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Throughput of Underwater Wireless Sensor Nodes with Energy Harvesting Capabilities Using RF and Optical Links

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Abstract **—Underwater communication has been gaining a lot of attention as it is one of the challenging and promising wireless communications. It may experience considerable latency and attenuation with respect to the distance which degrade the overall performance of the system. Moreover, literature has been investigating several techniques for Energy Harvesting (EH) for Underwater Communications (UWC). Thus, integrating underwater wireless sensor nodes (UNs) with EH abilities to communicate underwater is considered in our work. An Underwater Wireless Sensor Network (UWSN) is proposed, the network model uses optical harvesters in constraint of using optical transmitters in the power communications/harvesting. On the other hand, the communications between UNs are investigated to use Radio Frequency (RF) and optical links. Also, network throughput in both scenarios of RF and optical communications between the UNs is studied with respect to the depth of the nodes.**

Index Terms **—optical and radio frequency communications, underwater communications, underwater communications with energy harvesting underwater wireless sensor network**

I. INTRODUCTION

Underwater communication has been gaining a lot of attention as it is one of the challenging and promising wireless communications. Underwater environment is different from terrestrial wireless communication in network design [1]. Due to the increase of the exploration of the marine resources, underwater communication development is restrained due to the data rates and communications distance between the nodes [1]. Early, underwater communication is used to increase the transmitted power in order to achieve long distance transmission [1]. Nowadays there are new approaches in the research to enhance the communications without increasing the power. Literature has been proposing new approaches to enhance the communications between the nodes underwater. There has been three different types of links been used in the research which are; optical links, Radio Frequency (RF) links and acoustic links.

Authors of [2] and [3] surveyed the pros and cons of several communications technologies in underwater networks. Authors of [4] and [5] showed the main challenges and opportunities with respect to the applications of marine underwater communication networks. While, other papers focused on the modulation scheme, coding techniques and channel characterization for each transmission type such as; optical systems in [6]. Authors of [7] implemented an Underwater Wireless Sensor Network (UWSN) optical system using free space optical communications (FSO) links for different underwater environmental parameters of clean, coastal ocean and during turbulences. Authors of [3] and [8] investigated several routing protocols in acoustic. The work in [9] showed commercial optical transceivers for 40m with data rates of 10 Mbps. On the other hand, the work in [10] worked on data rates that reach 12.5 Mbps for a network model with maximum 150m. Authors of [11] implemented UWSN model using RF links of 2.4 GHz which shows that the lost packets and round trip time are increasing with the increase of the distance till 20m. Authors of [12] showed an experiment results of the power and attenuation over 100 m. Authors of [13] investigated a multi hope underwater system with Visible Light Communication (VLC) and the results show that the received power optical system is decreasing with the increase of the distance with different water type of tap, canal or sea water. Other implementations have explored optical and acoustics techniques such as [14] which worked based on 450 nm optical transmitter and the data was modulated using 16-QAM in tap water resulting a transmission capacity of 10Gbps for less than 2 m distance. Also, the work in [15] used Multiple Input Multiple Output (MIMO) scheme in their Optical Underwater Wireless Network (OUWC) and other works used Orthogonal Frequency Division Multiplexing (OFDM) as in [1] and for acoustic networks as in [16]. Markovian model has been used in wireless sensor nodes (WSNs) in terrestrial wireless communications as in [17] and [18], but only few works have considered it in underwater communications to consider achievable BER as in [19] and [20].

Literature has successfully overview of the present state of the art and it identifies the key resources that have been used in implementing similar networks. However, it may lack from comparing the two techniques by the same

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system parameters in order to maintain differences between the two techniques. Thus, this paper proposes a network model that uses optical harvesters in UWSN. The underwater wireless sensor nodes (UNs) communicates with remotely operated underwater vehicle (ROV) via RF/optical links. The harvesting of energy in the network is represented using two-state Markovian mode. Moreover, the throughput in both cases is investigated. On the other hand, the transmitter and receiver have to be in Line-of-Sight (LoS). Thus beam misalignment, water turbulences and unexpected obstacles are considered in our design. This paper is organized as follows: Section II discusses the proposed network model, Section III addresses the simulation results and discussion, Section IV concludes the work in this paper.

II. NETWORK MODEL

A centralized underwater wireless sensor network is proposed in Fig. 1. The network model is based on light harvesters with abilities in *k* nodes (UNs), ROV and communication buoy on the surface. All WSNs are equipped with energy harvesters and the communications occur via ROV. The network is based on two power and communications links in the network model. The harvesting links as the source of energy is working on optical techniques while the communications links are discussed in optical and RF links.

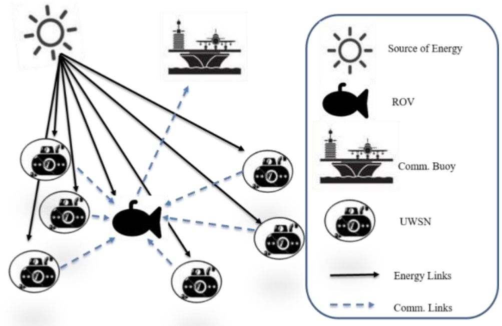

Fig. 1. Underwater wireless sensor network Architecture.

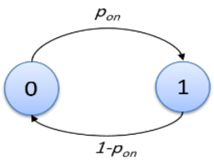

Fig. 2. Two-State markovian model.

Two states Markovian model of energy harvesting underwater wireless sensor nodes (EH-UN) model is considered in Fig. 2. This two states represent energy storage of each EH-UWS. The transition between the two states is based on energy arrival process which is directly depends on probability of energy harvested $\mathrm{p_{on}}$ or not harvested.

The probability of harvesting P_{on} depends on attenuation occur between the EH-UN and the source of light on the surface which is effected by the channel loss. The output power and the relation between the probability of harvesting with the depth are represented as:

Fig. 3. Frame structure of UWSN network model.

$$P_{out} = P_{in} d^{-n} \quad (1)$$

$$p_{on} \propto d^{-n} \quad (2)$$

The probability of harvesting have mapped with the maximum attenuation to make a probability of the harvesting based on the depth of the harvester underwater where, at the maximum depth the probability is 0 and at zero depth, the probability is 1. Fig. 3 shows the frame structure of the UWSN model of transmission and harvesting time. Harvesting time is used for harvesting the energy and the transmission time is used to transmit the data. Literature has been assigning 80% of the frame time to the transmission time in similar systems.

The transmission time is calculated according to Fig. 3 as:

$$T_{\tau} = T - T_h \quad (3)$$

Channel degradation has been used using path loss exponent loss. The exponent loss has proved that it is independent on the operating frequency according to [21]. The network throughput of optical communications and power links can be derived as

$$R = T_{\tau} R_{\tau} p_{on} L_{ij}^{-n} \quad (4)$$

where R_{τ} is the maximum transmission rate underwater, P_{on} is the probability of harvesting, L_{ij} is the distance between node *i* and node *j* and n is the path loss exponent. While the network throughput based on RF communications links and optical power links is derived with regard of the Friis formula as

$$R = T_{\tau} R_{\tau} p_{on} \frac{4\pi L f \sqrt{\varepsilon_r}}{c} \quad (5)$$

where f is the operating frequency and $c/\sqrt{\varepsilon_r}$ is the maximum speed of propagation.

III. MODEL RESULTS AND DISCUSSION

The system parameters used in the system in listed in Table I. The modulation scheme has not been considered in this work and the transmission rate has been taken based on commercial UWSN. Fig. 4 shows the energy harvesting attenuation of the UN using optical links signal in dB with respect to the depth of the EH-UNs. Attenuation has been investigated with respect to the exponent loss (n) which varies from 2-4 in such environments according to [22]. As expected, with the increase of the exponent component the attenuation increases as well. The attenuation of the communications is negligible compared to the attention from the harvesting.

TABLE I: SYSTEM PARAMETERS

Notation	Description	Value
R_τ	Transmission data rate	10 Mbps [9], [10]
n	Exponent loss	2-4 [22]
D	Depth	1-30 m
L	Distance between node i and j	5 m
T_τ	Transmission time	0.8T
T_h	Harvesting time	0.2T
T	Frame time	100ms
f	Operating Frequency	2.3 GHz (ISM band)
$c/\sqrt{\varepsilon_r}$	Maximum Speed of Propagation in water	C=3×103 ε_r =0.2

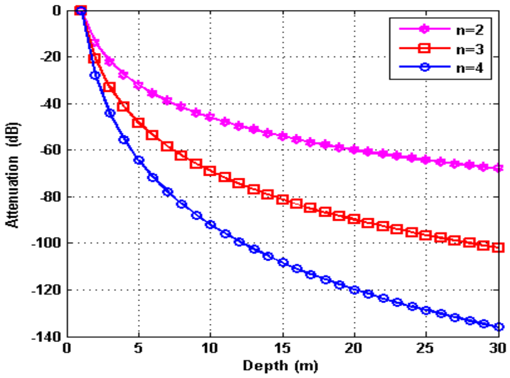

Fig. 4. Energy harvesting attenuation vs depth

In Fig. 4, the attenuation degrades from 0 at the surface till the 30 ms based on the amount of water clearances and path loss in the sight. This definitely affects the probability of harvesting; i.e. if the attenuation is very high the probability of harvesting will be quite low and the transmission as well. With the path loss exponent of 2 the attenuation reaches –70 dB which is acceptable and reachable with some high quality commercial UWSN, while in the other two cases, the sensitivity of the commercial cannot serve the 30 m depth as the attenuation reaches –100 dB and –130 dB. Thus, based on the clearances of water, the placement of the EH-WSNs can be determined.

While, Fig. 5 investigates the throughput in dB with respect to the depth in meter, the throughput is calculated using optical communications links. The throughput is varied different path loss exponent which reflects the underwater environment of turbulences and suddenly obstacles between the EH-UNs and ROV and from the source of energy and EH-UNs.

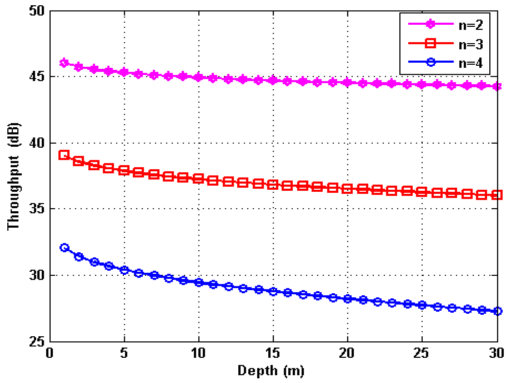

Fig. 5. Throughput vs depth using optical links

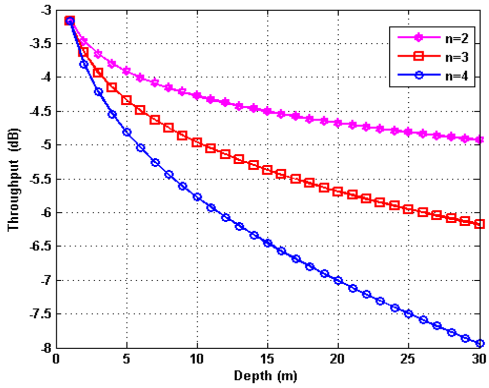

Fig. 6. Throughput vs depth using RF links for communications between UN and optical links for Power links

In Fig. 6 shows the throughput in dB with respect to the depth in meter, the throughput is calculated using RF (2.3 GHz) communications links. The throughput is varied different path loss exponent which reflects the underwater environment of turbulences and suddenly obstacles between the source of energy and EH-UNs. Also, the attenuation from the EH-UN and ROV is considered in the RF attenuation equation.

In Fig. 5 and Fig. 6 show the throughput using optical and RF communications links, respectively. The performance of the optical links is much better than in RF links by tens of decibels. Achievable throughput using RF links degrades from –3 dB to –8 dB, –6 dB and –5 dB for exponent loss of n=4, 3 and 2, respectively. On the other hand, it degrades from 33 dB to 27 dB, from 39 dB to 36 dB, and from 46 dB to 44 dB for n=4, 3 and 2, respectively. They show that for long distances, the attenuation using RF links are much more than using optical links. Both techniques may require to LoS to avoid any loss of data. Some RF techniques use different RF techniques that enable it to transmit without LoS. Optical links can't cross water/air later which makes using RF in the transmission with vehicles above water more convenient. With near transmission of the UN, both can work effectively but for larger distance, the use of optical links is recommended as long as it does not cross water/air layer due to less attenuation effect. Also, RF transceivers are very bulky and expensive than optical nodes.

IV. CONCLUSION

An underwater wireless sensor network (UWSN) is proposed using communication links of RF/optical transmitters and receivers. The UWSNs harvest their energy from light harvester. Moreover, Network throughput is investigated using RF and optical links. The results show that optical links have way better performance as long as the transmission goes through underwater ROV as a gateway and does not need to cross air/water later. The simulations proves that performance of the two techniques differ ten of decibels for the optical links. Furthermore, the high cost, complexity and bulk size of the RF technique motivate to build UWSN using optical transceivers. This work can be extended to use frequency space optical communications links instead of normal optical technique as it is known of high bandwidth and license free technology.

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