High-Data Rate Carrierless Impulsive Communications For Underwater Acoustic Networks

Emrecan Demiros, Deniz Unal, G. Enrico Santagati, Tommaso Melodia
Institute for the Wireless Internet of Things, Northeastern University, Boston, MA 02115, USA
Email: {edemiros, deniz, santagati, melodia}@ece.neu.edu

ABSTRACT

Underwater networks of wireless sensors deployed along the coast or in the deep water are the most promising solution for the development of underwater monitoring, exploration and surveillance applications. A key feature of underwater networks that can significantly enhance current monitoring applications, is the ability to support sufficiently high data rates that can accommodate real-time video information on an underwater communication link. Unfortunately, the intrinsic characteristic of the underwater propagation medium have made this objective extremely challenging. In this paper, we present the first physical layer transmission scheme for short-range and high-data rate ultrasonic underwater communications. The proposed solution, which we will refer to as Underwater UltraComm (U2C), is based on the idea of transmitting short information-bearing carrierless ultrasonic signals, e.g., pulses, following a pseudo-random adaptive time-hopping pattern with a superimposed rate-adaptive Reed-Solomon forward error correction (FEC) channel coding. We extensively evaluate the U2C performance through water tank experiments. Results show that U2C links can support point-to-point data rate up to 1.38 Mbps, and that by leveraging the flexibility of the adaptive time-hopping and adaptive channel coding techniques, one can trade between link throughput energy consumption.

KEYWORDS

Carrierless, Impulsive, High-Data Rate, Adaptive

1 INTRODUCTION

Underwater networks of wireless sensors deployed along the coast or in the deep water are the most promising solution for the development of underwater monitoring, exploration and surveillance applications. For example, a dense network of underwater sensors can enable environmental monitoring functionalities such as pollution levels monitoring, or prevention and recovery of catastrophic environmental disasters, e.g., oil spills form rigs or pipelines, or seabed dynamic tracking, e.g., monitoring of submarine volcano activities [1, 2]. A key feature of underwater networks that can significantly enhance current monitoring applications, is the ability to accommodate real-time video information on an underwater communication link. In fact, while today monitoring rely on the exchange of simple discrete information, e.g., water temperature, and particle concentration, among others, by introducing real-time streaming capability of non-static images between wireless underwater nodes one can completely revolutionize the whole underwater monitoring scenario.

To achieve this goal, underwater links are required to support sufficiently high data rate, compatible with the streaming rates of the transmitted video sequence. Unfortunately, the intrinsic characteristic of the underwater propagation medium have made this objective extremely challenging. Specifically, due to the physical properties of the propagation medium, underwater acoustic signals suffer from severe transmission loss, time-varying multipath propagation, Doppler spread, limited and distance-dependent bandwidth, and high propagation delays. These formidable challenges limit the available bandwidth, and therefore the achievable data rates in underwater acoustic communications. As a consequence, currently available underwater acoustic technology can support mostly point-to-point, low-data-rate, delay-tolerant applications. Most existing commercial point-to-point acoustic modems use signaling schemes that can achieve data rates lower than 35 kbit/s with a link distance of 1 km over horizontal links [3–6]. Most recently, a commercially available modem has been advertised to achieve data rates of 62.5 kbit/s over a horizontal underwater link of 300 m [7].

In this paper, we present the first physical layer transmission scheme for short-range and high-data rate ultrasonic underwater communications. The proposed solution, which we will refer to as Underwater UltraComm (U2C), is based on the idea of transmitting short information-bearing carrierless ultrasonic signals, e.g., pulses, following a pseudo-random adaptive time-hopping pattern with a superimposed rate-adaptive forward error correction (FEC) channel coding. Low duty cycle impulsive transmission and adapting channel coding combat the effects of multipath and scattering and provide a reasonable degree of robustness to multi-user interference. U2C operates at high frequency ranges of the acoustic spectrum, i.e., ultrasounds, and it is designed to enable multipath-resilient and high-data rate transmissions, up to several hundreds of kbps. However, the price we pay for

---

This work was supported by the National Science Foundation under Grant CNS-1503609 and Grant CNS-1726512.

these benefits is a higher acoustic attenuation, increasing with frequency, that limits the achievable distance ranges from few meters up to approximately 100 m. We evaluate extensively the U2C performance in real-scenario underwater experiments at the PHY layer, i.e., Bit Error Rate (BER). Results show that U2C links can support point-to-point data rate up to 1.38 Mbps, and that by leveraging the flexibility of the adaptive time-hopping and adaptive channel coding techniques, one can trade between link throughput and energy consumption, still satisfying application layer requirements.

The remainder of the paper is organized as follows. In Section 2, we discuss U2C PHY transmission scheme In Section 3, we extensively evaluate the performance of U2C through on-field experiments in a water test tank. Finally, in Section 4, we conclude the paper.

2 U2C: UNDERWATER ULTRACOMM

U2C is an impulse-radio inspired ultrasonic transmission technique based on the idea of transmitting short information-bearing carrierless ultrasonic pulses, following a pseudo-random adaptive time-hopping pattern with a superimposed an adaptive variable-rate FEC channel coding.

Underwater UltraComm (U2C) Transmission Scheme. Baseband pulsed transmissions enable high data rate, low-power communications, low-cost transceivers, and have been proposed for RF short-range, high data rate communications [8, 9], although with much shorter pulse durations (and consequently larger bandwidth) than achievable in ultrasonic communications. In ultrasonic communications domain, baseband pulsed transmissions are first used for intra-body communications and networks in very short distances(in the order of tens of cm), where the propagation medium has similar characteristics to the underwater propagation medium [10–12] .

The fine delay-resolution properties of pulsed transmission are well-suited for propagation in the channels strongly affected by multipath effect due to reflections and scattering. When replicas of pulses reflected or scattered are received with a differential delay at least equal to the pulse width, they do not overlap in time with the original pulse. Therefore, for pulse durations in the order of hundreds of nanoseconds [13], pulse overlaps in time are reduced and multiple propagation paths can be efficiently resolved and combined at the receiver to reduce the bit error rate. Finally, carefully designed interference mitigation techniques may enable MAC protocols that do not require mutual temporal exclusion between different transmitters. This is crucial in the ultrasonic transmission medium since the underwater propagation speed is about 1500 m/s and consequently the propagation delay is five orders of magnitude higher than in RF in-air channels (where the propagation speed is about $3 \cdot 10^8$ m/s) and carrier-sense-based medium access control protocols are ineffective [2].

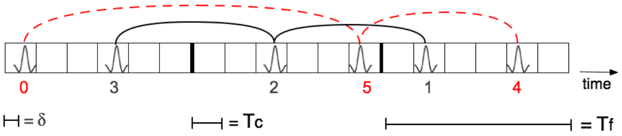

Figure 1: Two concurrent transmissions with $N_h = 6$, time-hopping sequences $\{3, 2, 1\}$ and $\{0, 5, 4\}$ and transmitted bit sequences $\{1, 1, 0\}$ and $\{1, 0, 0\}$.

Adaptive Time-Hopping. Consider, as in Fig. 1, a slotted timeline divided in slots of duration T_c, with slots organized in frames of duration $T_f = N_h T_c$, where N_h is the number of slots per frame. Each user transmits one pulse per frame in a slot determined by a pseudo-random *time-hopping sequence*. Information is carried through pulse position modulation (PPM), i.e., a '1' symbol is carried by a pulse delayed by a time δ with respect to the beginning of the slot, while a '-1' symbol begins with the slot. The resulting transmitted signal for a symbol d can be modeled as

$$s(t) = \sum_{j=0}^{N_s-1} p(t - c_j T_c - jT_f - d\delta) \tag{1}$$

where $p(t)$ is the pulse shape, $\{c_j\}$ is the time-hopping sequence with $0 \leq c_j \leq N_h - 1$, and δ is the PPM shift of a pulse representing a '1' chip. The resulting data rate, in pulses per second, is expressed as:

$$R(N_h) = \frac{1}{T_f} = \frac{1}{N_h T_c}. \tag{2}$$

For a given time-hopping frame length N_h, we define the average transmitted power as the total energy irradiated in the unit time:

$$\bar{P}_t(N_h) = \frac{E_p}{N_h T_c} \tag{3}$$

where E_p is the energy required for transmitting one pulse that is obtained as $P\,T_p$, with P the instantaneous transmission power and T_p the pulse duration. By regulating the time-hopping frame length N_h, i.e., the average inter-pulse time, a user can adapt its transmission rate, and as a consequence modify the average transmitted power.

Rate-Adaptive Channel Coding. Since a single pulse may collide with pulses transmitted by other users with a probability that depends on the frame size N_h, or alternative the pulse can be distorted by the time-varying channel condition, we superimpose a rate-adaptive forward error correction (FEC) channel coding technique that leverages the error correction capability of Reed-Solomon (RS) codes.

RS codes are linear, block error-correcting codes widely used in data storage and data transmission systems. A RS code can be denoted as $RS(s, n, k)$, with s is the symbol size in bits, n is the block length and k is the message length, with $k < n$. The maximum block length depends on the symbol length as $n_{max} = 2^s - 1$. A RS encoder takes k s-bit information symbols and adds t *parity* symbols to make an n symbol block. Therefore, there are $t = n - k$ overhead symbols. On the other hand, a RS decoder is able to decode the received n-symbol block, and can correct up to $\frac{t}{2}$ data symbols that may contain potential errors due to the channel fluctuation or collisions with interfering pulses. The RS code rate can be defined as the ratio between the message length and the block length, i.e., $r_c = k/n$. The information rate, or the net rate, after the channel coding become:

$$R'(N_h, r_c) = R(N_h) r_c = \frac{r_c}{N_h T_c}. \tag{4}$$

Note that there is a tradeoff between robustness to channel fluctuation and multi-user interference (which increases with lower coding rate), and the information rate (which decreases with higher coding rate). For example, a $RS(8, 255, 192)$ encoder considers 8-bit symbols, and for every 191 information symbols gives as output a block of 255 symbols.The decoder can correct up to 32 symbols randomly located in the received block, independently of the number of bits wrong in each symbol (e.g., in the worst case scenario the bits in the 32 symbol can be all wrong). The resulting code rate is 3/4, thus the net rate after the channel coding is reduced of 1/4 with respect of the original information rate.

Signal to Interference-plus-Noise Ratio. We can express the signal to interference-plus-noise ratio (SINR) for impulsive transmissions at the receiver of link i as [8]

$$\mathrm{SINR}_i(\mathbf{N_h}, r_c) = \frac{1}{r_{c,i}} \frac{P_{r,i}\ N_{h,i} T_c}{\eta + \sigma^2 T_c \sum_{k=1}^{K} P_{r,k}}, \tag{5}$$

where $P_{r,i}$ is the average power per pulse period at the receiver of the i^{th} link, η represents background noise energy and σ^2 is an adimensional parameter depending on the shape of the transmitted pulse and the receiver correlator. Parameter K represents the number of pulses that interferers with link i in a time frame T_f, and $P_{r,k}$ is the average power of the interfering pulses measured at the receiver of the link i. The interfering pulses can belong either to co-located transmission links or to multipath component of the link itself, i.e., self-interference. In absence of interference, when no FEC coding and time-hopping is used, (5) give us what we defined SNR per pulse measured at the receiver, given by the ratio of the energy per pulse over the background noise energy

$$\mathrm{SNR}_p = \frac{P_{r,i}\ T_c}{\eta} \tag{6}$$

Note that increasing (or decreasing) the code rate of the link i, $r_{c,i}$, leads to an decrease (increase) in the SINR. This models the error correction effect of the FEC channel coding, i.e., the lower the code rate the higher the correction capabilities of the code. When the i^{th} link increases (decreases) its frame length, $N_{h,i}$, while the number of interfering pulse K remains constant, i.e., in condition of self-interference, the SINR increases (decreases). When the transmitting pulses belong to other co-located transmission links, the number of interfering pulses K scales with the frame length, thus increasing or decreasing the frame length does not affect the SINR.

Finally, no close forms of the BER as a function of the RS code rate and time-hopping frame length are available. However, intuitively, by increasing the code rate, i.e., reducing the code overhead, the BER may increases. By decreasing the time-hopping frame length, the BER may increase or remains constant. Thus, we can in general express BER as a non-strictly decreasing function on the SINR in (5).

3 PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed transmission scheme in a water test tank through programmable Internet of Underwater Things (IoUT) platforms [14–18]. Specifically, we evaluate the performance of the U2C in terms of BER as a function of the code rate, time-hopping frame length, and the SNR per pulse in (6).

Testbed Architecture. To evaluate the performance of the U2C, as a first prototype, we built U2C combining both hardware and software programming to leverage the offered reconfiguration flexibilities on the USRP based platform [15, 17]. Specifically, the U2C signal processing is implemented in the ultrasonic software-defined node using a framework that combines (i) the GNU Radio software development toolkit and (ii) the open source Hardware Description Language (HDL) design for the FPGA embedded in the USRP. We interfaced each platform with a *standard immersion W-series ultrasonic transducers, Ultran WS37-5* [19]. The nominal bandwidth central frequency is about 5 MHz and the bandwidth at - 6 dB goes from 50% to 100% of the bandwidth central frequency, i.e., 2.5 – 5 MHz. Furthermore, the standard immersion W-series is designed to operate in contact with water, and they come in a waterproof case with an UHF waterproof connector. To operate in fully underwater immersion, we use Olympus BCU-58W [20] waterproof cables with BNC to waterproof UHF connectors. The experiment setup consists of two IoUT platform prototypes communicating through water in an underwater tank. The distance between the two transducers is kept fixed to 1.83 m.

BER Vs SNR Per Pulse. In this experiment we evaluated the U2C PHY layer performance in terms of BER. To this purpose we transmit a sequence of 100000 packets each with

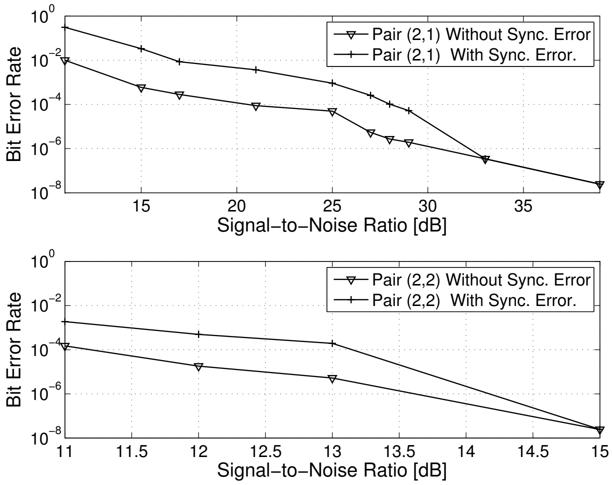

Figure 2: BER with and without synchronization error, as a function of the SNR measured at the receiver, for the pair (2,1) and (2,2).

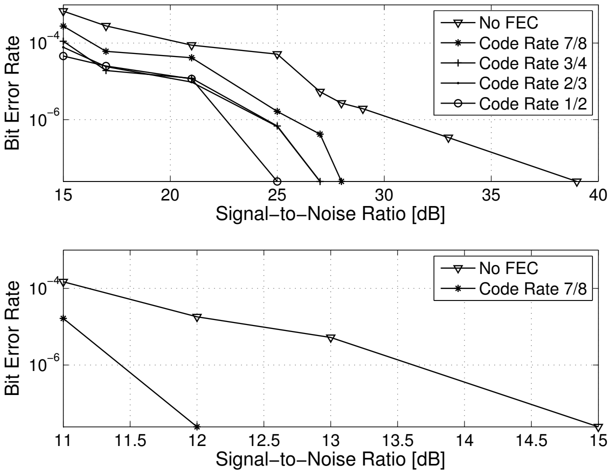

Figure 3: BER without synchronization error, as a function of the SNR measured at the receiver, for the pair (2,1) and (2,2), for different value of code rate.

256 bytes, i .e., approximately 20 Mbits of pseudorandom-generated raw data, and we vary different PHY layer parameters, e.g., SNR per pulse at the receiver, number of potential interfering pulses per time-hopping frame, FEC code rate and time-hopping frame length. At the receiver, the transmitted sequence is known, and the BER is calculated.

First, we evaluate the BER as a function of the SNR per pulse, defined in (6), measured at the receiver, in the absence of external interference. In order to vary the SNR per pulse at the receiver, we connect a variable-gain attenuator between the LFTX daughterboard and the power amplifier we vary the input power at the Tx transducer between 22 dBm and -17 dBm, to obtain values of SNR between 50 to 10 dB, respectively. In this experiments, we used pulses that has a duration of approximately 300 ns with a PPM shift of 60 ns, within a time-hopping slot of 360 ns. Moreover, we consider an over-imposed repetition code of length 2, i.e., each bit is sent represented by two pulses in two consecutive time-hopping frames. The raw transmission data rate, i.e., before FEC is applied, varies from about 1.38 Mbps to approximately 700 kbps. The information rate may vary according to the channel coding rate in use.

Figure 2 shows the BER performances as a function of the SNR per pulse measured at the receiver, assuming frame length of 2, without repetition code (top), i.e, pair (2,1), and with repetition code of length 2 (bottom), i.e., pair (2,2). Each plot reports the BER with and without considering errors due to packet synchronization failures. Finally, this results assume a channel coding rate equals to 1, i.e., no FEC is applied.

In Figure 3, we repeat the same experiments also varying the channel coding rates in {1, 7/8, 3/4, 2/3, 1/2}, for the pair (2,1) (top) and (2,2) bottom. Since the FEC works on the payload error only, the BER reported in this Figure does not consider errors due to packet synchronization failures, that however would be independent form the channel coding rate. The information rate varies from 1.38 Mbps to 700 kbps using the pair (2,1), and from 700 kbps to 350 kbps using the pair (2,2).

4 CONCLUSIONS

In this paper, we presented the first physical layer transmission scheme for short-range and high-data rate ultrasonic underwater communications. The proposed solution, which we referred to as Underwater UltraComm (U2C), is based on the idea of transmitting short information-bearing carrier-less ultrasonic pulses, following a pseudo-random adaptive time-hopping pattern with a superimposed rate-adaptive forward error correction (FEC) channel coding. We presented the design of the first prototype of a software defined underwater ultrasonic transceiver that implements U2C PHY transmission scheme through which we evaluate extensively the U2C performance in real-scenario underwater experiments at the PHY layer, i.e., Bit Error Rate (BER). Results shown that U2C links can support point-to-point data rate up to 1.38 Mbps, and that by leveraging the flexibility of the adaptive time-hopping and adaptive channel coding techniques, one can trade between link throughput and energy consumption.

REFERENCES

[1] J. Heidemann, M. Stojanovic, and M. Zorzi. Underwater sensor networks: applications, advances and challenges. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 370(1958):158–175, 2011.

[2] T. Melodia, H. Kulhandjian, L. Kuo, and E. Demirors. Advances in Underwater Acoustic Networking. In S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, editors, *Mobile Ad Hoc Networking: Cutting Edge Directions*, pages 804–852. John Wiley and Sons, Inc., Hoboken, NJ, second edition edition, 2013.

[3] DSPComm, AquaComm Underwater wireless modem, http://www.dspcomm.com/.

[4] AquaSent Acoustic Modem, http://www.aquasent.com.

[5] Teledyne Benthos Smart Products, http://teledynebenthos.com/.

[6] LinkQuest. http://www.link-quest.com/.

[7] EvoLogics Underwater Acoustic Modems, https://www.evologics.de.

[8] M. Z. Win and R. A. Scholtz. Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications. *IEEE Trans. Communications*, 48:679–689, 2000.

[9] F. Cuomo, C. Martello, A. Baiocchi, and F. Capriotti. Radio Resource Sharing for Ad Hoc Networking with UWB. *IEEE Journal on Selected Areas in Communications*, 20(9), Dec. 2002.

[10] G. E. Santagati, T. Melodia, L. Galluccio, and S. Palazzo. Distributed MAC and Rate Adaptation for Ultrasonically Networked Implantable Sensors. In *Proc. of IEEE Conf. on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, New Orleans, USA, June 2013.

[11] G.E. Santagati, T. Melodia, L. Galluccio, and S. Palazzo. Medium access control and rate adaptation for ultrasonic intra-body sensor networks. *IEEE/ACM Transactions on Networking*, 2015.

[12] G.E. Santagati and T. Melodia. Experimental evaluation of impulsive ultrasonic intra-body communications for implantable biomedical devices. *IEEE Transactions on Mobile Computing*, 16(2):367–380, 2016.

[13] E. Lacaze, S. Michau and P. Mauchamp. 20 MHz ultrasound array for medical imaging: from design to image evaluation. In *Ultrasonics Symposium*, October 2001.

[14] E. Demirors, B. G. Shankar, G.E. Santagati, and T. Melodia. SEANet: A Software-Defined Acoustic Networking Framework for Reconfigurable Underwater Networking. In *Proc. of ACM Intl. Conf. on Underwater Networks & Systems (WUWNet)*, October 2015.

[15] E. Demirors, G. Sklivanitis, T. Melodia, S. N. Batalama, and D. A. Pados. Software-defined underwater acoustic networks: toward a high-rate real-time reconfigurable modem. *IEEE Communications Magazine*, 53(11):64–71, November 2015.

[16] E. Demirors, J. Shi, R. Guida and T. Melodia. SEANet G2: A Toward a High-Data-Rate Software-Defined Underwater Acoustic Networking Platform. In *Proc. of ACM Intl. Conf. on Underwater Networks & Systems (WUWNet)*, Shanghai, China, October 2016.

[17] E. Demirors, G. Sklivanitis, G. E. Santagati, T. Melodia, and S. N. Batalama. A high-rate software-defined underwater acoustic modem with real-time adaptation capabilities. *IEEE Access*, 6:18602–18615, 2018.

[18] E. Demirors, J. Shi, A. Duong, N. Dave, R. Guida, B. Herrera, F. Pop, G. Chen, C. Cassella, S. Tadayon, M. Rinaldi, S. Basagni, M. Stojanovic and T. Melodia. The SEANet Project: Toward a Programmable Internet of Underwater Things. In *Proc. of IEEE Underwater Communications Conf. And Workshop (UComms)*, Lerici, Italy, August 2018.

[19] ULTRAN Group Transducers. http://www.ultrangroup.com/.

[20] Waterproof Transducer Cables, http://www.olympus-ims.com/en/ultrasonic-transducers/transducer-cables/.