Smart Transmitters and Receivers for Underwater Free-Space Optical Communication – A Review

Navneet Kaur Bajwa[1] and Vishal Sharma[2]
[1,2]Department of Electronics & Comm. Engineering,
Shaheed Bhagat Singh State Technical Campus, Ferozepur–152004, Punjab, India
E-mail: [1]navvbajwa@gmail.com, [2]er_vishusharma@yahoo.com

***Abstract*—New communication systems and networking protocols are required to manage the increasing number of unmanned vehicles and devices being positioned underwater. The present underwater communication systems comprise of traditional point to point links and have rigid pointing and tracking needs. Underwater free space optical communication is determined to augment the short range, mobile and multi-user communication in future underwater systems. In this paper, we review compact smart transmitters and receivers for underwater free space optical communication. The transmitters transmit highly directional beams and have separately addressable LEDs for electronic switched beam-steering and have co-positioned receivers to estimate the water quality by collecting back scattered light. The receivers have sectioned wide range of view and are able to evaluate the angle of arrival of signals. They collaborate together to form a promising technology for modern networking schemes in the stream of unmanned devices underwater.**

Keywords: Free Space Optical, Underwater Communication, Autonomous Underwater Device, Unmanned Underwater Device, Angle Diversity

I. Introduction

Underwater communication is of great importance for military, industry and scientific fields. The devices and equipments deployed underwater require data rates in the range of few to tens of Mbps. A wireless link is desirable in many situations although fiber optic or copper cablings are used for bulky and immobile devices. Free space optical communication is considered as a promising alternative as it overcomes low data rates, high latencies and multipath issues offered by prevailing acoustic communication [27],[29]. FSO system has also provided a promising solution to the "last mile problem" [26].

In recent years, free space optical communication has glimpsed and increase in interest from advancements in blue-green sources and detectors [1], [2], [3], [4], [5], since blue-green wavelengths of electromagnetic spectrum are not much weakened underwater. Both Laser-based systems and LED-based systems are employed underwater by taking in account their various advantages. While Laser-based systems offer extended ranges of communication, high data rates of information transfer and low latencies [7], LED-based systems are employed for their low cost, low power and compactness. Certain internal and external parameters of FSO communication systems have to be considered as the environmental changes are inevitable during the designing of various components [28].

Underwater communication, especially on mobile platforms is considered to form point to point links and require definite pointing and tracking. Systems that use collimated laser links and have dedicated gimbal systems generally employ such links. There are systems that use very large aperture (approximately 20 inch) photomultiplier tubes (PMTs) that enlarge the receiver field of view (FOV) [2]. There are a few recent studies exploring possible techniques and systems for underwater optical communication [25].

Large area PMTs offer a disadvantage of being expensive and bulky. Hence, compact systems are desired which do not have much volume budget or energy budget for sophisticated pointing and tracking. Smart antennas are used in traditional RF wireless systems, which make them capable of signal processing to provide angle of arrival information and broadcast beam-forming. In indoor optical wireless communication, several antennas with spatial diversity and angular diversity are employed for non-line-of-sight communications, ambient light rejection, electronic tracking and pointing, corresponding localization, and multi-hop networking. Energy efficiency of the modern networks is also very much required [30]. It is obvious to consider the benefits of such techniques being extended to the underwater environment [1].

This paper is divided into three sections. Introductory concepts and advantages of underwater free space optical communication are discussed in section 1 followed by section 2, in which we analyse an optical front-end for underwater free-space optical communication. The front end introduces the notion of smart receivers and transmitters. The smart transmitters are able to estimate and evaluate the water quality from its backscattered light collected by its co-located receiver. The smart receivers have segmented wide FOV and are able to detect angle of arrival of signals in order to adapt and align FOV towards the wanted signal. Finally, section 3 represents the conclusion.

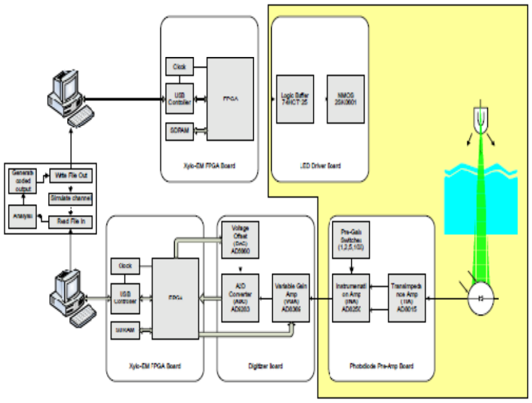

Fig. 1 A General Front end Design of Transmitter and Receiver [21].

II. Benefits, Background and Description of Smart Optical Systems

A. *Benefits of Smart Optical Systems for UUVs*

Focus of this review paper is the concept of smart transmitters and receivers that allow technology for coordinated sensing and communicating.

As a reference, examine smart optical transmitters and receivers that can evaluate and estimate the obvious optical effects of water, transmit a beam of light in a fixed direction, and find out the direction of the light beam and peculiarity of the light beam that is being received. Gain and power of transmission of receiver during detection and acquisition of another platform can be changed by evaluating water quality.

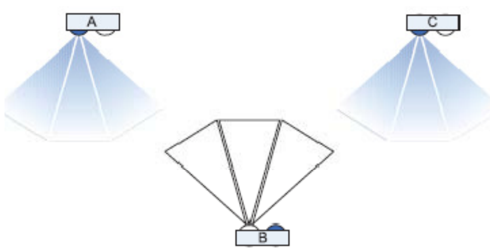

Fig. 2 Multi user Reception System Using three Nodes – A,B and C; A and C are Transmitting Nodes while B is Receiving Node [1].

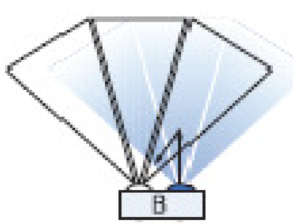

Fig. 3 Optical Backscatter Estimation and Evaluation at the Node B from its co Located Transmitter [1]

Knowledge of device orientation, its identity, and its relative angle can be utilized to localize and evaluate the relative positions of devices. Concise illustrations of possible benefits are listed in sub-sections below:

1) *Non-mechanical Pointing and Tracking on a Moving Underwater Device*

An optical transmitter or receiver mounted on a device can go in and out of sighting with another stationary or fixed platform. This process depends upon the state of sea and commands of the underwater device. An optical front end capable of varying its effective FOV, detecting angle of arrival at its receiver and electronically direct its output beam, can possibly maintain a communications link in such an environment. Furthermore, one can use signal diversity expertise to improve and enhance signal reliability [1].

2) *Maintaining Link with a Stationary Node as an Underwater Device Drives by*

It is quite difficult for underwater devices to maintain a precise relative position. The ability to interrogate and obtain information from a stationary sensor node as a device drives by can add significant operational capability. Thus, a quasi-omni-directional receiver is valued which is able to continually adapt its FOV and optical power.

3) *Providing Sensory Information to Underwater Devices*

In a swarm environment, localization information can be collected from angle of arrival information as different nodes communicate with one other. This information can be transmitted to the device to augment its other sensory data for navigation and collision abstention purposes. A smart optical front-end can also contribute to other sensory information such as water quality measurements obtained from the communications link [1].

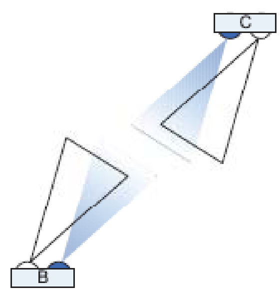

Fig. 4 Electronic Switched Pointing and Tracking, B can Sense the Direction of C and point [1]

4) *Duplex Multi-user System*

Each transceiver is composed of a smart receiver and a smart transmitter which allow synchronous reception from two non co-located transmitters. Since each transmitter is CDMA coded, the receiver at one location is also capable of associating data streams of another smart receiver with different location by its corresponding directions [1]. Whenever two smart receivers lie on the same line, the CDMA code still permits for dividing the two transmit streams at the receiver on the first smart receiver.

In a mesh network scenario, as illustrated in Fig. 2, node A and node C are not in the range of each other. Supposing localization data from angle of arrival is kept at each node, node B can broadcast messages between the node A and the node C through a hop network. If B is a mobile node, it can be placed to adequately expand the optical communication range between A and C when needed [1].

5) *Optical Backscatter Estimation and Evaluation to Assess Water Quality*

The bidirectional system delivers a way for a receiver to observe optical backscattering while its co-located transmitter is active. Background noise and un-modulated light are isolated based on the modulated schemes used. Using volume scattering information, an estimation of the attenuation coefficient can be made found on the measured amount of backscatter. Also, SNR measurements can be obtained from the tx/rx signals [1].

6) *Electronic Switched Pointing & Tracking*

The transmitter receives the information about angle of arrival from its co located receiver. The transmitter can hence switch to a light beam which points its output in the direction of to be received beam to optimize the link [1].

B. *Background*

1) *Underwater Optical Channel*

The underwater free-space optical channel is not the same as the atmospheric channel. Although, there have been detailed studies on the optical properties of water and remote sensing applications. Thus, the underwater channel from an optical communication prospect is still very much unknown [8], [9], [10].

From an optical communications reference, the three important properties are beam attenuation coefficient, volume scattering function, and albedo. Light interacts with water and the materials suspended and dissolved in it by two separate ways: absorption and scattering [1]. Absorption is the change of electromagnetic radiation into other forms of energy such as heat. Scattering is the redirection of electromagnetic radiation.

Photons change their course of direction by means of reflection, refraction, and diffraction. In small particles, Mie and Rayleigh scattering control the magnitude and direction of the scattered photon [8]. This reliance can be described by a phase function which is usually strongly forward peaked in water. There can also be a significant backscattered component [9].

Beam attenuation coefficient can be defined as the ratio of energy absorbed or scattered from an incident power per unit distance. Absorption coefficient $a(\lambda)$ and scattering coefficient $b(\lambda)$ add up to give the value of beam attenuation coefficient. It has units of m-1 and can be given by the relation:

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (1)$$

Beer's law defines the attenuation of an optical signal as a function of attenuation coefficient and distance d as [1]:

$$I = I0 + e - c(\lambda)\, d \quad (2)$$

Single-scattering albedo is defined as the ratio of scattering coefficient to beam attenuation coefficient and indicates the possibility that a photon will be scattered rather than imbibed [1]. It is a unit less term and is represented by $\omega 0$. It is defined as

$$\omega 0 = b(\lambda) / c(\lambda) \quad (3)$$

Highly scattering environments yield albedo near 1, and highly absorbing environments yield albedo near 0. Single scattering albedo is also known as the likelihood of photon survival because scattered photons are not changed to other forms of energy.

Another term known as Volume scattering function (VSF) is defined as the fraction of scattered power (Φs) to incident power (Φi) as a function of direction ψ scattered into a solid angle $\Delta\Omega$. It has units of m−1sr−1 and is denoted by $\beta(\psi, \lambda)$ [1].

2) *Existing Systems and Methods*

a. In underwater optical communication: Photomultipliers tubes (PMTs) are used to achieve wide FOV since they have very large apertures. They have an advantage of short rise time and wide spectral response, not to forget the blue green window used in optical communication. PMTs also have a wide extent of aperture sizes ranging from 10 mm to 500 mm (20 inches) in diameter [1]. These are utilized in underwater optical communication systems to elude pointing and tracking needs [2].
b. Modulating retro-reflector: A modulating retro-reflector can be used to address power, size, and pointing requirements at the receiver [15]. A modulating retro-reflector strikes out the requirement for a transmitting laser on a platform containing data and reduces the pointing specifications by retro-reflecting the modulated light again to the communicating source.
c. Indoor optical wireless: There has been some exploration in the field of indoor optical wireless in the work of spherical photodiode arrays for enlarging FOV [17]. Initial prototypes have been built having depressed attenuation channels such as the indoor optical wireless channel [18]. An

improvement in range by a diminution in path loss, multipath distortion, and background noise can be made possible by optimally combining the photodiode outputs [20].

d. In RF communication: Terrestrial RF communications have gained from recent growth in spatial diversity and smart antennas. Mobile communications also give an idea about some of the implementations workable with an antenna. However, in optical systems, we do not have the RF implementation of being able to use cogent beam-forming or phased arrays [1].

C. *Smart Transmitter*

The smart transmitter has the following characteristics [1]:

- Electronic switched beam-steering.
- Increased directionality.

The LED (Light Emitting Diode) is a semiconductor device that produces a relatively narrow spectrum light, dependent on the material used with a particular brightness dependent on the forward bias current applied. The speed at which an LED can be modulated is usually limited by the die size for high brightness LEDs. This implies a trade off between power and speed, since larger die size provides higher brightness [21], [22].

The smart transmitter is composed of a shortened hexagonal pyramid with a large number of LEDs. Each LED in the transmitter is coupled with its own lens that converge the extensive FOV of the LED to a limited beam in a particular direction. Each LED is uniquely addressed and driven, which allows the modulator to select an output direction. This constructs the procedure for a basic switched beam-steering at the transmitter side [1].

For a multi-user environment it is mandatory to provide a multiple access to the medium. LEDs at different wavelengths can be used, but receivers would require multiple filters. Time

Division Multiple Access would thus need synchronous clocks [1].

D. *Smart Receiver*

Like smart transmitter, the goal of the smart receiver is to develop a quasi omni-directional system to reduce pointing and tracking requirements generally associated with free-space optical systems.

Further, to potentially reduce pointing and tracking requirements, this design also potentially allows one to estimate and evaluate angle of arrival. This can be used in combination with a CDMA type multiple access system. Thus, the signals from distinct platforms can be differentiated from their coded signals and have a demonstration of their location. This increases the number of applications and includes applications such as localization, navigation assistance, and mesh networking.

Using multi input multi output (MIMO) techniques, this optical approach possibly also imparts angle and spatial diversity for enhancing the representation of point-to-point links [1].

The smart receiver has the following characteristics:

- Increased field of view
- Angle of arrival estimation

There are many design considerations that have to be kept in mind due to their significance to underwater free-space optical communication. First of all, unlike the optical front-end arrays in terrestrial free-space optics and indoor optical wireless use either photodiode arrays with no lenses, the smart receivers that are used in the underwater communication need to be mounted with an array of lens [1]. This is done to estimate the angle of arrival of signals being focused on the receiver.

It is always been the requirement of free space optical communication underwater to have an improved FOV and is considered one of the primary issues to work upon. A significant improvement in the FOV can be made by using quasi omni-directional lenses at the receiver side.

A smart transmitter can perform evaluation of the water quality by utilizing its backscattered return light and a co-located receiver to estimate the attenuation coefficient (channel state) of the channel at the transmitter. This expertise has the benefit of knowing the water quality without counting on a back-channel for back-telemetry or even a different instrumentation sensor [1]. Knowing this information allows the transmitter to, for example, adaptively change its transmitting power, data rate, code rate, or other parameters. The question to this expertise is that the return beam from backscatter, depending on the attenuation coefficient of the channel, can be as low as roughly six orders of magnitude below the output power of the transmitter [1]. To some degree, this can be elucidated by a few methods including: sending a higher power training sequence for the cause of enlarging the amount of backscattered light used for estimation and evaluation, the receiver associated the captured light to the genuine information being transmitted, or even temporarily increasing the receiver gain. Expertises such as the use of a lock-in amplifier can be used and are aided by the fact that the transmitter and the backscatter-receiver are co-located [1], [23].

III. CONCLUSION

The ease and importance of executing the use of a smart transmitters and receivers for free-space underwater optical communication systems are presented in this work. An increased field of view and the capability to evaluate the angle of arrival by the smart receiver along with the estimation of water quality by measuring the optical backscatter from transmitted light by the transmitter is depicted. This smart transceiver proposal reduce pointing and tracking needs, which otherwise pose a major problem with the communication platforms used by the unmanned devices underwater. The main focus of this work is to identify the importance and future need of promising non-traditional network technologies in the swarm of unmanned devices underwater.

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Fuzzy Systems using GPGPU – A Survey

Satvir Singh[1] and Shivani Kakkar[2]
[1,2]*Department of Electronics & Communication Engineering,*
Shaheed Bhagat Singh State Technical Campus Moga Road, Ferozepur–152004, Punjab, India
E-mail: [1]drsatvir.in@gmail.com, [2]kakkarshivani47@yahoo.in

***Abstract*—This paper presents a survey on use GPGPU (General Purpose computing on Graphics Processing Unit) to implement Fuzzy Logic Systems (FLSs). Features such as massively parallel, multithreaded operations, many-core processor make Graphics Processing Unit (GPU) suitable for real-time applications. Inherent parallel nature of Type-1 and Type-2 FLSs has been exploited for parallelization on GPU. Various applications, like fuzzy clustering, image processing, robot navigation, and fuzzy arithmetic library, etc. have been studied for better performances on GPU using CUDA (Compute Unified Design Architecture) programming model. In present scenario of High Performance Computing (HPC), GPGPU is most significant low cost solution for many engineering problems.**

Keywords: GPU, GPGPU, CUDA, Type-1 and Type-2 FLSs

I. INTRODUCTION

Graphic Processing Unit (GPU) developed in 1970s is traditionally used for texture and video rendering. GPU is exceptionally suited for HPC just because of its large number of computational cores. The high speed processors inside GPU have 100s of ALUs running 1000s of identical threads in parallel to execute instructions simultaneously. Tasks performing identical operations which are independent of each other execute on many data elements in parallel. CPU spends a lot of time on computations as compared to GPU. So, the GPU is faster as compared to CPU owing to larger number of computations being performed on processing cores of GPU simultaneously. GPU being classically used for texture and graphics applications is now playing a vital role in speed up of many computationally intensive algorithms. This general-purpose parallel computational functionality of GPU is supported by the scalable CUDA programming model [16][18]. In 2007, first release of CUDA explored the parallel architecture of GPUs for parallel computing for various applications other then graphics. It enables GPU to execute programs written in C. It is a small set of extensions to C/C^{++} and enable heterogeneous programming including provisions for both host (CPU) and device (GPU) through PCI express bus. Data parallel portions of an algorithm are executed on the device as kernels. One kernel is executed at a time by many threads in a block. CUDA threads on a GPU can be executed independently and each thread performs the same operation and execute same kernel as shown in Fig. 1, from architectural point of view.

CUDA uses software and hardware required for making GPU hardware easily accessible to programmers. Not only CUDA, there are many other programming platforms, like Shader, OpenCL, and open GL, etc. for exploiting GPGPU. In CUDA, to start application data is copied from CPU to GPU memory over a PCI Express bus followed by load and execute program. Then program results are copied back from GPU memory to CPU memory.

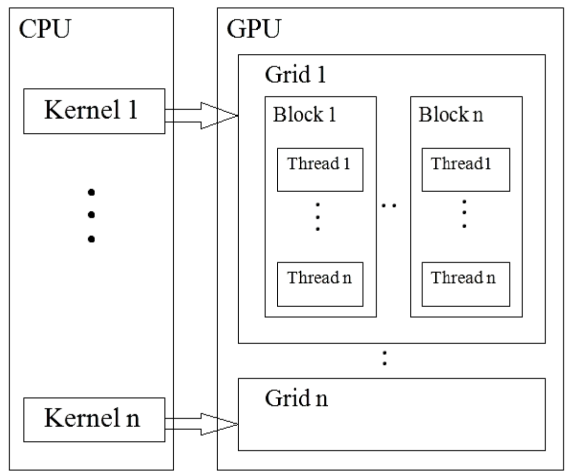

Fig. 1 CUDA processing Model Design

As FLSs possess inherent parallel nature [1], it is easy to exploit them on parallel architecture of GPUs for implementation. This paper presents various Fuzzy Logic engineering problems where GPU has been investigated for increased speedups. Organization of rest of this paper as: Section I presents an overview of Type-1 and Type-2 FLSs. Section II discusses about basics of Type-1 and Type-2 FLS and Section III reports various GPGPU implementations for FLS concepts and applications. Finally, Section IV summarizes the paper and presents motivational offshoots for the HPC researchers working on FLSs.

II. FUZZY LOGIC SYSTEMS

The term Fuzzy Logic was introduced by Lotfi A. Zadeh in 1965 [2][3]. In 1970s, research groups formed in around the world investigated fuzzy logic where conventional mathematical tools face difficulties in handling engineering (especially, control) problems. Fuzzy sets provide provision for dealing with vagueness and ambiguity. In fuzzy sets, each element is mapped within [0, 1] by an analog membership function [4]. Rulebase is extracted from experiential fuzzy knowledge of experts to control the output variable. A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion. For example, if *temperature* (input variable) is *cold* (fuzzy set) then output command is *heat* (fuzzy set). Aggregated fired fuzzy rules are