UnRest: Underwater Reliable Acoustic Communication for Multimedia Streaming

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***Abstract*—Due to the low data-rate, high propagation delay, floating node mobility, and high error probability, underwater multimedia communication is still challenging. In this paper, we propose an acoustic-based reliable streaming network for resource-constrained underwater communication. The proposed protocol uses a Null Data Packet (NDP)-based contention and acknowledgment mechanism to reduce control overhead and improve reliability and energy efficiency. With the use of a lightweight Traffic Indication Map (TIM) and video compression technique, our system's efficiency for multimedia transmission is further improved. The proposed schemes provide multimedia communication without compromising on the quality of the data transmitted. We experimentally demonstrate the proposed scheme in a hydrodynamic water-tank facility on our campus. The testbed we have built in this facility is capable of running real-time video streaming. The system's performance, which is evaluated using parameters such as coverage, range, latency, and energy consumption, was found to prove the proposed solution's validity.**

***Index Terms*—Underwater Communication, Multimedia Streaming, Null Data Paket (NDP), Traffic Indication Map (TIM), Lightweight Protocol.**

I. Introduction

Underwater acoustic networks are used for various applications such as video streaming, oceanic exploration, and undersea surveillance [1], [2]. Moreover, there is an ever-growing interest in real-time multimedia operations [3], including picture transfer, video transfer, and video conferencing. However, the development and deployment of underwater acoustic communication are challenging due to low data-rate, venerability to jamming, high-energy requirements, and susceptibility to self-noise.

Acoustic waves are considered as the most reliable form of communication in underwater channels. However, multipath fading caused by reflection and refraction in water due to varying sound speeds at different depths results in inter-symbol interference (ISI) on the receiver side [4]. In the water environment, RF-based communication is not appropriate because of two facts that the radio waves require large antennae and high transmission and less coverage range [5].

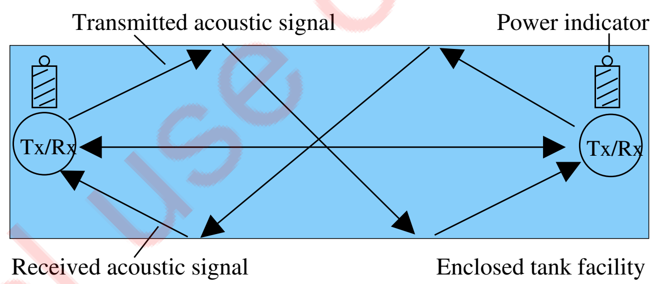

Fig. 1: Underwater communication with battery operated acoustic modems

Acoustic or ultrasonic waves are suitable for achieving data-rate and coverage in underwater. Fig. 1 shows a point-to-point and reflected communication system with the battery-operated acoustic modem. However, improved reception of reflected ultrasound required the proper position of the receiver nodes. On the other hand, streaming requires a considerable bandwidth for smooth traffic flow, in-spite-of underwater channel issues such as substantial propagation delay, limited acoustic channel, and high error probability. Video streaming over acoustic scenarios is an intricate issue.

Due to a lack of proper network infrastructure and control in the existing acoustic communication protocol solutions, achieving reliability and energy efficiency is a challenge. They acquire reliability and traffic scheduling with high network overhead. It is important to have reliable traffic packet transmission and traffic scheduling with low network overhead. Null Data Packet (NDP) and compression techniques can reduce complexity and provision a lightweight communication approach in the considered underwater network. In this work, we propose a reliable acoustic communication for multimedia streaming *UnRest*– for resource-constraint underwater sensor network. In summary, the following are the key contributions of this paper:

- An infrastructure-based reliable streaming network architecture is designed with PHY and MAC layer

enhancements for the extremely resource-constrained acoustic environment.
- An efficient Medium Access Control (MAC) protocol is proposed, which uses NDP as a control packet for contention and acknowledgment purposes for achieving reliability in multimedia streaming.
- video and bitmap compression techniques are used for reducing the overall overhead of the network.
- We develop a low-cost underwater acoustic communication system using off-the-shelf electronics and transducers and performance are measured over the same. The transmission of the system is measured in a hydrodynamic-tank scale testbed.

II. Related Work

We discuss the current works from two perspectives – simulation-based and real-time testbed based. Underwater reliable streaming addresses different research challenges, though the researchers focus on various issues such as energy consumption of the underwater sensor nodes, reliability of the acoustic communication in the form of bandwidth utilization, and storage issues in underwater sensor nodes.

Simulation-based Schemes: Various simulated results address the problem of reliable streaming, storage, and energy in underwater [6], [7], [8], [9], [10], [11]. Han *et al.* in [6] proposed a unique protocol, namely M-FAMA. This protocol is efficient in the presence of collision, as the source node can calculate its neighbor node's transmission delay and schedules. Each sensor node has specific energy levels [12]. For a while, if we only consider neighbor node's transmission delay and tables, then the other aspects, such as energy levels, pose difficulties for the seek-of network lifetime. Towards this, Zenia *et al.* [7] provides a solution for addressing the problem of energy consumption changes by adapting various routing algorithms. Underwater sensors are extremely energy-constrained. Each sensor node needs to use the energy efficiently [13] to provide a significant network lifetime. Challenges exist to address the problem of handshaking between energy consumption and reliability, as it is complicated. Chitre *et al.* [8] considers a scenario where the sensor nodes are interacting in a half-duplex mode of communication, and an acknowledgment is sent to the transmitter, successfully reaching the data to the receiver. They have shown that their proposed Juggling-like Automatic Repeat Request (J-ARQ) is suitable for handling large data packets but provides poor performance for a small one.

Real Testbed-based Schemes: Underwater wireless communication takes place through radio waves, optical waves, or acoustic waves. Introducing multi-hop WSN in underwater is more challenging due to the reflection of waves and the change of direction due to this. Han *et al.* [14] study the complex communication behavior by introducing acoustic as well as the optical waves in underwater networks. Che *et al.* [15] proposed an on-demand routing protocol considering radio frequency propagation in underwater. The simulation results also show that even though node failure, the network performance stays acceptable due to the adoption of

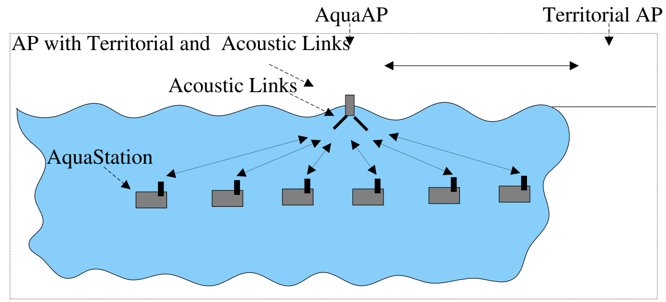

Fig. 2: The proposed network architecture

the AODV protocol. Jang *et al.* [16] developed a testbed using piezo-acoustic waves. It is battery-less and capable of covering up to 10 meters with a data rate of 3 kbps. This system used the back-scatter phenomenon to transmit the acoustic signals, instead of any direct communication between the transmitter and the receiver. The system consumes high power to energize the piezo-acoustic back-scatter node.

Synthesis: Most of the existing solutions in the literature achieve reliability at the cost of enormous energy consumption and overhead. They are deficient in considering the resource-constrained nature of the underwater network. The current testbed-related deployments are not suitable for streaming due to their low data-rate and underwater communication coverage. Provisioning underwater streaming with the required data-rate is still challenging.

III. The Proposed Protocol

The proposed underwater reliable network solution provides multimedia streaming feasibility employing a lightweight Traffic Indication Map (TIM) and NDP-based control packet processing. A controller node (i.e., AquaAP) initiates the sleep scheduling for the stations (i.e., AquStation) to save the energy in the network. Finally, video compression techniques allow reducing network communication further overhead. Fig. 2 shows the proposed infrastructure network architecture. The AP node and stations maintain a contention and transmission time for scalability and energy-saving purposes. The proposed scheme deals with constrained underwater stations in an efficient manner.

A. An Energy-Efficient MAC Protocol

An AquaAP node uses the proposed scheduling algorithm for enabling Tx/Rx of streaming data of the AquaStation. Before the start of Tx/Rx, AquaAP ensures the time synchronization among the nodes with the use of a probe message, information such as time, Contention Duration (start and end time), and TIM, which is sent periodically. The overall time frame is divided into Contention Duration (CD) and Reservation Duration (RD). An AquaStations sends '1' and '0' for data transmission and reception, respectively. Consequently, such frames have null MAC layer overhead. A response of '1' or '0' by the AquaAP during RD indicates a positive or negative acknowledgment, respectively, from the AquaStation, respectively. Traditional back-off-based contention [17]

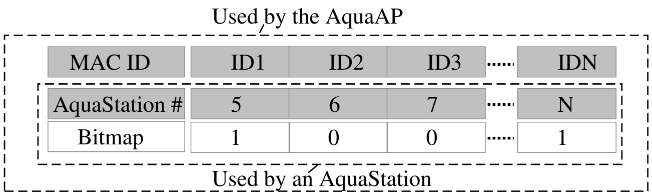

Fig. 3: Bitmap structure for proposed infrastructure network

is used by the stations to win channel access during the contention phase. For data Tx, the proposed scheme follows the steps:

1) The developed acoustic transducer takes inputs as in ASCII values. Therefore, we encode the data in a binary string in the form of their ASCII value.
2) For sending over the proposed network, the multimedia stream is split into multiple packets of the same size. The transmitting node's MAC address is attached at the front and the sequence number at the back. Also, a checksum value is padded at the end of data for error correction.
3) The AquaAP node creates TIM for sending and receiving data to and from the AquaStations, respectively.
4) Then the AquaAP node waits for a '1' during the CD period. This happens before sending the next packet in its buffer.
5) When all the data is finally transmitted to end transmission, the station sends a '0'.

For receiving a frame, the below steps are followed:

1) An AquaStation periodically wakes up and listens to the incoming TIM.
2) For a received TIM, it checks the mapping, it keeps itself in sleep mode if the bitmap is '0'.
3) Otherwise, the station keeps itself in the RD period for receiving the multimedia file.
4) Verify the sender's station number and checksum value that is padded at the end.
5) If the received packet is valid, return '1', else wait for the next packet.
6) If the received packets sequence number is out of bounds, send '0', and quit the current receiving state.

B. Bitmap and Video Compression Techniques

A bitmap map structure for N number of stations is demonstrated in Fig. 3. The value of bitmap is set to'1' for indicating the presence of traffic. The AquaStations are identified as the MAC address. The use of MAC address to identify the devices creates a huge overhead, especially in case of a resource constraint network in Underwater. Therefore, The AquaAP maintains a local station mapping table to map a 10-bit field station against the MAC address of 48-bit.

Before the transmission, each station compresses video with an application layer-based compression technique. We use H264 compression to enable the transfer of multimedia data over the resource-constrained aquatic medium. Further,

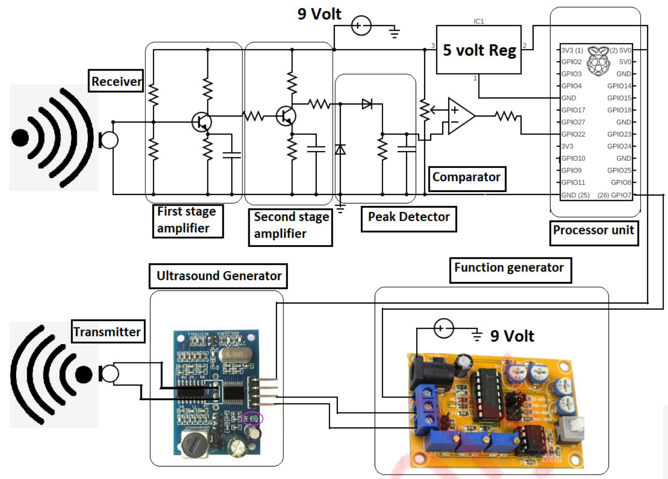

Fig. 4: Circuit diagram of the underwater acoustic transducer node.

the colormap of the captured image or video is changed to Grayscale from the regular RGB format. With this, a typical 100×100 RGB model will have 100×100×3 pixel values. However, the transmission of only 100 × 100 pixel values is required upon conversion to Grayscale, consequently making it more feasible for underwater communication.

IV. Performance Evaluation

We discuss the implementation and evaluation process of the proposed network in a low-cost underwater acoustic communication setup.

Piezo-crystals generate an ultrasonic sound when an alternating electrical signal is applied across that material. The electrical signal causes a vibration into the material, which creates ultrasonic sound [18]. On the other hand, the ultrasonic sound causes an electrical signal when it vibrates the piezo-crystal [19]—the circuit diagram in Fig. 4 shows how the acoustic transmitter and receiver works [20]. An acoustic transducer is latched with a first stage amplifier where the amplifier is an NPN transmitter based voltage divider amplifier. The amplifier's output signal acts as an input of the second stage amplifier, and its output then passes through a peak detector. This two-stage amplifier amplifies the received signal, and the peak detector detects the highest peak after that. If we do not use this peak detector circuit, then also the receiver circuitry works. The only things are if we use a peak detector, op-amp generates fixed minimal pulse-width as it only depends upon the variable reference voltage applied on the non-inverting terminal.

On the other hand, eliminating the peak detector causes a rapid reduction of the pulse-width. The output of the op-amp with the non-inverting reference will generate a shorter pulse-width resulting in good data-rate at the receiver end. The op-amp output then bridged to the GPIO (general purpose input-output) of the processor unit with a resistor to protect it.

TABLE I: Testbed Parameters

Parameter	Value
Testbed area	$10 \times 150\ m^2$
Number testbed nodes	3
Mobility model of the stations	Static
Power	3 Cell Lipo Battery
Channel	Single
Sensor types	Scalar/Vector
Function Generator	IC 8038 based module
Ultrasonic Transmitter	JSN-SRT04 Module
Processor Unit	Raspberry PI 3 model B
Active Components	Diode, transistor(NPN), LED, Battery, Op-Amp(LF356)
Passive Components	Resistor, Capacitor, Switch, Variable Resistor
Underwater types	Shallow
Acoustic Component	Utrasonic Transducer Probe
Voltage Regulator	IC 7805

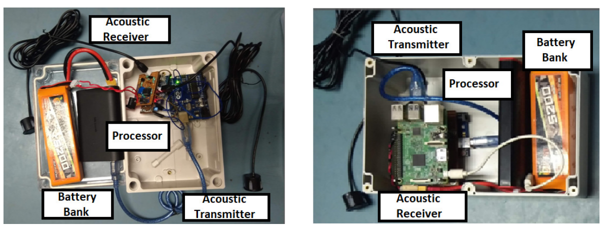

Fig. 5: Developed AquaStation and AquaAP nodes

We use LF 356 op-amp instead of CA 3140; it gives the output correctly with proper tuning of the reference voltage. We use Raspberry Pi 3 model B; it has a quad-core 64-bit ARM Cortex running at 1.2 GHz. The transmitter transmits the acoustic signal after a trigger signal comes from a function generator to the acoustic signal generator module. The function generator is an 8038 IC-based module and is capable of generating a wide frequency band. Though we can use IC 555 based multi-vibrator, getting a wide range of frequencies at the same time instant is tedious. GPIO of the processor unit instructs the function generator based upon the availability of the data; before that, it stays in idle mode and does not transmit any data, so unless and until GPIO gives the instruction ultrasonic sound generator stay silent, resulting less interference. Underwater acoustic communication suffers from interference due to less availability of the bandwidth.

The developed AquaStation and AquaAP devices are shown in Fig. 5. A complete device also contains battery and processing modules along with the transducer components (as discussed above). The developed modules are deployed in a campus-based water tank facility. Fig. 6 shows a setup of the modules with the implemented communication and processing module in the underwater environment.

The proposed infrastructure-based solution uses TIM-based

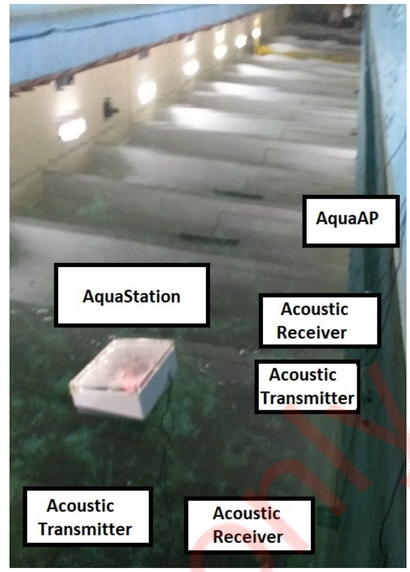

Fig. 6: Underwater acoustic testbed setup in the campus-scale hydrodynamic-tank facility

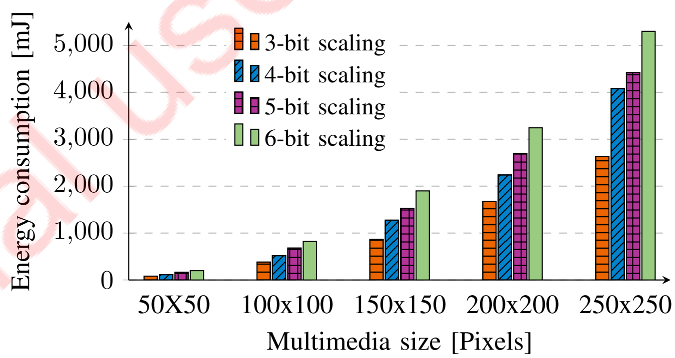

Fig. 7: Energy required for complete delivery of multimedia files

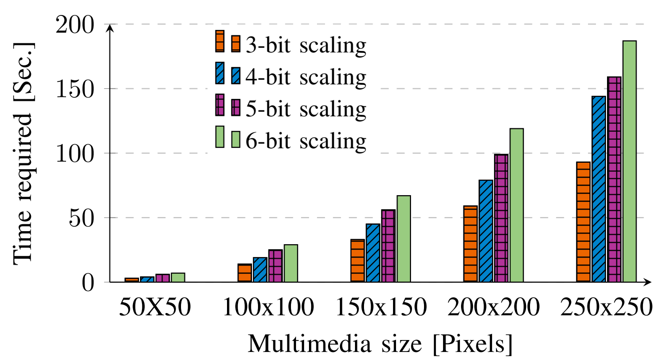

Fig. 8: Time required for complete delivery of multimedia files

beacons to keep the AquaStations in sleep mode. From the TIM, a station can check for its transmission schedules. A bitmap value '0' is to indicate that there is no traffic for itself. In addition to the Tx time, successful file transmis-

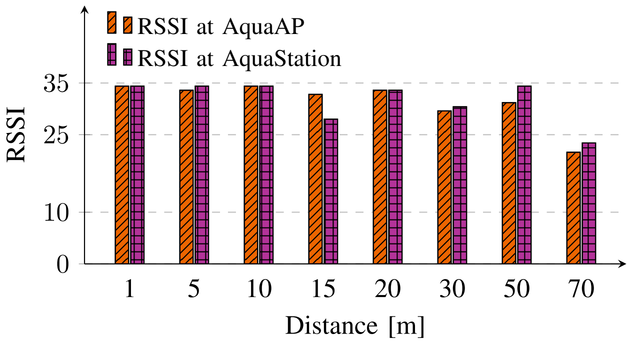

Fig. 9: Received Signal Strength (RSSI) with varying distance for AquaAP and AquaStation

sions require contention, wait, and acknowledgment time. Transceiver may be in Rx, Tx, idle, and sleeping mode for the duration, T_{Rx}, T_{Tx}, T_{Idl} and T_{Slp}, respectively. Multiplying these operations and the respective power consumption gives the total energy consumed by the station, and it can be shown as [21]:

$$E = T_{Rx}P_{Tx} + T_{Tx}P_{Tx} + T_{Idl}P_{Idl} + T_{Slp}P_{Slp} \quad (1)$$

where P_{Tx}, P_{Rx}, P_{Idl}, and P_{Slp} are the required power consumption at transmitting, receiving, Idle mode, and sleep mode, respectively. Energy consumption in Fig. 7 increases when the multimedia image size increases and, on the other hand, multimedia image size in Fig. 8 increases with the increment of time required. Fig. 10 shows that the proposed scheme can save energy significantly. However, with an increasing number of nodes, total energy saving is reduced. This is due to the busyness of the time frame for doing Tx/Rx operation. Note that the Tx/Rx operation takes the highest energy than the idle and sleep mode of stations.

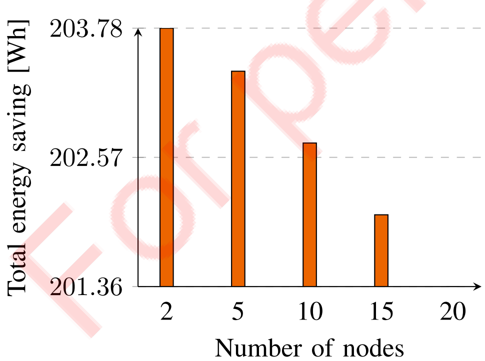

Fig. 10: Total energy saved for a varying number of nodes in the proposed scheme

The implemented video compression technique helps in reducing the network overhead up to a great extent. As per the requirements in the network, the AquaAP has the option to choose a scaling mechanism among 3-6 bit. The probe message carried the selected bit-scaling to the AquaStations, as shown in Fig. 11, the compression techniques reduce the multimedia size as maximum to 30%.

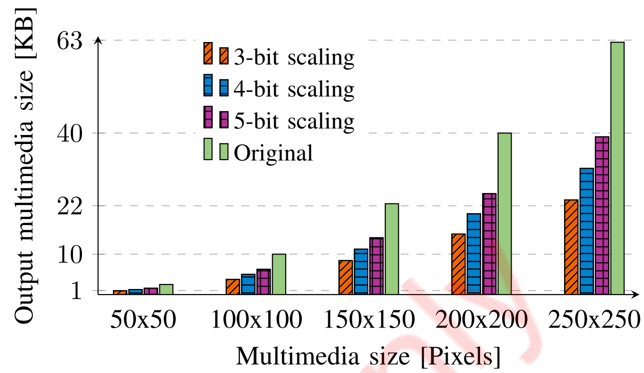

Fig. 11: Various multimedia pixels with respect to various image size for different image compression

We analyze the control packet overhead in the proposed scheme. The proposed protocol reduces total overhead in the network significantly due to NDP, Bitmap, and video compression. In the proposed network, MAC layer overhead is the ratio of all control frames required to be processed for the multimedia frames (of a single file) transmitted. It includes the control information exchanged from contention until the end of Tx. The overhead ratio (Or) can be calculated as:

$$Or = \frac{(\sum_{i=1}^{n} N_{cfs} + \sum_{i=1}^{n} N_{cfr})C_{size}}{\sum_{i=1}^{n}(N_p^d \times P_{size}) + (\sum_{i=1}^{n} N_{cf} + \sum_{i=1}^{n} N_{cf})C_{size}} \quad (2)$$

where C_{size} and P_{size} are the size of a MAC layer control and data frame, respectively. For sending a data frame, N_{cfs} and N_{cfr} numbers of control frames are transmitted by the sender and receiver node, respectively. N_p^d is the number of data frames, and the value of n may not be the same for all cases. The AquaStations in the proposed scheme uses NDP, which has negligible overhead at the MAC layer. Similarly, in the case of a control packet from AquaAP, compressed TIM is processed. Fig. 12 shows the average packet delivery ratio in the proposed scheme as compared to the traditional network.

Finally, we check the reliability of the system in terms of Bit Error Ratio (BER), which is defined as the number bit in errors (N^b_{error}) over the total number of transferred bits (N^b). The BER in the proposed scheme is calculated as:

$$BER = \frac{N^b_{error}}{N^b} \quad (3)$$

Fig. 13 shows the measured BER for AquaAP and AquaStation. In the case of smaller coverage, the proposed scheme shows better BER; however, it reduces gradually for a broader range. The value may not always offer the same trends due to external factors such as waves and wind.

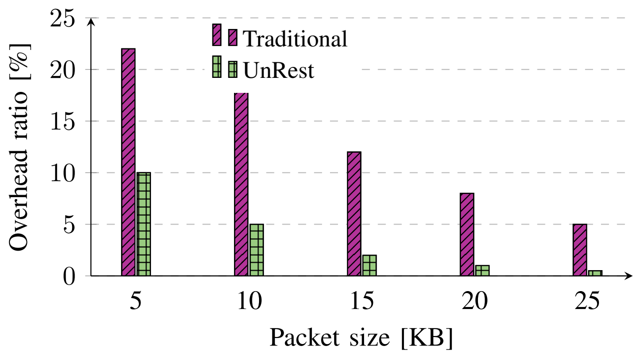

Fig. 12: Total overhead ratio in the proposed scheme as compared to the traditional one.

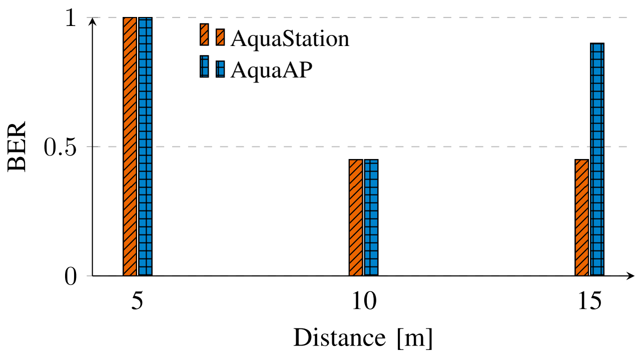

Fig. 13: BER with varying distances for AquaStation and AquaAP

V. Conclusion

This paper presented an infrastructure-based streaming network for improved reliability and energy efficiency. We implemented the proposed protocol in the PHY and MAC layer with off-the-shelf electronics and hardware. The developed modules are tested in the underwater acoustic environment. We analyzed the proposed network by transferring multimedia files of different sizes. Parameters such as RSSI, coverage range, latency, and energy consumption are analyzed over the testbed. After that, total energy saving is measured with the help of different power modes of the stations. The proposed scheme improves energy efficiency, up to a significant amount. The proposed bitmap and video compression techniques reduced the overall overhead and increased the effectiveness of the network. The developed transducer 40KHz can significantly improve data rates and cover range. In the future, we plan to build a theoretical model for the delay, and throughput performance will be developed. Moreover, a large number of sensor nodes in the testbed will be deployed to see the utilization of the proposed system further.

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