u-OCEAN: An Underwater Omnidirectional Communication Environment using Acoustic Sensor Nodes

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***Abstract*—This paper proposes a scheme for developing a low-cost underwater acoustic communication link and implements a portable underwater wireless sensor node capable of monitoring sub-aquatic parameters and transmitting them back to a land-based base station. The designed underwater communication link utilizes ultrasonic vibrations from off-the-shelf ultrasonic transducer pairs modified to achieve underwater wireless communication. The underwater sensor node is equipped with temperature and pressure sensors, measurements from which are periodically transmitted to the surface base station. The surface base station can additionally connect to various smartphones and computers using a Bluetooth interface. The proof of concept implementation shows consistent performance under laboratory conditions.**

***Keywords*—Massively Constrained Networks, Wireless Sensor Networks, Underwater Sensor Networks, Ultrasonic Communication**

I. Introduction

Modern day wireless sensor networks (WSNs) are used for a plethora of operations on terrestrial as well as, aquatic environments, ranging from surveillance of flora and fauna [1] to deep sea communication between AUVs [2]. However, as compared to the wide variations in the range of terrestrial WSN operations, the use of WSNs in sub-aquatic domains is severely restricted by the availability and pricing of communication equipment for tasks such as underwater habitat monitoring, ocean floor mapping, shoreline surveillance, ocean current monitoring, and others. The present day cost of existing underwater wireless solutions is the main deterrent in popularizing the common usage of underwater sensor networks (UWSN). In this work, we propose an economic solution for implementing UWSNs using commonly available off the shelf electronic components. The implemented system using the proposed approach is capable of measuring underwater parameters, such as pressure and temperature, and wireless transmit the measured values to a land-based/ above water base-station, as shown in Fig. 1. The base-station, in turn, can communicate with various handheld devices by means of a Bluetooth interface, enabling near real-time availability of the sensed underwater measurements on a user's smartphone or computer.

The high cost of available underwater wireless communication systems can be attributed to the limitation of electromagnetic (EM) and optical waves for underwater communication. Both EM and optical modes of underwater communication are prone to severe attenuation owing to the conductivity of water, which leads to problems like multi-path propagation loss, lesser usable bandwidths and channel time variations [3]. Till date, acoustic transmission has been found to be a more reliable means of underwater communication as compared to EM or optical communication methods [4] [5]. However, acoustic channels are prone to lower data transfer rates and inter symbol interference (ISI) owing to varying speeds of acoustic waves at varying depths. The small scale use of commercially available acoustic communication systems, which are designed for long range underwater transmission, are not only significantly costly and power hungry, but also prone to noise and ISI due to powerful back echoes generated during their operation over comparatively smaller distances such as in lakes, ponds and pools.

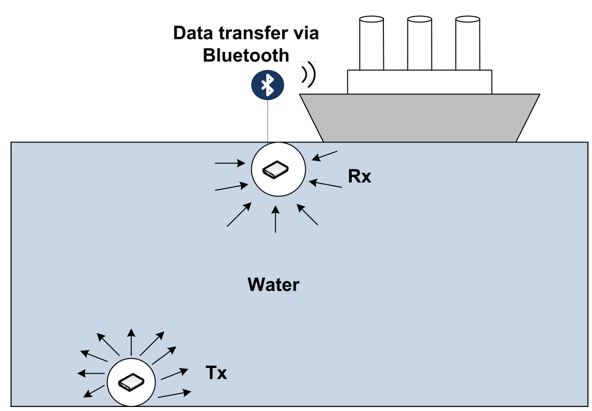


Fig. 1: A typical underwater sensor node deployment scenario.

A. Motivation

The motivation behind this system is to develop a low-cost and functional underwater wireless sensor node, and enable the recorded sensed data to be transmitted to a surface base station wirelessly. Underwater parameter monitoring aims at quantifying sub-aquatic physical parameters such as – temperature, pressure, and depth. These physical parameters can be used for a range of applications such as, water quality measurement [6], water pollution indicator, metabolic rates of living organisms and thermal stratification in water bodies. More complex operations of these underwater sensor nodes include measuring solar radiation, ocean currents, detecting underwater volcanic explosions, emergency communications from underwater vehicles, and surveillance.

B. Contributions

In this paper, an architecture, and a scheme for deployment of low-cost acoustic communication links for underwater sensor nodes is implemented. The scheme – *uOCEAN* – enables the transfer of data from underwater sensor nodes to land-based base-stations. In view of the work done, the following specific contributions have been made,

- A wireless means of creating underwater communication channel between two nodes, i.e., the physical channel between two nodes. The transmitters and receivers have been designed to be omnidirectional, so as to remove its dependencies on the orientation of the transducers.
- An underwater wireless sensor node capable of quantifying sub-aquatic physical parameters such as, temperature, pressure, and depth.
- Pulse Width Modulation (PWM) based conversion of digital data to transferable acoustic signal levels, i.e, MAC layer schemes for encoding data.

II. Related Works

Underwater Sensor Networks, its physical implementations and the challenges associated with them [7] [8] have been consistently pursued and widely studied. Studies on modeling of acoustic channels is crucial to emulate the behavior of an underwater sensor network as a whole. These emulations take into account, the various parasitic effects such as noise and attenuation [9]. Vasilescu *et al.* [10] used a combination of optical and acoustic communication for maximized performance of their underwater sensing system. Similarly, Farr *et al.* [11] also proposed and demonstrated a system with fused optical and acoustic communication for achieving faster data transmission. They achieved real-time video streaming with data transfer speeds in the vicinity of 10 mega bits per second for a range of 100 meters.

Won *et al.*. [12] proposed an omni-directional underwater modem based on the Cortex M3 processor. Their reports considerably less power consumption, an omni-directional beam pattern formation and cheap implementation cost. To alleviate the problems faced by radio frequency communications their system used transducers operating in the ultrasonic range. Similarly Renner *et al.*. [13] proposed a method for communication between micro autonomous underwater vehicles which can be implemented as a standalone system at no additional hardware costs. Their underwater systems were tasked with ranging and other applications including monitoring water standards and quality.

In lieu of using commercially available underwater communication solutions, Benson *et al.* [14] used self-designed underwater transducers in conjunction with underwater sensor nodes. The achieved data transfer range was reported at 350 meters with a bit error rate of 30%. Another approach of using self-designed underwater communication modem – *rModem* – was demonstrated by Stojanovic *et al.* [15]. Their system was made using Cyclone FPGAs and a daughter card interface for amplification by using Simulink and Real-Time Workshop Toolbox from Mathworks The modem reported higher processing gains and had an integrated graphical user interface (GUI) for ease of use. Other interesting works include the prototype for software-defined acoustic modem as proposed by Demirors *et al.* [9]. Their work relies mainly on simulations for quantifying the effects of various virtual environments besides providing extensive future research challenges in the field of underwater real-time monitoring.

Despite the bulk of works done on underwater acoustic modems, there is a consistent stand-off between cost, power and range of these underwater modems. In this work, we aim to bargain between such parameters using commercially available and easy to use items so as to elicit as much performance as possible. Towards this, we have used commonly available, off-the-shelf electronic components to implement an integrated underwater modem and sensor node. Additionally, the transmitter and receiver have been made omni-directional to remove the dependencies of the transmitter and the receiver on their orientation with respect to each other.

III. Acoustic Data Transfer Modeling

This section deals with modeling various system parameters and quantifying them for ease of calculation. This section is divided into three parts, namely – 1) Sensing and Pre-transmission, 2) Transmission, 3) Post-transmission and Processing.

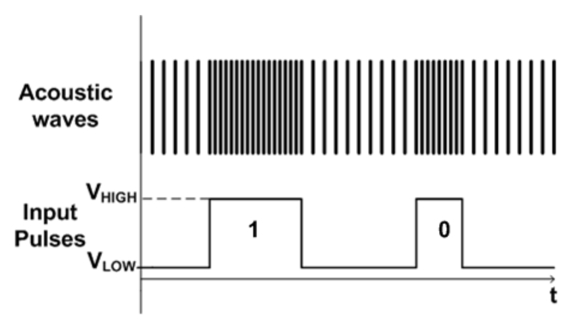


Fig. 2: Underwater wave propagation by conversion of voltage inputs to compression and rarefactions of the ultrasonic acoustic wave.

A. Sensing and Pre-transmission

In this work, the underwater sensor node is armed with two sensors denoted by S_1, S_2. The sensed analog voltages at the processor of the sensor node is given by $\phi_1(t)$ and $\phi_2(t)$ for S_1 and S_2, respectively. A quantization operation on the digital processor converts these sensor voltage levels into 10 bit quantized signals denoted by $\phi_1(n)$ and $\phi_2(n)$. The generalized function for the processed signal which is primed for sending is denoted as

$$\Phi(n) = f(\phi_1(n), \phi_2(n)....) \tag{1}$$

The primed signal is then modulated using PWM for transmission over an analog acoustic transducer. The modulated signal is represented by $M_c(t)$, and given by Equation 2.

$$M_c(t) = \sum_{n=-\infty}^{\infty} [g_k(t - nT)] \tag{2}$$

such that, for k denoting values ranging from $0-9$, whitespace character, negative sign, decimal point, header, footer, and acknowledgement signal, $g_k(t)$ is represented as,

$$g_k(t) = \begin{cases} logic\,1 & for\, 0 < t < \tau_k < T \\ logic\,0 & otherwise \end{cases}$$

In the ultrasonic transducer, the signal $M_c(t)$ induces vibrations which sends information encoded compressed and rarefied acoustic waves in all directions. The radiated acoustic waves from the acoustic transmitter can be visualized as an isotropic sphere, as shown in Fig. 3. The transfer of the information loaded wave can be denoted by $a(t)$ as shown in Fig. 2 such that, for E denoting electrical energy and M denoting mechanical energy.

$$M_c(t) \underset{M \leftarrow E}{\overset{M \rightarrow E}{\rightleftarrows}} a(t) \tag{3}$$

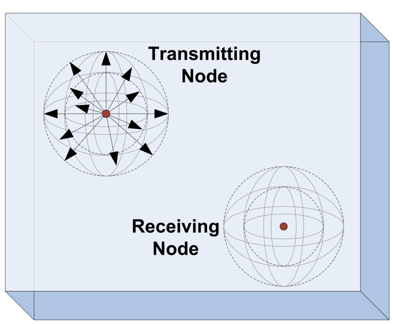


Fig. 3: A 3D representation of underwater communication between an ultrasonic transmitter and receiver.

B. Transmission

The acoustic channel data reception on the receiver side can be can be modeled and mathematically represented as, in terms of the mechanical signal sensed by the receiving transducer, which is denoted by $r(t)$, such that,

$$r(t) = h(d_o) \times (a(t - \tau_o)) + I_x(t) \pm \varepsilon \tag{4}$$

where,

d_o = radial distance between the two communicating nodes.

h(d) = path loss as a function of distance d [16]

$$h(d) = \underbrace{k \times \log_{10} d}_{Spreading\,Loss} + \underbrace{10 \times \log_{10} \alpha \times d}_{Absorption\,Loss} \tag{5}$$

I_x(t) = Inter Symbol Interference (ISI) caused by two factors, namely - *reverberation caused at the transducer*, and *ray bending during change of medium*.

τ_o = path delay which is determined by the velocity of sound wave in water.

k = spreading factor.

α = absorption coefficient.

The signal $r(t)$ is used for retrieving the contained information from the signals received at the ultrasonic receiver.

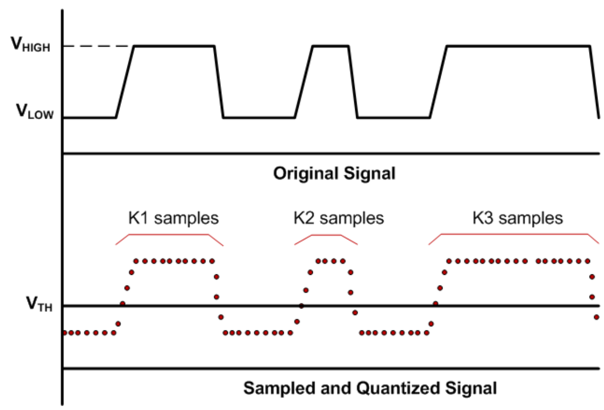


Fig. 4: A/D conversion of the received and amplified signal $y(t)$

C. Post-transmission and Processing

This stage represents the conversion of the received mechanical signal ($r(t)$) and its conversion to the corresponding analog signal s_2(t) as shown in Equation 6.

$$r(t) \xrightarrow{M \rightarrow E} s_2(t) \tag{6}$$

The analog front-end consists of an ultrasonic receiver connected to a precision instrumentation amplifier which is nearly linear in nature and amplifies the sensed analog signal s_2(t). Let $y(t)$ denote the amplified signal. Then,

$$y(t) = A \times s_2(t) = A \times m(t) + n(t) \tag{7}$$

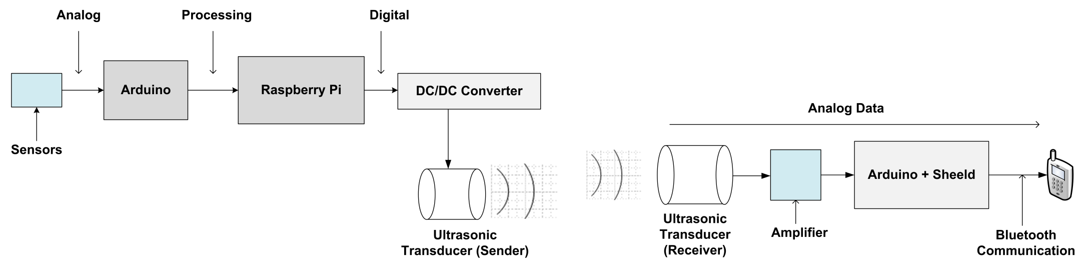
where,

$$h(d_o) \times (a(t - \tau_o)) \xrightarrow{M \rightarrow E} m(t) \tag{8}$$

$$I_x(t) \pm \varepsilon \xrightarrow{M \rightarrow E} n(t) \tag{9}$$

Post amplification, $y(t)$ is sampled and quantized by the microprocessor as given by Equation 10 with a higher sampling rate to obtain $Y[n]$ for digital filtering and decoding purposes. This analog to digital (A/D) signal conversion at the receiver is denoted as,

$$y(t) \xrightarrow{A/D} Y[n] \tag{10}$$



(a) Underwater Sensor Node

(b) Base-station

Fig. 5: The functional blocks for the components used in the task implemented in this work.

With reference to Fig. 4, for K samples of each peak in the signal $Y[n]$, and for ω[n] = $K1, K2, K3, \cdots, Y[n]$ is represented as,

$$Y[n] \xrightarrow{h(t)} \omega[n] \tag{11}$$

The impulse response $h(t)$ of the implemented filter with reference to Fig. 4 and Equation 11, and which is a result of the comparison between the input voltages (V_{HIGH}, V_{LOW}) and the threshold voltage (V_{TH}), is represented as,

$$V_{\text{TH}} = \frac{V_{\text{HIGH}} + V_{\text{LOW}}}{2} \tag{12}$$

The filter counts the number of consecutive samples, say K, and decodes the acquired symbol sent from the transmitter side. This process allots a particular symbol to each decoded pulse based on the value of K. This helps in the reconstruction of the sensed data on the receiver side.

IV. System Architecture

There exist plentiful architectures for deployment of underwater sensors in various scenarios, and under various conditions [17], [18]. The proposed system deployment is done as shown in Fig. 1. The internal functional blocks of the underwater sensor node is shown in Fig. 6. The data collection form these nodes can be done from anywhere in the functional communication range of the receiver node. The more advanced specifications are sequentially described in the consecutive sub-sections.

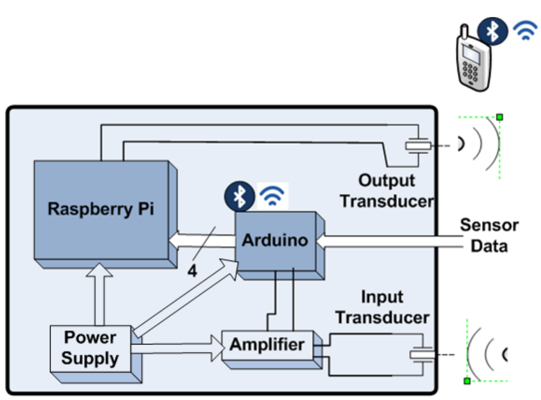


Fig. 6: Functional dependencies of various independent units integrated in a single sensor node

A. Underwater Sensor Node

The underwater sensor node consists of an Arduino and a Raspberry Pi interfaced together with the ultrasonic transducer. As the raspberry Pi cannot directly handle analog signals, an Arduino board is used for converting received analog signals to digital signals by means of its inbuilt A/D converter. This is essential for for producing the functionality of the modem. However, as the Raspberry Pi can handle complex algorithms, it is mainly used for implementing complex on-board detection and recognition tasks. This provides for on-board decision making for certain scenarios requiring immediate responses. For data collection, two sensors have been considered – Adafruit 1893, which is a barometric pressure sensor that also measures altitude and temperature, as well as the LM35, an analog temperature sensor [17]. The ultrasonic transducer has been encased in a metallic case which allows the propagation of the acoustic data in multiple directions. The functional blocks for the underwater sensor node is shown in Fig. 5(a).

B. Base-station

The received acoustic signals at the base station are captured by the paired ultrasonic receiver, which is also encased in a metallic case for omni-directionality. The captured signals are transferred to a signal amplifier that enhances the voltage gain to a level suitable for processing before transferring them to an Arduino board for converting the analog signals to digital signals. The Arduino at the base station additionally facilitates communication and data sharing from the base station to other handheld devices such as smartphones and laptops via a Bluetooth interface. The base station functional blocks are shown in Fig. 5(b).

C. Implementation

The underwater sensor node follows the following sequence of operations for transmitting sensor data encoded acoustic signals:

- Sensors are powered by the Arduino and the data is received at the analog pins.
- The Arduino is programmed to convert the sensed data to digital signals, which are then level shifted (reducing logic level from +5v to +3.3v) for communication with Raspberry Pi.

- Instead of serial data transfer, for faster transmission, data is sent in parallel so as to enable faster processing.
- The digital signals received by the Raspberry Pi is modulated using Pulse Width Modulation. The signal is then transferred to the DC/DC Converter to generate bipolar oscillations of electrical signal about a DC value.
- The converted analog signal is sent to the transmitting ultrasonic transducer for transmission.

Similarly, at the base-station, the following sequence of events occur from the onset of data capture to its decoding,

- The acoustic data received at the acoustic transducer is applied to a high-gain amplifier, preferably a low cost instrumentation amplifier like AD620 which is advantageous because of its wide power supply range.
- The amplified signal is then transferred to the Arduino board, which is also integrated with Bluetooth for communication with external devices, such as smartphones.
- Using the integrated arrangement, the Arduino board is programmed to demodulate the received data by comparing the width of the received pulses to a predefined list set according to the delays implemented at the receiving end. By comparison, the data is received without any errors at the base-station side.
- Received data is transferred via Bluetooth to any nearby device, preferably to the smartphone of users.

V. Performance Evaluation

The proposed system is implemented on a lab-scale tank with a volume of 33×21×6 cm^3 for both fresh and saline water. The variation of total time of transmission with respect to the orientation of the transducers is shown in Fig. 7. The figure also summarizes the results for the variation of total time of transmission with respect to the distance between the transducers in the tank.

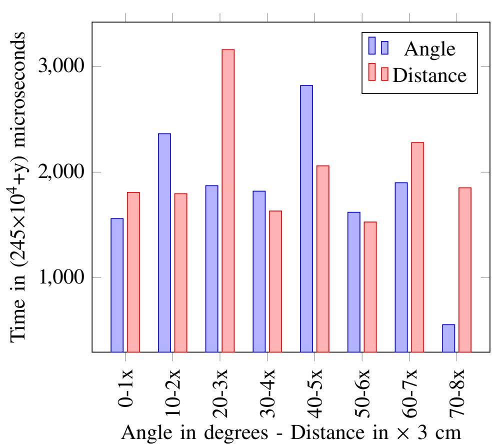


Fig. 7: Plot of Angle and Distance in terms of scale with respect to time taken for transmission.

A ray-tracing operation is performed to explain the deviation of the obtained results from regular behavior. According to the trace, as shown in Fig. 8, it is seen that the angles for which the acoustic reflections from the tank sides converge into the receiver take the least amount of time to complete data transfer, as compared to those rays which require larger reflections to converge onto the receiver. It is to be noted that in an open environment such as a lake or sea, the reflection of acoustic waves may not necessarily occur which may result in partial or total loss of signal. It is seen that for angles 0° and 70°, the time taken for data transmission is lowest, as seen in Fig. 7. This can be attributed to the fact that after multiple reflections, the transmitted acoustic waves reach the receiver node directly, while the others hit the node partially causing signal attenuation. The range of the ultrasonic sensors allows each signal to be decoded, whether it has reached it directly or not. The delay can be attributed to the extra processing needed to efficiently remove errors in the attenuated data.

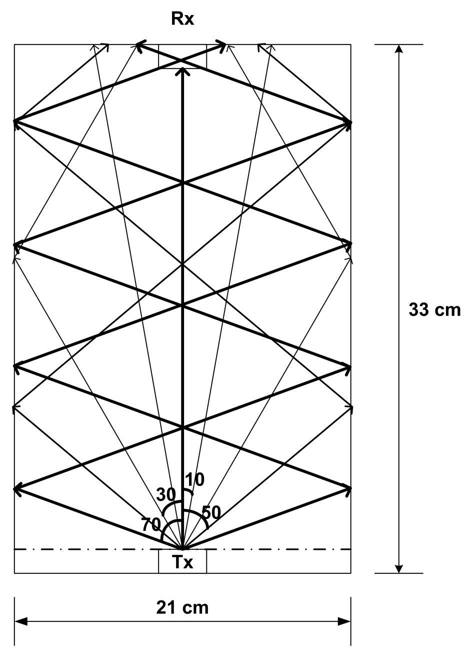


Fig. 8: Ray tracing of the transmitted acoustic waves in the laboratory test-bed for analyzing the effect of transducer orientation on the data transfer time.

The system functionality is tested by checking the functionality of the system as a whole – from sensing data underwater, transmitting it wirelessly through water, and finally receiving the data from the receiving base station onto a smartphone.

TABLE I: Sensor Measurements

Location	Temperature	Altitude
Room (with central cooling on)	23 °C	170 ft
Room (without central cooling on)	28 °C	170 ft
Underwater		
Above water	21 °C	169 ft
Below water	17 °C	165 ft

The sensors are modified for underwater use by placing them securely inside a metallic container and waterproofing the container. The choice of metallic container enables for ease of transfer of underwater temperature behavior, without getting the sensor wet. Table I shows the sensed parameters transmitted through the system and received at a user's smartphone. Despite the dissimilarities between the clock speeds of the devices involved in and with the system, the sensed and transmitted data is received at the smartphone in less than 2 seconds.

A plot for number of bits transmitted and the bit transfer time taken to transfer the data from the underwater sensor node to the land-based base station is shown in Fig. 9. This gives an idea of the system's bit rate, and the effect of latency of the symbols used in encoding schemes, which are in addition to the symbols required for denoting data values.

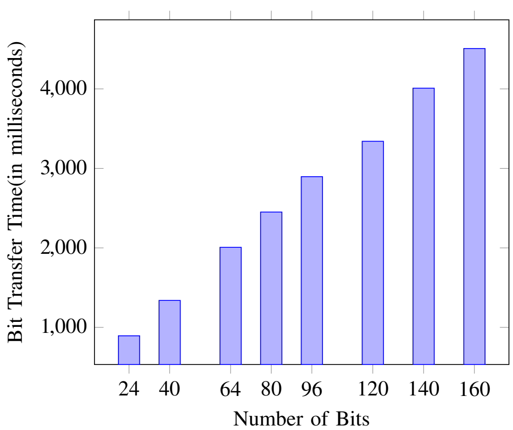


Fig. 9: Plot of number of bits transferred with respect to transfer time

VI. Conclusion

The proposed system that has been put forward is a relatively simple one, with modifications that allow for connections with multiple sensors for sensing data in underwater environments. As the proposed system is very low-cost and portable, with the main focus on ease of deployment, under various underwater conditions, the system is slower owing to the different clock frequencies of the Raspberry Pi and Arduino processors. However, carefully calculated delays have been introduced to prevent desynchronization of the transmitter and the receiver in the middle of a transmission. The Bluetooth interface allows for transmission of sensed data to multiple users via smartphones. This interface can be customized to include long range radio solutions such as GSM.

In the future, we plan on integrating multiple coupled transmitters and receivers of higher frequencies to create an optimization approach for faster, versatile and long range of data transfer.

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