Short Paper: An Ultrasonic Communication System for Biotelemetry in Extremely Shallow Waters*

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ABSTRACT

This paper introduces an ultrasonic communication system for biotelemetry in extremely shallow waters (under 3 meters). This application domain is notable for its tight constraints on device size, weight, and energy. We have developed this communication system as a fundamental component of the RaPTEX toolchain, which aims to simplify the prototyping and analysis of underwater communication systems.

This paper's primary contribution is hardware and software for an ultrasonic communications system which successfully operates in extremely shallow waters. It is tailored for short-range disposable biotelemetry applications, as it can be implemented with simple hardware and inexpensive, power-sipping microcontrollers, rather than more demanding digital signal processors. The system presented also has a very low part count, not only making it small and lightweight but also cheap so it can be deployed in large numbers. We present the system design and then evaluate its performance.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Special-Purpose and Application-Based Systems—*Real-time and embedded systems*; D.3.4 [**Software**]: Programming Languages—*code generation, compilers, optimization*

General Terms

Algorithms, Experimentation, Design, Performance

Keywords

ultrasonic communication; static timing analysis; biotelemetry

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1. INTRODUCTION

The ability to study the underwater migratory patterns of aquatic life at sufficient distances to avoid interference has historically been limited. This is unfortunate because the study of such migratory patterns can be used to properly direct environmental protection to minimize harm to both animals and people. Above water such migrations can be studied using radio tracking collars which can be extremely low power and reliable over great distances. However, in underwater environments radio communication becomes prohibitive, forcing the development of an ultrasonic communication system for biotelemetry capable of operating in extremely shallow waters while maintaining the constraints on device size, weight, and energy [1].

As the underwater acoustic channel presents formidable challenges, choosing the right protocol, or a combination thereof, can be nontrivial, often requiring extensive experimentation. To this end, we have developed new methods and implemented them in a tool enabling rapid prototyping of application software for embedded systems. The tool offers a collection of commonly used communication protocols and sensor modules. The designers will be able to construct their systems by interconnecting the software modules they need for their systems and customizing the parameters to meet requirements. The modular interface of the tool will allow the facile introduction of new, custom protocols, and a quick re-deployment for evaluation.

The remainder of this paper is organized as follows: In section 2, we summarize the related work. In section 3 we lay out the hardware design and implementation of an extremely small and efficient transmitter board and a quickly deployable receiver board. In section 4 we describe the packet reception techniques utilized by the communication system. In section 5 we describe the operation of the RaPTEX toolchain. In section 6 we present the relative performance of the various communication configurations tested as well as a battery life analysis. Finally, in section 7 we draw our conclusions and suggest future work.

2. RELATED WORK

There are various commercial and experimental underwater acoustic communication modems available today. We are doing work related to these other modems, but our constraints are different because we focus on disposable biotelemetry applications we face stringent size, weight, cost, and power constraints.

Yan, *et al*, [2], Iltis, *et al.*, [3], Doonan, *et al.*, and Sozer and Stojanovic [4] each developed a reconfigurable acoustic

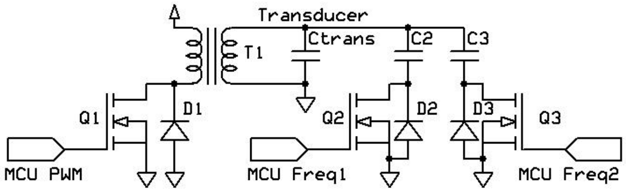

Figure 1: Schematic of the Transducer Driver

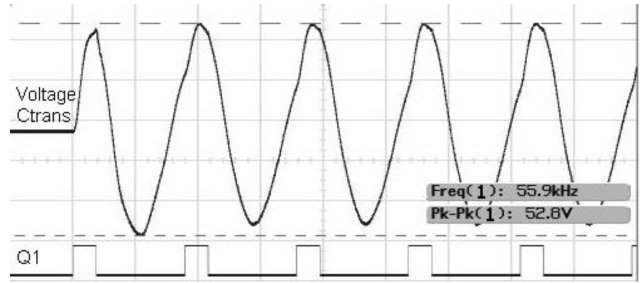

Figure 2: Voltage across the Transducer and the voltage applied to Q1

modem based upon a DSP architecture with an emphasis on long range and fast data-rates. Meanwhile, our design targets a low part count with an inexpensive processor.

Freitag, *et al.*, [5] have developed a compact, low-power, underwater acoustic communications and navigation subsystem, the WHOI Micro-modem, based on a TI C5416 DSP, with power consumption at about 80mW for low-power mode and 180mW for full-power mode. While this design comes closest to our own in terms of power consumption, it is still substantially larger and more costly.

3. HARDWARE

The hardware consists of separate transmitter and receiver boards. The transmitter board contains very few components, consisting only of the transducer driver in Figure 1, the microprocessor, battery, and required sensors. The receiver board contains many more parts, occupying a printed circuit board measuring 3.8 by 2.5 inches. The receiver board also includes extra features to simplify prototyping and testing: a graphical LCD, user input switches, indicator LEDs, and a buzzer. In addition, a large microcontroller was selected to maximize available I/O. Both microprocessors are from Atmel's 8-bit AVR architecture, offering efficient code execution, nearly one instruction per clock cycle, at speeds of up to 24MHz.

3.1 Transmitter

The purpose of this design was to create a user friendly and customizable ultrasonic transmitter capable of efficiently emitting a discrete number of frequencies into an ultrasonic ceramic transducer at requisite voltages. The circuit was designed with the future goal of sufficient miniaturization to be used to collect biotelemetry from under-water life while containing sufficient sensors to make the task worthwhile. Therefore, the transmitter needs to both be extremely low power and have a very low part count.

The processor chosen for the transmitter is the Atmega168 with 16kb of flash and 1kb of SRAM clocked internally at 8MHz. Because the processor will be spending most of its time powered-down between packets, it was important that the processor consume as little power as possible while in this state. Similarly, the processor must be able to maintain performance over a range of supply voltages from 1.8V to 5.5V because the MCU is to be driven directly from the battery.

The high voltage sine-wave on the transducer is produced by coupling the secondary of a small transformer with the capacitance of the transducer itself, producing a natural LC oscillator at the desired frequency. This natural frequency can then be changed by the MCU by controlling the two transistors Q2 and Q3 in figure 1 to selectively introduce additional capacitance to the LC circuit to reduce the natural frequency. With C3 being twice the value of C2, the current circuit can produce four distinct frequencies for the purpose of frequency shift keying. Energy is then applied to this LC circuit through inductive coupling from the primary coil of the transformer which is driven through Q1 with a frequency and pulse-width modulated signal generated by a timer/counter unit integrated into the MCU, as depicted in Figure 2. These signals from the MCU do not drive the transducer directly, instead they are timed to only impart energy near the top of a sinusoidal upswing of the LC circuit with just enough energy to replace the energy lost to the water, leaving actual signal generation to the LC circuit. In the choice of transistors for this design it was important that they could operate at gate voltages below 3V, a feat uncommon among power MOSFETs.

When the transmitter needs to change to another frequency, first the application changes the oscillator to the desired capacitance for the target frequency and then it changes the frequency of the timer/counter to match. The driver circuit is able to reach full amplitude from startup within a single period of operation. Similarly, the circuit is able to stabilize at a new frequency within a similar timeframe.

A major advantage of driving the transducer in this manner is that the processor only needs to be active when it comes time to start or stop the driver, or shift to a different frequency. Therefore, the transmitter application is able to put the processor to sleep while transmitting, only maintaining power to two internal timers, one used to drive the transformer and another to wake the processor up when the symbol ends.

3.2 Receiver

The receiver board (Figure 3) is capable of receiving and decoding up to 4-channel frequencies from an external ultrasonic transducer, which are combined to produce a single frequency shift keyed communication channel. The circuit is powered by battery, so it's portable and deployable outside.

The MCU used in the design is the Atmega324 running at 20MHz, which is a high-efficiency, low-power AVR 8-bit microcontroller with 32K bytes of in-system programmable flash memory. To maintain a dynamic real-time software environment, the receiver software utilizes a prioritizing run-to-completion scheduler.

The signal from the ceramic transducer is first amplified with a software controllable gain of between 4000 and 36000. This signal is then decoded by four LM567 tone decoders, one for each frequency produced by the transmitter. We

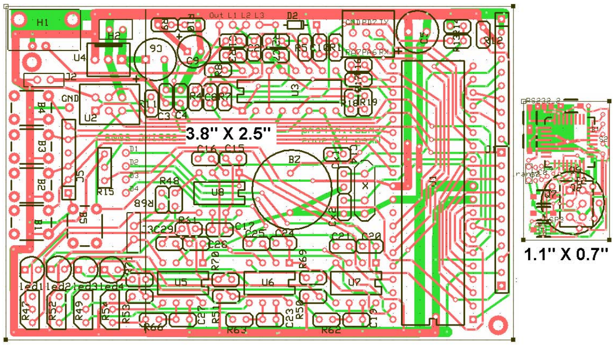

Figure 3: First generation receiver with through-hole components (left) and second generation transmitter with surface-mount components (right)

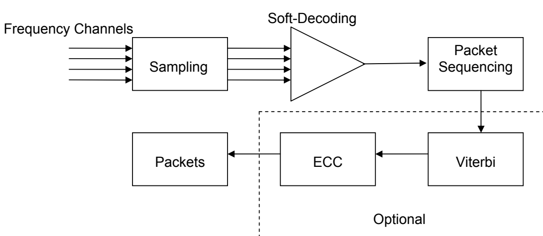

Figure 4: Packet Processing Modules

opted for hardware tone decoders in order to reduce computational complexity and hence processing requirements. The decoded-frequency range is from 0.01Hz to 500KHz and is tuned by hand using multi-turn potentiometers to the current frequency set of 41, 43, 48, and 54kHz. The signal strength from each tone decoder is then sampled by an analog-to-digital converter interrupt service routine (ADCISR) at a configurable rate.

4. PACKET PROCESSING

Figure 4 shows how the received signals are processed. Because we use decoders without a hardware comparator, we implemented several soft-decoding algorithms to combine the four frequency channels being sampled by the ADCISR into a single bit-stream. Every channel is sampled 8 times and then accumulated; the one with the largest magnitude is presumed to be the correct bit-stream.

In order to improve the communication quality, we implement two error-correction schemes to reduce the bit error rate. One is a simple 5-bit ECC scheme to correct up to one bit and the other is a convolutional-viterbi communicationov scheme [6]. In the viterbi scheme, every packet is convolutionally encoded on the transmitter to a bit-sequence roughly twice the length of the original packet. The scheme employs a simple (2,1,2) viterbi trellis diagram to decode the original packet. Once the packet is reconstituted, the 8-bit CRC is checked to insure it was received properly. If this is an error free packet, it will be processed; otherwise, it will be ignored.

With the viterbi decoding scheme, we can theoretically correct up to a 23.5% bit-error rate, or as many as 7 errors in our 4-byte test packets. However, the viterbi scheme is a very complex decoding algorithm which consumes considerable resources. Currently, CPU utilization is 28.8% when the baud rate is about 42bps, compared with 3.8% without the viterbi scheme.

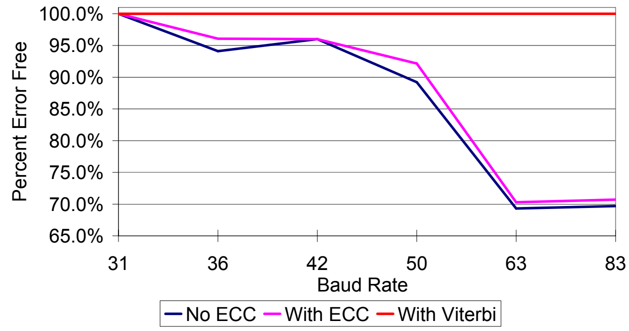

Figure 5: Percent of Error Free Packets at 30 meters

5. THE RAPTEX SOFTWARE TOOLCHAIN

The RaPTEX software toolchain provides a graphical user interface for quick construction and configuration of the embedded software for the ultrasonic receiver or transmitter. First, the designer can add or remove software modules to the respective design, such as additional packet processing such as ECC, compression, or even network layers. Then, the designer can change parameters to customize characteristics such as packet length, symbol length, etc. Next, the toolchain customizes and compiles the code modules. Finally, the toolchain performs static timing analysis on the code produced by the previous two steps to determine various performance characteristics and resource requirements such as minimum processor speed, memory size, average power consumption, and estimated battery life. This instant feedback to the user is a critical feature of the toolchain and enables a more effective exploration of the offered trade-off space. Once these results are satisfactory, the code can then be loaded onto processor for deployment.

6. RESULTS AND DISCUSSION

All tests were performed on open water at Lake Wheeler just south of Raleigh, North Carolina. Floating piers available at the site were used as platforms for the current stage of experimentation with fresh-water communication. The depth in this area is extremely shallow, less than 5 meters. The boards were kept on the pier and the transducers were suspended approximately three feet below the surface. The water conditions were moderate with no nearby motorized boating activity.

6.1 Performance

Figure 5 shows the percentage of packets recovered without error both with and without recovery. As we can see, just five bits of ECC in a 32-bit packet to recover one wrong bit does not improve performance substantially. However, switching to convolutional encoding with Viterbi decoding manages to attain error free communication for all tested baud rates. While this comes with substantial overhead, at higher baud rates it does improve throughput.

	MCU	LC Driver	Total
Shutdown	4.60uA	0.10uA	4.70uA
Idle	799.0uA	0.10uA	799.1uA
Active	1,060uA	22,400uA	23,435uA

Figure 6: Transmitter Board Current Draw at 2.8V

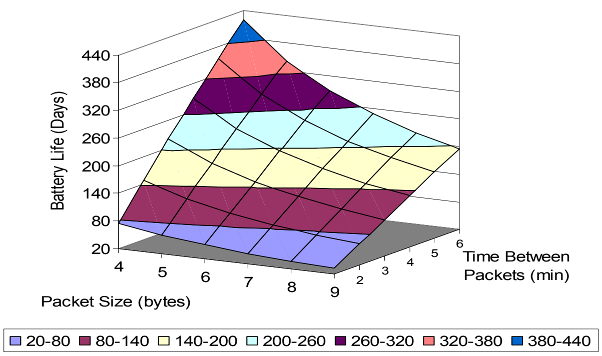

Figure 7: Battery life of CR2450 Lithium at 42 baud

6.2 Transmitter Power Consumption

As our results show, operating at a distance of 30 meters with a transmission rate of 42 baud, or 768ms for a 32 bit packet, nearly all of the packets sent were received correctly without the need for any error correction. At this rate of transmission and using the measured current consumption of the transmitter from Figure 6 and converting all time units to hours, we can calculate the coulombs consumed using equation 1 to be 5.00 coulombs per packet per hour.

$$C_{Packet} = t_{Packet} \times I_{Active} \quad (1)$$

Next we calculate the shutdown coulomb consumption in an hour using the current consumption from Figure 6, 4.70uA, to get 0.0169 coulombs per hour. A rough estimate of the total charge supplied by a reasonably small battery supply such as the CR2450-3 Lithium Button-cell battery, which is rated at 550mAh, is 1,980 coulombs. Combining these three terms into equation 2 with the number of packets per hour requested by the field researchers, we can estimate how long the system would be able to operate barring mishap, as shown see in Figure 7.

$$t_{Life} = \frac{C_{Battery}}{C_{Packet} \times f_{Packet} + C_{Shutdown}} \quad (2)$$

If longer battery life is needed then with larger creatures more batteries can be included, or for slower creatures the packet frequency can be reduced, as in Figure 7. Battery life could be further extended by reducing the packet duration, either by increasing the baud rate, compressing the data, including only critical data, or by utilizing fewer ECC bits. To save even more the transmitter could reduce its ultrasonic power output directly. Although many of these techniques would act to increase the error rate, a capable viterbi algorithm does prevent it from negatively impacting performance.

6.3 Receiver Power Consumption

While active, the receiver consumes 243mW, consisting of 114mW for the four tone decoders and 129mW for the processor running at 20MHz. As the receiver board will be surface tethered, the receiver was design with less stringent constraints on power and size, making this power consumption acceptable. However, as 47% of power is consumed by the LM567 tone decoders, there is room for improvement by having this task performed in either software or an FPGA. Similarly, if sufficient slack is available, the processor can utilize a slower clock.

6.4 Range Evaluation

An attempt was made to determine the maximum effective range of the current communication system by moving the two transducers as far away from each other as was possible with the pier configuration available, for a distance of approximately 100 meters. For this test the transmitter was re-configured to produce a larger output compared to the previous tests of approximately 87V peak-to-peak at 31 baud. Without utilizing the viterbi scheme the receiver managed to correctly decode 67% of the packets sent and with viterbi it was able to correctly decode over 94% of the packets sent.

7. CONCLUSIONS AND FUTURE WORK

This paper describes our work on designing and developing an ultra-low power ultrasonic transmitter for underwater biotelemetry with an accompanying portable receiver. We also explored the use of two mechanisms of error correction with their respective performance. For future work we will optimize our Viterbi decoder to obtain higher baud rates while maintaining error-free operation. We will also miniaturize the transmitter to surface mounted components with the lowest possible weight and size in order to reach sizes small enough for attachment to fauna with a minimum of interference with the creatures natural behavior. Finally, we will parameterize the transmitter and receiver software modules and add them to the RaPTEX library to allow higher-level design and optimization.

8. REFERENCES

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