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Wireless-Powered Hybrid Terrestrial and Underwater Cooperative Communication System

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***Abstract*—In this paper, we consider a hybrid terrestrial and underwater RF wireless cooperative communication system. We improve the energy awareness of the system by employing simultaneous wireless information and power transfer (SWIPT) technique. The impact of the system performance parameters, such as signal-noise-to-ratio, bit error rate, outage probability and throughput are extensively investigated. All theoretical results are validated by numerical results. Furthermore, the impact of the time allocation in time-switching protocol is investigated. Simulation results, which are based on theoretical analysis and underwater experimental data, verifies that SWIPT integrated proposed system improve the overall energy awareness while maintaining the system performance.**

***Index Terms*—5G communication, RF wireless power transfer, simultaneous wireless information and power transfer, underwater wireless communications.**

I. Introduction

The Earth is commonly known as the water planet in which two-third is covered by water. Underwater wireless communication (UWC) plays a major role in assisting researchers in aquatic environmental exploration systems. Thus, UWC has obtained rapid development in both commercial and military applications [1]. UWC uses wireless carriers, i.e radio frequency (RF), acoustic and optical waves to transmit information in an unguided aquatic environment [2]. Each aforementioned UWC technique has its own characteristics with its own pros and cons. These characteristics of UWC techniques mainly depend on the physical constraints and chemical characteristics of the water. Optical UWC systems are able to achieve very high propagation speeds. Nevertheless, suspended particles cause a strong backscattering and also affected by the turbidity of the water making optical wireless carrier vulnerable for high error rates in long distance communications. Acoustic waves are less sensitive to the water turbidity and to particles in the water, with compare to optical waves. In addition, acoustic waves are the mostly used in UWC applications due to the fact that the acoustic waves are able to use for communication over longer distances, i.e. over 20 km [3]. However, acoustic communication suffers from low data rates, i.e., 0 b/s to 20 kb/s due to low carrier frequency, high attenuation near surface and strong reflection in turbid water with large particles. RF UWC are able to achieve communication data rates up to 100 Mb/s in very short distances. Electromagnetic (EM) waves in RF range are less sensitive to refraction and reflection effects in shallow water than acoustic waves [1]. In vertical UWC, EM-RF waves have advantages such as reduced latency due to the faster propagation and high data rates due to the higher frequency of EM waves as compared to acoustic wireless carriers [4].

Most of the existing UWC deployments use acoustic or low frequency techniques. There are few literature published in RF-UWC since this technology is not well investigated in UWC. In [1], [2], [4], authors have used EM-RF waves to perform UWC mostly concerning propagation channel modelling. In [1], authors reviewed physical fundamentals and engineering implementations of UWC. Underwater channel characterization explained in [2], by using the conduction in UWC. Propagation of EM waves through seawater explained in the work of [4]. In [3], authors have investigated the relationship between different propagation parameters of EM waves. They have identified four parameters to categorize EM propagation, which are permittivity, permeability, conductivity and volume charge density. In [5], the authors have identified that the RF UWC offers higher performance than the acoustic UWC in short ranges up to 30m. In the era of 5G, RF energy harvesting (EH) can be of fundamental importance to improve systems energy awareness [6]. Thus, RF-EH provides a contemporary solution to the energy constraint problems in communication nodes. To the best of our knowledge, there are no prior research conducted at the direction of wireless powered hybrid terrestrial and underwater cooperative communication system.

Thus, in this paper we propose a down-link (DL) hybrid RF terrestrial and underwater cooperative communication scheme, where the base station is located inland, transmits signals to surface buoy (SB) on the water reservoir via a terrestrial RF link and the relay forwards received signal to the autonomous underwater vehicle (AUV) through the underwater RF link. The harvesting at the relay node is done using hybrid solar and RF energy. Time-switching (TS) SWIPT receiver architecture is used in the SB to harvest RF energy and to decode infor-

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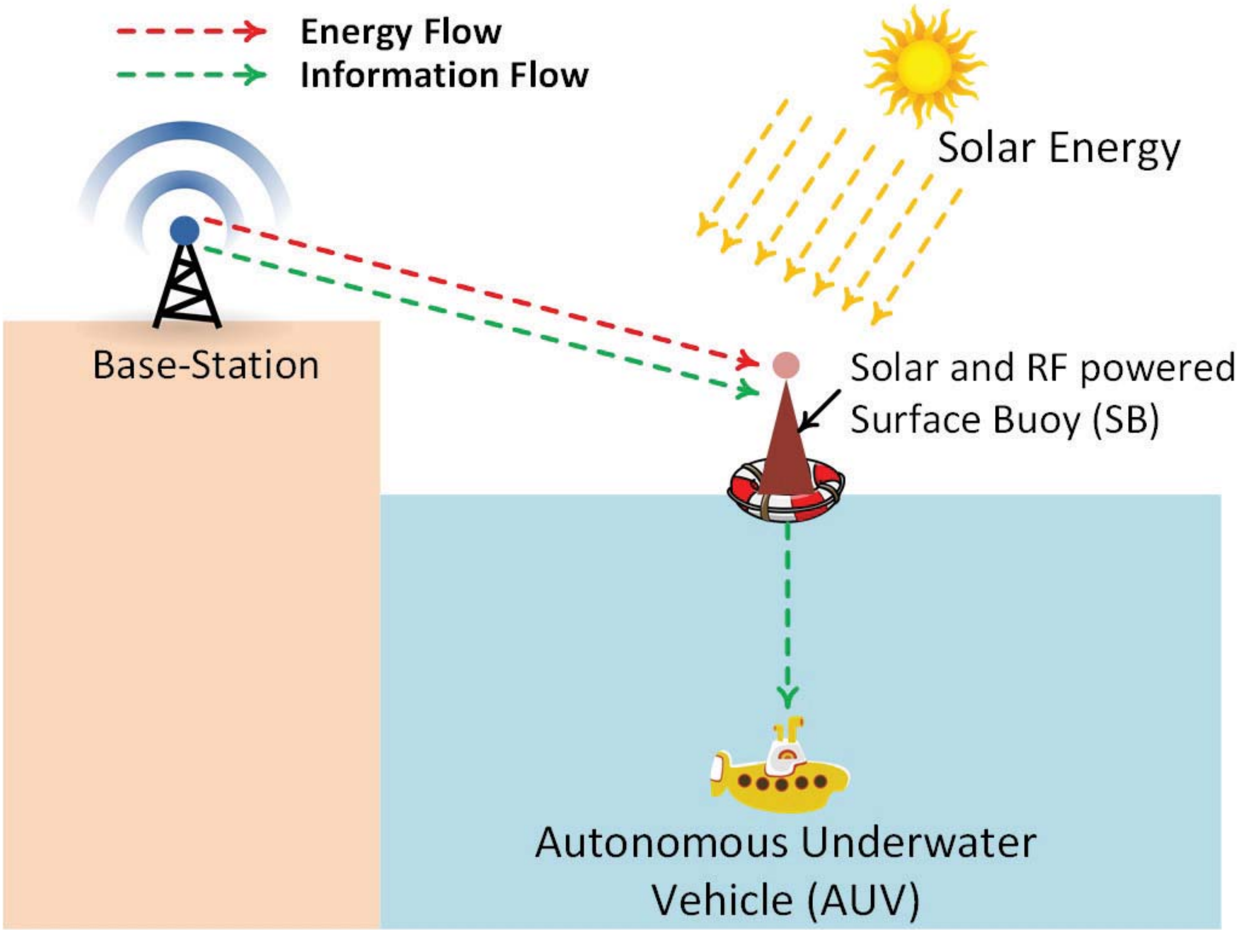

Fig. 1: Reference system model for wireless powered hybrid terrestrial ad underwater cooperative communication system.

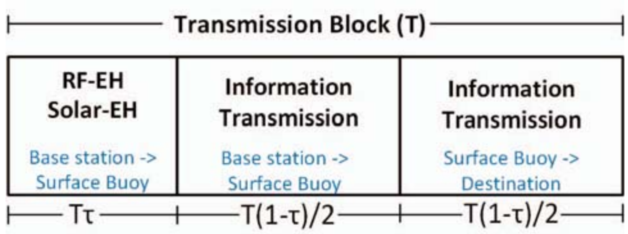

Fig. 2: Transmission block diagram of the proposed system model where τ denotes the time allocated for EH.

mation. SB uses harvested RF and solar energy as transmit power to forward the signal to AUV. First, we calculated the amount of energy harvested at both SB and AUV, and then we evaluated end-to-end SNR. Furthermore, analytical expressions for outage probability and ergodic capacity were also derived. Simulation results were obtained to verify analytical expressions and to analyse system performance.

II. System Model

The system model of the proposed dual-hop decode-and-forward (DF) relaying system is illustrated in Fig. 1, where the information is transferred from the base station to AUV through a SB. No direct communication between base station and AUV is possible due to the shadowing and heavy attenuation at the water surface. It is assumed that both SB and AUV has a single antenna for both EH and information decoding (ID). The SB is equipped with both a rechargeable battery (B_1) and a conventional solar battery (B_2). Moreover, though B_1 is energy constraint, it can be recharged via harvested RF energy from the received signal. Transmission block diagram of the proposed system represents in Fig. 2. Each transmission block has the time duration of T and τ is the amount of time reserved for RF-EH at the SB, where $0 < \tau < 1$. The remaining fraction of the block $T(1-\tau)$ is allocated for information transmission from base station to AUV. The terrestrial channel experiences independent Rayleigh fading given by h_{sr} while the underwater channel h_{rd} experiences Rayleigh fading with considering different factors, i.e multipath propagation, time variation, strong attenuation related to UWC [7]. The AWGN with the zero mean and variance σ_{xy}^2 is used to model the noise n_{xy} between the nodes x and y with $x, y \in \{s, r, d\}$. Noise PDF in UWC also remained Gaussian [7], though the AUV contains RF conduction antenna which increased the noise variance. To avoid the function $f_s^{(NL)}(.) : \mathbb{C}^N \rightarrow C^N$ that models non liner power amplifier of the base station in time domain single carrier frequency division multiple access (OFDM), OFDM scheme is used in underwater communication links from SB to AUV. We also assumed that the solar energy arrival rate at the SB is constant. Thus, E_{solar} has a fixed value during each time block T.

A. EM Properties of Water

The high frequency RF range EM waves provide higher data rates for large bandwidths compare to optical and acoustic UWC techniques. Nevertheless, EM waves are attenuated severely underwater reducing the communication distance between communications nodes. Following EM properties of water need to be investigated in order to identify possible effects on EM waves that propagate underwater.

1) Permeability (μ): Permeability is the ability of the medium to store magnetic energy. Seawater has the same permeability as vacuum since seawater in nonmagnetic medium [8]. Therefore, permeability of water has no effect over the EM propagation.

2) Permittivity (ϵ): The relative permittivity, also known as the dielectric constant, explain the ability of a medium to transmit an electric field [9]. In general, permittivity of seawater is a complex value, which depends on salinity of seawater, temperature and propagating frequency.

3) Conductivity (δ): The conductivity directly affects the EM wave transmission through a particular medium. As the conductivity of the medium increase, transmitted signal will face more attenuation loss.

B. Underwater Channel Propagation

The seawater is highly conductive and is considered as a high-loss medium [10]. Moreover, the conductivity of seawater is almost 400 time greater than compared to fresh water that can be found in inland water reservoirs [11]. In order to realize the impact of EM properties of water, complex-value propagation constant k is introduced and it can be given by [12]

$$k = \omega \sqrt{\mu \epsilon (1 - \frac{\delta}{\omega \epsilon})}, \tag{1}$$

where μ, ϵ, δ and ω represent the permeability, permittivity, conductivity and radial frequency, respectively. The exponential attenuating wave expression is one of the simplest underwater propagation models is used in UWC. Thus, underwater channel co-efficient can be expressed as [4]

$$h_{rd} = k A_0 e^{-\alpha_0 d_{rd} \sqrt{f}}, \tag{2}$$

where A_0 and α_0 represent the model parameters and d_{rd} represents the distance between SB and AUV. We have used two different experimental values for α_0 from the work [4]. Table 01 shows the computation of $\alpha_0 r$ based on two different seawater mediums, i.e., Water 1 - seawater from near region of coastal area and water 2 - seawater from non-shallow area of the sea.

Medium	α_0	**Distance**	$\alpha_0 r$
Water 1	0.0824	5 m	0.412
Water 1	0.0824	10 m	0.824
Water 1	0.0824	20 m	1.648
Water 2	0.09304	5 m	0.4652
Water 2	0.09304	10 m	0.9304
Water 2	0.09304	20 m	1.8608

TABLE I: The value of $\alpha_0 r$ with related to α_0 and communication distances.

III. System Performance Analysis

1) First-Hop (Base-station to floating relay, terrestrial link): During the first-hop, the base station transmits the BPSK modulated signal for $T(\tau + 1)/2$ time, using power P_s from its power supply. The amount of RF energy harvested by the SB node

$$E_{RF} = \eta P_s h_{sr}^2 \tau T, \tag{3}$$

where $0 < \eta < 1$ represents the energy harvesting efficiency at the SB's receiver. The received signal at the SB during the transmission block is given by

$$y_{sr} = \sqrt{P_s} h_{sr} x(t) + n_{at} + n_{sr}, \tag{4}$$

where P_s denotes the transmitted signal power from the base station, $x(t)$ represents the normalized BPSK modulated signal with the value $E\{x(t)\}$ and n_{at} represents the antenna noise at the SB. SNR at the SB node can be expressed as

$$\gamma_{sr} = \frac{P_s h_{sr}^2}{(\sigma_{SB}^2 + \sigma_{sr}^2)}, \tag{5}$$

where σ_{SB}^2 indicates the antenna noise variance of the SB receiver.

2) Second-Hop (Floating relay to AUV, underwater link): For the second hop UWC, the total transmission power at the SB is the sum of the power from RF and solar energy harvesting. Thus, transmission power for a duration of $T(1 - \tau)/2$ at the SB can be expressed as

$$P_r = \frac{2(E_{RF} + E_{solar})}{(1 - \tau)T}, \tag{6}$$

where E_{solar} represents the energy harvested through solar power during the time period $T\tau$. Receive signal at the AUV can be expressed as

$$y_{rd} = \sqrt{P_r} h_{rd} \widetilde{x} + n_{AUV} + n_{rd}, \tag{7}$$

where $\widetilde{x}$ denotes the re-modulated BPSK symbol by the DF protocol. The SNR of the remaining portion of the information signal useful for ID can be written as

$$\gamma_{rd} = \frac{P_r h_{rd}^2}{(\sigma_{AUV}^2 + \sigma_{rd}^2)}, \quad (8)$$

where σ_{AUV}^2 represents the antenna noise at the AUV receiver.

IV. System Performance Analysis

In this section, we evaluate outage probability and ergodic capacity of the proposed system. The ergodic capacity (C) of the proposed system is the average of the rate of the communication links, base station-SB and SB-AUV. This can be represented as

$$C = \mathbf{E}(min(R_{sr}, R_{rd})), \quad (9)$$

where E(.) indicates the expectation operator. The rates R_{sr} and R_{rd} can be written as

$$R_{sr} = [log2(1 + P_s|\widetilde{h}_{sr}|^2/(\sigma_{SB}^2 + \sigma_{sr}^2))][(1-\tau)T/2], \quad (10)$$

$$R_{rd} = [log2(1+P_r|\widetilde{h}_{rd}|^2/(\sigma_{AUV}^2+\sigma_{rd}^2))][(1-\tau)T/2]. \quad (11)$$

In the third time slot $(1-\tau)T/2$ as illustrates in Fig. 2, SB forward the receive information from the base station to AUV. The outage event at the AUV for the split information signal by the PS protocol can be expressed as

$$[OE(\gamma_{sr})] \cup [OE^c(\gamma_{sr}, 2R) \cap OE(\gamma_{rd}, 2R)], \quad (12)$$

where OE^c represents the complimentary outage event of the base station to SB link. Thus, outage probability of the proposed system can be obtained from

$$P_{out} = \int_0^{\frac{2^{2R}-1}{P_r}} \left(1 - exp\left(\frac{zP_s - (2^{2R}-1)}{P_r h_{rd}^2}\right)\right) \frac{1}{h_{sr}^2} exp\left(\frac{-z}{h_{sr}^2}\right) dz, \quad (13)$$

where R represents the transmission rate in bits/sec/Hz. By solving the above integral, outage probability of the proposed system can be approximately expressed as

$$P_{out} \approx (2^{2R}-1)\left[\left(\frac{\sigma_{sr}^2 + \sigma_{SB}^2}{P_s h_{sr}^2}\right) + \left(\frac{T(1-\tau)(\sigma_{rd}^2 + \sigma_{AUV}^2)}{4(E_{RF} + E_{solar})h_{rd}^2}\right)\right]. \quad (14)$$

V. Simulation Results

In the simulations, we have used two different water mediums with the signal frequency of 1 MHz and water medium 1 has less noise compared to the water medium 2. Underwater channel model parameters A_0 and α_0 were computed as per Table 01. We set the noise power spectral density (PSD) value as $N_0 = -165dBm/Hz$. Also we have used different distances between SB and AUV, i.e., 5m, 10m, 20m and 30m and investigated the differences in BER and outage probability.

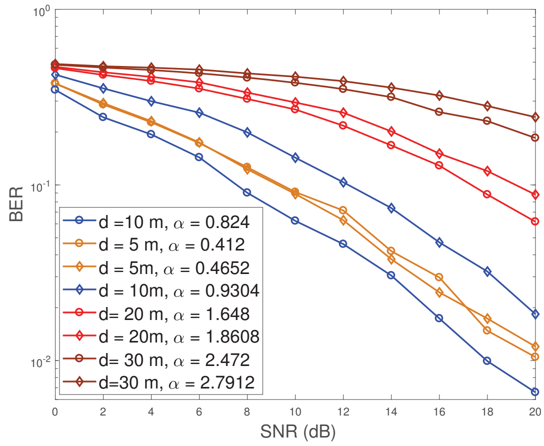

Fig. 3: Comparison of BER value at the AUV in signal frequency of 1 MHz over different distances between the SB and AUV.

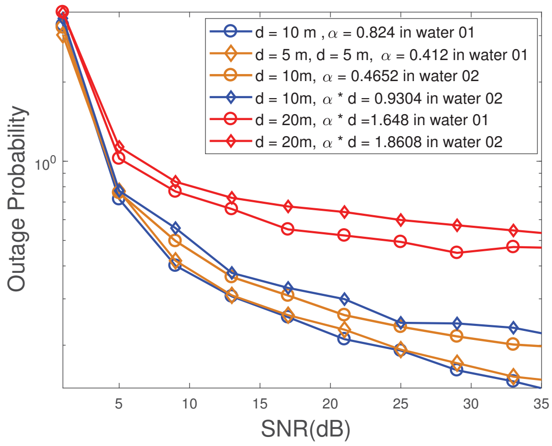

Fig. 4: Comparison of outage probability at the AUV in signal frequency of 1 MHz with related to different distances between the SB and the AUV.

In Fig. 3, we present the BER curves of the considered UWC model in relation to different depths of water 1 and 2. It can be seen that the BER of 10 m in water have the lowest error rate as compared to the that of 5 m in both water 1 and 2. It is due to the fact that water in 5 m depth appears to have more scatter effects than water in 10 m depth. This can be explained by the fact that there is less noise at a depth of 10 m than closer to the surface [12]. However, the amount of noise increases after the depth of 10 m and maintain the BER values without showing any deviations from what we expected. In Fig. 4, we have demonstrated the outage probability of the proposed model. Here outage probability increased with the SNR without showing any anomalies in both water 1 and 2. It is also can be observed from the Fig. 4 that lowest outage probability achieved in the depth of 10m. Thus, jointly considering the results depicted in Fig. 3 and Fig. 4, RF-EM

UWC can be used effectively with RF-EH techniques as it improves energy awareness of UWC.

VI. Conclusion

This paper provides a performance analysis of hybrid RF terrestrial and underwater communication scenario together with RF energy harvesting (EH) techniques, in which surface buoy (SB) self-powered through solar energy and RF-EH. Harvested energy through solar and RF-EH used by the SB to forward information to the autonomous underwater vehicle. We investigated the outage probability and the bit error rate to identify proposed systems performance. The simulation results validated the theoretical analysis and it is shown that RF can be used in UWC up to 20-30m distance underwater while guaranteeing the minimum QoS. The proposed system can be deployed in large water reservoirs or in shallow sea areas to communicate with operational AUV assigned to different underwater operations such as underwater environment monitoring, military operations etc.

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