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Optical-acoustic hybrid network toward real-time video streaming for mobile underwater sensors

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ABSTRACT

Underwater sensor networking is generally regarded as an emerging technology in conducting oceanic exploration and research in an automated and effective manner. As underwater operations become more sophisticated and Autonomous Underwater Vehicles (AUVs) become more advanced, there is an increasing demand for real-time video streaming from AUVs to remotely steer them and to probe the environment. However, real-time video streaming requires high bandwidth. To help overcome this obstacle, we propose a hybrid solution that combines acoustic and optical communications. In our hybrid solution, optics provide good quality real-time video streaming. Acoustic maintains a "thin" channel for the network topology and transmission control. The acoustic channel is also used for still frame video delivery when the optical channel fails. In particular, we enable optical communications by acoustic-assisted alignment and use acoustic communications as a backup when the optical signal is interrupted. The main contribution of this research is to enable reliable, real-time video streaming without underwater optical cables. Another important contribution is the smooth transition between the acoustic and optical video delivery mode, by leveraging image processing algorithms to compress the key frames before transmitting them on the acoustic channel.

1. Introduction

Although the ocean covers more than 70% of the Earth surface, a vast majority of it, approximately 95%, remains unexplored according to the National Oceanic and Atmospheric Administration in the United States. Since the ocean can be thousands of meters deep and is difficult for human divers to explore, researchers have turned to underwater sensor networks to gather information in an efficient and automated manner. While traditional sensors provide tabular data (e.g., salinity, temperature, and pressure), recently the need for still images and even real-time video streaming has emerged in the research community [1]. Autonomous Underwater Vehicles (AUVs) have the ability to meet the video demands posed by applications such as ocean bottom monitoring, oil spill detection, and mineral exploration. If real-time video streaming could be provided from AUVs to support surface ships, these explorations could be undertaken more efficiently and interactively.

Traditional underwater modems have used acoustic communications to transmit data through the water using acoustic waves. Acoustic waves travel underwater over distances of several kilometers and do not require direct line-of-sight between the senders and receivers. However, acoustic communications have disadvantages; namely, the long propagation delay of sound waves compared with electromagnetic or light waves, limited bandwidth and the ease of detection and eavesdropping by the enemy (a critical issue in tactical operations).

Recently, optical communications have received significant attention [2–6]. Farr et al. [5] presented insightful optical communication scenarios and demonstrated video monitoring up to 15 m. Doniec et al. developed AquaOptical II, a bidirectional underwater optical communication system capable of transmitting a few Mbps with the effective range over 15 m. They further elaborated a previ-

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ous system that primarily focused on video streaming and successfully transmitted video over 25 m range [3]. Generally, optical communications have a higher bandwidth capacity and consume significantly less energy than acoustics. Moreover, the speed of light through water is faster than the speed of sound, which results in a lower latency in optical communications. However, light waves have a larger attenuation. At most, optical modems can transmit at distances of approximately 100 m [5] in excellent water conditions. Due to the nature of optical communications, a clear line-of-sight is required between the sender and the intended receiver, although there are efforts to overcome this obstacle [7–9]. This requires the optical modems to be aligned in order to provide reliable data transmission. It has been reported that optical modems can have a field of view of up to 120°; however, the transmission distance decreases as the transmission angle increases.

In this article, we propose a hybrid solution for real-time video streaming from sensors to a monitoring center (e.g., a surface ship). The primary objective is to realize real-time underwater video streaming in both acoustic and optical modes (where the acoustic mode is the backup mode). In case of optical channel failure, the acoustic channel can take over the support of real-time streaming. However, acoustic channel may not quite adequate to sustain real-time streaming due to its low bandwidth and long propagation delay. To enable real-time streaming in this bandwidth-limited environment, underwater images should be significantly compressed.

In this article, we wanted to design a bridging technology that can provide a reasonable real-time video streaming service via optics with acoustic-assisted alignment and acoustic thin channel, which affords transferring of a series of compressed images. We explored several image processing methods and showed the feasibility by implementing a prototype of an acoustic image transferring system. Our proposed hybrid solution is a viable in underwater environment. We have significantly extended the original paper [10] and concretely make the following contributions as follows:

- We rewrite and reorganized the whole manuscript of Han et al. [10] to make it comprehensible to readers outside underwater research community.
- We significantly extend application scenarios to make the technical content accessible to the wider spectrum of readers (Section 2).
- We added our hybrid solution details and its design space (Section 3).

2. Scenarios for the hybrid solution

Deep sea bottom video exploration. One important reason for using the optical channel underwater is to exploit its high bandwidth (up to several Mbps) for interactive video. The classic application of this is the deployment of an underwater robot equipped with a video camera at great depths from a surface vessel for exploratory or recovery operations. While at low depths, the robot can be guided via a cable that carries the data and possibly also power; at great depths, the guiding cable is not practical, because it may become entangled and cannot be untangled by human divers. A proposed solution is to drop a “base station” to the bottom from the surface ship. The base station is stationary and is connected by a cable to the surface ship. Multiple robots can roam from the base station in different directions. These robots carry video cameras that are monitored by operators on the ship and are used to remotely guide the robots. If the robots are more than 50 m from the base station, they will not be able to communicate directly. One interesting scenario is the autonomous deployment of a mesh network that supports one or more video streams from the robots to the base station and ship. The central concept is to create an optical tree from the robots to the base station. The data and commands in the reverse direction (base station to robot) are carried via acoustic channels. The short distance, e.g., <200 m, guarantees low delays (<200 ms) even for acoustic propagation, and it does not compromise real-time interactivity.

Underwater scouting team. Another application of the hybrid concept is the establishment of high-speed video connections among a team of mini-submarines participating in a scouting expedition. In this scenario, each submarine sends its video to all other submarines. The acoustic modems are used to position the submarines and to align the optical modems. In order to establish an optical multi-hop mesh network, each submarine carries two or more optical transmitters and several optical receivers, so that a mesh can be maintained at all times. Many known protocol components are integrated in this application: first, the acoustic positioning; second, the maintenance of a fully connected acoustic mesh among submarines; third, the alignment of the optical transmitters and receivers, and the establishment of a connected multihop optical mesh; and finally, the support of many-to-many cast video streaming.

Mixed pure and murky environments. Optical transmissions can be used only in clear waters. In murky water, we must use acoustic transmissions instead. The data rate must be dramatically scaled down from Mbps to a few hundreds of bps, i.e., from motion video to still frames. In underwater operations near the surface or in shallow waters, the path conditions may change continuously and intermittently (from a clear path to a murky path, and vice versa). This is where the hybrid solution is essential. We switch back and forth between the optic and acoustic channels. If the switchover frequency is excessive, it may be more convenient to use the two paths (optical and acoustic) in parallel with a combination of still frame and video traffic. Similar challenges have been faced in tactical scenarios that combine satellite links and ground path backup links to connect mobile ground assets.

Covert AUV to Ship communications. Consider that a ship deploys several AUVs in a 1000 m radius to detect possible attackers or to scout the terrain with cameras. Enemy submarines may be listening and the operation must be undertaken covertly. While the presence and position of the ship is known, the AUVs should not be detected nor intercepted by submarines when they are transmitting data. A possible strategy could work as follows. The ship trails an underwater acoustic/optical mini base station. The base station periodically sends an acoustic beacon similar to sonar regardless whether the AUVs are present or not. This beacon is encoded with a prearranged secret key and carries data. When a friendly AUV in the area recognizes the ping, it uses this beacon signal to approach the base station and to establish alignment. To extend the probing range, a two hop optical mesh can be established under the base station instructions because the AUVs can move around and direct their transmission beams to each other. Note that this optical mesh network is established and maintained in a completely covert manner; that is, the optical links cannot be detected by the enemy. The ping is repeated periodically and cannot be distinguished from conventional sonar pings. However, covert operations pose a restriction of no acoustic transmissions from the AUVs.

3. The hybrid solution

Network architecture. Our solution provides real-time video monitoring between AUVs and the base station. Nodes are equipped with both acoustic and optical modems (see Fig. 1) to exploit the

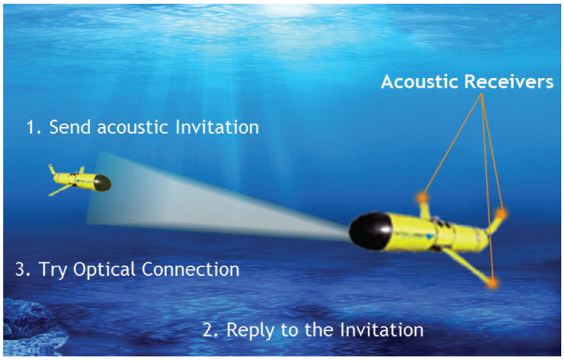


Fig. 1. Optical/Acoustic alignment between AUVs.

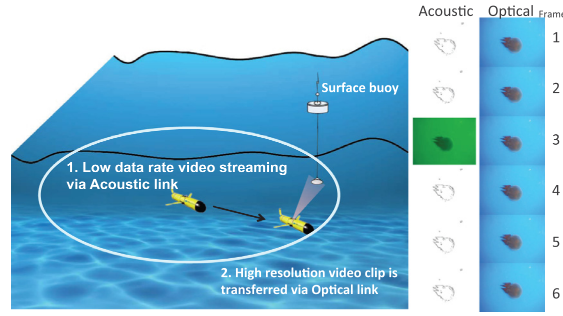


Fig. 2. Real-time video streaming via Acoustic/Optical.

benefits of these media, thus providing connectivity and bandwidth requirements. Also, additional acoustic receivers are included to improve the transmission redundancy as well as to provide additional data for localizing another transmitter and aligning the optical modems. During the alignment process, we continue to send data through the acoustic communications until the optical modems are aligned properly. Once the optical modems are aligned, high resolution videos are sent using the optical communication to exploit the increased bandwidth. The acoustic communication is continued used for exchanging control signals (e.g., topology control and acknowledgements), and sending still video frames (e.g., 3–5 frames per second) if optical links are not available. Naturally, the system should withstand mobility, e.g., submarines, drifters, and base station all drift with the currents. A hybrid acousto-optic mesh can be dynamically configured and can maintain high-speed optical links between its nodes. The control is completely supported using acoustic links, and the high-speed data travels through the optical links.

Optical alignment occurs as follows. The sending node sends a request to the receiving node over the acoustic medium. The receiving node responds to the request using the acoustic transmitter as well, and both sender and receiver use time-difference-of-arrival (TDoA) technique to localize each other (i.e., trilateration), move toward each other, and to reach optical alignment. Readers might want to review of Han et al. [8] for more details. Once the nodes can communicate over the optical modem and are within range of each other, they begin to use the optical medium for data transmissions. In the event that multiple sources are transmitting, the acoustic beacon is encoded with a unique source identifier to align the potential receiving optical sensor appropriately.

Image and video compression. In our scenarios, optical links are used to provide high quality streaming. If optical links are not available, acoustic links are alternatively used to provide low quality video streaming or still frame video delivery. When thin acoustic links are used, underwater images should be pre-processed and compressed properly. In the pre-processing stage, we can lower the bandwidth demand by reducing the resolution of an image, and changing color representation formats, e.g., from RGB to grayscale. In the compression stage, we can employ various image compression algorithms such as chroma subsampling and transform coding (e.g., Discrete Cosine Transform (DCT) in JPEG and H.261). Furthermore, we can reduce temporal redundancy in a series of images in a video by adopting inter-picture motion prediction that is commonly used in the standardized video compression methods such as H.261. In this article, our goal is to perform a feasibility study of real-time streaming in the hybrid scenario. Thus, we focus on the pre-processing step of image compression, and experimentally demonstrate the feasibility of real-time still frame video delivery.

Network protocol design. Our hybrid solution should also consider various layers in the communication stack, including Medium Access Control (MAC), routing, and transport protocols. In our scenarios, acoustic channels are mainly used for controlling optical links and nodal mobility for optical alignment. We use multiple heterogeneous communication interfaces with different characteristics and control mobility of nodes for topology control. This means that there is a considerable interdependence among layers in the communication stack (i.e., MAC and routing), thus requiring a cross-layer design of network protocols [11]. Furthermore, the system requires the transport layer that handles network congestion and delivers video quality in the presence of packet loss; thus, existing transport protocols such as Reliable Transport Protocol (RTP) and error control methods such as erasure codes and network codes could be adapted to this environment. Since this article is to show the feasibility of the hybrid solution, we leave detailed protocol design as a future work.

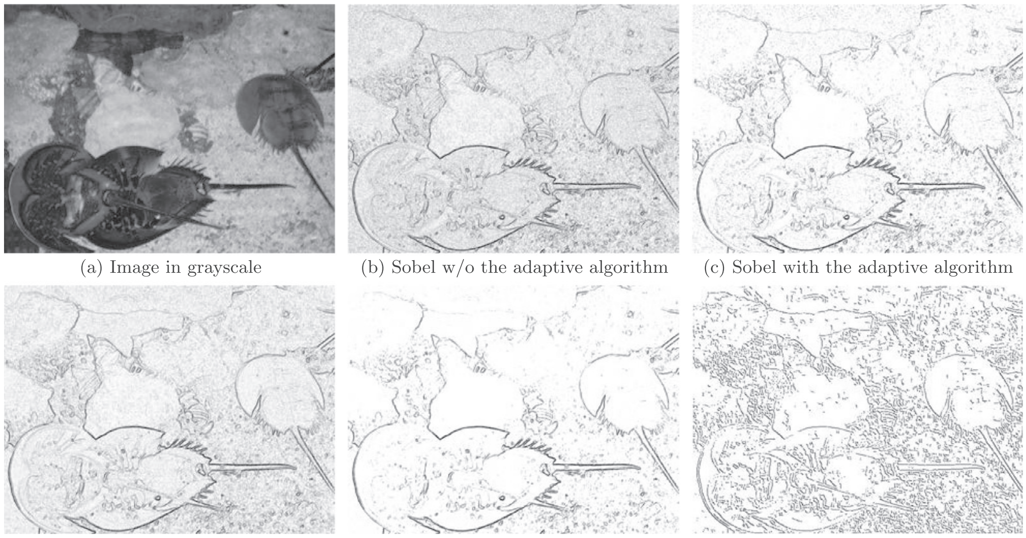
4. Image processing and video compression for underwater scenarios

We consider various image and video processing techniques that can effectively reduce the bandwidth requirement in our scenarios where low resolution images are periodically delivered via acoustic links (i.e., still frame video delivery) and high definition video is transmitted via the optical links. In particular, we explore how to enable still frame video delivery over the acoustic links, which requires significant reduction of data rates. We propose to use standard lossy compression techniques along with image processing methods that consider underwater specific application and environment characteristics (i.e., object tracking and underwater color space). Fig. 2 shows an example of processed frames.

4.1. Simple image processing techniques

The blue and green colors travel the longest in the water because they have the shortest wavelengths. Therefore, the images taken in the water are always dominated by blue-green colors. Moreover, red, orange, and yellow colors disappear in relatively shallow water depths due to their wavelength [12]. Therefore, underwater image enhancing techniques primarily focus on the skewed color compensation caused by light scattering and color changes [13]. Accordingly, we can use a variant of this technique that we call “greenscaling” to set the green values of each pixel to the new value and to set the other red and blue values to zero; this results in an image with a green hue and reduces average image size to about 30% of original JPEG image, but the prominent features of the image can be distinguished.

Following this, we apply a primitive edge detection algorithm that emphasizes the sharp differences in the RGB values through horizontally traversing the image, which is useful for object tracking and recognition. Using the grayscale image as a starting point,



(a) Image in grayscale (b) Sobel w/o the adaptive algorithm (c) Sobel with the adaptive algorithm (d) Gaussian and Sobel w/o the adaptive algorithm (e) Gaussian and Sobel with the adaptive algorithm (f) Canny edge detection

Fig. 3. Image processing techniques.

we used the mathematical differences in the average RGB values to determine where the edges were in the image. This simple algorithm can hugely reduce the average size, resulting to the size of only 17% of the original JPEG size. However, three out of the five resulting images produced pixels that were too lightly colored to detect, which caused the entire image to appear to be nearly white. To alleviate this problem, existing edge detection algorithms, which detect a smaller number of edges with a higher resulting contrast, are further discussed in the following section.

4.2. Sobel image processing

The Sobel algorithm [14] is a gradient algorithm that looks for the maximum and minimum of the first derivative of the values in the image. The result of the Sobel algorithm is presented in Fig. 3(b). In addition to the original Sobel algorithm, we propose the adaptive cutoff method. In this method, we discard the small gradients and set those pixels to white in order to decrease the file size and to emphasize the major edges. For the determinations, it is necessary to set appropriate threshold values. If the threshold were set too low, some images would be white or almost entirely white, and would be useless. However, if the threshold were too high, then other images would have very few pixels removed and have a significantly larger file size than necessary. To set an adequate threshold value using the proposed adaptive cutoff method, we began with a numerical threshold for the RGB value of 250, which already eliminated a small portion of the grayscale spectrum. Then, we evaluated the percentage of pixels that represented the edges compared with all pixels in the image. If the percentage of pixels representing edges was greater than 25% (a variable determined by the image type), then we decreased the threshold by 10 (granularity of adaptation) and reevaluated the percentage until less than 25% of the pixels represented edges. In this way, lighter edges that were not essential to understanding what the image represented were removed. The result can be seen in Fig. 3(c).

4.3. Gaussian blurring

The objective of the blurring is to remove noise from the image through calculating the weighted average of the current pixel as well as the neighboring pixels, and then replacing the current pixel with the result [15]. This removes the sudden color changes that are generally isolated and that are not essential to understanding the image using the average to lessen the effects of outliers. Following Gaussian blurring, we applied the Sobel algorithm as described above. As presented in Fig. 3(d), this process resulted in a file size reduction to 19% of the original JPEG size without sacrificing the image quality. As seen in Fig. 3(e), we also implemented the adaptive cutoff method following the Gaussian blurring and Sobel algorithm to further reduce the file size. With this, we were able to reduce the file size to an average of 15% of the original JPEG size. In addition, this method produced images that contained the essential edges for almost all test cases.

4.4. Canny edge detection

We also examined the Canny edge detection [16]. We used the degree measure of the direction angle found and round it to the nearest 45-degree increment. The next step was to determine if a pixel was part of an image. We examined the two neighboring pixels on either side of the current pixel in the direction that we found in the previous step. If the current pixel's magnitude of the gradient was larger than that of both neighboring pixels, then we considered it to be an edge and marked the pixel as black, or (0,0,0) in the RGB space. Otherwise, we determined that it was not an edge, and we marked it as white, or (255,255,255) in the RGB space. It is possible that with further threshold and/or algorithm adjustments the outlier issue would be resolved, because there are many extra edges in the image that can be seen in Fig. 3(f).

5. Evaluation

To evaluate our solution, we performed an experiment with a system that takes pictures, applies image processing to them, and then transmits them between computers using acoustic communication.

5.1. Implementation details

To evaluate the feasibility of our approach, we performed a data transfer experiment between two AquaSeNT acoustic modems [17] as depicted in Fig. 4. The application allowed for a set number of JPEG images to be transmitted over acoustic communications in a small water tank with a base of approximately 2 feet by 1 foot

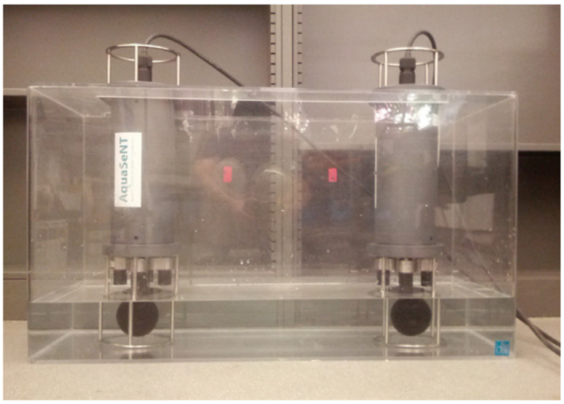


Fig. 4. AquaSeNT OFDM modems.

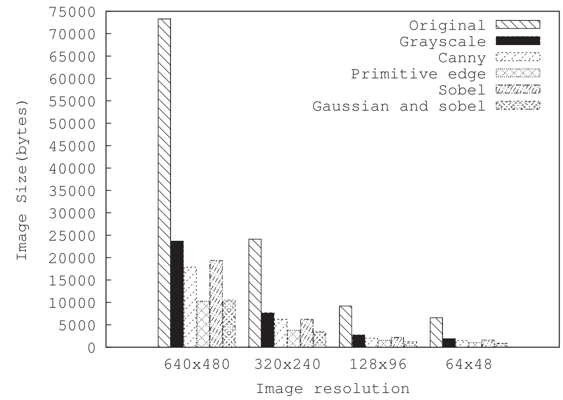


Fig. 5. Average file sizes for different image resolutions.

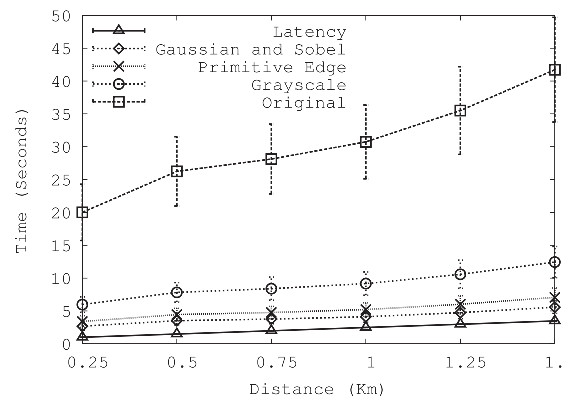


Fig. 6. Average time interval for video frame delivery (128×96).

in size. The acoustic modem had a bandwidth of 14–20 kHz and a data rate of 3200 bps. This provided an upper limit on the transmission rate and caused difficulties in transferring large images with the bounded latency required for real-time video streaming.

The framework does not use conventional network protocols because the modem does not include such support. The only features supported are the file size verification and partial acknowledgment transmissions. In order to perform the transmissions, the image files were resized to be sufficiently small to transmit over the acoustic medium. Before each transmission, both the sending and receiving buffers were flushed before 608 *bytes* were transmitted at a time. The program inserts delays into the transmission time to ensure that the receiver has sufficient time to receive and process the signals. The images were captured using a webcam with the libav *avconv* package. The pictures were displayed upon successful transmission of the file to the receiving program using a GNU *display* utility.

5.2. Data rate and latency

The above system was estimated to have a transmission rate of 83.29 bytes per second, or 12.294 seconds per kilobyte (s/kB), when a baud rate of 9600 bps was used. Although the transmission rate could increase to 400 bytes per second according to the specifications [17], we conducted the test in a small water tank so that the modems are inevitably affected by severe multipath fading due to the tank wall reflections. Using this information combined with the size of the typical image file, we can determine what effects the image processing would have on the transmission time and, consequently, the ability to transmit real-time video.

For our purposes, we ran our primary algorithms on four image sizes of 64×48, 128×96, 320×240, and 640×480 pixels; the results are presented in Fig. 5. Because the file size varied depending on the content of the original image, some trends were detected that could guide the choice of image processing method. Because the bandwidth of an acoustic modem is very constrained, it is not feasible to send full-size images obtained using ordinary digital cameras; however, sending an unprocessed image may take up to several hours in the worst case scenario. Our proposed Gaussian and Sobel method reduced the transmission time to twenty minutes or less. This is a significant improvement, albeit it remains inadequate for real-time streaming.

We also analyzed the estimated time required to transmit the images over the acoustic medium. In the 640×480 case, it required 15 min to transmit the JPEG file without any processing from the sender to the receiver. Converting the image to grayscale reduced the latency to approximately 5 min, while Sobel reduced the latency to 3.5 min and adding Gaussian blurring yielded an approximately 2 min latency. Again, while this is a significant improvement, it does not support real-time video transmission.

However, we note that with the image sizes of 128×96 and 64×48, we were able to transmit the unprocessed images with an average of 113 s and 81 s, respectively. With the Gaussian and Sobel combination, an image could be transmitted every 16 s at a resolution of 128×96, and every 10 s at a resolution of 64×48. While these images were not real-time video grade, this rate allows the user to interact in real time with the environment and, for instance, determine what the sensors are detecting. It is possible that changes in the baud rate, distance between the sender and receiver, or acoustic modem model might improve the latency of the data transmissions. For example, one possible method to obtain more frames per second is to use multiple antennas in a MIMO (Multi-Input Multi-Output) that can achieve higher transmission rates. Another method is to use inter-frame prediction-based video compression techniques such as $H.264$, $MPEG-2$, *Ogg*, and *Theora*. Presumably, through only transmitting the difference between the continuous images, we could increase the frame rate. This technique would work well underwater given the slow speed of the AUV and the small changes in the scene from frame to frame.

In order to further evaluate our proposed solution with existing solutions, we also performed simulations and measured the elapsed time intervals required to deliver an image frame from a variable distance via QualNet. We set the data rate to 9600 bps and the packet size to 512 bytes; we also selected the image resolution of 128×96 pixels. To minimize the latency increments according to the increased data sizes, we used the recently proposed M-FAMA protocol [18]. M-FAMA supports packet pipelining in the same link with significant throughput improvements through mitigating the problem that results from the long propagation delays of the acoustics. We measured the network latency and demonstrated the time required to deliver one packet from the AUV to the destination as a function of distance. As depicted in Fig. 6, the delivery times for all solutions were proportional to the distance, as expected. In order to show minimum boundary, we plotted network latency which is measured one-way trip time duration from the source sending a packet to the destination receiving it. The Gaussian and Sobel algorithms outperformed other widely used solutions. It is noteworthy that the original images that were more than 250 m away required 20 s, while our proposed Gaussian and Sobel method reduced this time to 2.7 s.

6. Conclusions and future work

In this article, we investigated a hybrid solution that involves both acoustic and optical communications as a step toward real-time video transmission for underwater mobile sensor networks. The optical channel is “fragile” and intermittent, because it can easily break up due to modem misalignment, mobility, and water impurity. In the proposed hybrid system, the acoustic channel is alternatively used for exchanging control messages and providing low-rate real-time video streaming. In order to achieve this, the video signal must be compressed to such a level that the acoustic channel can deliver the video (or images) at a rate that enables real-time streaming. We also examined the use of image processing as a compression technique to reduce image file sizes by considering application and environmental characteristics. We evaluated the feasibility of several image processing methods, and we demonstrated that the proposed hybrid solution is a viable technique that makes a significant impact on the latency and bandwidth. We further proposed adaptive Gaussian and Sobel algorithm that reduces the images to 15% of the original JPEG file size, and we finally estimated the latency of the data transfer.

There are several directions for future work. First of all, we can optimize the proposed methods to conform to the computational time and power constraints of typical underwater networking devices. For example, we can decrease the file size and computational time through analyzing the critical points of the algorithm to eliminate bottlenecks and to parallelize portions of the algorithm. Second, work needs to be undertaken regarding the extension of these techniques to video coding such as *H.264* and *Theora* (as opposed to JPEG files), as well as the evaluation of additional image processing techniques. Third, our hybrid solution requires a cross-layer design of network protocols such as MAC, routing, and transport layers to further squeeze highly limited thin bandwidth and meet the QoS goals [19,20]. We can design an efficient protocol for the hybrid solution by fully exploring various design alternatives.

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