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A Brief Survey on Underwater Optical Wireless Communications

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***Abstract* – Acoustic, radio frequency (RF) and optical waves systems are the technologies that are used to carry out underwater wireless communications. In scientific, military and industrial sectors, the development of robust and efficient submarine wireless communication links is of enormous interest. To achieve secure short-range wireless communications, the Underwater Optical Wireless Communication (UOWC), which uses the 450-550 nm spectral range of the electromagnetic spectrum, is a good technology. Recently, UOWC applications have been proposed for environmental monitoring, offshore exploration, and military operations. There are many review articles published on this topic. However, research in this field evolves rapidly as does existing literature. The article deals with current and potentially available UWOC technologies in the near future. It is aimed at those who want to undertake studies in this field. Obviously, this paper does not attempt to cover every single aspect of UWOC.**

I. INTRODUCTION

Underwater wireless communication (UWC) has many potential applications in the military, industrial and scientific research fields, but, for practical applications significant data bandwidth is required [1-3].

Generally, underwater wireless communication takes place via acoustic waves due to their relatively low attenuation. Unfortunately, acoustic systems have low bandwidth and high latency. Therefore, they are not suitable for applications that require data-intensive information exchange and real-time response processing in real time. However, since acoustic transmission is the only technology capable of ensuring communication over long distances, extensive studies are continuously conducted to improve the performance of the acoustic communication channels [4-6]. Anyhow, acoustic underwater communication is susceptible to malicious attacks [7].

Therefore, complementary technology capable of achieving secure broadband underwater communications is required. Wireless communication via radio frequency (RF) waves is the most widespread technology in terrestrial communications. Unfortunately, this technology is not suitable for underwater use; in fact, in the water, the radio frequency waves are strongly attenuated [8].

Optical communication is defined as remote communication using light to carry information. Potentially, it can solve the problem of broadband and low latency submarine wireless transmission. Recently, in terrestrial application, Visible-Light Communication (VLC) technology was developed to provide both lighting and data transfer with the same infrastructure [9-10]. VLC techniques transmit information wirelessly by rapidly pulsing visible light using Light Emitting Diodes (LEDs); recent work has shown the possibility of replacing the Wi-Fi connection, based on radio frequency waves, with a VLC link. Generally, the information data is overlaid on the LED light without introducing flickering. The exhaustion of low-frequency bands to cope with the exponential growth for the high-speed wireless access is another reason for exploring new technologies. The visible light spectrum is unlicensed and hardware readily available, which can be used for data transmission. Furthermore, the exponential improvement in the high-power light emitting diodes is an enabler for high data rate VLC Network. Like VLC systems are the Underwater Optical Wireless Communications (UOWCs) [11-13], where potential light sources are Laser Diodes (LDs) instead of LEDs. Both are extremely interesting, LDs for their feature higher modulation bandwidth respect to LEDs, while, these latest, for their higher power efficiency, lower cost, and longer lifetime, seem more suitable for medium bit rate applications.

Optical communication is defined as communication at a distance using light to carry information. An optical fiber is the most common type of channel for optical communications, as well as the only medium that can meet the needs for enormous bandwidth in such an information age. Replacing the channel from an optical fiber to free-space underwater, we achieve UOWC that can be regarded as the underwater transmission of unguided optical signals.

Compared to acoustic and radio frequency communication, UWOC has great potential; with it, we can make communications with high bit rate and very low latency. Currently, the performance of UOWC systems is limited to short range applications [14]. Submarine optical communication systems are starting to be commercially available [15,16]. However, in-depth studies are still necessary to create systems that can be used in real operational scenarios. Researches are needed to allow submarine optical transmission even over long distances.

Figure 1 compares the performance of acoustic, RF and UOWC, based on the transmission range and the data speed (bandwidth).

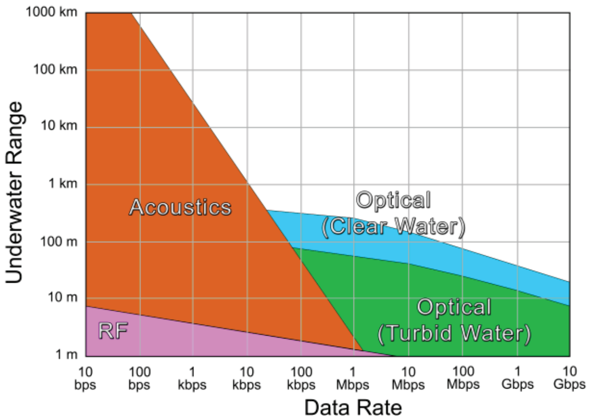

Fig. 1. Theoretical communication performance of acoustics, RF and optical underwater communication technologies.

In order provide a basic overview, we will go through and provide summary is to highlight the prospects of UOWC technologies. The focus of this is to examine current technologies and those potentially available in the next few years, for UOWC. The study in this field can open great opportunities since current optical underwater communication solutions are still of large dimension, expensive and power-consuming.

Military field is one of the fastest growing related to this innovative communication technology, due to its intrinsic security and superior bandwidth availability. One possible application is divers direct communication. During military incursions with divers, it is very important for the command to have secure communications that are difficult to locate. Figure 2 shows a typical behavior where two divers have the necessity to exchange tactical information.

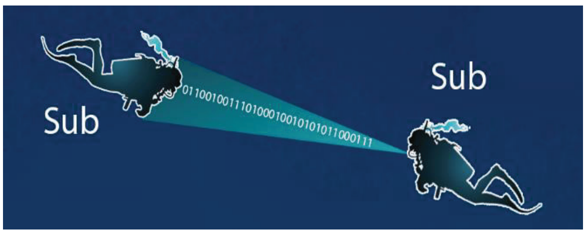

Fig. 2. Secure optical communication between subs.

In this scenario, UOWC is an excellent technology. It has the advantage that it is much more difficult to intercept than traditional underwater acoustic communications. This specific application does not require long range and high band communications. Therefore, the systems can have implemented are simple, small, lightweight and with low power.

Figure 3. It is a Dynamic Positioning Buoy [17], capable of communicating with satellite and via bidirectional UOWC with optical surveillance station positioned on the seabed. The surveillance station can be powered by nuclear batteries [18] and in real time control, through digital optical correlation [19,20], if something intrudes into the monitored area. In case of suspect object (e.g. a submarine) the image and related alert is sent back to the buoy and, from it, to the ground costal station via satellite link. This application can grand a very accurate underwater video surveillance.

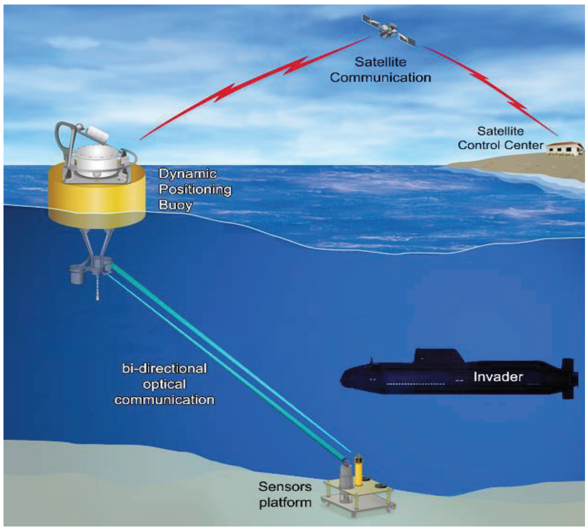

Fig. 3. Underwater video surveillance scenario.

Figure 4 shows a typical UOWC scenario. It shows several platforms (divers, ships, submarines, submarine sensors, etc.) connected by beams of light.

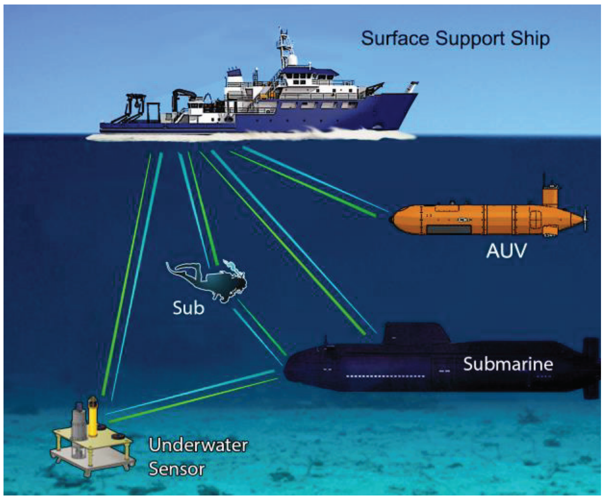

Fig. 4. Typical application scenarios of UWOC.

II. OPTICAL TRANSMISSION IN WATER

The optical channel model is defined by means of Beer-Lamber. After the beam propagates z length, the propagation loss factor (L_P) is:

$$L_P = h \cdot \exp[-c \cdot z] \quad (1)$$

where c in m^{-1} is the total attenuation coefficient, and h is a constant. The total attenuation coefficient is a sum of the effects of the absorption coefficient and of the scattering one, respectively called a and b. Therefore, $c = a + b$.

The absorption and scattering coefficients, with inverse meter units, are determined by the contribution of water molecules, particulate algal/sediment matters and colored organic contents dissolved [21,22].

The spectral attenuation of radiation depends upon the constituents (in particular Chlorophyll) and their concentration in a volume of seawater. Chlorophyll profile is significant to underwater communication link [23] and a relationship has been determined between attenuation coefficient and chlorophyll concentration. The chlorophyll profile for depth of Z(m) since surface is referred in [24].

Generally, in turbid harbor, the attenuation is minimum in the spectral region 550 to 600 nm. For coastal ocean, the wave band is 520 to 570 nm and for clear ocean, the minimum attenuation wave band shifts to still lower wavelength region i.e. 450 to 500 nm.

In this way, the absorption coefficient a and the scattering coefficient b can be expressed as a function of the wavelength λ and the concentration of chlorophyll C_{chlor} [25]:

$$a(\lambda) = [a_w(\lambda) + 0.06 \cdot a_c(\lambda) \cdot C_{chlor}^{0.65}]\{1 + 0.2 \cdot \exp[-0.014(\lambda - 440)]\} \quad (2)$$

$$b(\lambda) = 0.30 \frac{550}{\lambda} C_{chlor}^{0.62} \quad (3)$$

where, a_w points out the pure water absorption coefficient while, a_c is a nondimensional number, statistically derived that points out the absorption coefficient specific for the chlorophyll. Therefore, the chlorophyll concentration C, expressed in $mg \cdot m^{-3}$, can be used as the free parameter to calculate $a(\lambda)$ and $b(\lambda)$.

The measured values for the absorption $a(\lambda)$, for the total scattering $b(\lambda)$ and for the extinction $c(\lambda)$ are outlined in Table 1.

Table 1. Table caption.

Water types	$a(\lambda)$ [m^{-1}]	$b(\lambda)$ [m^{-1}]	$c(\lambda)$ [m^{-1}]	Operate Wavelength
Clear Ocean	0.114	0.037	0.151	450-500 nm
Coastal Ocean	0.179	0.220	0.339	520-570 nm
Turbid Harbour	0.366	1.829	2.195	550-600 nm

Seawater light transmission model is shown in Figure 5.

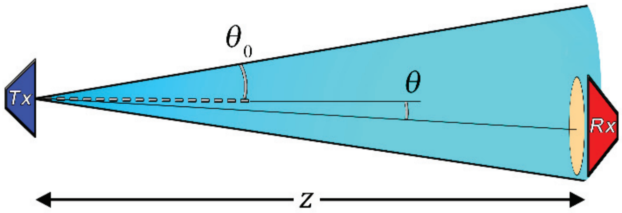

Fig. 5. Seawater light transmission model.

The optical power reaching the receiver can be written as [26]:

$$P_{Rx} = P_{Tx} \cdot \eta_{Tx} \cdot \eta_{Tx} \cdot \exp\left[-\frac{c(\lambda) \cdot z}{\cos\theta}\right] \cdot \frac{A_{R_x} \cdot \cos\theta}{2\pi \cdot z^2 (1 - \cos\theta_0)} \quad (4)$$

where P_{Tx} is the transmitted power, η_{Tx} and η_{Rx} are the optical efficiencies of the Tx and Rx correspondingly, $c(\lambda)$ is total attenuation coefficient, z is the perpendicular distance between the Tx plane and the Rx plane, θ_0 is the Tx beam divergence angle, θ is the angle between the perpendicular to the Rx plane and the Tx- Rx trajectory, and A_{Rx} is the receiver aperture area.

The transmitted power is limited by the energy that can be used by the transmitter apparatus. It is essential that this energy be as small as possible. In this way, it is possible to have low power supply, very useful in underwater applications.

The Eq. 4 shows that for the same energy used by the transmitter, if you want to increase the transmission distance, it is essential, among other things, to improve the efficiency of the transmitter and receiver.

Obviously, the transmission distance can also be increased by using reception systems capable of capturing, theoretically, even the single photon.

As far as light sources are concerned, the technology offers increasingly efficient and reliable devices. Current LED systems have excellent efficiency, high reliability and low cost. On the contrary, as far as the receiver is concerned, much research work still needs to be done.

III. BASIC COMPONENTS OF UOWC

A UOWC link can be schematized in three parts, the transmitter unit, the water channel, and the receiver module. The schematic in Fig. 6 shows the components of a typical system.

The transmitter, which consists of four principal components: a modulator and pulse shape circuit, a driver circuit, converts the electrical signal to an optical signal suitable for transmission and a lens to realize optical link configuration.

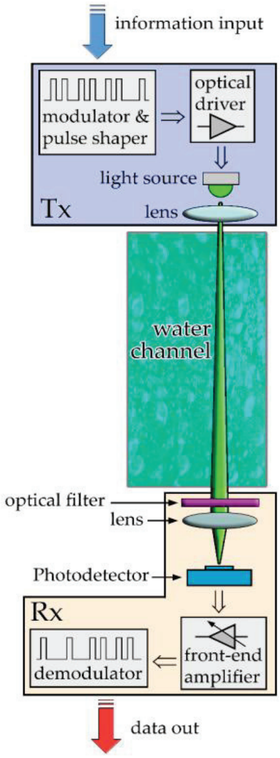

Fig. 6. Schematic of a typical UOWC link. The transmitter (TX) is composed of a modulator, optical driver, light source and projection lens. The receiver (RX) is made of optical bandpass filter, photodetector, Low noise electronics and demodulator.

The function of the transmitter is to transform the electrical signal in optical one, projecting the carefully aimed light pulses into the water. The optical light sources are based on LED or LD one [27-30]. Compared to LEDs, Laser Diode switch faster and support a higher optical power output. On other hand, the LEDs systems are cheaper, simpler and more reliable and anyway switch sufficiently fast to allow UOWC for medium range distance. Diode lasers are preferable for long distance communications. Instead, at short distances, communications via LEDs are preferable. Finally, since LEDs can be used for bi-directional communication, they can be employed to make simple, cheap short-range communication systems between divers.

Joined to the specific requirements and considering that underwater systems are obliged to respect power and mass constraints, the choice of one of the two optical available technologies, LED or laser, in specific blue-green portion of the spectrum, could be conditioned by the research of the maximum efficiency. Generally, blue-green LEDs are the better choice for buoy system operating in shallow water. Instead, for systems operating in deep clear ocean water, the laser-based transmission systems are preferred.

The receiver has the task of capturing the transmitted optical signal and transforming it into an electrical signal. In many applications, it is important to select a specific wavelength that impact on the light detector [31]. The light coming on the receiver should have no noise introduced by sunlight and the presence of other light sources [32]. To try to solve this problem, the wavelength band (the one transmitted) is selected by using a narrow optical band-pass filter [33].

There are many different types of photo detectors currently commonly used, e.g., the photodiodes. These devices, for their characteristics of small size, suitable material, high sensitivity and fast response time, are commonly used in optical communication applications. There are two types of photodiodes: the PIN photodiode and the Avalanche Photodiode (APD). Unfortunately, due to the high detection threshold and high noise intensity, linked to Trans-Conductance Amplifier, that limit their practical application, photodiodes are not advisable for long distance UOWC systems. For traditional detection devices and methods, due to the exponential attenuation of the water, the optical communication distance is less than 100 m. This constraint severely limits the performance of UOWC systems. Especially for the management of AUVs and remote control vehicles (ROV) [34-36].

Recent researches are focused on the possible application of Single Photon Avalanche Diodes (SPADs) technology to UOWC systems. The Avalanche Photodiodes have a similar structure of the PIN ones and operate at a much higher reversed bias. This physical characteristic allows to a single photon to produce a significant avalanche of electrons. This way of operation is called the single-photon avalanche mode or even the Geiger's mode [37-39]. The great advantage of SPADs is that their detectors do not need to a Trans-Conductance Amplifier.

IV. CONCLUSIONS

Recently many studies have been conducted to use UOWC technology to transmit information safely with high data rate in underwater environment. Today, UOWC systems usable in real operating conditions (with some exceptions) are not yet available. Therefore, a lot of research in this area has yet to be done. In particular:

- Currently, an inevitable phenomenon for UOWC Link is the misalignment between transmitter and receiver. Although some researches on smart transceivers to limit the impact of the link misalignments have been proposed, the need to develop more intelligent UOWC transceivers is pressing.
- The design innovative modulation and coding schemes that can adapt the characterizations of underwater environment.
- Since most UOWC systems are integrated into a battery-powered platform, energy efficiency is therefore important. The systems must be designed with energy efficiency optimization.
- Possibility of simultaneously using different colored

source light to increase data transfer rate and/or consent simultaneous use by multiple users.

- Development of new underwater communication channel modeling. When environmental conditions deviate from ideality, the light signal rapidly degrades. It is essential to study the propagation of the light beam with models that simulate real conditions as much as possible (even in "difficult" environments). All this to allow the optimization of transmission and reception techniques, both in terms of transmitter and sensor used as receiver.

Finally, almost all the studies available in the literature are conducted by simulation or by laboratory experiments. Studies in real marine environment are needed.

The interest in UOWC is mainly outside the academic field. In fact, the possibility to use UOWC is on the basis of future military application for secure Under Water Telephones (UWTs), necessary for allowing secure communications between vessels and submarines, taking into account the possibility to use both direct and spread light channels. In addition, the usage of Point-to-Point optical communications can allow a better usage of torpedoes, not specifically for their guidance, but for reporting sonar information back to the basis with a high rate, even in case of not wire-guided solution.

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