Ad Hoc Networks 83 (2019) 1–7

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

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

Seongwon Han[a], Youngtae Noh[b,1,*], Uichin Lee[c,2,*], Mario Gerla[d]

[a] Samsung Research, Seoul, South Korea
[b] Inha University, Incheon, South Korea
[c] KAIST, Daejeon, South Korea
[d] UCLA, California, USA

ARTICLE INFO

*Article history:*
Received 19 February 2018
Revised 4 June 2018
Accepted 29 August 2018
Available online 5 September 2018

*Keywords:*
Underwater wireless networks
Acoustic & optical communications

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-

* Corresponding authors.
*E-mail addresses:* ytnoh@inha.ac.kr, ytnoh@cs.ucla.edu (Y. Noh), uclee@kaist.ac.kr (U. Lee).

[1] This work was partly supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2016R1C1B2011415).

[2] This work was also supported in part by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIT) (no. R7124-16-0004, Development of Intelligent Interaction Technology Based on Context Awareness and Human Intention Understanding).

https://doi.org/10.1016/j.adhoc.2018.08.020
1570-8705/© 2018 Published by Elsevier B.V.

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