Implementation of a Spread-Spectrum Acoustic Modem on an Android Mobile Device

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Abstract

Underwater acoustic modems can be expensive and inflexible. Software-defined underwater modems provide flexibility to modify the protocols and modulation schemes.

The motivation of this research is towards producing minimal cost, low-power systems. The focus in this paper being the concept of a surface receiver consisting of a hydrophone plugged into a mobile device such as a smart phone or tablet. Applications could be where data or diagnostics are required from a distributed network of underwater sensors in the field that incorporate an integrated acoustic modem.

Spread-spectrum signals with large bandwidth-time products are considered including binary orthogonal keying (BOK) using linear frequency modulated (LFM) chirps (Chirp-BOK) and pseudorandom noise m-ary orthogonal code keying (PN M-OCK). Bandwidth of $8\,\mathrm{kHz}$ to $16\,\mathrm{kHz}$ is utilised for simulated performance of the modulation schemes. The modulation schemes target low-power, low-received-SNR applications with rates between $23.4\,\mathrm{bit/s}$ and $375.7\,\mathrm{bit/s}$, targeting a BER of 10^{-4} at received-SNR of $-14\,\mathrm{dB}$ to $-6\,\mathrm{dB}$ respectively.

A receiver structure design is implemented on an Android mobile device with experimental validation carried out in a marina over a $100\,\mathrm{m}$ range. The receiver application was able to successfully demodulate, error-free, all packets received in real-time with received SNR of $34\,\mathrm{dB}$. The receiver modulation scheme was user-selectable at run-time. Recordings from the marina trials were combined with AWGN for varying SNR. These were played into the mobile device for real-time demodulation and showed the mobile device and receiver application produced the target BER of 10^{-4} for SNRs of $-12\,\mathrm{dB}$ to $0\,\mathrm{dB}$ for the rates $23.4\,\mathrm{bit/s}$ and $375.7\,\mathrm{bit/s}$ respectively.

Index Terms

spread-spectrum, underwater acoustic modem, software-defined underwater modem, low-power, low-cost, low-received-SNR, M-OCK, Chirp-BOK, mobile device, Android

I. Introduction

Software-defined underwater acoustic modems can provide flexibility for receiving from transmitters with various different modulation schemes and network protocols whilst using the same processing hardware. They are also used for adaptive links switching between different modulation schemes as channel conditions change.

Dol et al. review software-defined modems with the approach of altering the software/firmware of existing off-the-shelf acoustic modems; as well as covering the design of an acoustic modem based on a general processor and open-source operating system [1].

Demirors et al. have also conducted development of a software defined acoustic modem (SDAM) and associated network stack, SEANet, using specialist hardware including an FPGA-based software-defined radio (SDR) platform [2] [3].

In the drive towards minimal cost systems, the ability to utilise a readily available mobile device, such as a smart phone or tablet, allows us to develop new software receivers without requiring the purchase of specialised hardware each time we wish to receive from another underwater network.

The focus of this paper is the concept of a surface receiver consisting of a hydrophone connected to a mobile device, such as a smart phone or tablet, with the implementation of a software receiver. Target applications could include those where data or diagnostics are required from a distributed network of underwater sensors in the field that incorporate an integrated acoustic modem.

Lee et al. have carried out investigations into the use of mobile devices as aerial acoustic modems [4]. Here they were used for transmitting and receiving a 16-bit token before connecting to a server over the Internet. Their research also shows the wide range of performance characteristics of speakers and microphones across a variety of readily available mobile devices.

II. Aim

In this research we are interested in the potential of using low-cost mobile devices to receive underwater acoustic signals with frequencies up to $24\,\mathrm{kHz}$. Specifically, we are interested in spread-spectrum modulation schemes with large bandwidth-time products.

To test the concept, a receiver is implemented in software on a mobile device connected to a hydrophone via the microphone jack. Two modulation schemes are covered, binary orthogonal keying (BOK) using linear frequency modulation (LFM) chirps, i.e. Chirp-BOK, and pseudo random noise m-ary orthogonal code keying (PN M-OCK). Both signals have waveforms with relatively large bandwidth-time products for low-power, low-received-SNR applications.

A. Chirp-BOK

Chirp-BOK is a well-established, robust signalling scheme with excellent Doppler tolerant properties and is used in commercial products such as Seatrac for the robust low-rate $100\,\mathrm{bit/s}$ modulation scheme [5]. In Chirp-BOK the data symbols consist of an up-swept LFM chirp to represent a binary one data bit, and a down-swept LFM chirp to represent the binary zero bit.

Lee et al. are targeting ultrasonic frequencies, to be inaudible to humans, for their Chirp-BOK communication scheme [4]. However, the principles behind their receiver also apply here, where we are targeting the audible frequencies used by the transducer and hydrophone.

Also used by Demirors et al. in a software-defined underwater acoustic modem to provide a "robust feedback link for real-time adaption". Here it is named Binary Chirp Spread-Spectrum modulation (B-CSS) [6].

B. PN M-OCK

Initial research by Dimitrov el al. [7], and the authors [8] introduced the use of carrierless PN M-OCK in low-power, low-received-SNR, underwater acoustic communication. Here long duration and wide bandwidth pseudo-random-noise symbols provide the large spreading ratio, resulting in greater process gain. As increasing the modulation depth in orthogonal signaling has a positive effect on the BER performance [9], it can be seen that PN M-OCK is more attractive than Chirp-BOK as we move to greater values of M. Thus increasing data rates whilst maintaining symbol performance.

III. Methods

A. Signal Design and Packet Structure

Packets were constructed as described in Table I for demonstrating and comparing the two schemes as received on the mobile device. As described in more detail in a previous paper by the author [8], the K11 and K13 corresponds with an 11th order m-sequence and a 13th order m-sequence respectively. Where synchronisation headers are described as K13M512 this indicates the code at the 512-index of the set of 13th order m-sequences. The m-sequences were bandlimited to $8\,\mathrm{kHz}$ to $16\,\mathrm{kHz}$. Up chirp and Down chirp symbols are LFM signals between the limits of the same bandpass filter as used in the m-sequences.

B. Receiver Structure Design

The receiver structure can be viewed as having two purposes and respective discrete parts, namely synchronisation and data demodulation.

TABLE I

PACKET STRUCTURE USING CHIRP-BOK AND PN M-OCK WITH $F_s = 48\,\text{kHz}$ AND BANDWIDTH $B = 8\,\text{kHz}$ FOR A TRANSMISSION OF 32 DATA BITS.

ID	Synchronisation Header (170.6 ms)	Data Modulation (32 bit)	Bits per symbol	Symbol Duration (ms)	Spreading Process Gain (dB)	Bit Rate Uncoded (bit/s)	Total Data Symbols	Data Duration (ms)
A	Up chirp	Chirp-BOK	1	42.6	25.3	23.4	32	1364.7
B	K13M512	K11 2-OCK	1	42.6	25.3	23.4	32	1364.7
C	K13M513	K11 4-OCK	2	42.6	25.3	46.9	16	682.3
D	K13M514	K11 16-OCK	4	42.6	25.3	93.8	8	341.2
E	Down chirp	Chirp-BOK	1	10.6	19.3	93.9	32	341.2
F	K13M515	K10 16-OCK	4	21.3	22.3	187.7	8	170.5
G	K13M516	K9 16-OCK	4	10.6	19.3	375.7	8	85.2

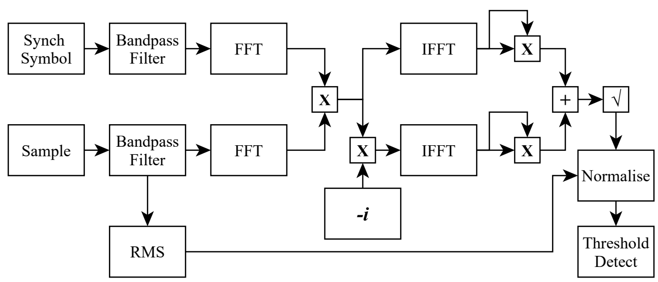

Fig. 1. Block diagram of receiver synchronisation structure.

1) Synchronisation: The synchronisation receiver structure is shown in Fig. 1.

Audio into the microphone is sampled at the specific native sample frequency of the given device, typically this is $48\,\text{kHz}$ or $44.1\,\text{kHz}$.

This signal is bandpass filtered in the time domain then converted to the frequency domain using a fixed-point FFT library. The signal is point-multiplied with the frequency domain instance of the time-reversed synchronisation symbol. A copy is taken and the Hilbert transform applied by point multiplying by $-i$. The correlated signal and its Hilbert transform are then converted back into the time domain by the inverse FFT. The Analytic Signal is then formed by summing the square of each result in the cross-correlation and Hilbert transformation. This envelope of the cross-correlation is then normalised using the root mean square of the bandpass filtered signal. The normalisation step removes fluctuations due to amplitude variance in the received signal and allows the use of a fixed threshold for detecting the synchronisation symbol.

2) Data Demodulation: The data demodulation structure is shown in Fig. 2. Each of the codes in the set are cross-correlated against the signal, but only over a narrow window where the symbol is expected to have arrived. This is to reduce the impact of inter-symbol interference (ISI). It also reduces the number of computations required per data symbol. The maximum-likelihood detector then selects the code that produces the greatest magnitude cross-correlation result within the expected window. The identified symbol is then demapped to produce the binary data bits. In the case of Chirp-BOK only two

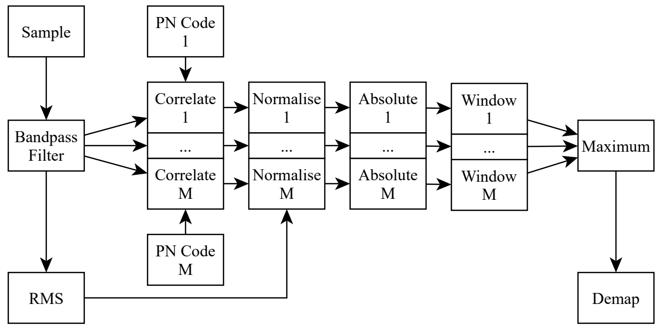

Fig. 2. Block diagram of receiver data demodulation structure.

sequences are compared: up-chirp and down-chirp. In the case of 4-OCK four PN sequences are compared with the greatest correlator peak within a window selected as the received symbol.

C. Chirpr Application

The receiver structure was implemented in C++ using the native development kit (NDK) for Android devices. The user interface was implemented in Java and XML in the application framework. As the program executed, sound was sampled from the microphone stream and provided to the receiver structure as buffers of audio samples became available. Packet data and error counts from the demodulator were saved to CSV files at the point the receiver was halted for later processing.

IV. Experimental Validation: Marina Trials 2017-03-10

An aerial view of the Royal Quays Marina, North Shields can be seen in Fig. 3. This shows the location of the transmitter and the receiver.

The marina consists of a sheer concrete wall with floating pontoons. Water depth is around 10m.

The transmitter setup consisted of a laptop playing audio through an acoustic power amplifier with the transducer suspended in water at a depth of 5m.

The receiver setup consisted of both a laptop recording audio and a mobile device running the Chirpr application for decoding the live audio stream. A bandpass filter and amplifier were connected to the hydrophone which was suspended in water at a depth of 5m. A 2 minute recording was taken by the laptop for each packet type whilst simultaneously carrying out 2 minutes of decoding by the mobile device.

The mobile device used was a 2013 Nexus 5 running the standard Android operating system 6.0.1.

After each recording the user interface on the application was used to select, at run-time, the next packet ID for the appropriate synchronisation header and corresponding modulation scheme.

A. Varying SNR

Recordings from the marina, corrupted by channel effects such as multipath, but possessing high SNR, were then combined with generated AWGN to produce recordings with realistic SNR conditions of $0\,\mathrm{dB}$, $-6\,\mathrm{dB}$, $-12\,\mathrm{dB}$, and $-21\,\mathrm{dB}$. These recordings were then played into the mobile device microphone jack and demodulated in real-time by the application. These recordings were used to assess the receiver performance with varying SNR.

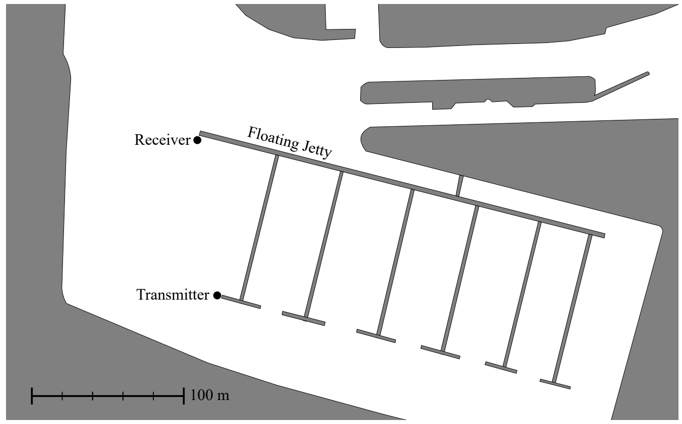

Fig. 3. Marina Aerial View

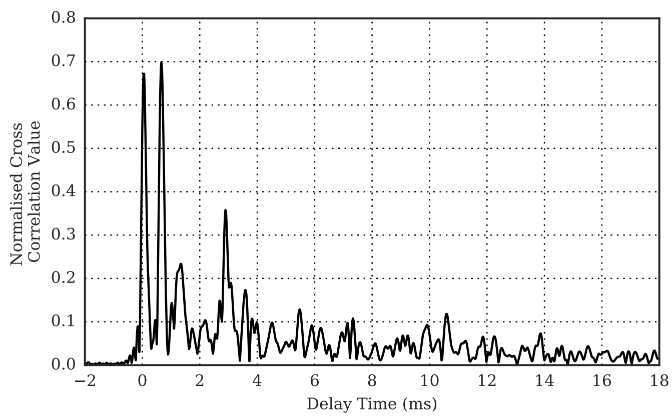

Fig. 4. Impulse Response of the Marina Trials Channel

V. Results

The results of the simulations for the modulation schemes are shown in Fig. 5.

The marina trials channel impulse response is shown in Fig. 4.

Results of decoded packets received in real-time by the mobile device and application are shown in Table II.

Results of recordings from the marina trials combined with AWGN then played back into the mobile device and demodulated in real-time are tabulated as $0\,\mathrm{dB}$ in Table III, $-6\,\mathrm{dB}$ in Table IV, $-12\,\mathrm{dB}$ in Table V, and $-21\,\mathrm{dB}$ in Table VI. These are combined into graphical form in Fig. 6.

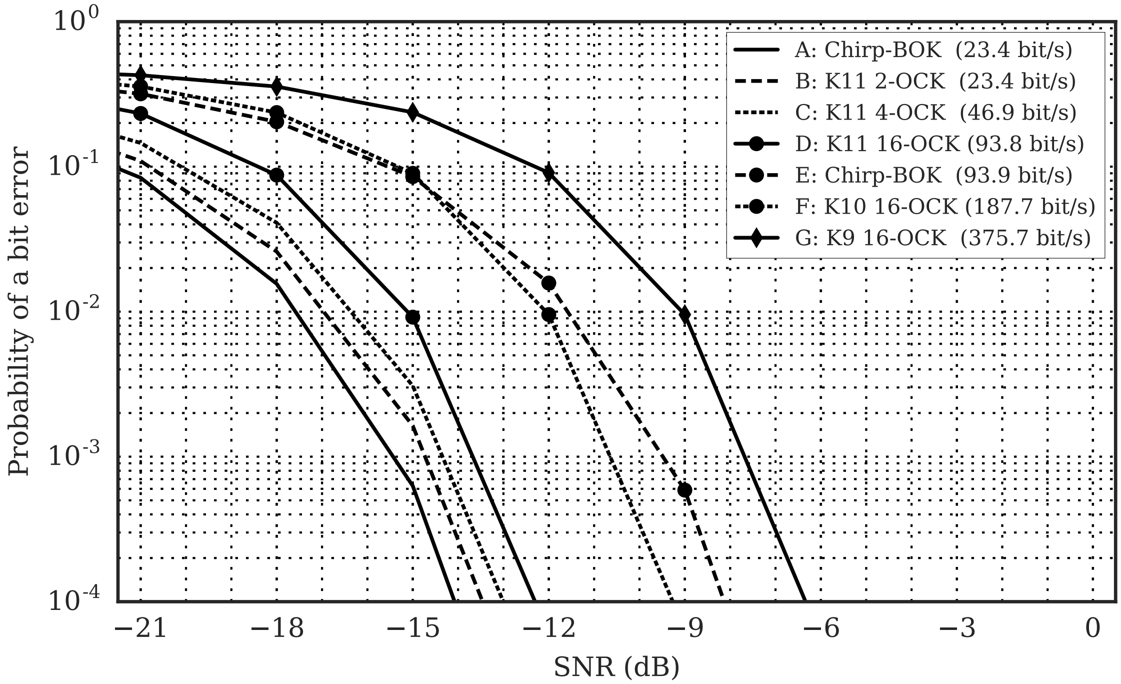

Fig. 5. Simulated performance of each modulation scheme in AWGN channel with Sample Frequency of 48 kHz and bandwidth of 8 kHz to 16 kHz. A. Chirp-BOK (23.4 bit/s); B. K11 2-OCK (23.4 bit/s); C. K11 4-OCK (46.9 bit/s); D. K11 16-OCK (93.8 bit/s); E. Chirp-BOK (93.9 bit/s); F. K10 16-BOK (187.7 bit/s); G. K9 16-OCK (375.7 bit/s)

TABLE II
RESULTS OF PACKETS RECEIVED AND DEMODULATED BY MOBILE DEVICE IN REAL-TIME AT THE MARINA TRIALS. SNR WAS MEASURED BASED ON THE RECORDINGS AS 34 dB

			Packets		Symbols		Bits	
ID	Data Modulation	Bit Rate Uncoded (bit/s)	Success	Total	Errors	Total	Errors	Total
A	Chirp-BOK	23.4	17	17	0	544	0	544
B	K11 2-OCK	23.4	17	17	0	544	0	544
C	K11 4-OCK	46.9	17	17	0	272	0	544
D	K11 16-OCK	93.8	17	17	0	136	0	544
E	Chirp-BOK	93.9	17	17	0	544	0	544
F	K10 16-OCK	187.7	17	17	0	136	0	544
G	K9 16-OCK	375.7	17	17	0	136	0	544

TABLE III

RESULTS OF PACKETS RECEIVED AND DEMODULATED IN REAL-TIME BY MOBILE DEVICE OF MARINA TRIALS RECORDINGS WITH ADDED AWGN. SNR MEASURED AT 0 dB

ID	Data Modulation	Bit Rate Uncoded (bit/s)	Packets		Symbols		Bits	
			Success	Total	Errors	Total	Errors	Total
A	Chirp-BOK	23.4	17	17	0	544	0	544
B	K11 2-OCK	23.4	17	17	0	544	0	544
C	K11 4-OCK	46.9	16	16	0	256	0	512
D	K11 16-OCK	93.8	17	17	0	136	0	544
E	Chirp-BOK	93.9	15	17	2	544	2	544
F	K10 16-OCK	187.7	17	17	0	136	0	544
G	K9 16-OCK	375.7	15	17	2	136	5	544

TABLE IV

RESULTS OF PACKETS RECEIVED AND DEMODULATED IN REAL-TIME BY MOBILE DEVICE OF MARINA TRIALS RECORDINGS WITH ADDED AWGN. SNR MEASURED AT -6 dB

ID	Data Modulation	Bit Rate Uncoded (bit/s)	Packets		Symbols		Bits	
			Success	Total	Errors	Total	Errors	Total
A	Chirp-BOK	23.4	16	17	1	544	1	544
B	K11 2-OCK	23.4	16	17	1	544	1	544
C	K11 4-OCK	46.9	15	15	0	240	0	480
D	K11 16-OCK	93.8	17	17	0	136	0	544
E	Chirp-BOK	93.9	0	17	80	544	80	544
F	K10 16-OCK	187.7	11	17	7	136	18	544
G	K9 16-OCK	375.7	1	17	48	136	104	544

TABLE V

RESULTS OF PACKETS RECEIVED AND DEMODULATED IN REAL-TIME BY MOBILE DEVICE OF MARINA TRIALS RECORDINGS WITH ADDED AWGN. SNR MEASURED AT -12 dB

ID	Data Modulation	Bit Rate Uncoded (bit/s)	Packets		Symbols		Bits	
			Success	Total	Errors	Total	Errors	Total
A	Chirp-BOK	23.4	7	17	15	544	15	544
B	K11 2-OCK	23.4	5	16	13	512	13	512
C	K11 4-OCK	46.9	8	16	13	256	18	512
D	K11 16-OCK	93.8	9	17	15	136	36	544
E	Chirp-BOK	93.9	0	17	167	544	167	544
F	K10 16-OCK	187.7	0	17	49	136	106	544
G	K9 16-OCK	375.7	0	17	89	136	190	544

TABLE VI

RESULTS OF PACKETS RECEIVED AND DEMODULATED IN REAL-TIME BY MOBILE DEVICE OF MARINA TRIALS RECORDINGS WITH ADDED AWGN. SNR MEASURED AT -21 dB

ID	Data Modulation	Bit Rate Uncoded (bit/s)	Packets		Symbols		Bits	
			Success	Total	Errors	Total	Errors	Total
A	Chirp-BOK	23.4	0	15	74	480	74	480
B	K11 2-OCK	23.4	0	16	106	512	106	512
C	K11 4-OCK	46.9	0	15	53	240	68	480
D	K11 16-OCK	93.8	0	17	61	136	136	544
E	Chirp-BOK	93.9	0	18	260	576	260	576
F	K10 16-OCK	187.7	0	17	92	136	177	544
G	K9 16-OCK	375.7	0	17	118	136	228	544

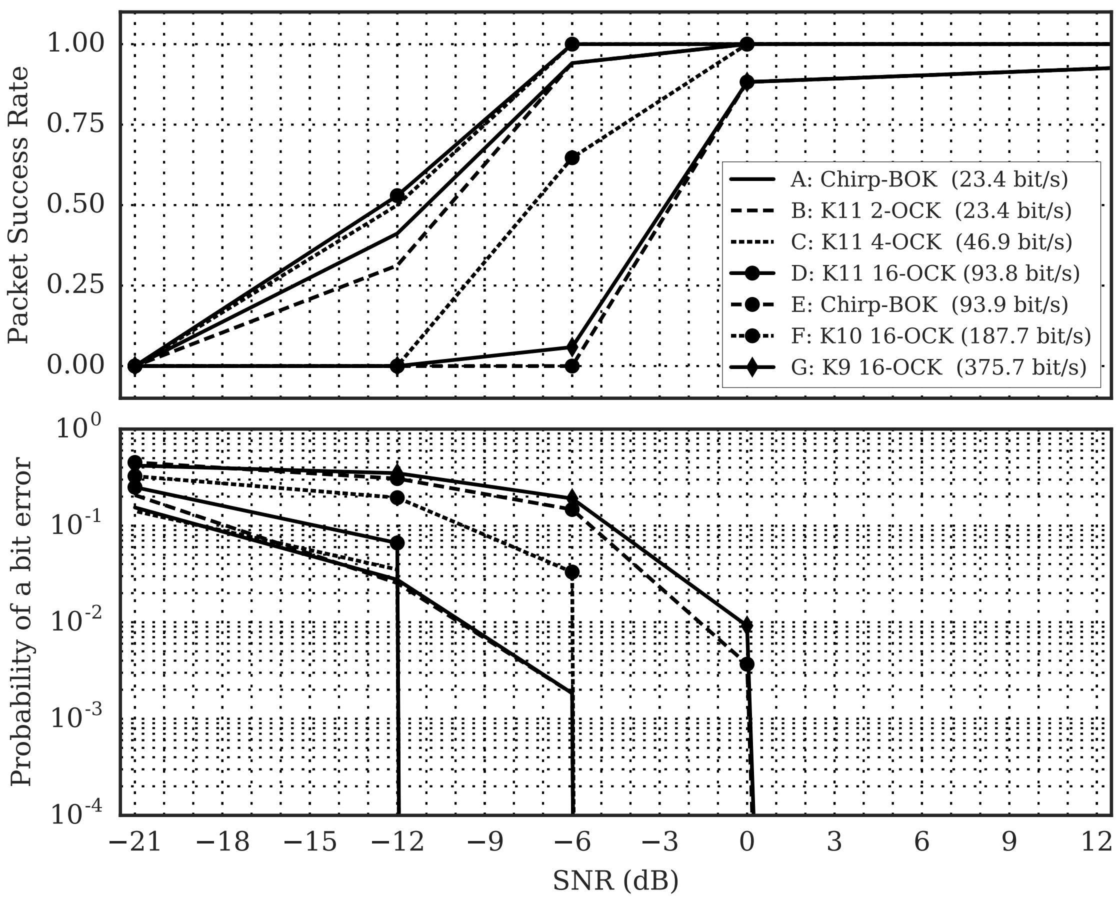

Fig. 6. Performance of marina trials recording combined with simulated AWGN. A. Chirp-BOK (23.4 bit/s); B. K11 2-OCK (23.4 bit/s); C. K11 4-OCK (46.9 bit/s); D. K11 16-OCK (93.8 bit/s); E. Chirp-BOK (93.9 bit/s); F. K10 16-BOK (187.7 bit/s); G. K9 16-OCK (375.7 bit/s)

VI. Discussion

A. Simulations

The simulations in Fig. 5 demonstrate the respective performance of each modulation scheme in a AWGN channel. Although an underwater acoustic channel presents further challenges than simply ambient background noise, these results provide a general comparison of the respective modulation schemes [10]. The long duration symbols of $10\,\mathrm{ms}$ and above are less susceptible to inter-symbol interference (ISI) in typical channels where the multipath arrivals of significant energy occur within $5\,\mathrm{ms}$ as shown in Fig. 4.

Comparing the equivalent modulation depth of M-OCK signals with decreasing symbol duration, K11 16-OCK ($42.6\,\mathrm{ms}$), K10 16-OCK ($21.3\,\mathrm{ms}$), and K9 16-OCK ($10.6\,\mathrm{ms}$), we see a degradation, for a BER of 10^{-4}, of $3\,\mathrm{dB}$ every time the duration is halved. This is expected when we consider that the process gain is related linearly to the bandwidth-time product.

For signals with equivalent data rates but different modulation schemes (A versus B), for BER 10^{-4} Chirp-BOK shows a performance gain of $0.5\,\mathrm{dB}$ over K11 2-OCK for the same data rate and modulation depth. However, when different modulation depths are included (D versus E), for BER 10^{-4} K11 16-OCK shows a performance gain of $4\,\mathrm{dB}$ for the equivalent data rate.

B. Experimental Validation

As seen in Table II, the live results of the application running on the mobile device show that it is possible to produce a software-defined underwater acoustic modem for use with off-the-shelf equipment. The marina channel is relatively noise-free providing an SNR of $34\,\mathrm{dB}$, so this didn't push the modulation schemes to the limits of their operation. However, it does show that the device and corresponding application are able to demodulate the received signal in real-time.

C. Varying SNR

The recordings from the marina trials had high SNR, but with other channel effects such as the multipath as seen in Fig. 4. Taking the recordings and adding AWGN for varying levels of SNR then playing these into the mobile device microphone socket, where they were then demodulated in real-time by the device and application, demonstrated the limits of the combined modulation schemes, application, and hardware. There aren't sufficient data points to produce curves of the same resolution as those in the simulations, however, they do correspond with respect to the relative performance of each packet type.

D. Implementation

The mobile device developer ecosystem is well supported with tools, documentation, examples, and community support. All of which are important factors when considering a target platform for research platforms or commercial products. In this specific case, the native development kit (NDK) providing compilers for C/C++ code means many signal processing techniques used on traditional modem micro-controllers can also be employed in this environment. When considering potential applications of gathering data or configuring networks of underwater sensors in the field this makes the more portable devices such as tablets more appealing as target hardware.

The mobile device also contains analogue front-end circuitry for phantom powering the external microphone, amplifying, and low-pass filtering the signals. A number of newer Android devices also support automatic gain control, configurable at run-time via the application software. These features make it possible to further reduce the external hardware requirements for receiving signals via a hydrophone/transducer.

VII. Conclusion

It has been shown that it is possible to utilise off-the-shelf equipment and mobile devices to produce software-defined underwater acoustic modems for spread-spectrum signals.

The M-OCK modulation scheme shows improved performance over Chirp-BOK for equivalent data-rate in simulations and experimental validation.

A. Future Work

Next steps with this research will include incorporation of suitable forward error correction codes and the implementation of the necessary encoders/decoders into the software application.

Further experimental validation will take place in additional acoustic channels with harsher noise environments.

The software required for transmission of signals is less complicated in the generation and playback of wave files. However the hardware for duplex communication from a mobile device running the software-defined modem will require feasibility studies of the power capabilities of the headphone audio output circuitry along with the impedance and frequencies of suitable transducers.

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