ENERGY EFFICIENT WAKE-UP SOLUTION FOR LARGE-SCALE INTERNET OF UNDERWATER THINGS NETWORKS

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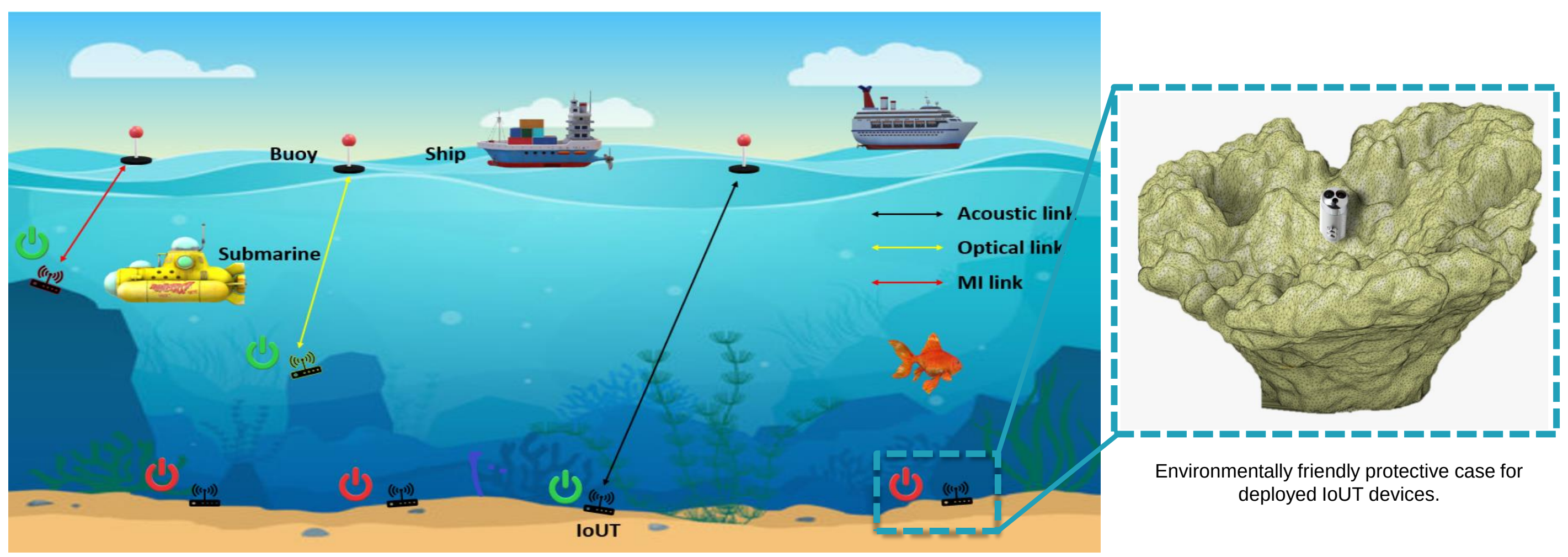
1. INTRODUCTION

- ❖**Internet of Underwater Things (IoUT)** allows **integration of sensing, transmission, and data aggregation,** which will facilitate the exploration of the hostile aquatic environment.
- ❖IoUT devices → battery driven → limited power source → difficult to replenish
- ❖**On-demand Wake-up radio (WuR)** proposed to substitute **Duty Cycling (DC)** to reduce energy consumption.
- ❖Duty Cycling requires regular and frequent wake-up consuming more energy.
- ❖**WuR** → wake-up on demand → significant energy reduction
- ❖A mathematical framework is developed using **stochastic geometry** to analyze **large-scale** deployment.



Environmentally friendly protective case for deployed IoUT devices.

2. ANALYTICAL FRAMEWORK

❖**Performance Metrics:** The proposed solution is validated through large-scale deployment, focusing on the following metrics:

- ❑ **Successful wake-up:** Probability that the IoUT device received enough power from the serving buoy to switch on.
- ❑ **False wake-up:** Probability of the total power at an IoUT device enough to wake it up, when it is not.

❖**Buoys and IoUT Devices Layouts:** Distributed as a homogeneous Poisson point process (PPP), where IoUT devices are denoted by $\Phi_s = \{x_i\}$ with density λ_s, whereas buoys are abstracted by $\Phi_b = \{y_i\}$ with density λ_b.

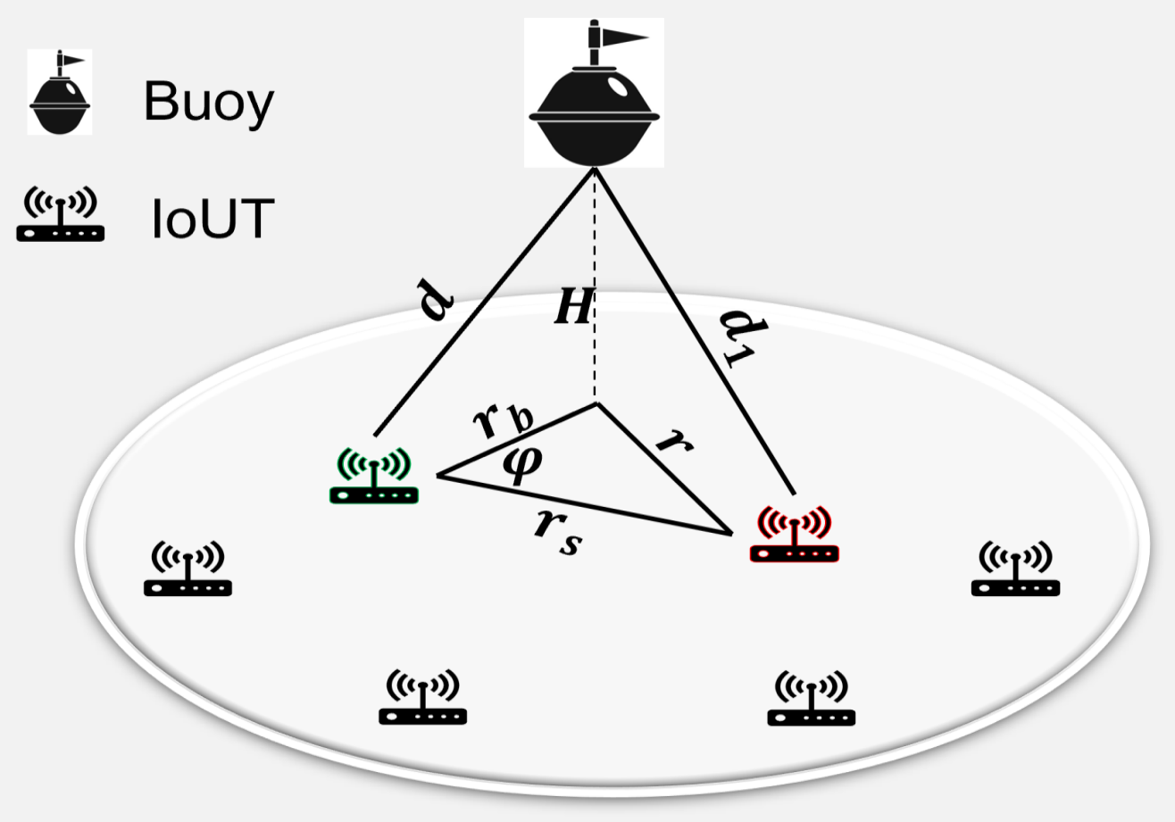
❖**Distance PDF:** The pdf for the 2D distance from the nearest device to the typical device served by a buoy is given as:

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

❖The successful and false wake-up probabilities are given by:

$$P_s = 1 - \exp\left(-\lambda_b\pi(\sigma^2 - H^2)\right) \qquad P_f = \int_0^{\sqrt{\sigma^2 - H^2}} f_Z(z)\, dz$$

where σ varies for acoustic, optical, and MI.



$$\sigma_a = \frac{10k \times W\left[\frac{L_{abs}(f) \times \ln 10 \times \sqrt[k]{\frac{\pi}{v\rho T_a}}}{k \times 2^{\frac{40k - S_L + 100}{10k}} \times 5^{\frac{40k - S_L + 120}{10k}}}\right]}{L_{abs}(f) \times \ln 10}$$

$$\sigma_o = \frac{1}{c(\lambda)} W\left[\frac{2Hc(\lambda)P_0A_r}{T_o\left(\pi H^2(1 - \cos\theta) + 2A_t\right)}\right]$$

$$\sigma_m = \sqrt[8]{\frac{\omega^2\mu^2N_tN_ra_t^3a_r^3H^2}{8T_m}}$$

3. NUMERICAL RESULTS

- ❖**Validation:** Monte-Carlo simulations affirm the analytical expressions for three distinct wake-up schemes.
- ❖**Visualization:** Success probabilities are depicted with solid lines, false probabilities with dashed lines, and simulations with markers.
- ❖**Fig. 1-Acoustic:** Success and false wake-up probabilities are influenced by frequency and device depth, showcasing better range at lower frequencies.
- ❖**Fig. 2-Optical:** Efficiency varies with device depth and beam divergence. Sea dynamics necessitate wider angles to ensure consistent connectivity.
- ❖**Fig. 3 (MI scheme):** Wake-up probabilities benefit from larger coil radii, offering lower false wake-ups in dense networks due to attenuation.
- ❖**Optimization:** Acoustic methods offer range but suffer from higher energy and latency, whereas optical and MI schemes present reduced false probabilities and latency, with some range tradeoffs.

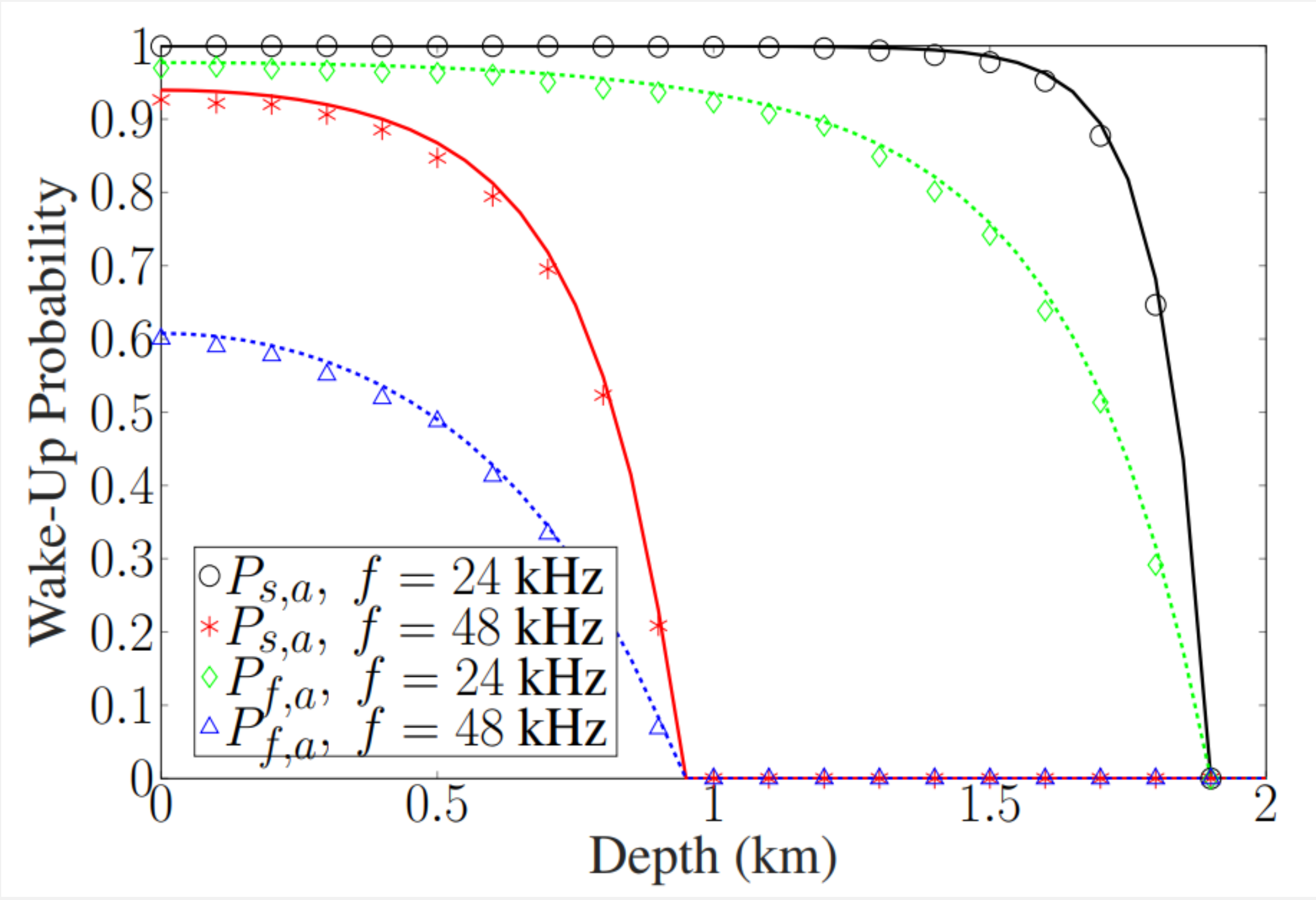


Fig.1. Acoustic success/false probabilities.

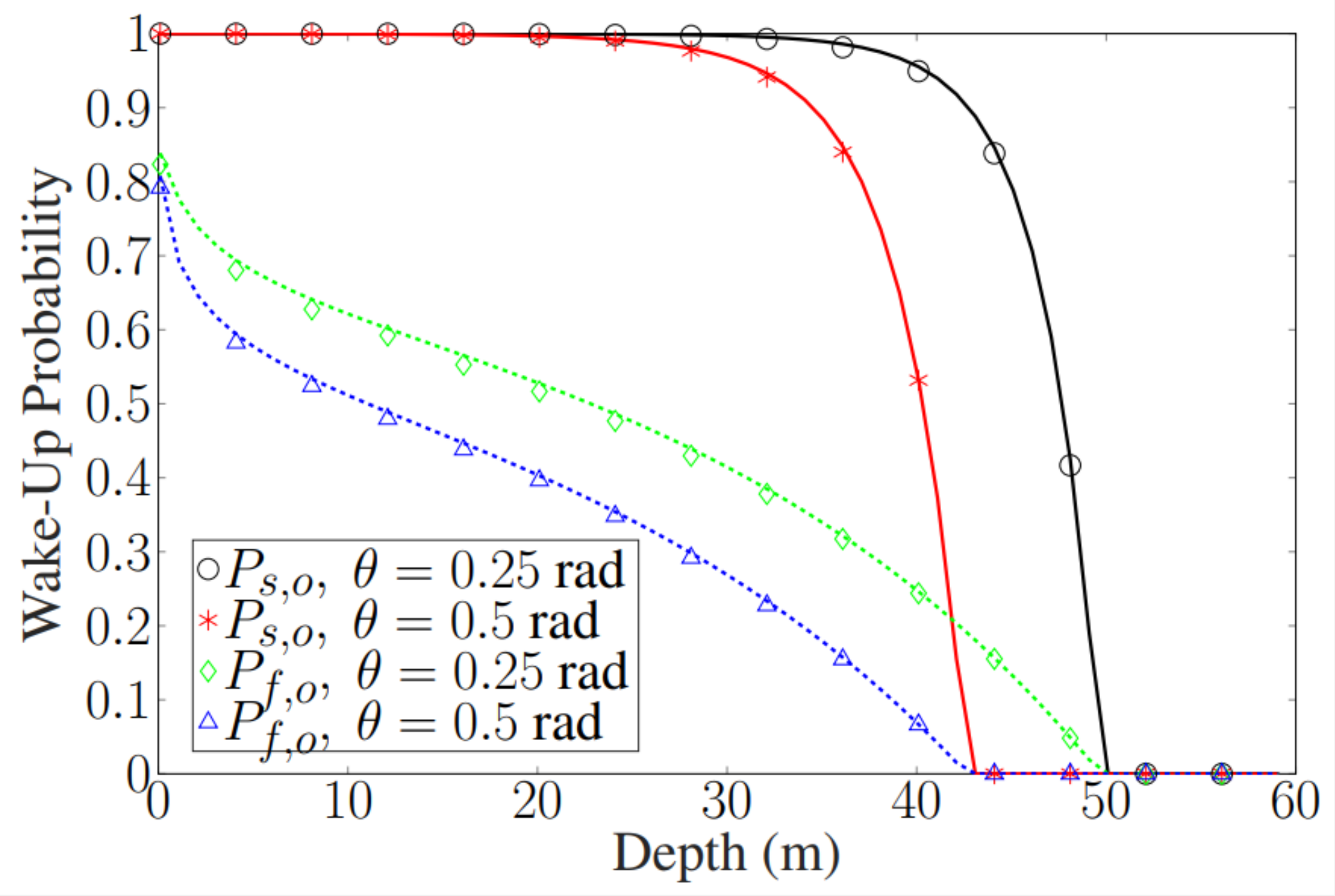


Fig.2. Optical success/false probabilities.

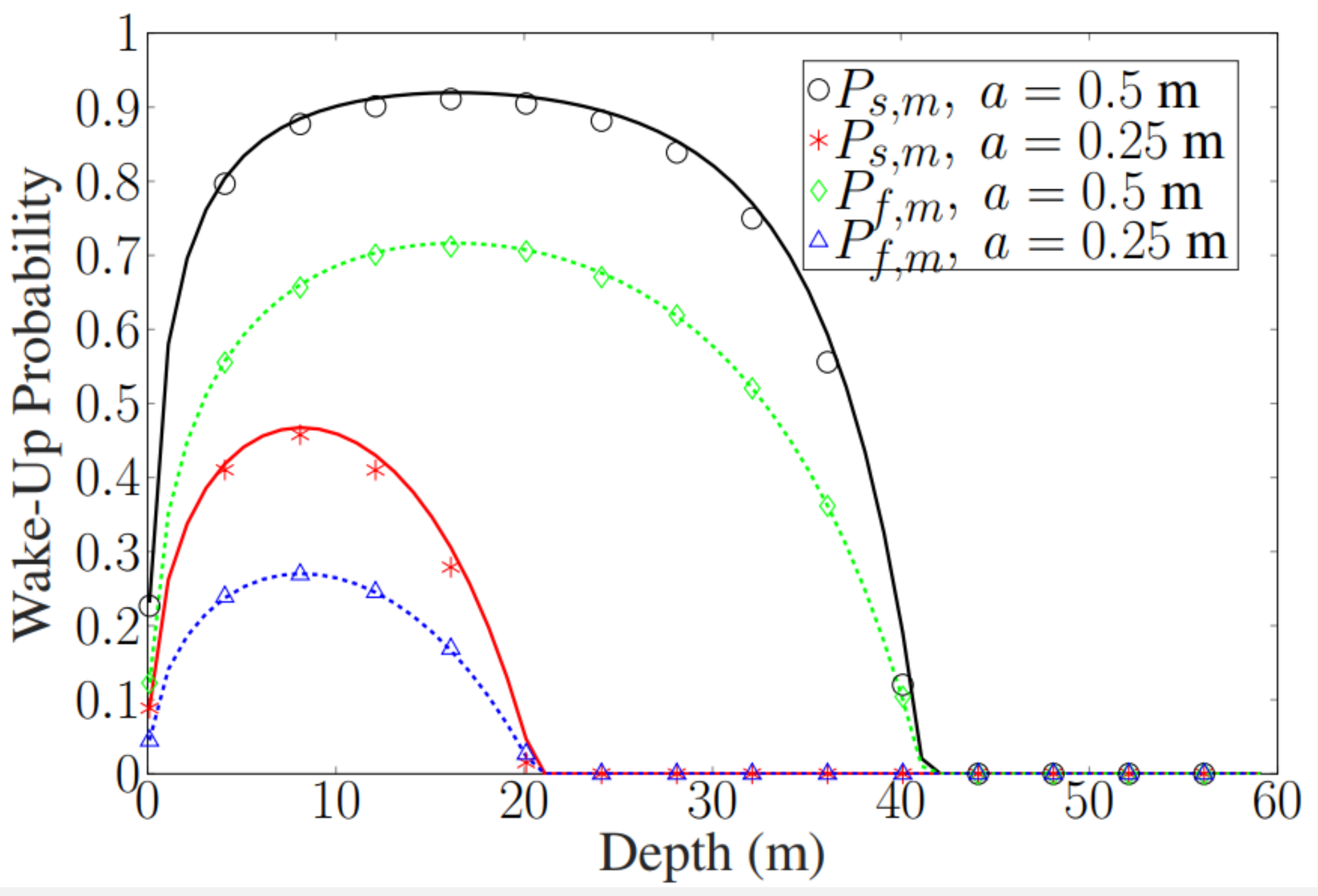


Fig.3. MI success/false probabilities.

4. ENERGY CONSUMPTION ANALYSIS

- ❖We assess the **energy savings** achieved through the implementation of the **wake-up** scheme in contrast to the traditional **Duty Cycling** method.
- ❖The **total energy** consumed by IoUT devices using the wake-up scheme with an active percentage D_{ON} is given by:

$$E_{WuR} = \Delta t \times [(P_sD_{ON} + P_f(1 - D_{ON}))P_{ON} + ((1 - P_s)D_{ON} + (1 - P_f)(1 - D_{ON}))P_{sleep}]$$

- ❖Whereas the total energy consumed by using the **DC** scheme is:

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

- ❖**Wake-Up Scheme:** Lowers energy by activating devices only when needed → Great for networks with lower active percentage time.
- ❖**Duty Cycling:** Devices stay on, consuming more power → Not efficient for energy saving.

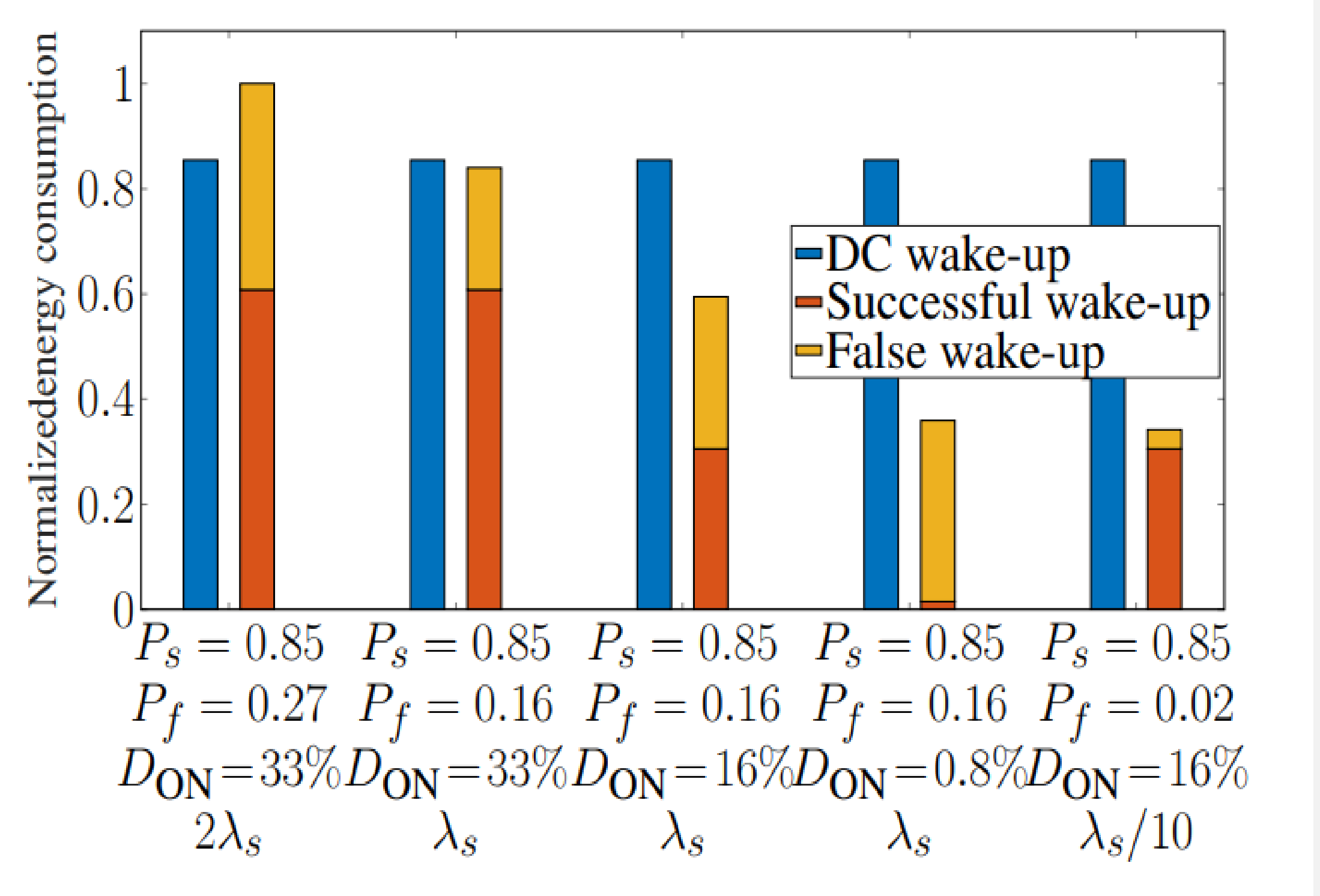


Fig.4. Energy consumption: Optical wake-up and the DC schemes.

- ❖**Network Density:** More devices → Higher energy use when using the wake-up scheme due to higher false alarms.
- ❖**Trade-off:** Wake-up scheme reduces energy use but with a slight risk of missing signals → A balance between saving energy and connection reliability.

5. CONCLUSIONS

- ❑On-demand wake-up solution for IoUT networks.
- ❑Used **stochastic geometry** to craft expressions for success and false wake-up probabilities.
- ❑Evaluated the performance evaluation of large-scale IoUT networks under various conditions.
- ❑The proposed wake-up solution resulted in reduced **overall energy consumption.**

6. FUTURE DIRECTION

- ❑A protective underwater case for submergence and testing in real aquatic environment
- ❑Advanced circuits design for ultra-low power wake-up receivers.
- ❑Explore the use of UAV-aided WuR for inter-medium communications.