# Energy Efficient Wake-Up Solution for Large-Scale Internet of Underwater Things Networks

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***Abstract*—Underwater monitoring and exploration have enhanced significantly due to the wide adoption of Internet of Underwater Things (IoUT). However, IoUT implementation is limited by batteries that require frequent replacement, which is costly and unfeasible due to the hostile aquatic environment. Therefore, it is crucial to implement an energy-efficient solution that maximizes the lifetime of IoUT devices, and hence reduce the overall cost of the system. Therefore, we propose the use of on-demand wake-up radios, where IoUT devices are activated upon receiving a wake-up call from the deployed surface buoys via different communication approaches (i.e., acoustic, optical, and magnetic induction). To analyze the performance of the proposed wake-up scheme, we derive an analytical-based solution for both the success and false wake-up probabilities for the different underwater communication techniques. Finally, we evaluate the performance of the proposed scheme under different design parameters and highlight the wake-up-based solution's gain.**

***Index Terms*—Internet of Underwater Things (IoUT), wake-up Radio (WuR), energy efficiency, stochastic geometry.**

## I. Introduction

THE recent advancement in underwater wireless communication networks prompted the interest in the development of Internet of Underwater Things (IoUT) technologies to enable a wide variety of applications such as monitoring, exploration, and underwater navigation [1]. IoUT networks consist of spatially distributed systems, with network sizes ranging from a few to thousands of sensor nodes capable of sensing, data processing, and wireless communication.

IoUT networks can employ radio, optical, acoustic or magnetic induction (MI) signals for communication. Although Radio frequency (RF) transmissions have been the main means for communication in terrestrial applications, RF waves get absorbed in underwater environments. Thus, acoustics have been the prime choice for IoUT due to their low attenuation rate, which allows the acoustic signal to cover long ranges [2]. However, acoustic waves have severe bandwidth limitations, and suffer from latency and low propagation speed. Optical signals, on the other hand, provide high bandwidth and low latency due to the high propagation speed [3]. However, optical signals suffer from absorption, scattering, and is highly affected by the water type. Similarly, MI signals provide low latency as it can propagate with relatively high speeds. Furthermore, unlike optical signals, MI waves are insensitive to the water type, however the attenuation of MI signals in the underwater medium is more severe than that of optical waves.

From a network lifetime point of view, a critical issue is the energy conservation of the IoUT nodes. IoUT devices are mostly battery operated and are often deployed in harsh underwater environments, which has a substantial impact on the network lifetime as replacing batteries is extremely challenging [4]. To achieve longer battery life of IoUT devices, a common method employed is duty-cycling (DC) [5]. In duty-cycling, the IoUT devices listen to the channel for potential incoming communications turning their radios on periodically, and remaining in sleep mode the rest of the time, with minimal energy consumption. The duty cycling solution, though simple, is not adapted for IoUT devices, generally characterized with infrequent transmissions. Other power-saving techniques include routing, Medium Access Control (MAC) protocols, energy harvesting and wake-up radio (WuR) [4], [6]–[8]. WuR has attracted major attention recently as it significantly reduces the consumption of energy. When the WuR solution is applied, the IoUT devices are put asleep and are only activated after receiving a wake-up call (WuC) signal from the transmitter. The WuR enables a more energy-efficient approach compared to duty-cycling, due to the elimination of the useless idle periods of the IoUT node [9].

In this work, we focus on the WuR solution as a means to reduce energy consumption of an IoUT device and present an analytical framework that uses tools from stochastic geometry to study its performance in large-scale IoUT networks. In the literature, several energy efficiency solutions were proposed based on the WuR technology [10]. However, these solutions have not been considered comprehensively yet for enhancing the power efficiency of IoUT networks; they have been widely used in terrestrial Internet of Things, with notable research advancements in hardware design for RF wake-up receivers [11].

Nevertheless, few solutions have been developed to address the sustainability of IoUT devices using the WuR technology [12]–[14]. For instance, the authors in [12] present the design of an efficient underwater acoustic node for long-lasting environmental monitoring in fish farming. The lifetime of the designed node in [12] is extended through the use of both the energy harvesting and wake up mechanisms. The work in [14] proposes the design of a wake-up signal based on the m-sequence for acoustic IoUT networks with low signal-to-noise-ratio (SNR) and small Doppler shift.

In view of prior work, most of the proposed solutions in the literature focus on designing efficient wake-up receivers and wake-up signals to reduce the energy consumption of a specific IoUT device without considering the impact of the proposed designs on the overall lifetime of the large-scale IoUT network. To the best of the authors' knowledge, this is

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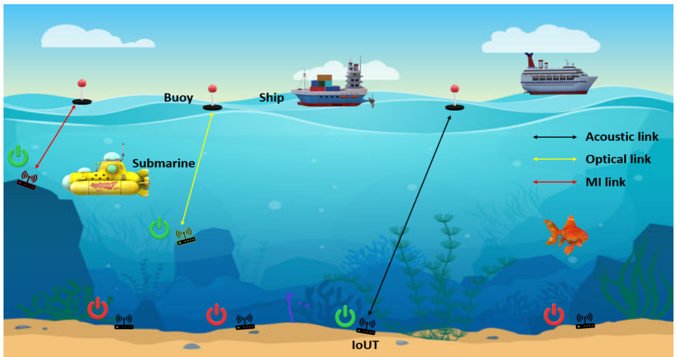

Fig. 1: An IoUT devices with different wake-up schemes.

the first work that bridges this gap by developing a tractable analytical framework using stochastic geometry to evaluate the performance of the WuR solution in large-scale IoUT networks. In this work, we model a large IoUT network where IoUT devices are equipped with the WuR solution and are only activated after receiving WuC signals from surface buoys. Using stochastic geometry, we derive tractable expressions for two main performance metrics, namely the success wake-up probability and the false wake-up probability and we study the effect of different system parameters. Furthermore, we consider acoustic wake-up, optical wake-up and MI wake-up for IoUT devices and highlight the differences and challenges for each technology. Finally, we investigate the energy efficiency gains of implementing the WuR solution in IoUT networks.

## II. SYSTEM MODEL

In this section, we discuss the proposed network model as depicted in Fig. 1. Furthermore, we highlight the different channel models used in this work.

### A. Network Model

The network models consists of IoUT devices arranged according to a homogeneous Poisson point process (PPP) $\Phi_s = \{\mathbf{x}_i\}$ with spatial density $\lambda_s$, where $\mathbf{x}_i \in \mathbb{R}^2$ denotes the location of the $i$-th IoUT device. We assume that all devices are deployed at fixed depth $H$ from the water surface and are initially put in the sleep mode to reduce the energy consumption. Each IoUT device is equipped with a front-end wake-up receiver that activates the IoUT device upon receiving a WuC from a surface buoy. The locations of the buoys are also abstracted with another homogeneous PPP $\Phi_b = \{\mathbf{y}_j\}$ of density $\lambda_b$, where $\mathbf{y}_j \in \mathbb{R}^2$ denotes the location of the $j$-th buoy.

We assume that each IoUT device is associated with its nearest buoy to receive the WuC. Furthermore, we define a successful wake-up event as the case when the IoUT device receives the WuC from its serving surface buoy with sufficient power. On the other side, an IoUT device in the sleep mode might receive unintended WuCs, which may cause undesirable wake-ups and further energy consumption. We denote such event as a false wake-up event, Hence, the performance of the WuR solution for IoUT networks is evaluated in terms of two metrics

1) *The success wake-up probability*: The probability that the received power at the IoUT device from its serving buoy exceeds a predefined power threshold sufficient for triggering the device to switch to the active mode.
2) *The false wake-up probability*: The probability that the received power at the nearest IoUT device to the device of interest exceeds the power threshold, given that this device in not intended to wake-up.

Without loss of generality, we focus on an IoUT device placed at the origin which is allowed by the Slivnyak's theorem []. Furthermore, we evaluate the performance of the WuR solution for three different implementations, namely, acoustic wake-up, optical wake-up and MI wake-up.

### B. Channel Model

*1) Underwater Acoustic Communication Model:* To model the transmission of acoustic signals from the buoy to the IoUT device in the underwater environment, we consider the following attenuation in dB [2]

$$L(d, f) = L_{spr}(d) + d_{km} L_{abs}(f), \tag{1}$$

where $f$ is the frequency of the acoustic signal, $d = \sqrt{||\mathbf{x}_i - \mathbf{y}_j||^2 + H^2}$ is the 3D distance separating the $j$-buoy from the $i$-th IoUT device. Furthermore, the spreading of the acoustic signal in the underwater environment is given by

$$L_{spr}(d) = k\ 10\ log(d), \tag{2}$$

where $k$ is the spreading factor. Also, for frequencies that are larger than few hundred of Hz, the absorption is given by [15]

$$L_{abs}(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 3\times10^{-4} f^2 + 3.3\times10^{-3}. \tag{3}$$

Therefore, the received sound level ($R_{SL}$) is

$$R_{SL} = S_L - L(d, f), \tag{4}$$

where $S_L$ is the transmitted sound level from the buoy. Also, the average intensity ($I_a$) in $W/m^2$ can be written as [16]

$$I_a = \frac{p^2}{\rho\ v}, \tag{5}$$

where $\rho$ and $v$ denote the water density, and sound speed and $p$ is the pressure given by

$$p = 10^{\frac{R_{SL}}{20}} \times 10^{-6}. \tag{6}$$

*2) Underwater Optical Communication Model:* To model the attenuation of the optical signal, we use Beer Lambert's law, which states that the aquatic medium can be described as a combination of absorption and scattering effects, which both vary according to the wavelength $\lambda$. In which $c(\lambda) = a(\lambda) + b(\lambda)$, where $a(\lambda)$, $b(\lambda)$,and $c(\lambda)$ are the absorption, scattering, and extension coefficient, respectively. Hence, the attenuation of the optical signal can be written as

$$I = I_0\ \exp(-c(\lambda) d), \tag{7}$$

where $I_0$ is the transmitted light intensity from the buoy, and $I$ is the received light intensity at the IoUT device receiver

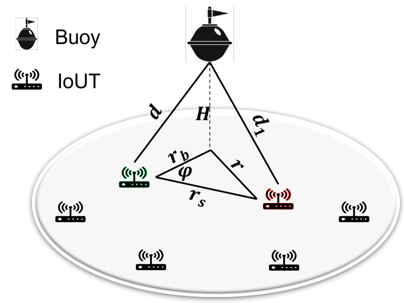


Fig. 2: Visualization of relevant distances.

located at a distance $d$ from the transmitter. Furthermore, to include the geometric loss we use the following [17]

$$P_{r_o} = \frac{2P_0 A_r cos(\beta)}{\pi H^2(1-cos(\theta)) + 2A_t} \exp(-c(\lambda)d), \tag{8}$$

where $A_r$ and $A_t$ are the receiver and transmitter areas at the IoUT device and the buoy, respectively, $\theta$ is the divergence angle, $H$ is the depth, and $\beta$ is the angle between between the trajectory of the buoy and the IoUT device's normal plane.

*3) Underwater MI Communication Model:* For MI wake-up, a coil of wire is used for the transmission/reception of MI signals between the buoy and the IoUT device. The received power of the MI signal depends on the magnetic coil, in which $a_t$, $a_r$ are the radii of the buoy and IoUT device coil, respectively. Hence, the received power is given by [18]

$$P_{r_m} = \frac{\omega^2 \mu^2 N_t N_r a_t^3 a_r^3 cos^2(\beta)}{8d^6} P_t, \tag{9}$$

where $N_t$ and $N_r$ are the number of turns of the buoy and the IoUT device, respectively, $\mu$ is the magnetic permeability, $\omega$ is the angular frequency, $d$ is the propagation distance, and $\beta$ is the angle between the trajectory of the buoy and the IoUT device's normal plane.

## III. SUCCESS AND FALSE WAKE-UP PROBABILITIES

This section presents the derivation of the successful and false wake-up probabilities for the different wake-up schemes in addition to relevant distance distributions.

### A. Relevant Distance Distributions

*1) Typical IoUT Device-Serving Buoy Distance Distribution:* In the proposed network, every IoUT device associates with the closest buoy to receive the WuC signal. The distribution of the distance separating the typical IoUT device from its serving buoy is given in the following lemma.

*Lemma 1:* In an IoUT network where IoUT devices and buoys are modeled as two homogeneous PPPs, the PDF of the 2D distance $r_b$ separating the typical device from the serving buoy is given as

$$f_{R_b}(r_b) = 2\pi\lambda_b r_b \exp\left(-\lambda_b \pi r_b^2\right), \tag{10}$$

where $\lambda_b$ is the density of the buoys PPP.

*Proof:* The cumulative distribution function (CDF) of $r_b$ is obtained using the null probability of the buoys PPP as follows

$$\begin{aligned} F_{R_b}(r_b) &= 1 - \mathbb{P}\left[\text{No buoy is closer than } r_b\right] \\ &= 1 - \exp(-\lambda_b \pi r_b^2). \end{aligned} \tag{11}$$

The probability density function (PDF) is obtained by deriving the CDF expression in (11). ■

*2) Nearest IoUT Device-Serving Buoy Distance Distribution:* In this section, we derive the distribution of the horizontal distance $r$ separating the nearest IoUT device to the typical device from the serving buoy as shown in Fig. 1. The following lemma presents the PDF of the second distance distribution.

*Lemma 2:* In a IoUT network where IoUT devices and buoys are modeled as two homogeneous PPPs, the PDF of the 2D distance separating the nearest device to the typical device placed at the origin from the buoy serving the typical device is given as in (12) at the top of next page, where $\lambda_b$ and $\lambda_s$ are the densities of the buoys and IoUT devices, respectively, and $H$ is the depth of the devices from the water surface.

*Proof:* We denote the distance separating the nearest device to the typical device and the serving buoy as $r$ as shown in Fig. 2. We also denote as $r_s$ and $r_b$ the horizontal distances from the typical IoUT device to its nearest device and to its serving buoy. As both $r_b$ and $r_s$ represent the distances to the nearest point in a PPP, they follow a similar distribution given in (10) and

$$f_{r_s}(r_s) = 2\pi\lambda_s r_s \exp(-\lambda_s \pi r_s^2), \tag{14}$$

where $\lambda_s$ is the density of the IoUT devices PPP. The distance $r$ separating the nearest device from the projection of the serving buoy is given as $r = \sqrt{r_s^2 + r_b^2 - 2r_s r_b \cos\varphi}$, where $\varphi$ is shown in Fig. 2.

To tackle the problem, we apply the following change of variables

$$\begin{cases} r_s = x, \\ r_b = y, \\ \varphi = \cos^{-1}\left(\frac{x^2+y^2-z^2}{2xy}\right). \end{cases} \tag{15}$$

Hence, we can write the Jacobian matrix as in (13) at the top of next page. The joint PDF $f_{x,y,z}(x,y,z)$ can be obtained using the joint PDF $f_{r_s,r_b,\varphi}(r_s,r_b,\varphi)$ and the determinant of the Jacobian in (13) as

$$\begin{aligned} f_{x,y,z}(x,y,z) &= f_{r_s,r_b,\varphi}\left(x, y, \cos^{-1}\left(\frac{x^2+y^2-z^2}{2xy}\right)\right)|J| \\ &\overset{(a)}{=} f_{r_s}(x) f_{r_b}(y) f_{\varphi}\left(\cos^{-1}\left(\frac{x^2+y^2-z^2}{2xy}\right)\right)|J| \\ &\overset{(b)}{=} 4\pi\lambda_s\lambda_b z \frac{\exp(-\pi(\lambda_s x^2 + \lambda_b y^2))}{\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}}, \end{aligned} \tag{16}$$

where (a) follows from the independence of $r_s$, $r_b$, and $\varphi$ and (b) follows from the PDFs of $r_s$ and $r_b$ given in (14) and (10), the determinant of the Jacobian in (13) and from the distribution of $\varphi$ that follows the uniform distribution in $[0,\pi]$. Note that the joint PDF expression is only valid for $x \geq 0$, $y \geq 0$, and $|x-y| \leq z \leq x+y$. Hence, the marginal PDF of the 2D distance separating the nearest IoUT device to the typical device from the serving buoy is obtained from properly integrating the joint PDF in (16) and the final expression is given in (12). ■

$$f_Z(z)=\int_0^z\int_{z-y}^{z+y}4\pi\lambda_s\lambda_b z\frac{\exp(-\pi(\lambda_s x^2+\lambda_b y^2))}{\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}}\,\mathrm{d}x\,\mathrm{d}y+\int_z^\infty\int_{y-z}^{y+z}4\pi\lambda_s\lambda_b z\frac{\exp(-\pi(\lambda_s x^2+\lambda_b y^2))}{\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}}\,\mathrm{d}x\,\mathrm{d}y. \tag{12}$$

$$J=\begin{bmatrix}\frac{\partial r_s}{\partial x} & \frac{\partial r_s}{\partial y} & \frac{\partial r_s}{\partial z}\\ \frac{\partial r_b}{\partial x} & \frac{\partial r_b}{\partial y} & \frac{\partial r_b}{\partial z}\\ \frac{\partial \varphi}{\partial x} & \frac{\partial \varphi}{\partial y} & \frac{\partial \varphi}{\partial z}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ \frac{-x^2+y^2-z^2}{2x^2y\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}} & \frac{x^2-y^2-z^2}{2xy^2\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}} & \frac{z}{xy\sqrt{1-\left(\frac{x^2+y^2-z^2}{2xy}\right)^2}}\end{bmatrix}. \tag{13}$$

### B. Success and False Wake-Up Derivation

In order to have a successful/false wake-up, the received power at the IoUT device should be greater than the threshold. The following theorem presents the successful and false wake-up probabilities.

*Theorem 1:* The successful wake-up probability of the optical-based scheme is given as

$$\mathbb{P}_\omega=1-\exp\left(-\lambda_b\pi(\sigma^2-H^2)\right), \tag{17}$$

where

$$\sigma=\frac{1}{c}W\left[\frac{2HcP_0A_r}{T_o\left(\pi H^2(1-cos(\theta))+2A_t\right)}\right]. \tag{18}$$

*Proof:* The probability that the optical received power is greater than the threshold $\mathbb{P}(P_{r_o}>T_o)$ is given as

$$\begin{aligned}&\mathbb{P}\left[\frac{2P_0A_r\cos(\beta)}{\pi H^2(1-cos(\theta))+2A_t}\exp(-c(\lambda)d)>T_o\right]\\ &\overset{(a)}{=}\mathbb{P}\left[\frac{1}{d}\exp(-c(\lambda)d)>\frac{T_o(\pi H^2(1-cos(\theta))+2A_t)}{2HP_0A_r}\right]\\ &\overset{(b)}{=}\mathbb{P}\left[d<\frac{1}{c}W\left[\frac{2HcP_0A_r}{T_o(\pi H^2(1-cos(\theta))+2A_t)}\right]\right],\end{aligned} \tag{19}$$

where $W(\cdot)$ is the Lambert function. Hence, using the derived distance distribution in (11), we can obtain the successful wake-up probability as shown in (17). ■

*Corollary 1:* The false wake-up probability for the optical-based scheme is

$$\mathbb{P}_f=\int_0^{\sqrt{\sigma^2-H^2}}f_Z(z)\,dz, \tag{20}$$

where $f_Z(z)$ is the derived distance distribution in (12).

*Corollary 2:* The success and false wake-up probability for the acoustic and MI schemes are given, respectively as

$$\mathbb{P}_\omega=1-\exp\left(-\lambda_b\pi(\xi^2-L^2)\right), \tag{21}$$

$$\mathbb{P}_f=\int_0^{\sqrt{\xi^2-H^2}}f_Z(z)\,dz, \tag{22}$$

where $\xi=\alpha$ in the acoustic scheme, and $\xi=\gamma$ for the MI scheme, and their corresponding values are given as

$$\alpha=\frac{10k\cdot W(10^{\frac{S_L}{10k}-\frac{12}{k}-4}\cdot L_{abs}(f)\cdot ln(10)\cdot\sqrt[k]{\frac{1}{v\rho T_a}})}{L_{abs}(f)\times ln(10)}. \tag{23}$$

$$\gamma=\sqrt[8]{\frac{\omega^2\mu^2N_tN_ra_t^3a_r^3H^2}{8T_m}}. \tag{24}$$

## IV. Numerical results

In this section, we will use the derived analytical solution in the previous section to analyze the performance of the proposed wake-up scheme under different set of scenarios.

### A. Performance Analysis

To simulate the performance of the proposed wake-up scheme, we use the parameter values listed in Table I. Fig. 3 illustrates the effect of varying the frequency in the acoustic-based approach, as decreasing the frequency will extend the wake-up range. That is due to the proportional relationship between the frequency and the absorption of the acoustic signal. Furthermore, we can observe the long wake-up range that the acoustic-based scheme offers as opposed to other communication approaches. Also, we can notice the false alarm probability for the given IoUT devices' density, where we can note that the acoustic scheme requires a very sparse network to achieve low false alarm probability due to the low attenuation of the acoustic signal.

in Fig. 4, we present the effect of varying the divergence angle in the optical-based scheme. Ideally, we want a very small divergence angle, however, the movement of water leads to uncertainty in the location of the IoUT devices. Hence, it is necessary to use an adaptive beamwidth to account for the uncertainty in the location of the IoUT devices. Also, it can be noted that the optical-based scheme can achieve low false alarm probability in a medium dense IoUT network due to the high attenuation of the optical signal in the underwater environment.

Fig. 5 shows the effect of varying the coil radius of the transmitter and receiver on the performance of the MI-based system. A large coil radius will enhance the wake-up probability, but it will increase the complexity of the implementation process. Furthermore, it can be seen from the figure that the MI-based scheme can achieve low false alarm probability in a dense IoUT network as the MI signal suffers from more severe attenuation than other communication techniques.

### B. Energy Efficiency Analysis

In this section, we calculate the total energy consumption of the proposed wake-up scheme, which will allow us to study

TABLE I: Simulation Parameters

| Acoustic | | Optical | | MI | |
|---|---|---|---|---|---|
| **Parameter** | **Value** | **Parameter** | **Value** | **Parameter** | **Value** |
| $S_L$ | 190 dB | $P_0$ | 1 $W$ | $P_t$ | 1 $W$ |
| $v$ | 1500 m/s | $A_t = A_r$ | 0.0011 $m^2$ | $N_t = N_r$ | 30 |
| $\rho$ | 1000 $kg/m^3$ | $c(\lambda)$ | 0.151 | $f$ | 75 $kHz$ |
| $T_a$ | -10 dBm [19] | $T_o$ | -53 dBm [20] | $T_m$ | -69 dBm [21] |
| $\lambda_b$ | $1/km^2$ | $\lambda_b$ | $10^{-3}/m^2$ | $\lambda_b$ | $10^{-3}/m^2$ |
| $\lambda_s$ | $0.75/km^2$ | $\lambda_s$ | $10^{-4}/m^2$ | $\lambda_s$ | $10^{-3}/m^2$ |

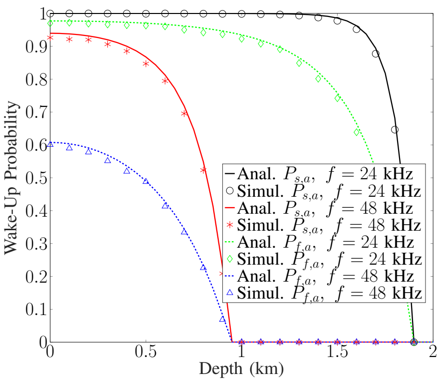


Fig. 3: Success and false probabilities for acoustic-based wake-up scheme.

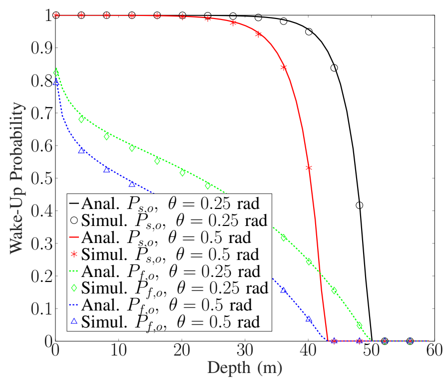


Fig. 4: Success and false probabilities for optical-based wake-up scheme.

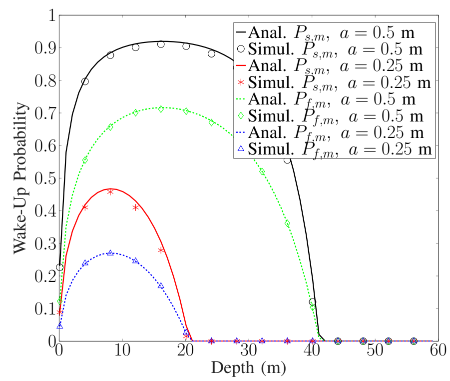


Fig. 5: Success and false probabilities for MI-based wake-up scheme.

the energy efficiency that we gain with this approach. To do that, we consider the optical-based wake-up scheme, in which we have a time-slotted system with a duration of $\Delta t$. To begin with, we calculate the total power consumption of the proposed system in both the active and sleep modes, which are donated as $P_{ON}$, and $P_{sleep}$, respectively, and can be written as

$$P_{ON} = P_{Main\_ON} + P_{WuR\_ON} \tag{25}$$

$$P_{sleep} = P_{Main\_sleep} + P_{WuR\_sleep} \tag{26}$$

Where $P_{Main\_ON}$ and $P_{Main\_sleep}$ are the power consumption of the main IoUT device during the active and sleep modes, respectively, whereas $P_{WuR\_ON}$, and $P_{WuR\_sleep}$ are the power of the added wake-up receiver during the active and sleep modes, respectively. As discussed in Section III, the IoUT device wakes-up successfully when it receives sufficient power ($P_r > T$), which will happen with a probability of $P_s$. Also, it is possible that the IoUT devices may receive a false alarm, and therefore it will have a false wake-up probability of $P_f$. Hence, the total energy consumption of the IoUT device using the wake-up approach with an active time percentage $D_{ON}$ is [9]

$$\begin{aligned} E_{WuR} =& \Delta t \cdot [(P_s \cdot D_{ON} + P_f(1 - D_{ON}))P_{ON} \\ &+ ((1 - P_s)D_{ON} + (1 - P_f)(1 - D_{ON}))P_{sleep}] \end{aligned} \tag{27}$$

To analyze the energy efficiency gain of the wake-up scheme, we compare it with the DC approach, in which IoUT devices are scheduled to wake-up during predetermined periods of time. Therefore, the total power consumption during the active and sleep modes will be the power consumption of the main IoUT circuit. Hence, the total energy consumption of the IoUT device using DC techniques is [9]

$$E_{DC} = \Delta t \cdot [D_{ON} \cdot P_{Main\_ON} + (1 - D_{ON})P_{Main\_sleep}] \tag{28}$$

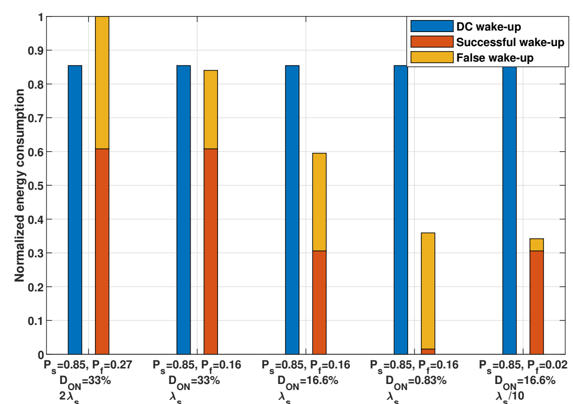


Fig. 6: Energy consumption of the proposed wake-up solution and the duty cycling technique under different settings.

To simulate the performance of the proposed system, we consider a scheduled wake-up system with an active percentage $D_{ON}$ of 33%, while the proposed wake-up solution can have different active percentage values. Furthermore, we consider IoUT devices' density of $\lambda_s$ that is given in Table. I for the optical-based scheme, and sparse network with a density of $\lambda_s/10$, we also consider another dense IoUT network with a density of $2\lambda_s$. Fig. 6 compares the energy consumption of the proposed wake-up scheme with the DC approach. We can notice that the proposed wake-up scheme achieves more energy efficiency especially in IoUT networks with lower active percentage time. Also, we can notice that for lower IoUT devices' densities, the proposed wake-up solution achieves reduction in the energy consumption as compared with the DC system as reducing the IoUT devices' densities will reduce the false alarm probability, and hence reducing the overall energy consumption of the proposed wake-up scheme.

## V. Conclusion

This work proposed the use of wake-up radios to enhance the energy efficiency of IoUT devices. The proposed solution offers on-demand data aggregation, where it will only be activated upon receiving a WuC. Hence it will significantly minimize the energy consumption. Furthermore, we used stochastic geometry tools to derive an analytical-based solution, which allowed us to analyze the performance of the proposed system under different set of scenarios. The obtained numerical results for the different underwater communication approaches showed the viability of the proposed wake-up solution in reducing the overall energy consumption of the IoUT network, especially in IoUT networks with low transmission frequency. Future work need to investigate the use of advanced electronic circuits design that can minimize the false alarm probability while achieving ultra-low power wake-up receivers.

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