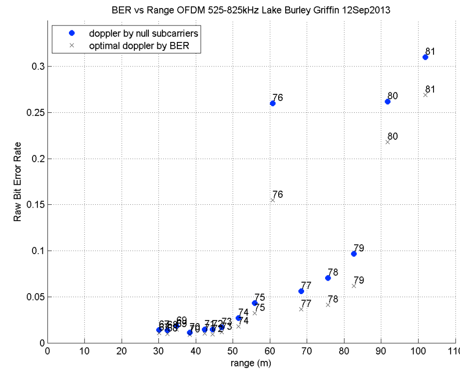

Fig. 4. BER vs Range for open water modem demonstration

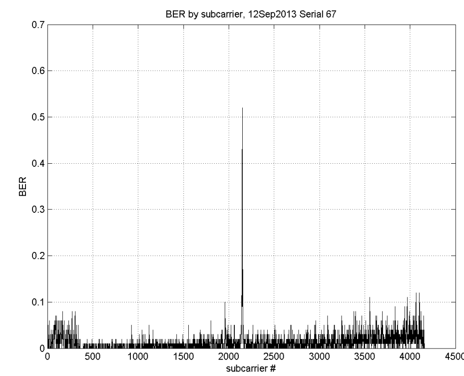

Fig. 5. BER vs Frequency for typical 1 second transmission

The two BER values for each test serial reported are (i) for Doppler correction based on minimizing the energy in the null subcarriers, and (ii) the lowest BER achieved for any Doppler correction option. In all cases Doppler correction is performed by simply removing or repeating samples in the 4 Msps recorded stream. No poly-phase filter or other resampling method is used, minimising computational cost and complexity in the modem.

VII. Achieved Range Data-Rate Product

Each OFDM symbol transfers 7600 bits of data in a period of 16.384 ms, equating to a raw data rate of 464 kbps. However each OFDM symbol is preceded by 2ms of zero padding, lowering the effective data rate to 413 kbps. Including the synchronization header and assuming only 50 OFDM data symbols per second as demonstrated in this test, the average data rate drops to 380 kbps.

Taking 80 m as an approximation of the maximum range achieved at acceptable raw BER, the demonstrated range-data rate product is:

$$380{,}000\text{bps} \times 80\text{m} = 30{,}400{,}000 \text{ b.m/s.} \qquad (1)$$

If we anticipate accommodation of a raw BER of no greater than 10%, then an efficient Forward Error Correction scheme should approach protected throughput of 80% of this value, or

24.3 Mb.m/s. Thus, depending on treatment of bit errors, these results equate to between 60% and 76% of the Kilfoyle and Baggeroer [1] indicative achievable value of 40 Mb.m/s.

We have experimented with higher order modulations, specifically 256 QAM, however distortion in the transmit and receive trains makes improvement on the QPSK results reported here problematic. Lower distortion devices may support a higher data rate and thereby may achieve a higher range-data-rate product.

VIII. EFFECT OF TRANSDUCER BEAMWIDTH

The 3-dB beamwidth of a uniformly illuminated aperture is widely understood to be explained by the Rayleigh diffraction limit, and is:

$$\Theta = 0.88\ \lambda/D \qquad (2)$$

Table I compares this expression with the measured results for a ring transducer of length 30 mm reported in [3], assuming a sound speed of 1450 m/s. The table also includes calculated beamwidths using a value of 0.95 in lieu of 0.88. Practical apertures are normally found to have a beamwidth broader than that predicted by (2), and 0.95 was the factor found to minimize the mean square error between the calculated and reported results.

TABLE I. SUMMARY OF BEAMWIDTH RESULTS FROM [3]

Frequency	Measured Beamwidth (°)	Calculated Beamwidth 0.88 λ/D (°)	Calculated Beamwidth 0.95 λ/D (°)
550 kHz	4.72	4.43	4.78
650 kHz	4.76	3.75	4.05
700 kHz	3.95	3.48	3.76
730 kHz	3.69	3.34	3.60
760 kHz	3.16	3.21	3.46
790 kHz	3.12	3.08	3.33
820 kHz	3.02	2.97	3.21
850 kHz	2.95	2.87	3.10
950 kHz	2.54	2.57	2.77

Fig. 6. Summary of Beamwidth Results from [3]

Our transducers are a very similar to the transducer described in [3]. Thus the above analysis will be used to estimate the elevation beamwidth of the transducers used in this test.

The ring transducer used in this test operates in the thickness mode, and it's vertical extent (ring length) is 12 mm. Using the 0.95 factor as the maximum likelihood estimate, the transducer elevation beamwidth in fresh water is estimated to range between 12.53° at 525 kHz and 7.97°at 825 kHz.

A key driver for the ease with which these results are obtained is this inherent directionality of high-frequency transducers. These signals are both radiated from, and collected by cylindrical piezo-electric transducers as described above. These transducers provide a radiation pattern spanning 360° in azimuth, but around 12° in elevation (varying as a function of frequency and cylinder length). Using these transducers, and provided the ratio of path length to distance from a reflective boundary (such as the surface or possibly the bottom) is no more than around 20:1, the reflected path is outside the main beam of both the transmitter and receiver, and is therefore much weaker than the direct path. For our 4 m deep transducers this corresponds to a range of up to around 80 m without substantial reflections.

We do concede that this requires some coordination on the part of the communicating terminals, which may be complex. However in our case we achieve the required coordination simply because the transducers are mounted approximately horizontally, and are at approximately the same depth. The tolerances on such requirements are not particularly taxing. Implementations for AUVs which adopt a neutral attitude and position themselves at approximately the same depth would also appear to be almost trivial to implement.

It is important to highlight that although OFDM is notionally tolerant of multipath, this is only true if the signal Doppler is completely compensated for. If there is motion on the water surface, or of either transducer than it is highly unlikely that the resultant Doppler can be completely removed from all paths simultaneously. Therefore minimising multipath with directional transducers is of great value in practical underwater acoustic communications.

IX. CONCLUSION

In this paper we presented results of demonstrated through water tests of high data rate – 380 kb in less than 1 second – hydroacoustic communication with acceptable error rates to beyond 80 m, representing a demonstrated raw range•data-rate product of just above 30 Mb.m/s, or potentially error protected throughput of 24.3 Mb.m/s. Such short range links are useful for short-range data transfer, either avoiding the use of cables in closely spaced networks, or enabling cable-free data download from moorings to underwater vehicles or suspended transducers.

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