6G is Coming

Vehicle-to-everything

E-Health

Extended Reality

Super eMBB

Artificial Intelligence

Industrial IoT

[1] S. Dang, O. Amin, B. Shihada, & M. −S. Alouini, **"What Should 6G Be?"**, Nature Electronics, 2020.

The Global Connectivity Divide

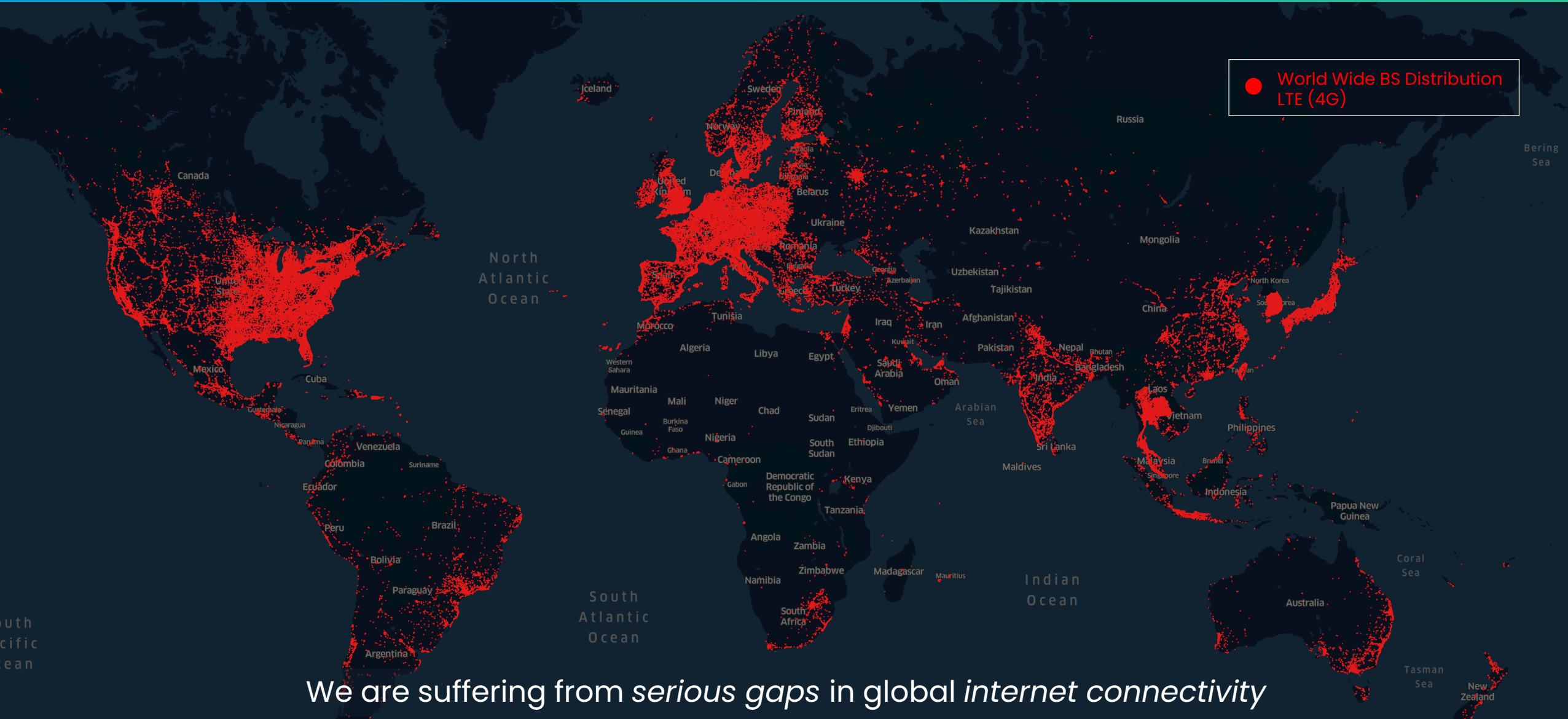World Wide BS Distribution LTE (4G)

We are suffering from *serious gaps* in global *internet connectivity*

E. Yaacoub and M.-S. Alouini, "**A Key 6G Challenge and Opportunity - Connecting the Base of the Pyramid: A Survey on Rural Connectivity**", Proceedings of IEEE, 2020.

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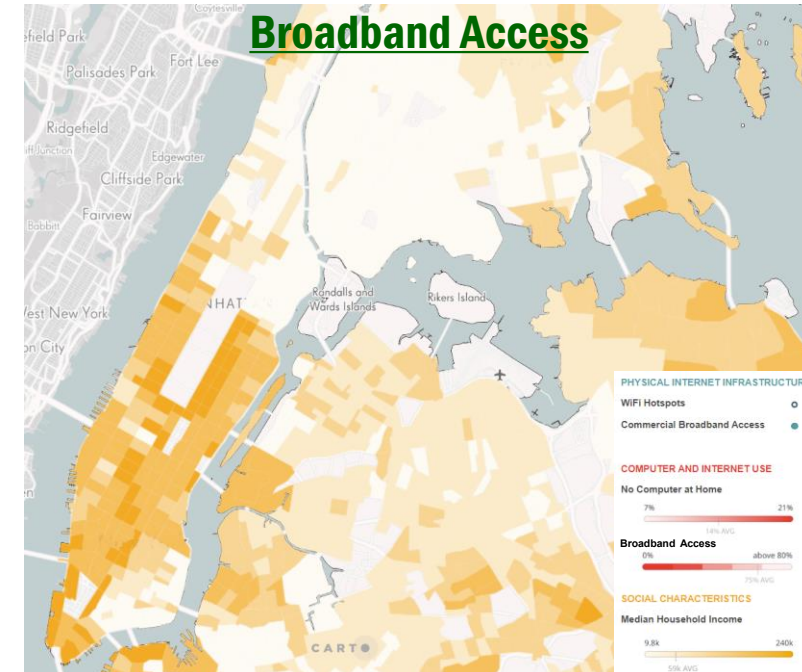King Abdullah University of
Science and Technology

Digital Divide Is Wider Than We Think. *The New York Times*

The Former Homeless Man Bringing Web Access to the Bronx. **BBC**

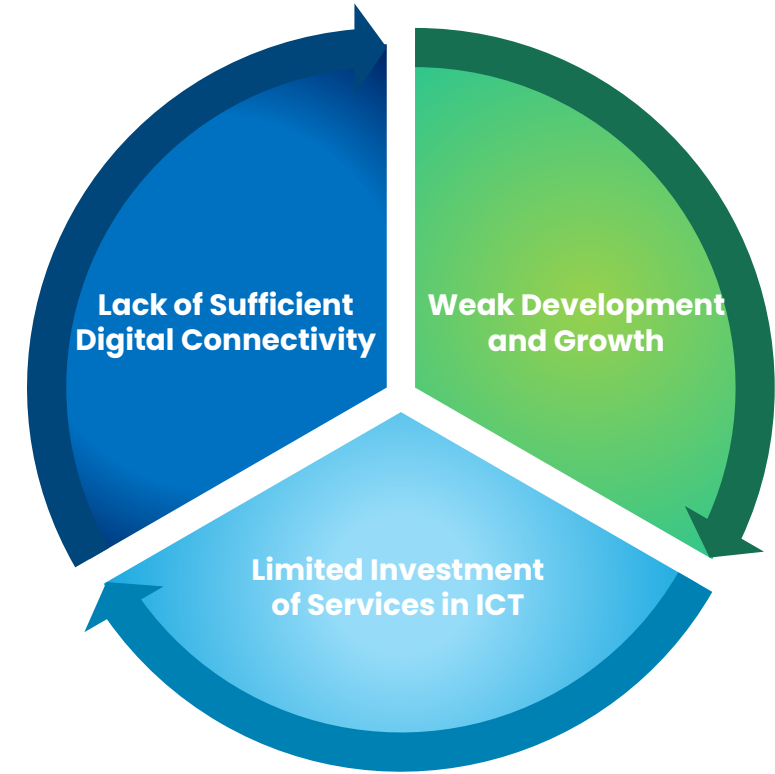Can San Francisco Finally Close its Digital Divide? **SFWEEKLY**
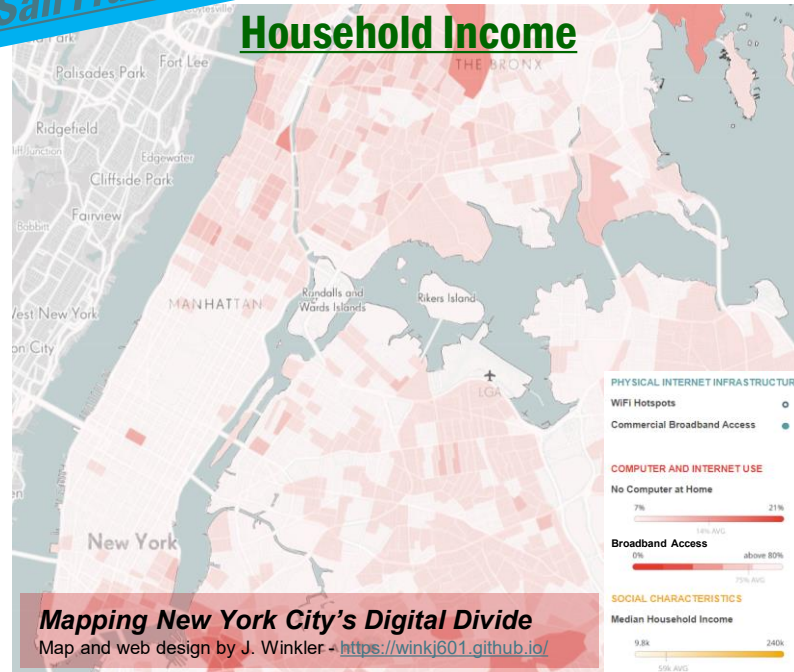
- In communities with low income, the digital disparity is much more profound.
- People who have high-quality internet service are more likely to benefit from health care, self-education and social/governmental services.
- It needs collaboration and agreement among various stakeholders, i.e., government, policy makers, service provider, manufacturer and community members.

Household Income

Broadband Access

VS

Mapping New York City's Digital Divide
Map and web design by J. Winkler - https://winkj601.github.io/

4

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Cooperation
needed to bring
reliable internet
to those without it

Social Barriers

Poor infrastructure

**Low quality of education
for schooling**

Shortage of healthcare

**Lack of Sufficient
Digital Connectivity**

**Weak Development
and Growth**

**Limited Investment
of Services in ICT**

**VICIOUS CYCLE of
DIGITAL DIVIDE**

[1] *E. Yaacoub and M.-S. Alouini,* "**A Key 6G Challenge and Opportunity – Connecting the Base of the Pyramid: A Survey on Rural Connectivity**", Proceedings of IEEE, 2020.

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Sustainability Development Goals (SDGs)

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The United Nations SDGs should **Drive** the evolution of 6G

6G
Inspired by
UN SDGs

6G should target

| Improved **Energy Efficiency** | No Bad Effects on **Environment** & **Human Health** | More **Security** and **Privacy** | Digital **Inclusion** | **Resilience**, **Robustness**, and **Dependability** |

Resilience with On-Demand Pop-up Networking

Exploration

IoT Everywhere

Urban Aerial Mobility/Aeronautical

Disasters

Military Mission

Special Events

Maritime

[1] *M. Matracia, M. Kishk, and M.-S. Alouini,* "**Post-disaster communications: Enabling technologies, architectures, & open challenges**", IEEE Open Journal of Communication Society, 2022.
[2] *F. Alqurashi, A. Trichili, N. Saeed, B. Ooi, and M. -S. Alouini,* "**Maritime communications: A survey on enabling technologies, opportunities, and challenges**", IEEE Internet of Things Journal 2023.

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Global Connectivity Holy Grail

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High

Quality of Experience
(High Data Rate + Low Latency)

Global Connectivity Holy Grail

Optic Fiber Cables

Classic
GEO Satellite

Microwave
Wireless Links

Low

High

Cost per User in Remote Low Population Density Areas

" *A telephone subscriber here may call up and talk to any other subscriber on the **Globe**. An **inexpensive** receiver, not bigger than a watch, will enable him to listen **anywhere**, on **land** or **sea**, to a speech delivered or music played in some other place, however **distant**.*

— **Nikola Tesla 1919**

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Satellite Constellations Backhaul

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Manufacturing Cost Down => Mass Production

Geostationary Earth Orbit (GEO) Satellite
- Fixed position in the sky at ~35,000 km
- Relatively large delay
- ViaSat 1, 2, 3

Medium Earth Orbit (MEO) Satellite
- 2,000~35,000 km
- Position and tracking
- O3B, SES Networks
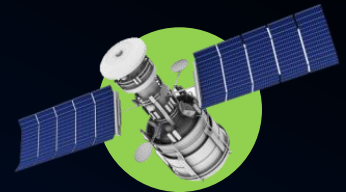
Low Earth Orbit (LEO) Satellite
- 160~2,000 km
- Hand-Over
- OneWeb, Starlink, Lightspeed, Kuiper, GW, G60

Bridging the Educational Divide: A Delay-Tolerant Networking Approach for Equitable Digital Learning in Rural Areas*

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Motivation

01 **Digital Divide**
2.9 billion people with no access to Internet [1].

02 **Digital Learning**
Amid COVID, most learning becomes online.

03 **Internet at schools**
50% of schools is not connected to Internet (UNESCO)[2]

04 **Backhaul Solutions**
Either expensive, or hard to install (Satellite, MW, fiber, etc)
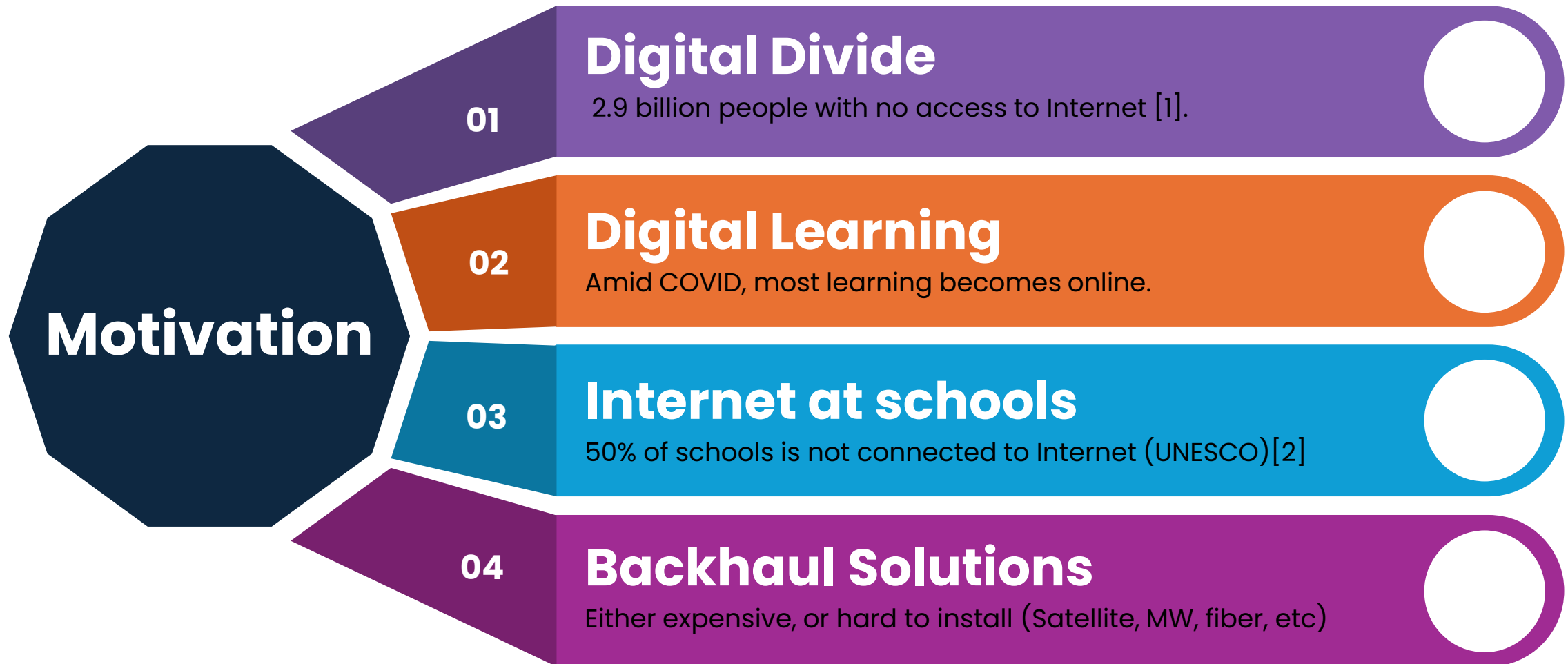
[1] "Global connectivity report - ITU," Apr 2023. [Online]. Available: https://www.itu.int/hub/publication/d-ind-global-01-2022/
[2] "Secretary-general's report on "our common agenda"," 2021. [Online]. Available: https://www.un.org/en/content/common-agenda-report

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DTN-Enabled Digital Learning Platform

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City Network

Mobile DTN node/s
(Data Mules)

Rural Network

DTN server

Internet

Cellular
Network

Digital
Learning
Platform

Update emails, educational
contents, students' records,
etc.

DTN server

Road

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Proof of Concept Deployment

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We designed and built a proof of concept for this system:

Mule node:
Potato AML-S905X-CC

Rural node:
Raspberry Pi 4
+
Power bank

Admin node:
Raspberry Pi 5
+
Power bank

Rural Node

DTN TO BRIDGE THE DIGITAL DIVIDE IN
EDUCATION
CTL LAB @ KAUST

Request

Content List

Search

Search   Clear   Add

Saudi Arabia

KAUST

Super car

Google

Tesla

Request new content
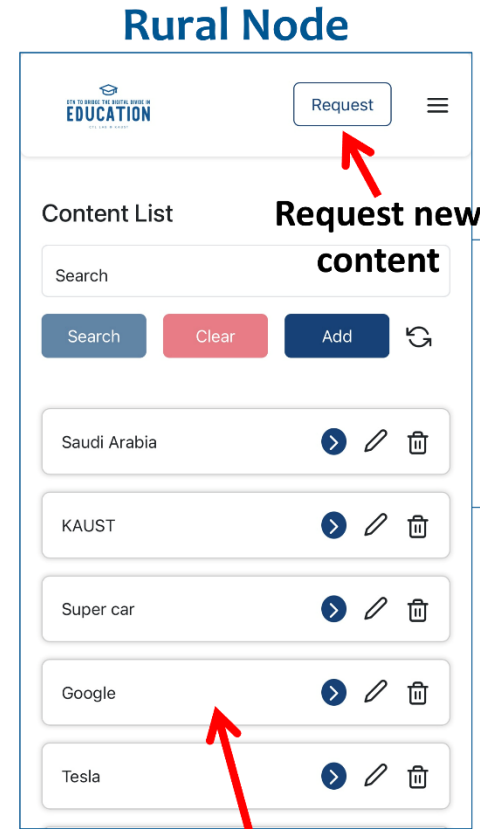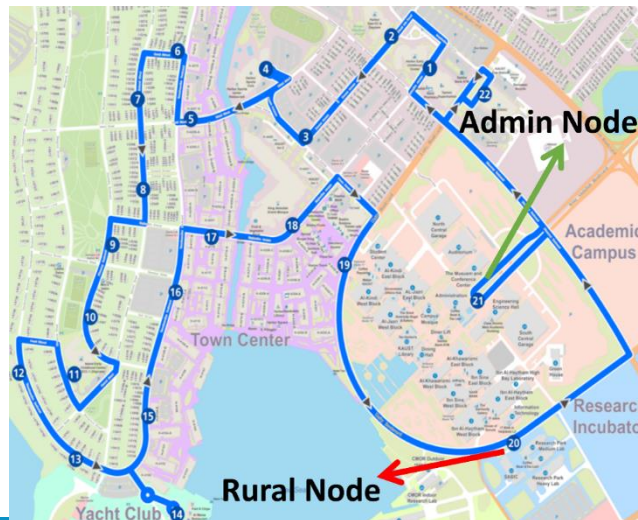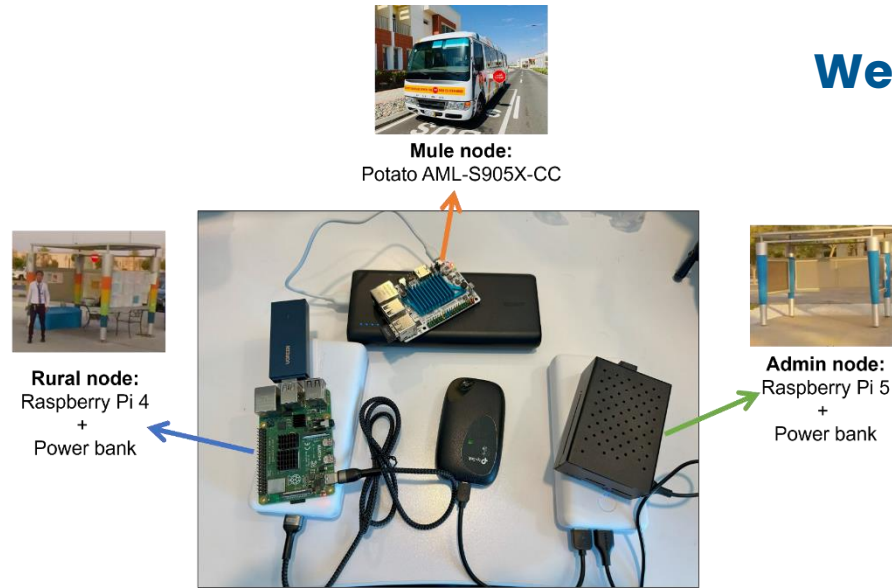
Read and modify available content

DTN TO BRIDGE THE DIGITAL DIVIDE IN
EDUCATION
CTL LAB @ KAUST

Application Logo

Admin Node

DTN TO BRIDGE THE DIGITAL DIVIDE IN
EDUCATION
CTL LAB @ KAUST

Log out

Content list

Requested Content

Settings

Add content manually

Check the requested content

Admin Node

Rural Node

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- Demonstrated a viable approach for digital learning in rural areas with limited or no internet access.
- DTN provides a cost-effective, backhaul-like solution for delivering educational content in remote regions.
- Initial tests on a campus bus using off-the-shelf components showed promising results for text-based content delivery.
- Planned improvements to support multimedia content and support broader community services and connectivity, increasing the system's impact.

Rural Network

Central DTN server

Community Hub

Health Clinic

School

Laser-Based Wake-Up and Wireless Power Transfer

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Laser-Based Wake-Up and Wireless Power Transfer

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Science and Technology
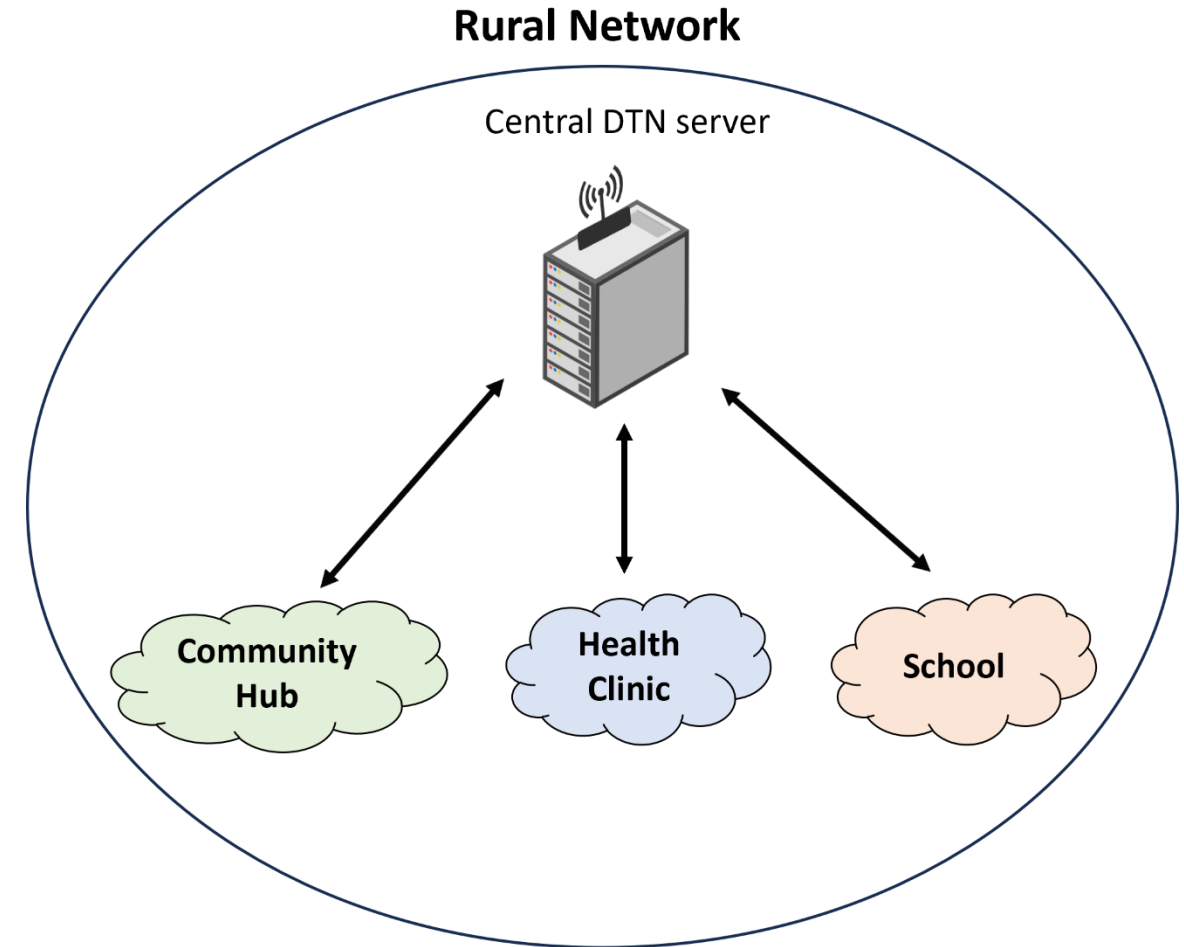
Remote Terrestrial Environments

•Step1: UAV transmits laser energy to wake up and power the ground sensor.

•Step2: The sensor sends collected data to the base station via LoRa.

Step1:Wake Up Sensor and Power Transmitting

Step2: Data Transmission to Base Station by Lora
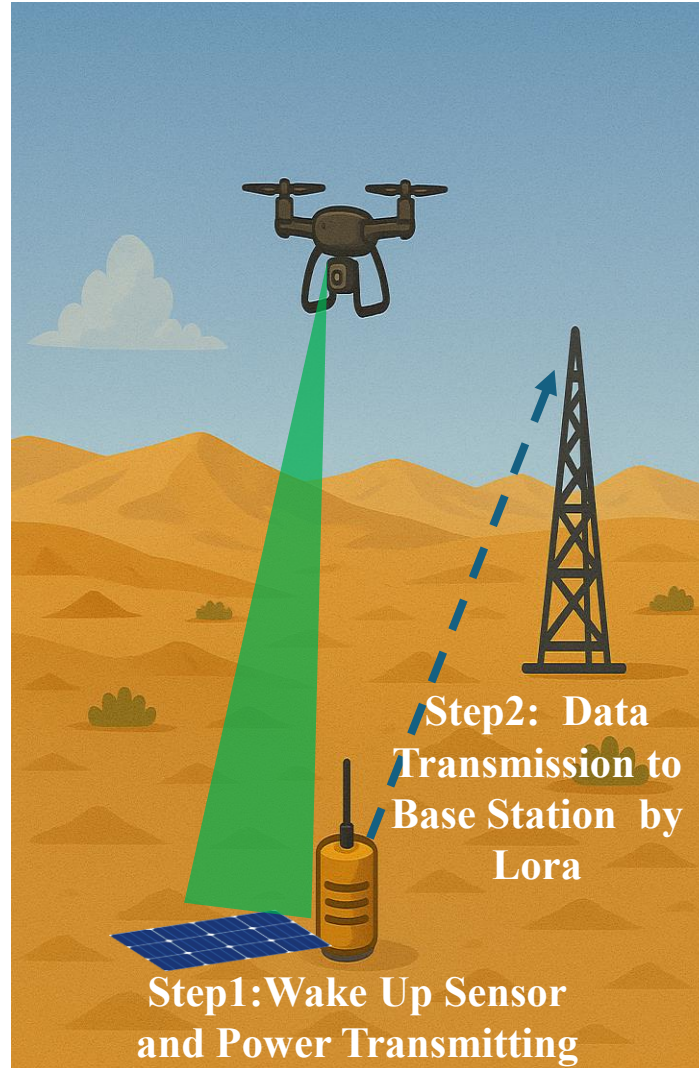
Underwater Environments

•Step 1: UAV delivers laser energy through the water to power the underwater sensor.

•Step 2: Sensor transmits data optically to the UAV.

•Step 3: UAV forwards data to the shoreline base station via LoRa.

Step2: Sensor Data Transmission Though Laser

Step3: Data Transmission to Base Station by Lora

Step1:Wake Up Sensor and Power Transmitting

Laser-Based Wake-Up and Wireless Power Transfer

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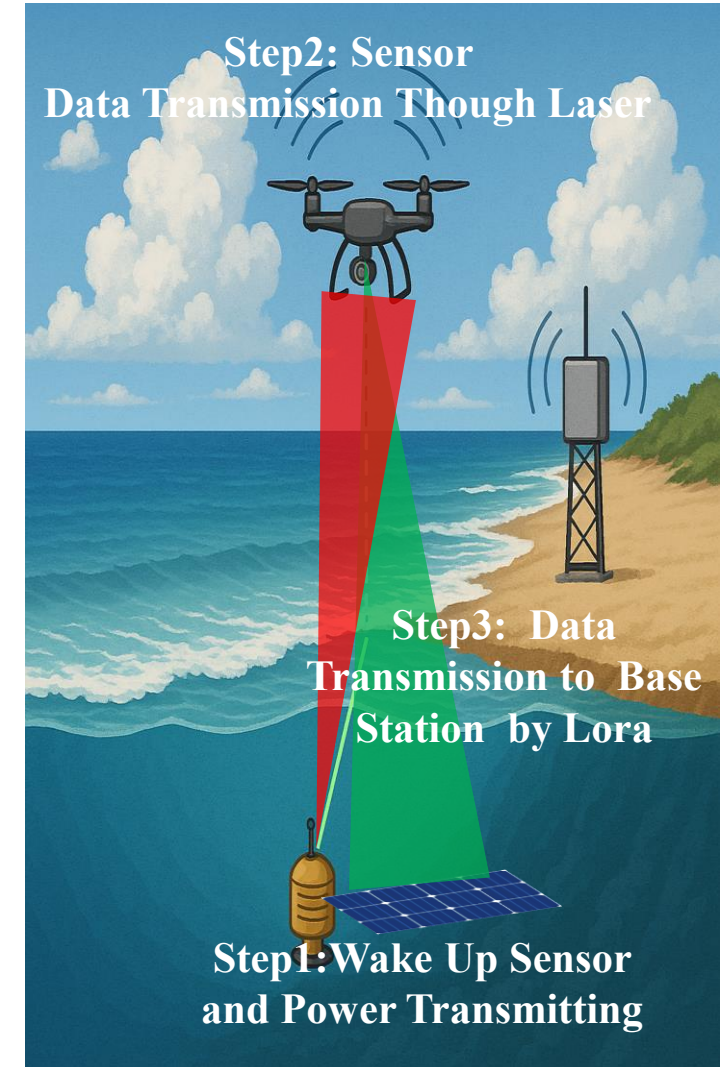
Principle and Implementation

Step1:Wake Up Sensor

Transmitter module

Downlink bits → a_n → iPPM Encoder → $s_{iPPM}(t)$ → Optical Source → Optical Modulator → $P_t s_{iPPM}(t)$ → Underwater Channel

Receiving module

Receive bits ← $\tilde{a}_n$ ← iPPM Decoder ← $y(t) = \eta_r P_t h_1 s_{iPPM}(t) + n_1(t)$

$P_t h_1 s_{iPPM}(t)$ → Optical detector

Electric capacity ← $P_s = \eta_r P_t h_1$ ← Optical detector
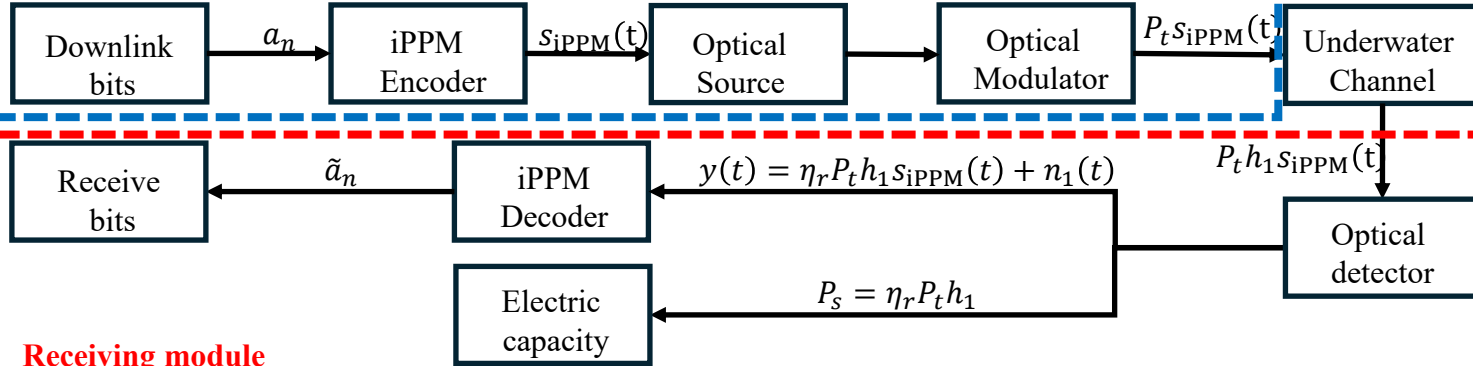
Step2: Sensor Data Transmission

Transmitter module

Uplink bits → b_n → Encoder → $s(t)$ → Optical Source → Optical Modulator → $P_s s(t)$ → Underwater Channel

Receiving module

Receive bits ← $\tilde{b}_n$ ← Decoder ← $y(t) = \eta_r P_t h_1 s(t) + n_2(t)$ ← Optical detector

$P_s h_2 s(t)$ → Optical detector
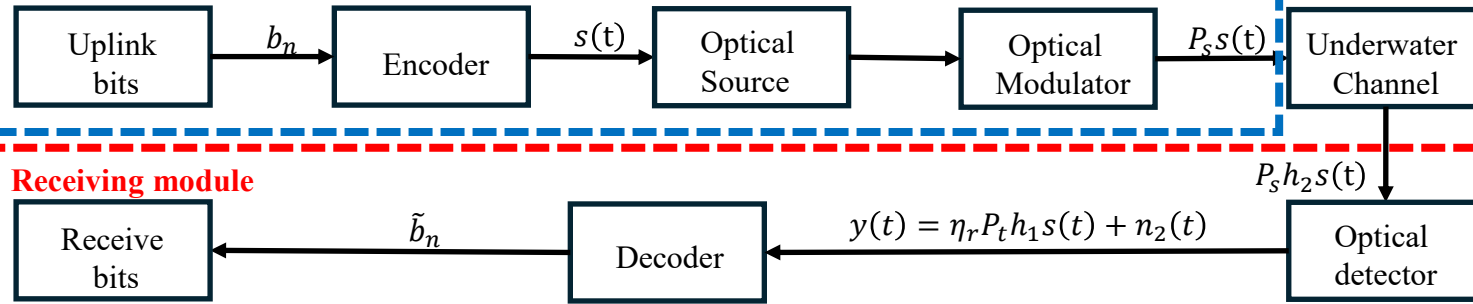
Component	Description
Laser Source	530 nm diode laser, Output power 10 W
Beam Collimator	Lens-based, beam divergence < 2 mrad
Modulation	iPPM
MCU	STM32
Solar Panel (Rx)	efficiency ~20%
Wake-Up Power	-20dBm
Lora Module	range > 2 km (LOS)

Capacitor-Enhanced SolarPanel Communication

Laser Receiver Unit

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Laser Transmitter Unit

Capacitor Energy Storage

Transmitter and Receiver Controller

Indoor experiments ~3m

Transimitter

Receiver

Solar Panel
Receiver

Laser Source

Computer

Oscilloscope
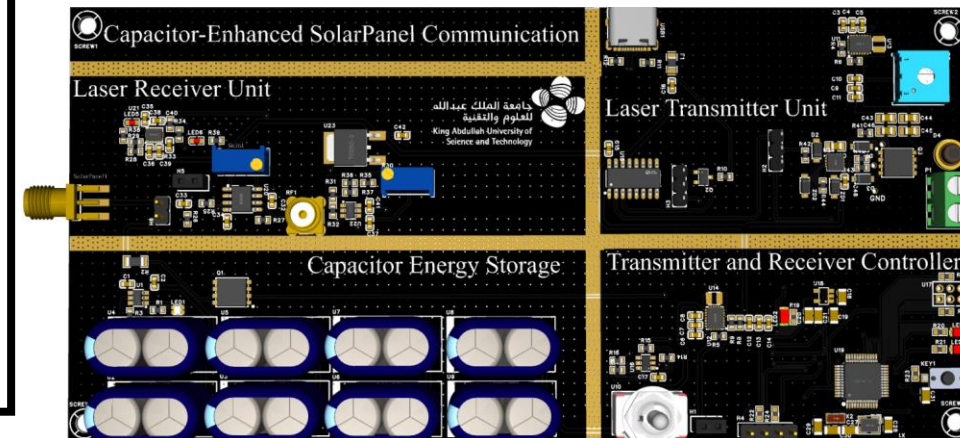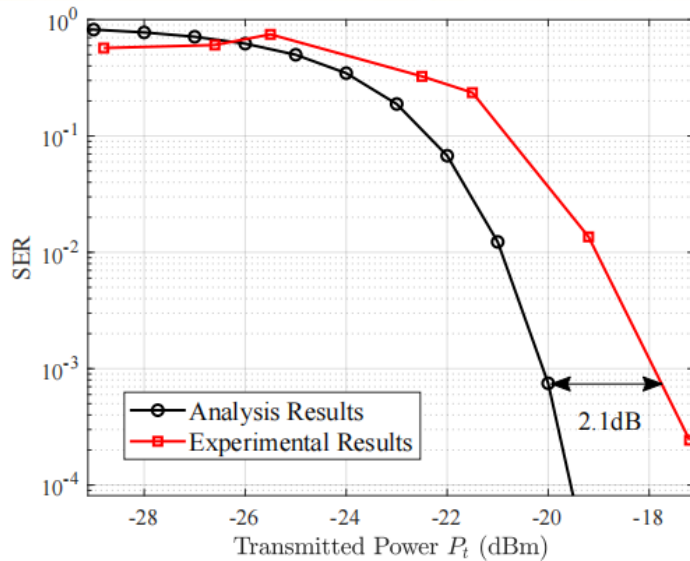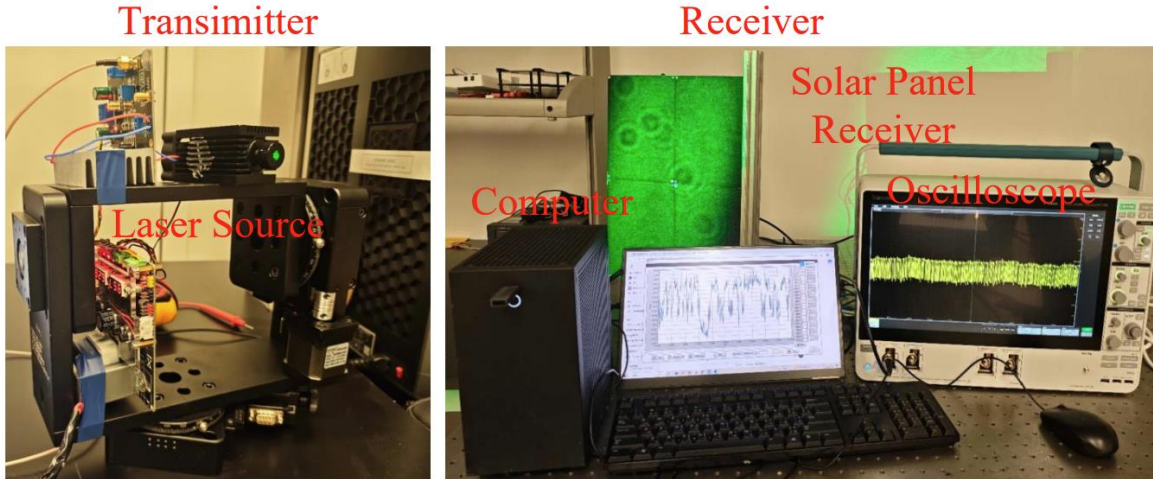
Laser Output Power	Electrical Power Output
1 W	0.14 W
2 W	0.28 W
4 W	0.56 W
5 W	0.70 W

Outdoor experiments ~5km

Paper:

[1] Z. Shi, Y. Zhang, J. Xu, and M.-S. Alouini, "Design and performance analysis of a UAV based capacitor-enhanced solar panel communication system," *Under Review.*

Outdoor experiments ~600m
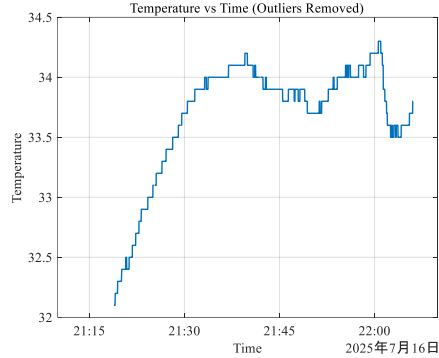
Temperature
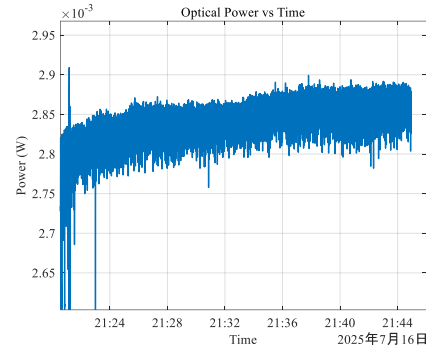
30cm X20 cm
Solar Panel
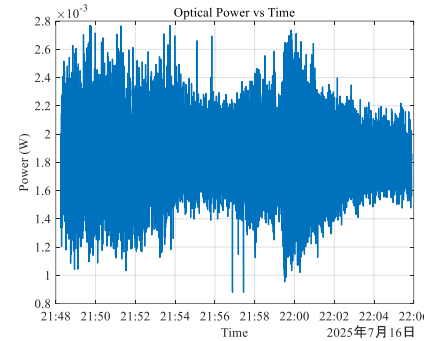
6cm X 6 cm
Solar Panel
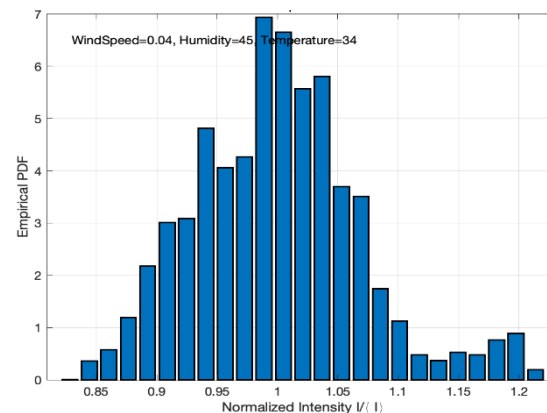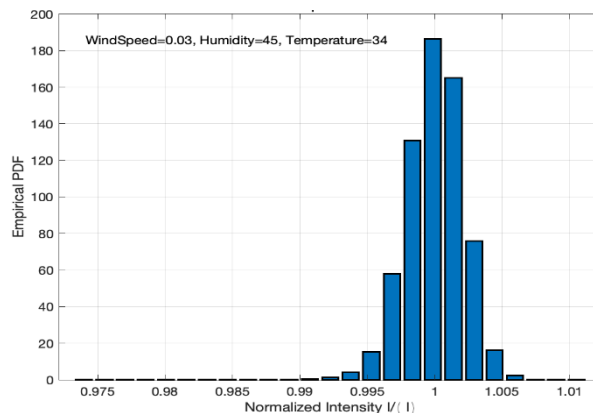
Larger solar panels (30cm × 20cm) demonstrate better resistance to atmospheric turbulence compared to smaller ones.
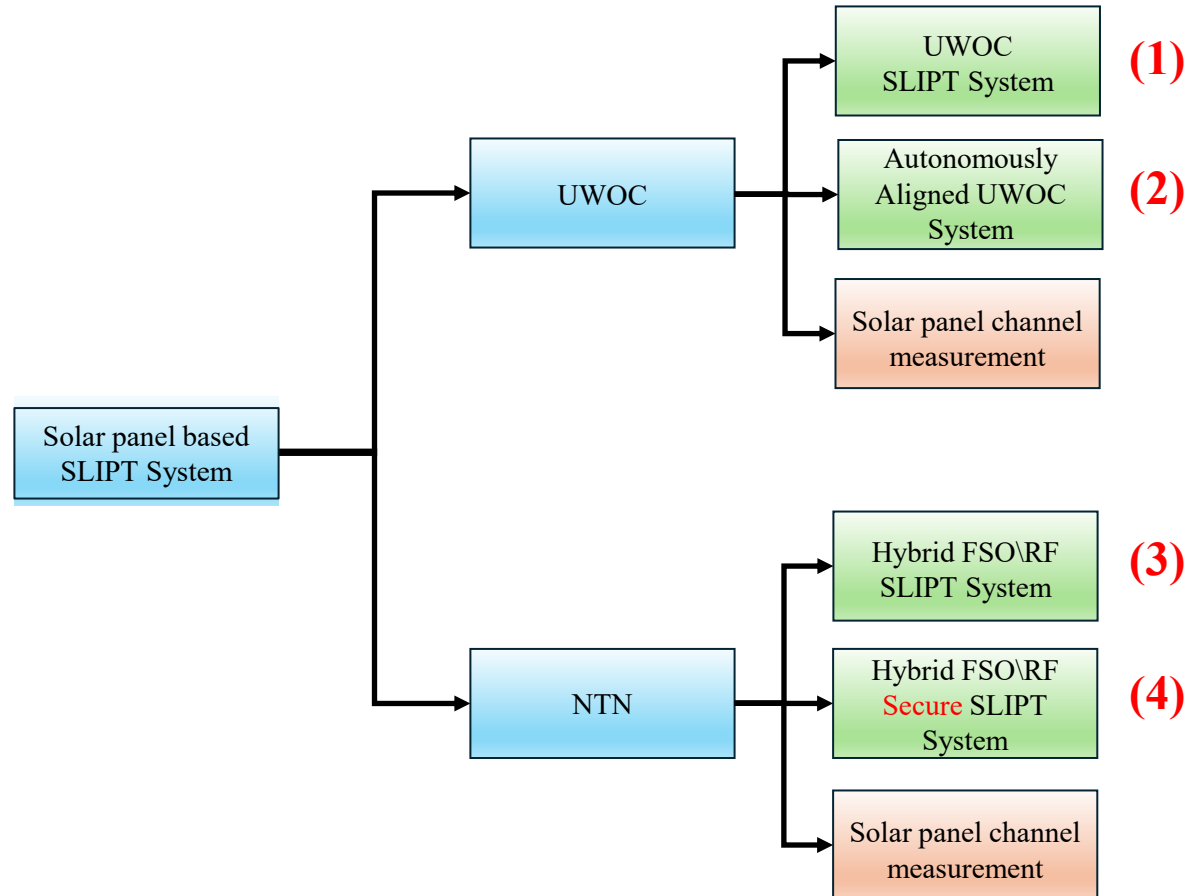
UWOC–SLIPT System (1)
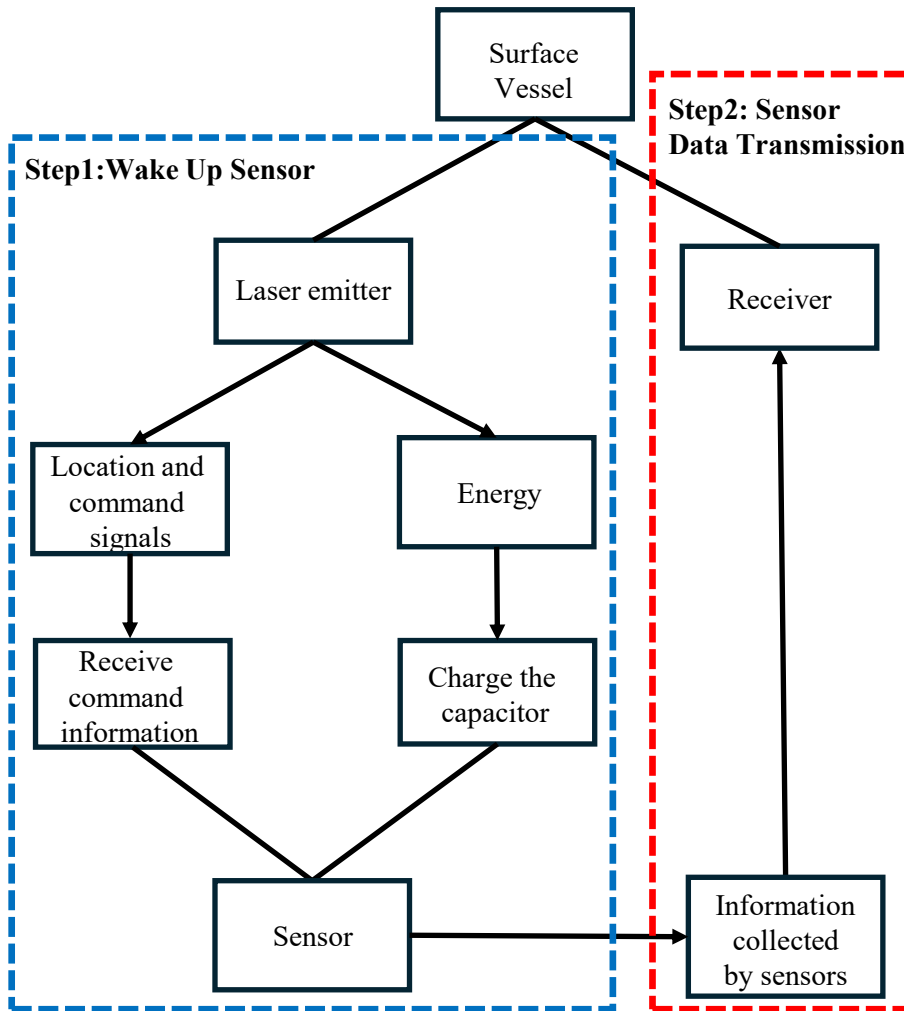
Fig.1 Workflow of Step 1–2: Wake Up → Charge → Data Uplink
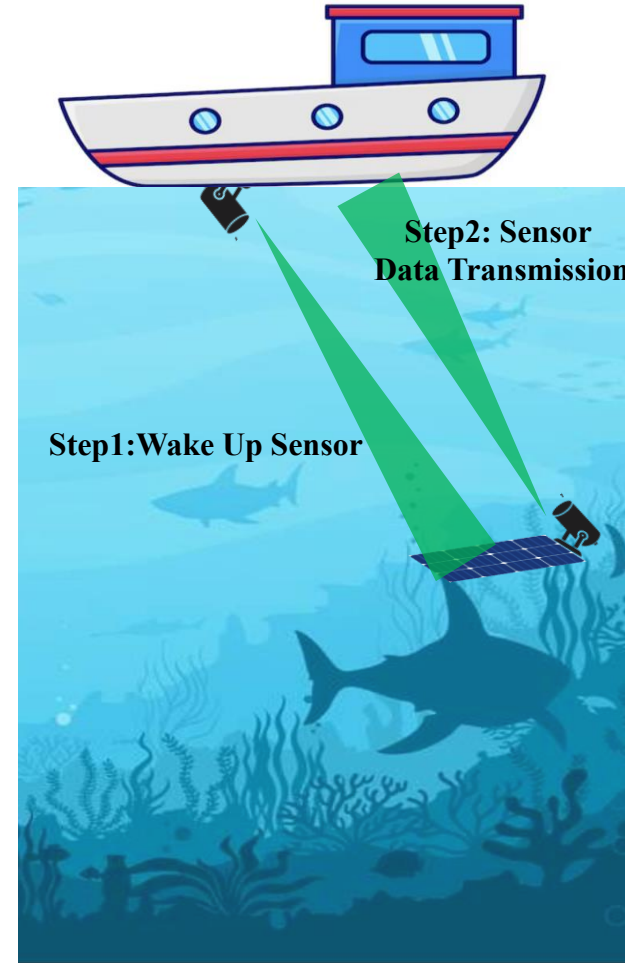
Fig.2 Application Scenario

Underwater communication,
RF is not a good option,
so our uplink also applies FSO

[1] S. Shang, Y. Y. Zhang, Z. Shi, and M.-S. Alouini, "Design and Performance Analysis of SLIPT for Underwater IoT Using Solar-Panel Receivers". (Under Preparation)
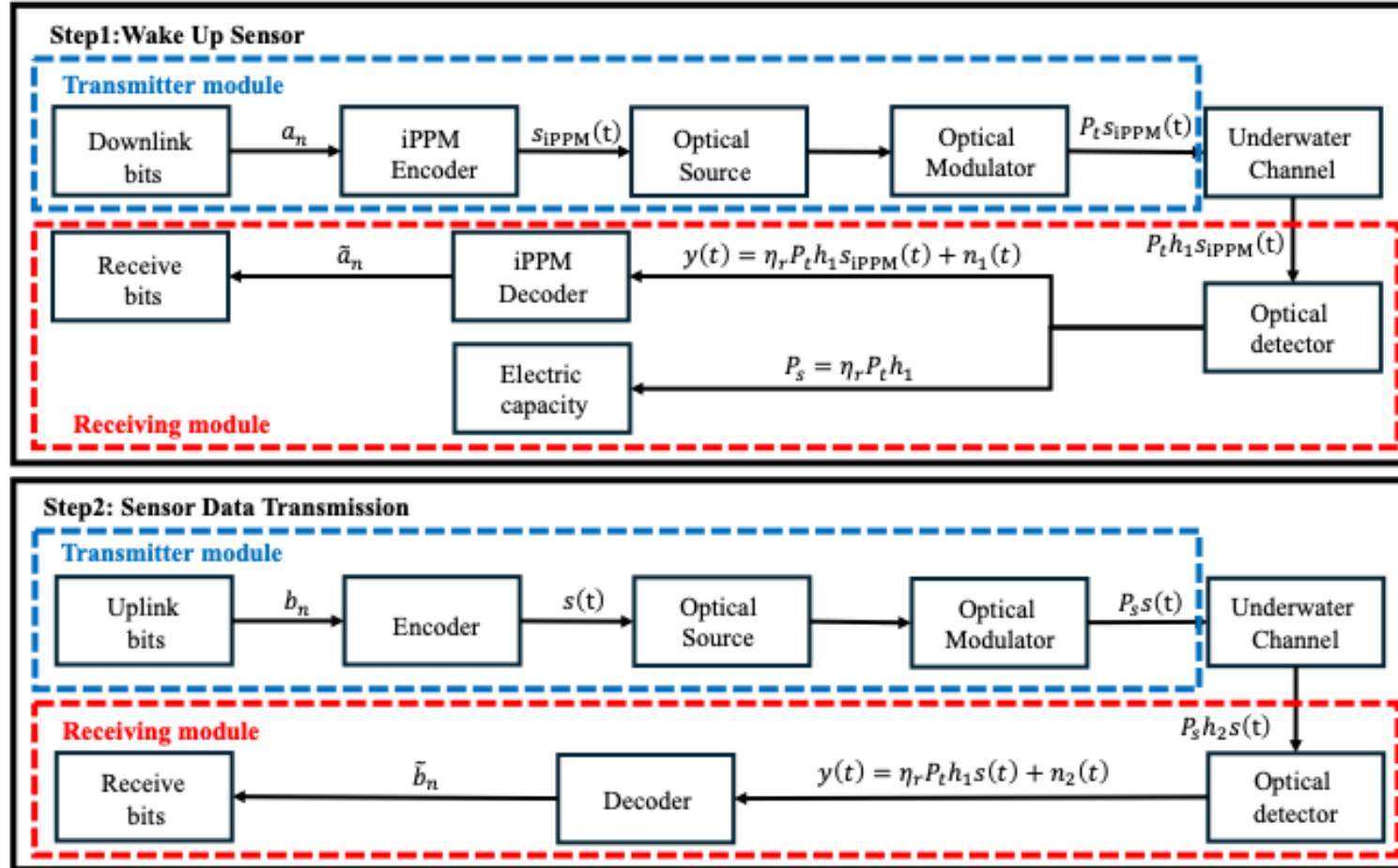
Fig.1 Two-phase SLIPT architecture for an underwater sensor

The transmission power is increased M times compared to PPM.
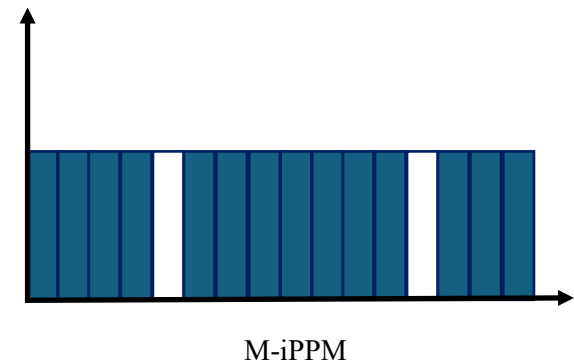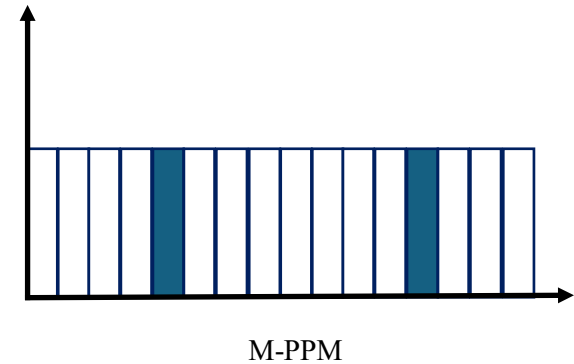
M-PPM

M-iPPM

Fig.2 M-PPM vs. M-iPPM symbol patterns (duty-cycle and average-power comparison).

[1] S. Shang, Y. Y. Zhang, Z. Shi, and M.-S. Alouini, "Design and Performance Analysis of SLIPT for Underwater IoT Using Solar-Panel Receivers". (Under Preparation)
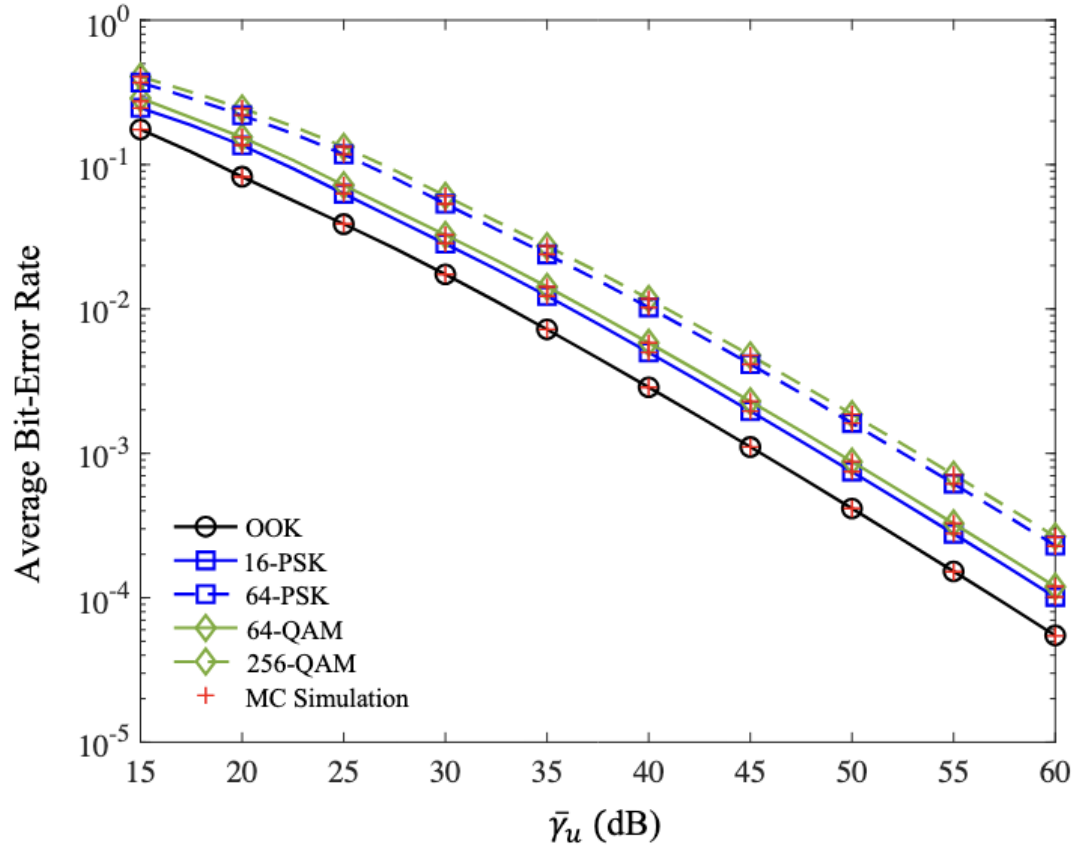
Fig. 1 Average BER versus average uplink SNR $\bar{\gamma}_u$ under various modulation schemes.
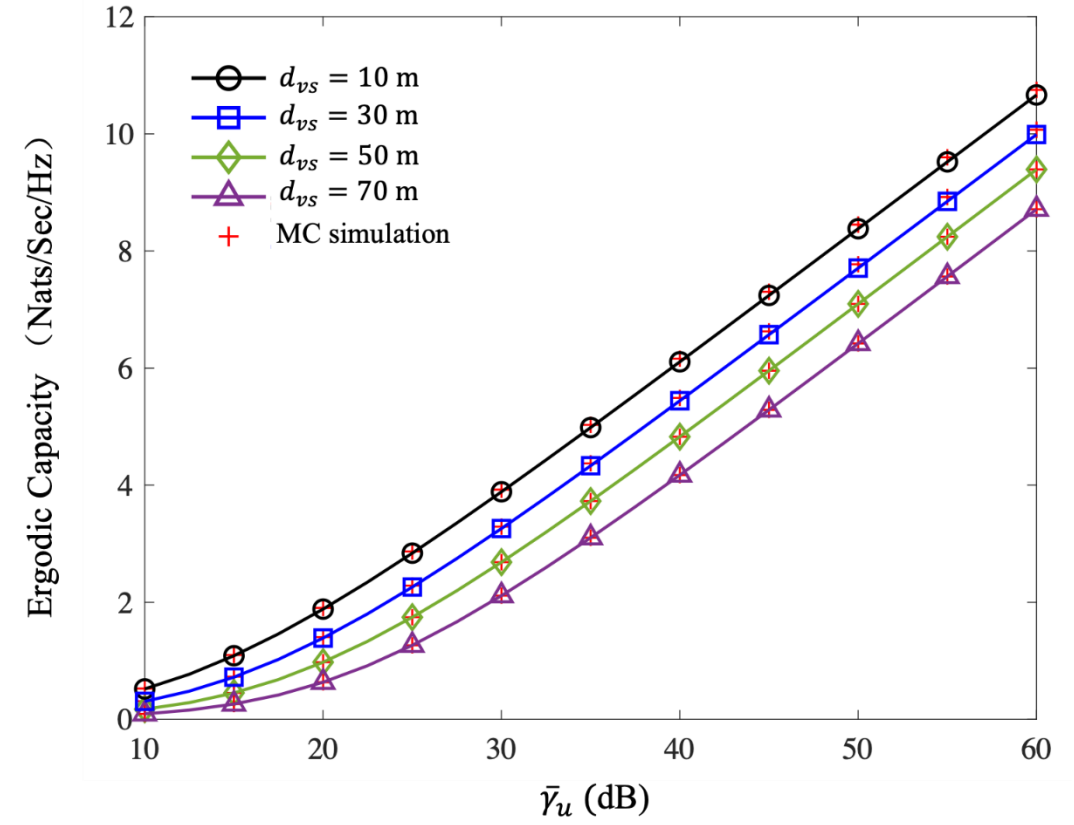
Fig. 2 Ergodic capacity versus average uplink SNR $\bar{\gamma}_u$ under different vertical distances d_{vz}.

[1] S. Shang, Y. Y. Zhang, Z. Shi, and M.-S. Alouini, "Design and Performance Analysis of SLIPT for Underwater IoT Using Solar-Panel Receivers". (Under Preparation)

Autonomously Aligned UWOC System (2)

Fig.1 Coarse-to-fine optical alignment for underwater SLIPT
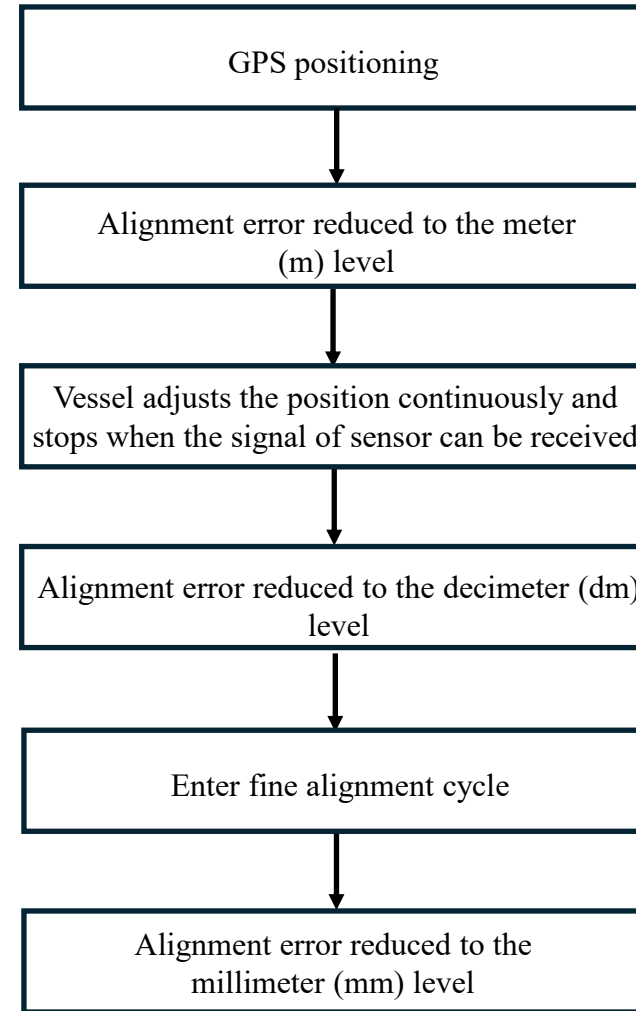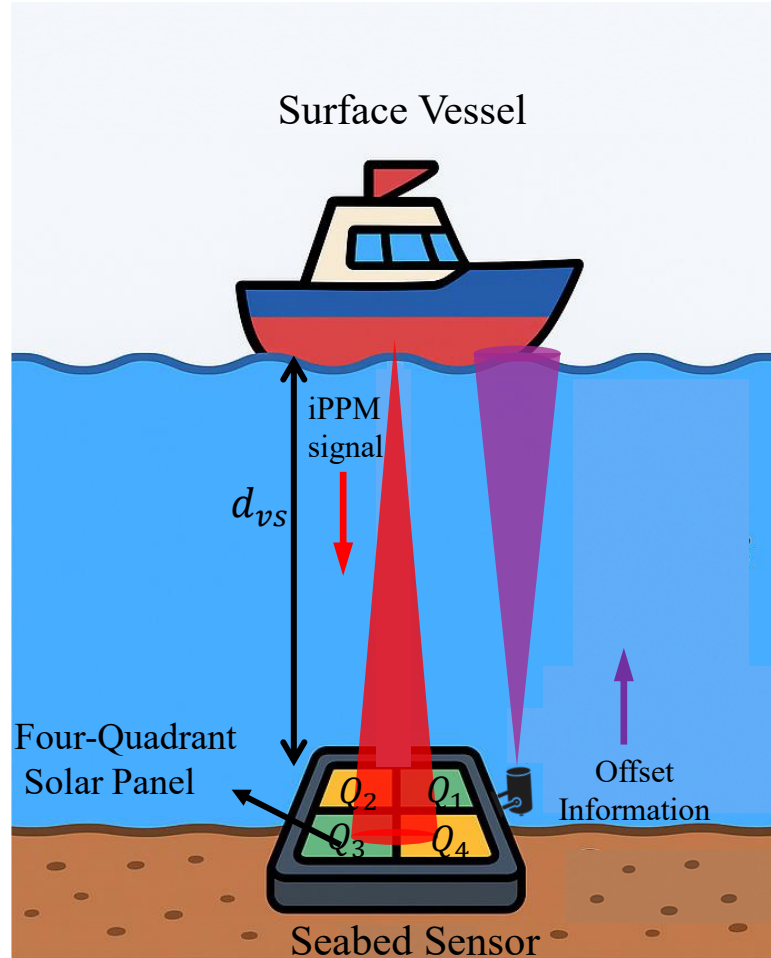
The biggest problem with underwater optical communication is alignment.

Traditional FSO communication uses a camera for alignment, which is too costly.

[2] S. Shang, Z. Shi, and M.-S. Alouini, "Autonomously Aligned UWOC System for Simultaneous Information and Power Transfer via Solar-Panel Receivers". (Under Preparation)

Fig.1 Closed-loop alignment using four-quadrant intensity feedback.

$$\text{sign}_\tau(x) = \begin{cases} 1, & x > \tau \\ 0, & \text{others} \\ -1, & x < \tau \end{cases}$$

τ is a dead-zone threshold introduced to suppress noise-induced actuation.

s denotes the fixed step size of the vessel.

[2] S. Shang, Z. Shi, and M.-S. Alouini, "Autonomously Aligned UWOC System for Simultaneous Information and Power Transfer via Solar-Panel Receivers". (Under Preparation)
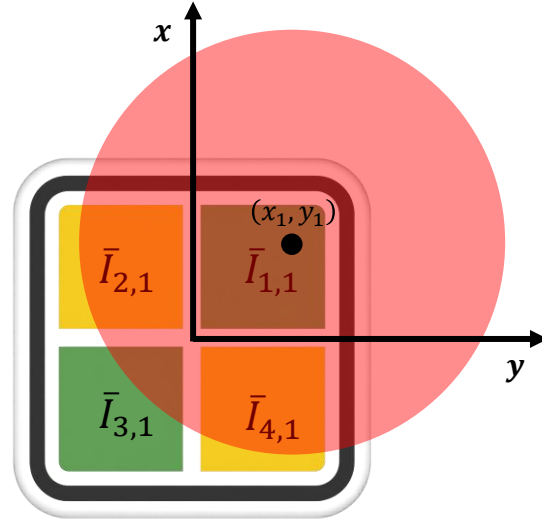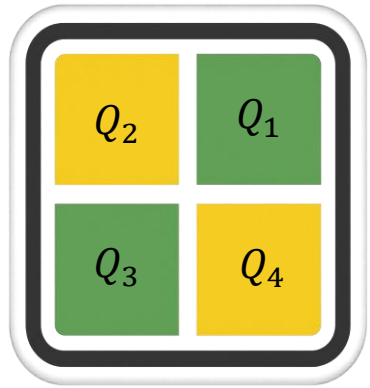
$$S_{x,1} = (\bar{I}_{1,1} + \bar{I}_{4,1}) - (\bar{I}_{2,1} + \bar{I}_{3,1})$$
$$S_{y,1} = (\bar{I}_{1,1} + \bar{I}_{2,1}) - (\bar{I}_{3,1} + \bar{I}_{4,1})$$

$$x_2 = x_1 - s\,\mathrm{sign}_\tau(S_{x,1})$$
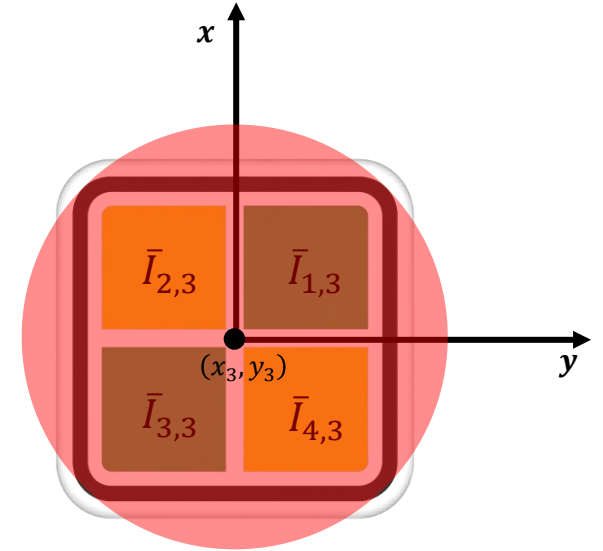$$y_2 = y_1 - s\,\mathrm{sign}_\tau(S_{y,1})$$
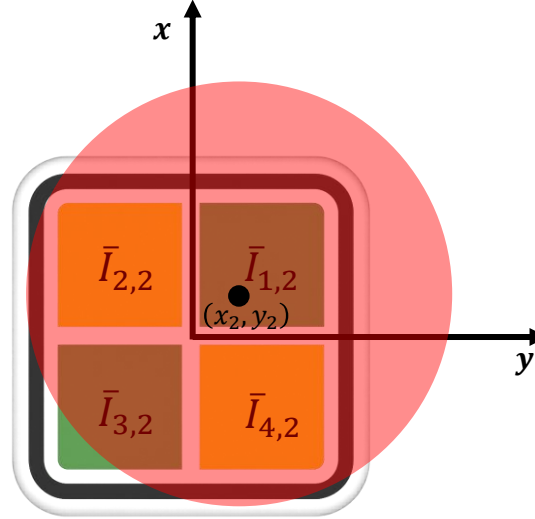
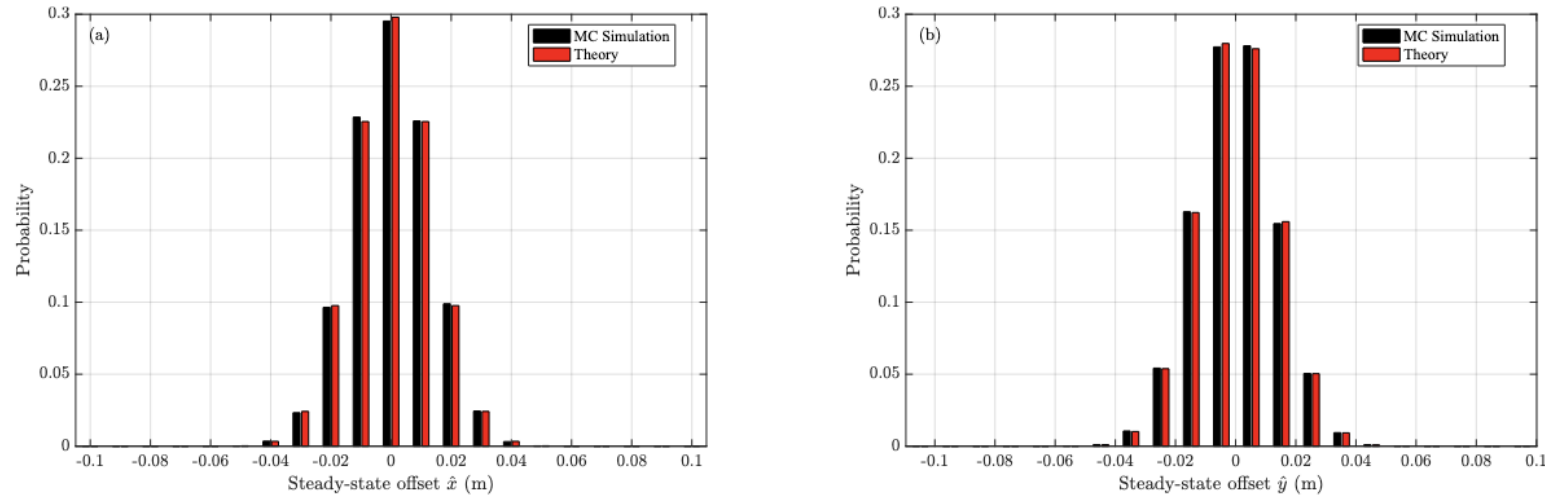$$S_{x,2} = (\bar{I}_{1,2} + \bar{I}_{4,2}) - (\bar{I}_{2.2} + \bar{I}_{3,2})$$
$$S_{y,2} = (\bar{I}_{1,2} + \bar{I}_{2,2}) - (\bar{I}_{3,2} + \bar{I}_{4,2})$$

$$x_3 = x_2 - s\,\mathrm{sign}_\tau(S_{x,1})$$
$$y_3 = y_2 - s\,\mathrm{sign}_\tau(S_{y,1})$$

[2] S. Shang, Z. Shi, and M.-S. Alouini, "Autonomously Aligned UWOC System for Simultaneous Information and Power Transfer via Solar-Panel Receivers". (Under Preparation)

Fig. 1 Marginal steady-state offset distributions for (a) $\hat{x}$ and (b) $\hat{y}$, comparing MC simulation (black) with the closed-form theory (red).
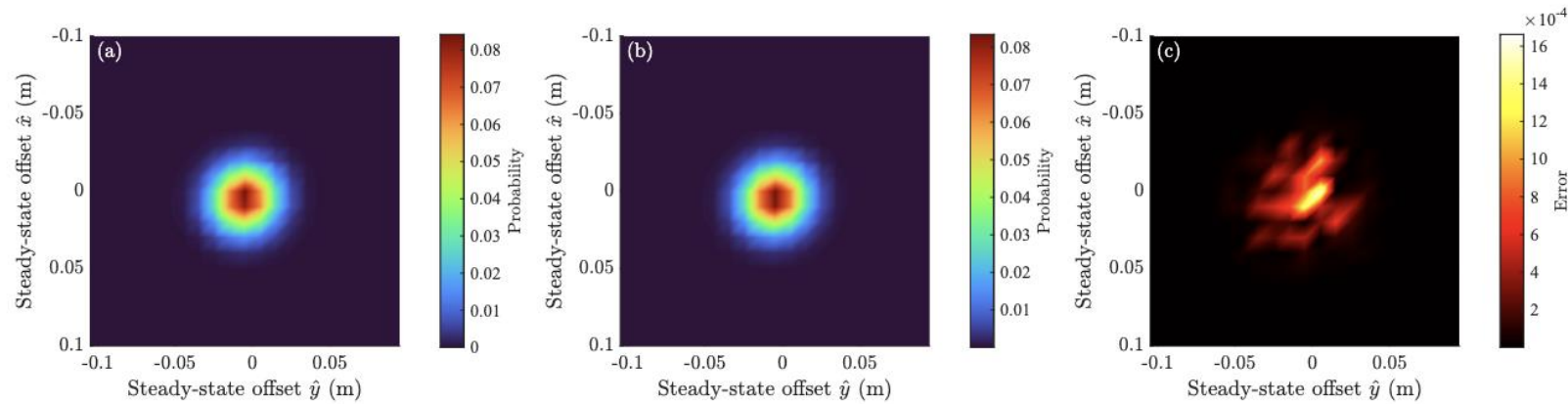

Fig. 2 Two-dimensional joint probability surfaces over the discrete state grid: (a) simulation, (b) theoretical, and (c) absolute error.

[2] S. Shang, Z. Shi, and M.-S. Alouini, "Autonomously Aligned UWOC System for Simultaneous Information and Power Transfer via Solar-Panel Receivers". (Under Preparation)

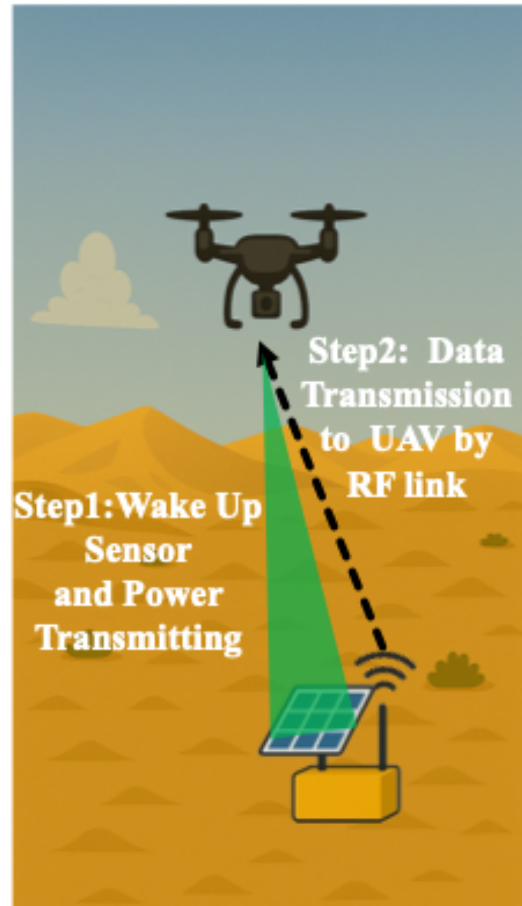# SLIPT Hybrid FSO/RF System (3)

Fig.1 Application Scenario

In ground communication, RF has more advantages than FSO.

1. Wide range of coverage

2. low energy consumption

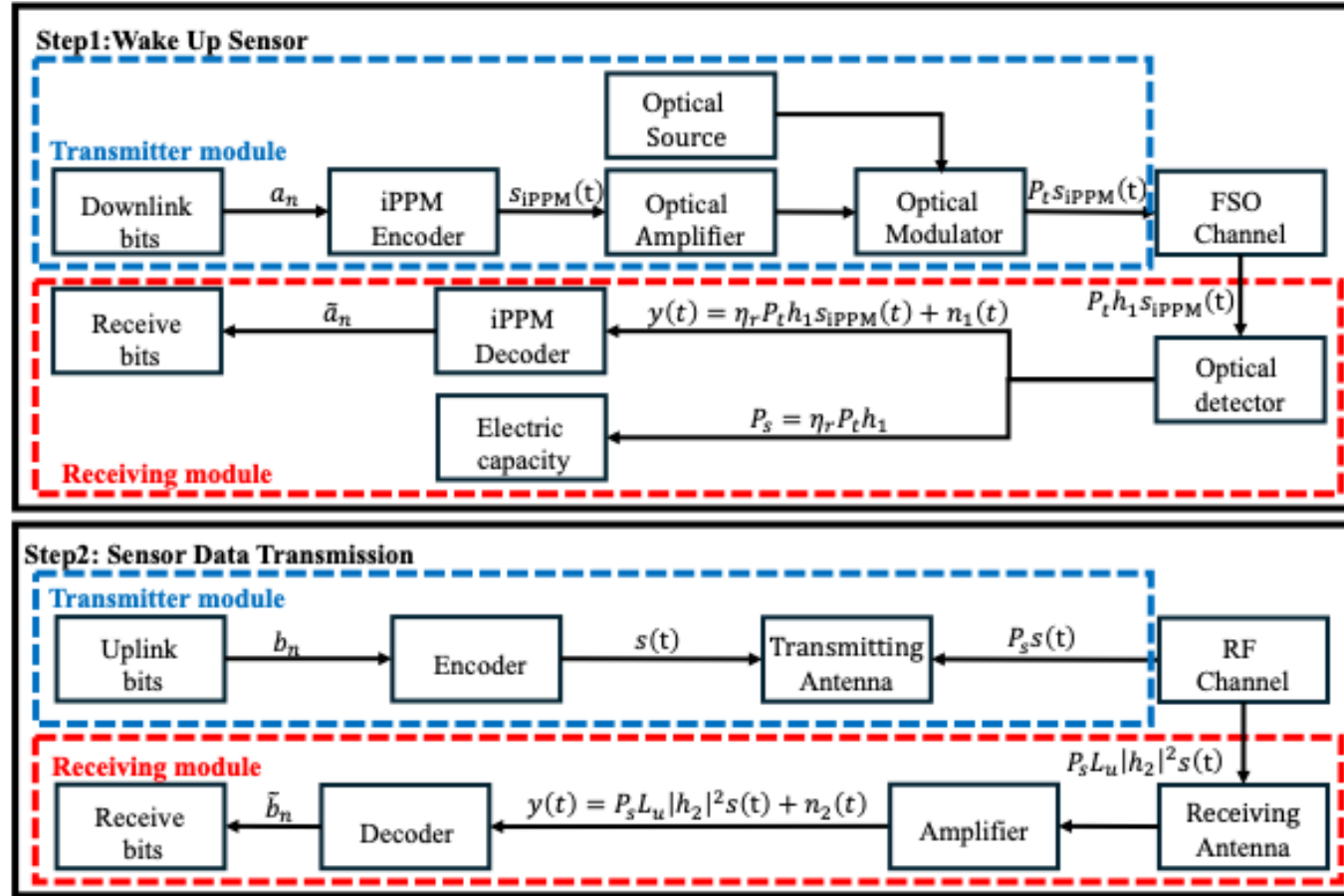However, RF may have the issue of information leakage.

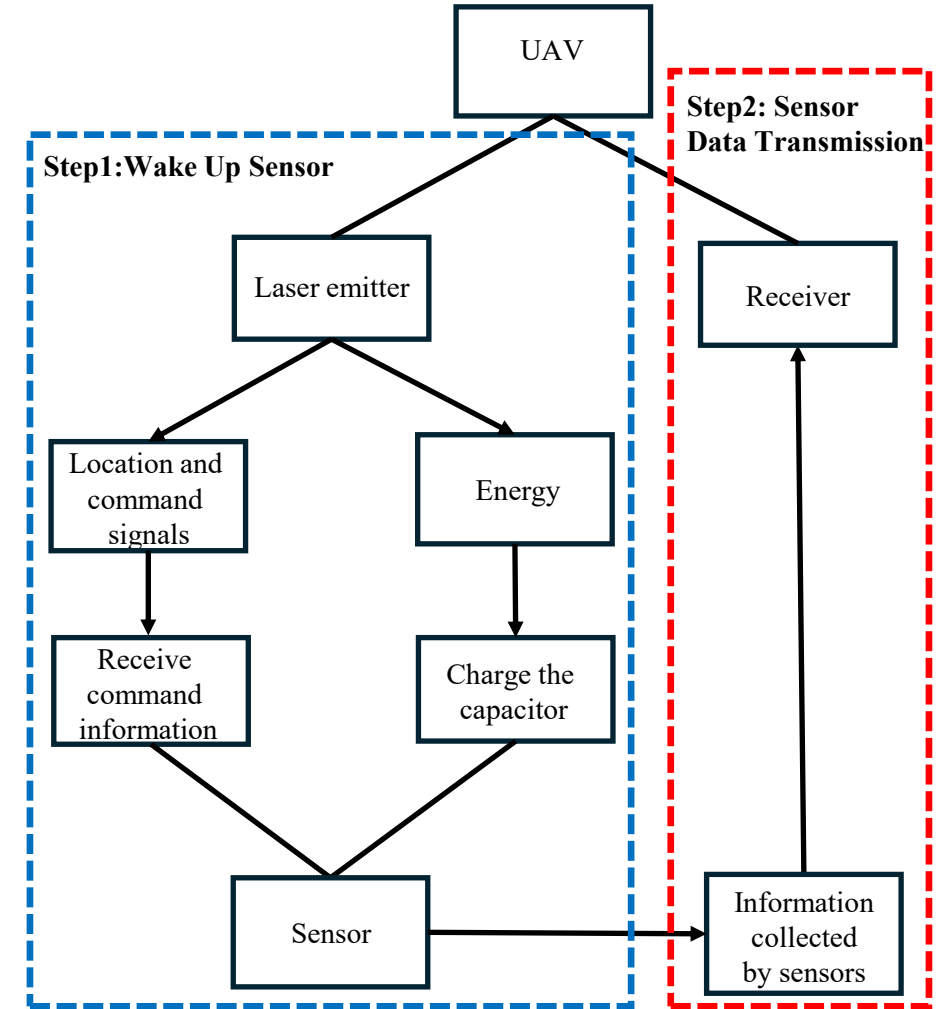[3] S. Shang, Z. Shi, and M.-S. Alouini, "Performance Analysis of Hybrid RF/FSO SLIPT Systems with Solar Panel-Aided Sensor". (Under Preparation)

Fig.1 Two-phase SLIPT architecture

Fig.2 Workflow of Step 1–2: Wake Up → Charge → Data Uplink

[3] S. Shang, Z. Shi, and M.-S. Alouini, "Performance Analysis of Hybrid RF/FSO SLIPT Systems with Solar Panel-Aided Sensor". (Under Preparation)

Secure SLIPT Hybrid FSO/RF System (4)
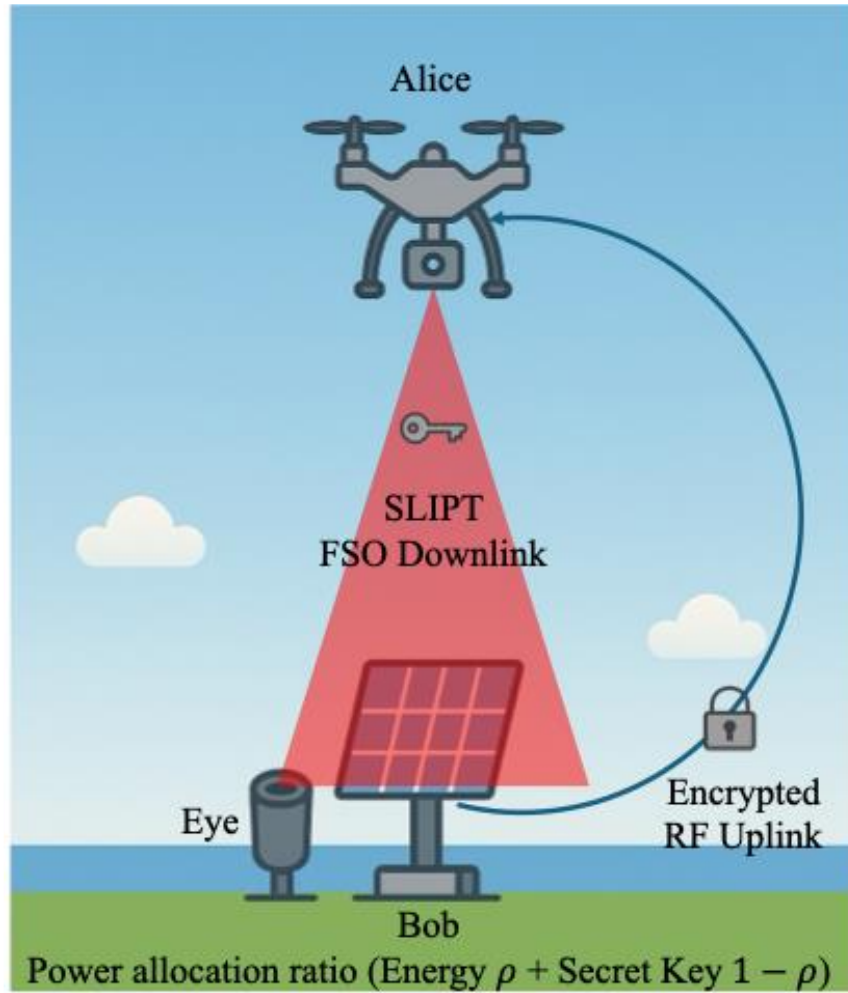
Fig.1 Application Scenario

Fig.2 Workflow of Step

[4] S. Shang, Z. Shi, and M.-S. Alouini, "A Novel Secure SLIPT Communication System with Solar-Panel-Aided Hybrid RF/FSO Links". (Under Review in JSAC)
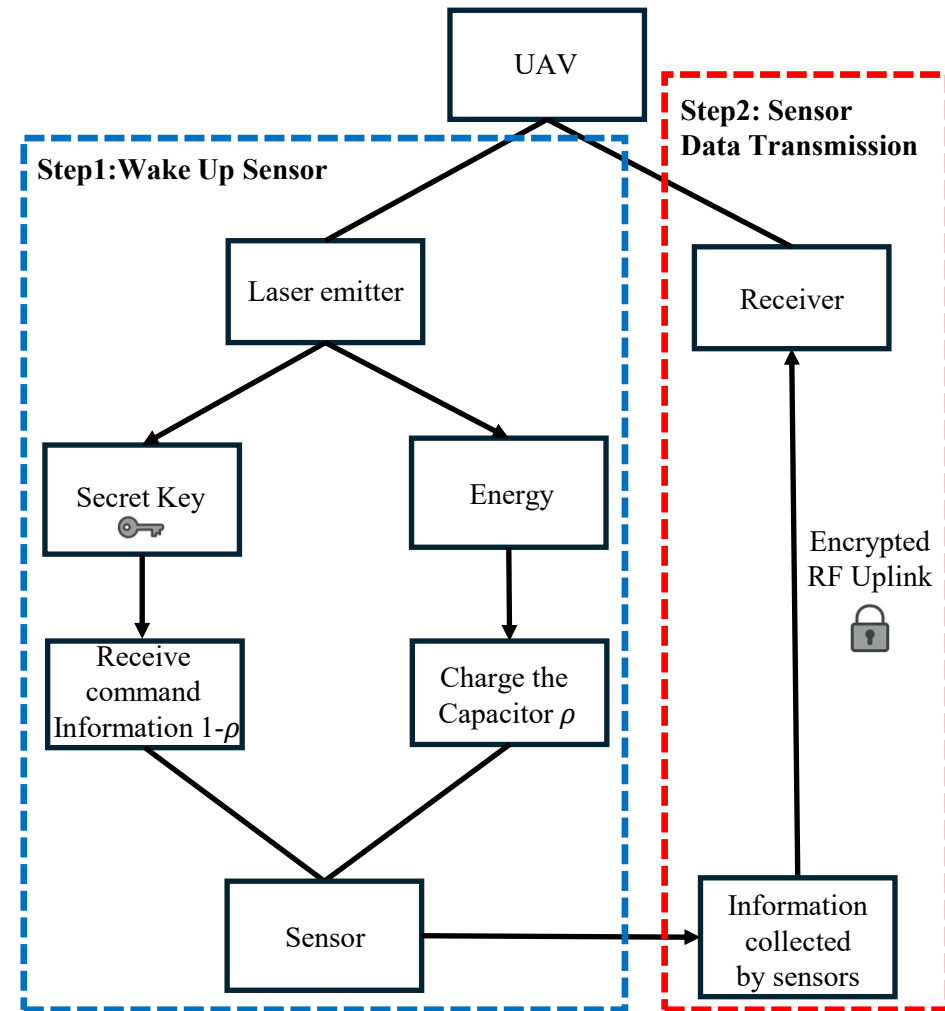
Secret capacity: $C_s = [C_b - C_e]^+$

Secret Outage Probability: $\text{SOP} = \mathbb{P}(C_s > C_{th})$

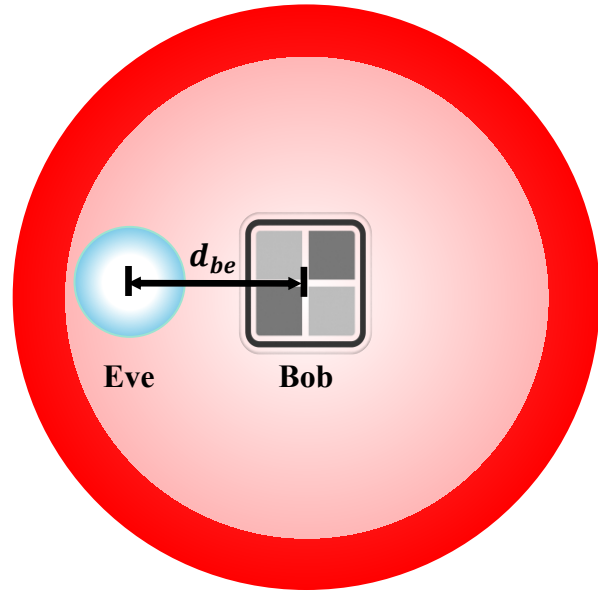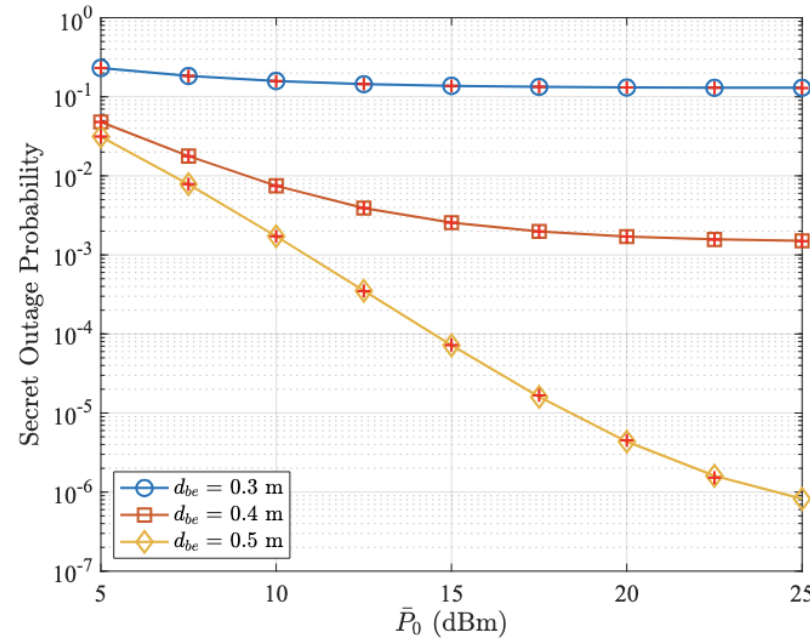Secret Coverage Probability: $P_C = 1 - \text{SOP}$

Fig.1 Application Scenario

Fig. 2. SOP versus average optical transmit power $\bar{P}_0$ under different sensor–Eye separation distances d_{be} with $\omega_b = 5r_a$.
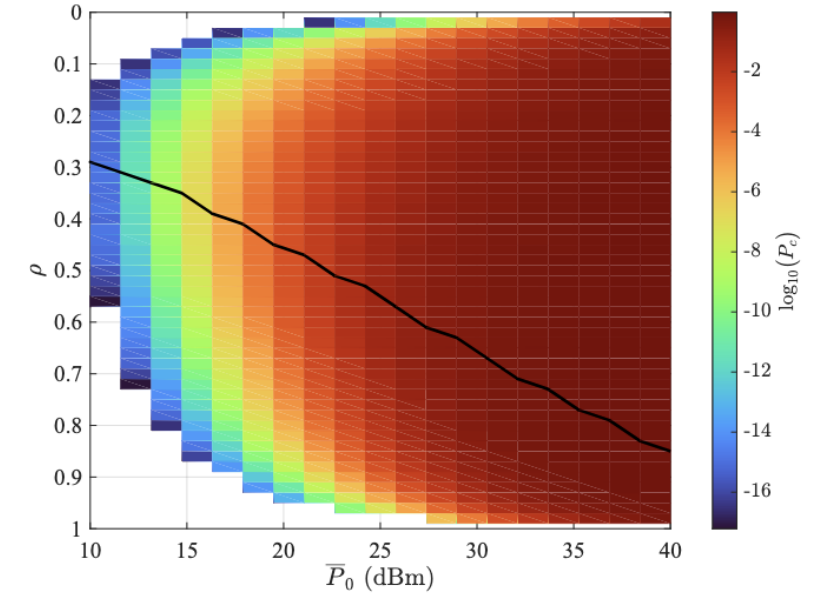

Fig. 3 Heatmap of the logarithmic CP $\log_{10}(P_c)$ versus average optical transmit power $\bar{P}_0$ and power splitting ratio ρ. The black curve indicates the optimal $\rho^\star$ that maximizes P_c for each $\bar{P}_0$.

[4] S. Shang, Z. Shi, and M.-S. Alouini, "A Novel Secure SLIPT Communication System with Solar-Panel-Aided Hybrid RF/FSO Links". (Under Review in JSAC)

Background & Motivation

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◆ Background

➢ NASA's TBIRD program successfully demonstrated > 100 Gbps link from a single CubeSat to the ground, which can be utilized in delay-tolerant networks (DTNs) for high-volume data transmission from LEO to Earth [1].

➢ Advantages of single-satellite system: Low computational and hardware complexity, reduced size, weight, and power (SWaP) requirements.

➢ Using free space optical (FSO) links overcomes traditional RF limitations.

◆ Motivation

➢ The DTN paradigm enables satellites to store data when out of contact and forward it during visibility windows, providing greater reliability.

➢ Satellite ergodic capacity performance is governed by orbital geometry.

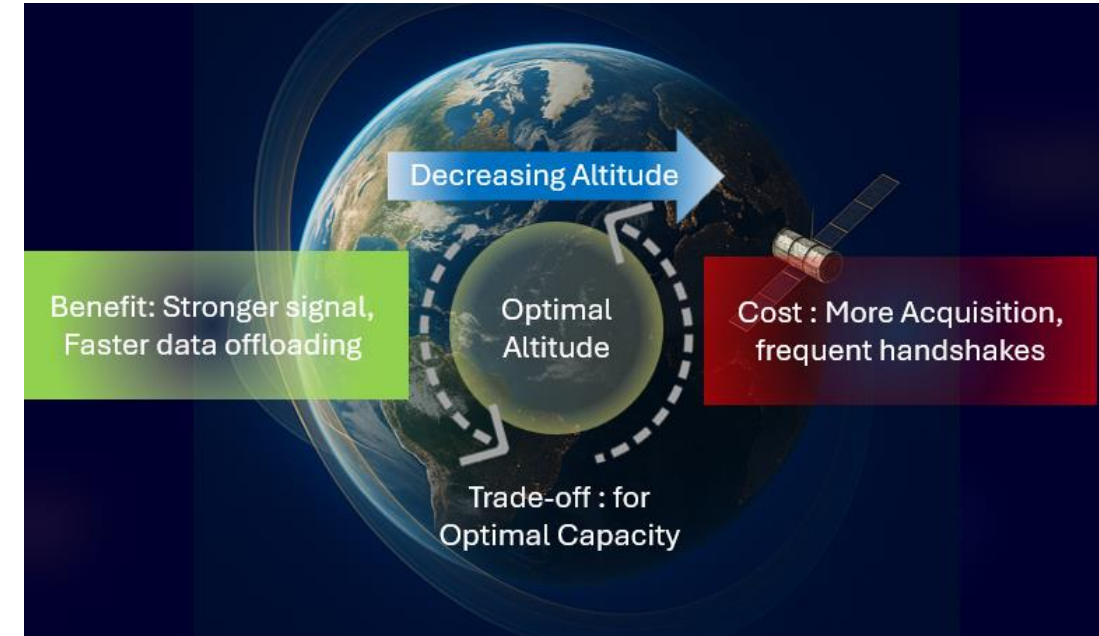➢ LEO satellites operate between 160–2,000 km altitude [2]

Fig.1 Satellite orbit trade-offs

[1] C. Schieler, B. Robinson, O. Guldner, B. Bilyeu, A. Garg, K. Riesing, J. Chang, F. Hakimi, J. Brown, F. Khatri, et al., "NASA's terabyte infrared delivery (TBIRD) program: Large-volume data transfer from LEO," 2019.
[2] https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#LEO

◆ Gap

➤ Existing missions (TBIRD, ARCSTONE, OCSD)[1],[3],[4] demonstrate feasibility but lack systematic optimization for jointly selecting:
  - ➤ Orbit altitude
  - ➤ Beamwidth
  - ➤ Transmit power
  - ➤ Elevation Angle

To maximize average downlink capacity and freshness of information under DTN constraints.

◆ Research Question

➤ How can we place satellites and choose orbits so that energy transfer windows coincide with the highest-capacity downlinks

➤ Objective: Maximizing data delivery with minimal loss and delay
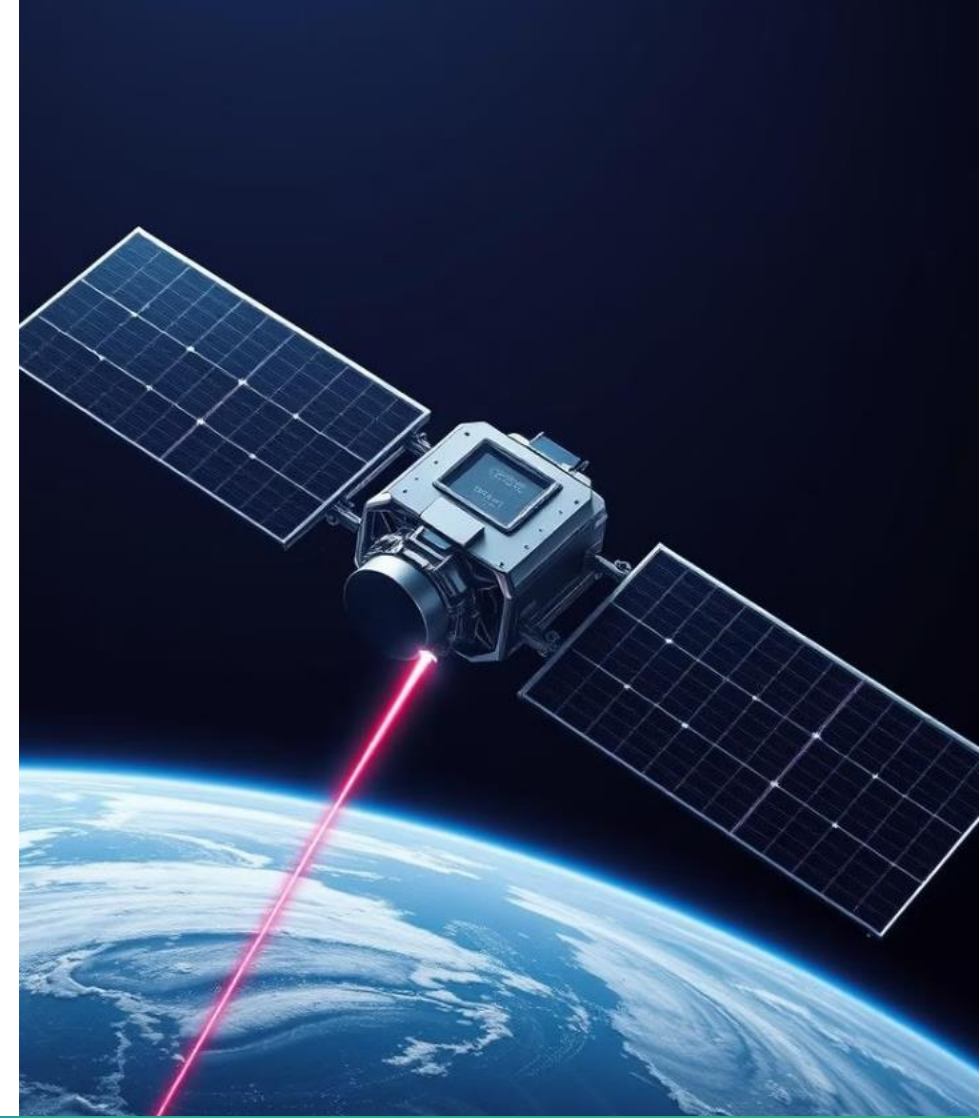
[3] Stone, Thomas C. "Acquisition of Moon measurements by Earth orbiting sensors for lunar calibration." IEEE Transactions on Geoscience and Remote Sensing 60 (2021): 1-6.
[4] Rose, Todd S., et al. "Optical communications downlink from a 1.5 U CubeSat: OCSD program." International Conference on Space Optics—ICSO 2018. Vol. 11180. SPIE, 2019.

◆ Orbit Type Selection for LEO Satellites

➢ Circular Orbits:
  ➢ Constant altitude, uniform coverage
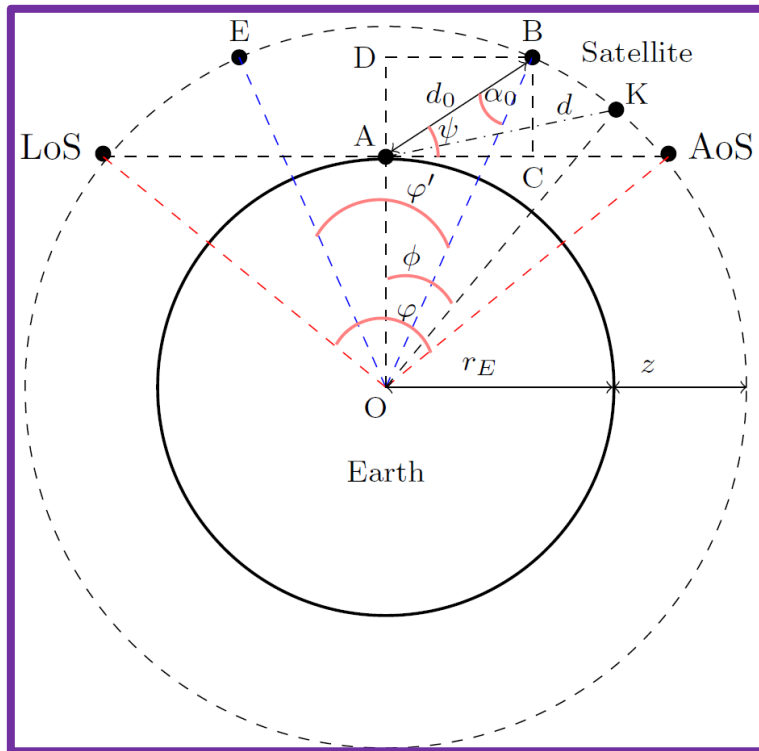 ➢ Ideal for Earth observation and consistent communication

➢ Elliptical Orbits:
  ➢ Varying altitude, Prolonged focus over regions
  ➢ Suitable for remote sensing, targeted high-latitude coverage

Fig.2 Satellite-Earth geometry of a satellite in circular orbit.
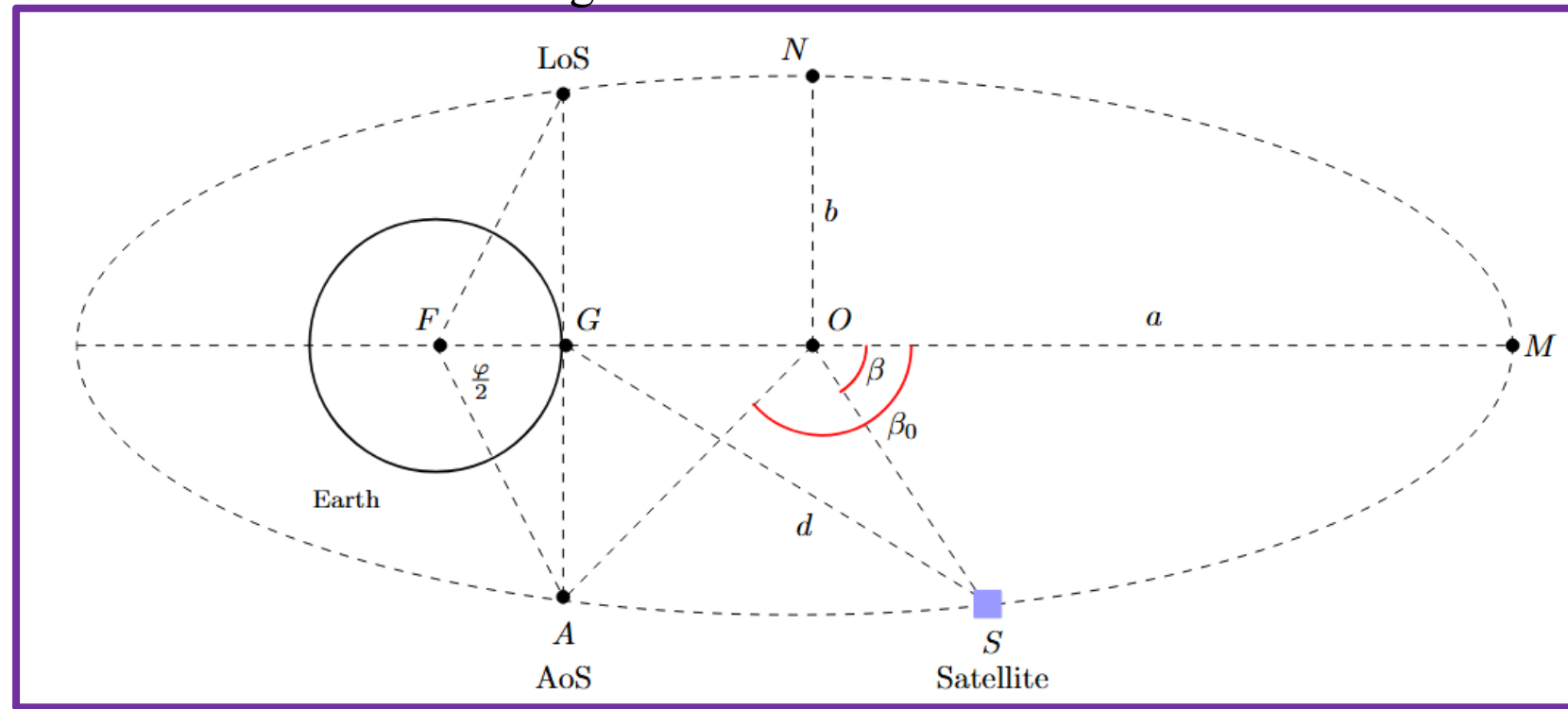
Fig.3 Satellite-Earth geometry of a satellite in elliptical orbit.

[5] Mouhammad, C. S., Bashir, M. S., Alouini, M.-S. Optimal LEO Satellite Orbit for Delay-Tolerant Networks." IEEE Internet of Things Journal,2025,submitted.

◆ 1. Circular Orbit FSO Channel Analysis
Joint optimization over orbit altitudes & laser beamwidth

The power received at a distance d from the transmittercan given the Gaussian beam and the point-receiver assumption in the presence of (random) pointing error, be expressed as

$$S(d) \approx \frac{2P_t}{2\pi w^2(d)} \exp\left(-\frac{R^2}{2w^2(d)}\right) \pi a_{rx}^2.$$

The pointing error follows a Rayleigh distribution as $f_R(r) = \frac{r}{\sigma_R^2} \exp\left(-\frac{r^2}{2\sigma_R^2}\right), \quad 0 < r < \infty.$

✓ The satellite velocity in a circular orbit is $v \approx \sqrt{\frac{\mu}{r_E + z}},$

✓ The orbital period is $T \approx 2\pi\sqrt{\frac{(r_E + z)^3}{\mu}}.$

✓ The largest angular visibility window when ψ = 0 is $\varphi = 2\arccos\left(\frac{r_E}{r_E + z}\right)$

✓ The maximum visibility window duration $\mathcal{W} = \frac{\varphi}{2\pi}T = \frac{T}{\pi}\arccos\left(\frac{r_E}{r_E + z}\right)$

$$z \le d \le d_{\max} = \sqrt{z(z + 2r_E)}$$

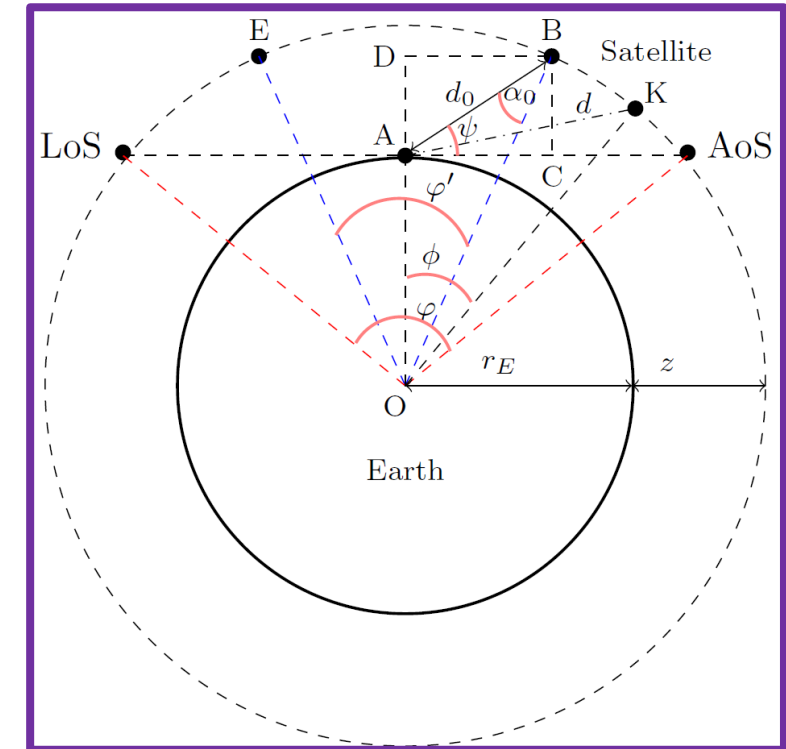$$d(z, \phi) = \sqrt{(z + r_E)^2 + (r_E)^2 - 2(z + r_E)r_E\cos(\phi)}$$

◆ 1. Circular Orbit FSO Channel Analysis

✓ In practice, obstructions near the horizon necessitate a minimum elevation angle constraint **ψ > 0** to maintain reliable line-of-sight communication.

✓ Reduces the effective visibility window and thus the link availability

$$\varphi'(\psi) = 2\left(\arccos\left(\frac{r_E}{r_E + z}\cos(\psi)\right) - \psi\right).$$

$$d_0(\psi) = \sqrt{z^2 + 2zr_E + r_E^2 \sin^2 \psi} - r_E \sin \psi,$$

$$z < d_0 < \sqrt{z(z + 2r_E)}.$$

Problem Formulation

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◆ 1. Circular Orbit FSO Channel Analysis

✓ The total signal current flowing out of the detection elements (after photoconversion) is $\mathcal{S} = \eta S(d)$,

✓ An upper bound on the normalized instantaneous capacity $\mathcal{C} = \log_2\left(1 + \frac{\mathcal{S}^2}{\sigma_n^2}\right)$ bits/s/Hz .

✓ The maximum amount of data, that can be offloaded to the ground station within one orbital period is $\mathcal{D}(z)$

$$\mathcal{D}(z) = \mathcal{W}\mathbb{E}[\mathcal{C}] = \mathcal{W} \int_{-\varphi/2}^{\varphi/2} \int_0^\infty \log_2\left(1 + \frac{\left(\eta\frac{2P_t}{2\pi\theta^2 d^2(z,\phi)} \exp\left(-\frac{r^2}{2\theta^2 d^2(z,\phi)}\right)\pi a_{rx}^2\right)^2}{\sigma_n^2}\right) f_R(r)f(\phi)\, dr\, d\phi. \text{ bits/Hz}$$

$$f(\phi) = \frac{1}{\varphi} \cdot \mathbb{1}_{(-\varphi/2,\varphi/2)}(\phi)$$

✓ The ergodic capacity for a pointing error dominant channel $C_{\mathsf{P}}(z)$

$\mathbb{1}_A(y)$ is 1 when $y \in A$ and 0 otherwise

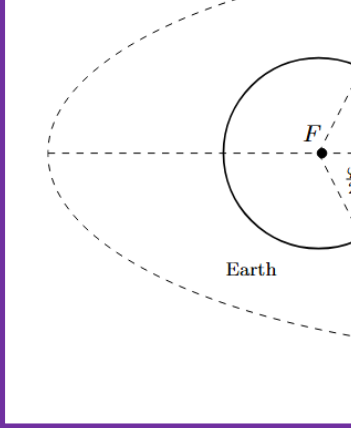$$C_{\mathsf{P}}(z) = \frac{\mathcal{D}}{T} = \frac{1}{2\pi} \int_{-\varphi/2}^{\varphi/2} \int_0^\infty \log_2\left(1 + \frac{\left(\eta\frac{2P_t}{2\pi\theta^2 d^2(z,\phi)} \exp\left(-\frac{r^2}{2\theta^2 d^2(z,\phi)}\right)\pi a_{rx}^2\right)^2}{\sigma_n^2}\right) f_R(r)\, dr\, d\phi. \text{ bits/s/Hz}$$

◆ **Atmospheric Turbulence and Pointing Error Impaired FSO Channel Analysis**

✓ When the FSO channel is subject to both pointing errors and atmospheric turbulence, the received power can be reproduced

as $S(d) = \dfrac{2\,IP_t}{2\pi\,w^2(d)}\,\exp\!\left(-\dfrac{R^2}{2\,w^2(d)}\right)\pi\,a_{rx}^2$

$$f_I(I;\alpha_{GG},\beta_{GG}) = \frac{2\,(\alpha_{GG}\beta_{GG})^{\frac{\alpha_{GG}+\beta_{GG}}{2}}}{\Gamma(\alpha_{GG})\,\Gamma(\beta_{GG})}$$
$$\times\, I^{\frac{\alpha_{GG}+\beta_{GG}}{2}-1} K_{\alpha_{GG}-\beta_{GG}}(2\sqrt{\alpha_{GG}\beta_{GG}\,I}),\; I > 0$$

✓ The ergodic capacity considering both the pointing error and scintillation due to atmospheric turbulence

$$C_{\mathsf{PT}}(z) = \frac{1}{2\pi}\int_{-\varphi/2}^{\varphi/2}\int_0^\infty\int_0^\infty \log_2\!\left(1 + \frac{\left(\eta\,\frac{2IP_t}{2\pi\,\theta^2\,d^2(z,\phi)}\exp\!\left(-\frac{r^2}{2\theta^2\,d^2(z,\phi)}\right)\pi\,a_{rx}^2\right)^2}{\sigma_n^2}\right) f_R(r)\,f_I(I;\alpha_{GG},\beta_{GG})\,\mathrm{d}r\,\mathrm{d}I\,\mathrm{d}\phi.$$

✓ Gauss-quadrature (GQ) approximation for smooth integrations with comparable accuracy using far fewer sample points

$$C_{\mathsf{PT}}(z) \approx \frac{\varphi}{4\pi}\sum_{j=1}^{N_\phi}\sum_{k=1}^{N_I}\sum_{i=1}^{N_r} w_j^{GL}\,\tilde{w}_k^{GLa}\,w_i^{GH}\,\log_2\!\left(1 + \frac{A^2(\phi_j,r_i)I_k^2}{\sigma_n^2}\right)|x_i|.$$
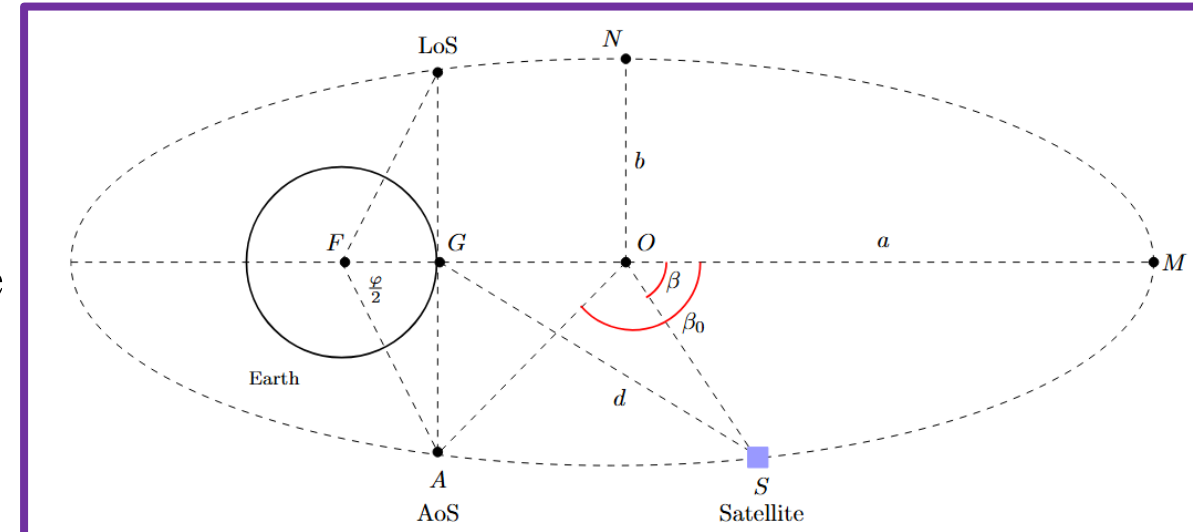
where:

- $\phi_j = \frac{\varphi}{2}t_j$, $r_i = \sigma_R\sqrt{2}|x_i|$, $\tilde{w}_k^{GLa} = w_k^{GLa}f_I(I_k)e^{I_k}$,
- $\{x_i, w_i^{\mathrm{GH}}\}_{i=1}^{N_r}$, $\{I_k, w_k^{\mathrm{GLag}}\}_{k=1}^{N_I}$, and $\{t_j, w_j^{\mathrm{GL}}\}_{j=1}^{N_\phi}$, denote the Gauss–Hermite, Gauss–Laguerre and Gauss–Legendre nodes/weights, respectively.
- N_r, N_I, and N_ϕ are the numbers of quadrature points for the r, I, and ϕ integrals, respectively.

◆ 2. Elliptical Orbit FSO Channel Analysis

✓ The eccentricity of the elliptical orbit $\mathcal{E} = \sqrt{1 - \frac{b^2}{a^2}}$

✓ The distance between centre of the Earth and the satellite on the ellipse is $\mathcal{D} = \sqrt{(a\cos(\beta) - \sqrt{a^2-b^2})^2 + b^2\sin^2(\beta)}$

✓ The velocity is furnished by $v = \sqrt{\mu\left(\frac{2}{\mathcal{D}} - \frac{1}{a}\right)}.$

✓ The orbital period (in seconds) of the satellite is $T = 2\pi\sqrt{\frac{a^3}{\mu}}.$

✓ capacity due to pointing error impairment at a certain angle β on the ellipse between

$-\beta 0$ and $\beta 0$ is $C(\beta) = \int_0^\infty \log_2\left(1 + \frac{\left(\eta\frac{2P_t}{2\pi\theta^2 d^2(\beta)}\exp\left(-\frac{r^2}{2\theta^2 d^2(\beta)}\right)\pi a_{rx}^2\right)^2}{\sigma_h^2}\right) f_R(r)\,\mathrm{d}r.$

If $\overrightarrow{GO} > 0,\ \beta_0 = \pi - \arctan\left(\frac{\left\|\overrightarrow{AG}\right\|}{\overrightarrow{GO}}\right)$

$\overrightarrow{GO} < 0,\ \beta_0 = \arctan\left(-\frac{\left\|\overrightarrow{AG}\right\|}{\overrightarrow{GO}}\right)$

✓ The total data transmitted during the visibility window $\mathcal{D} = \int_{-\beta_0}^{\beta_0}\mathrm{d}D(\beta) = \int_{-\beta_0}^{\beta_0}\frac{C(\beta)}{v(\beta)}\sqrt{a^2\sin^2(\beta) + b^2\cos^2(\beta)}\,\mathrm{d}\beta.$

✓ The average capacity—computed over one revolution of the satellite is $C = \frac{\mathcal{D}}{T} = \frac{1}{T}\int_{-\beta_0}^{\beta_0}\frac{C(\beta)}{v(\beta)}\sqrt{a^2\sin^2(\beta) + b^2\cos^2(\beta)}\,\mathrm{d}\beta$

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Optimization Problems

1) P_0:

$$\max_{z,\theta} \quad C(z,\theta)$$

$$\text{s.t.} \quad i)\ z$$

$$ii)\ \theta$$

The optimum geometry is circular unless an application needs extra dwell time over a specific region.

2) P_1:
$$\max_{a,b} \quad C(z)$$
$$\text{s.t.} \quad i)\ a > r_E + z_0,$$
$$iii)\ a > b.$$
$$iii)\ b > \sqrt{2a(r_E + z_0) - (r_E + z_0)^2}.$$

- Narrower θ increases both the maximum capacity and the optimal semi-major axis a^*
- Ergodic capacity reaches its maximum when a=b

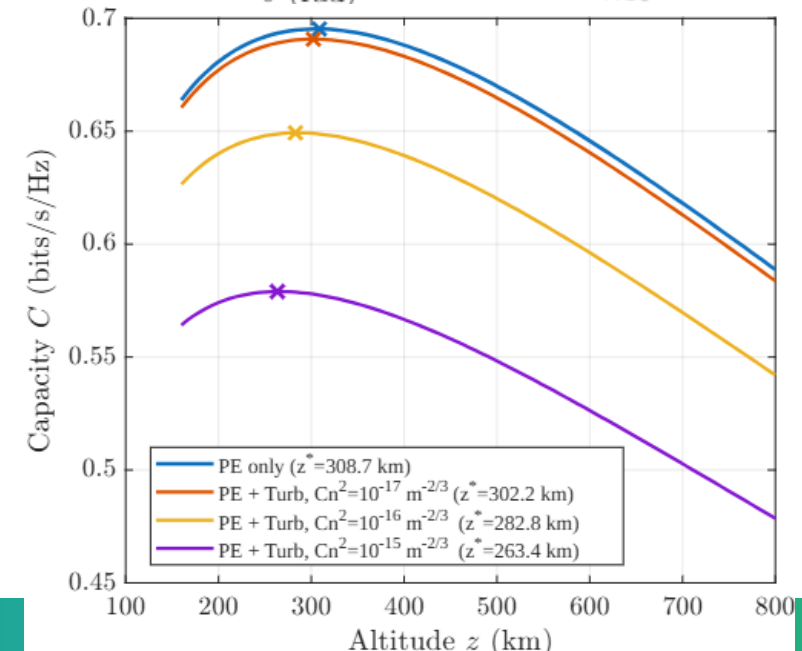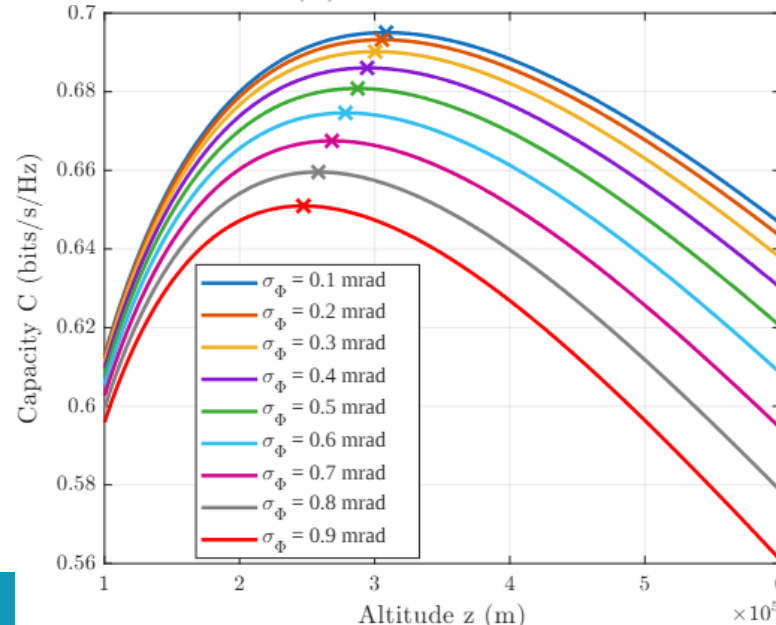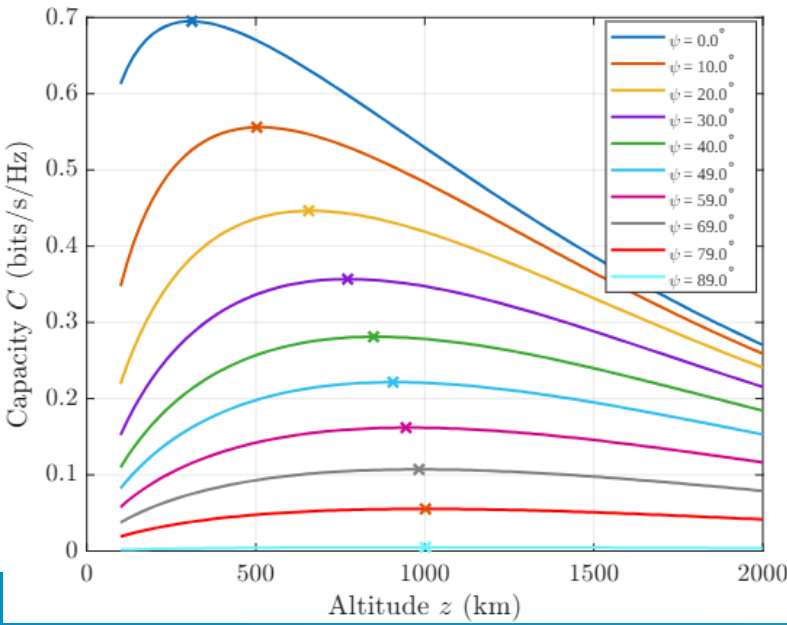Maximum capacity = 2.33 bits/s/Hz, which occurs at $\theta = 0.94 \times 10^{-6}$ rad and z = 1940 km.
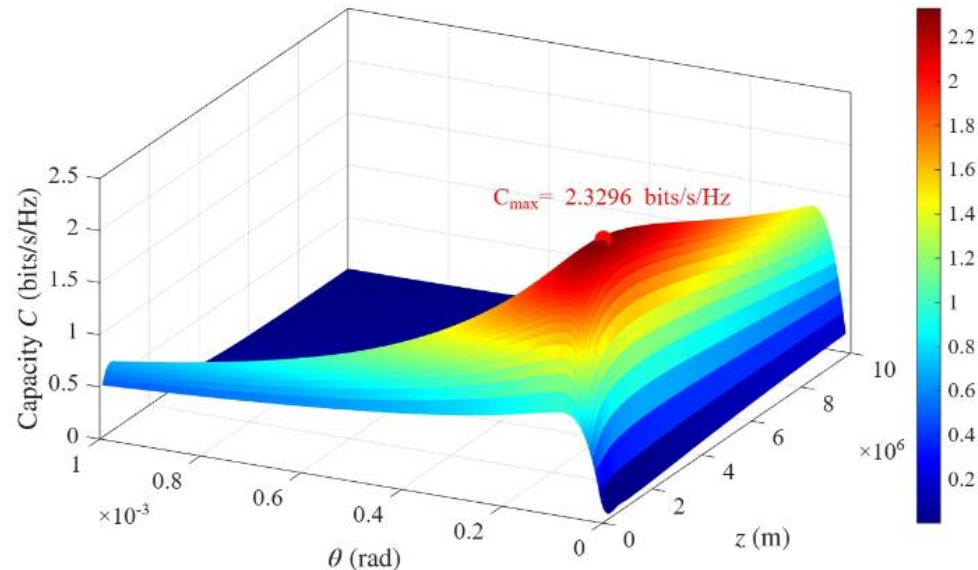
Fig.4 Ergodic capacity in a circular orbit.
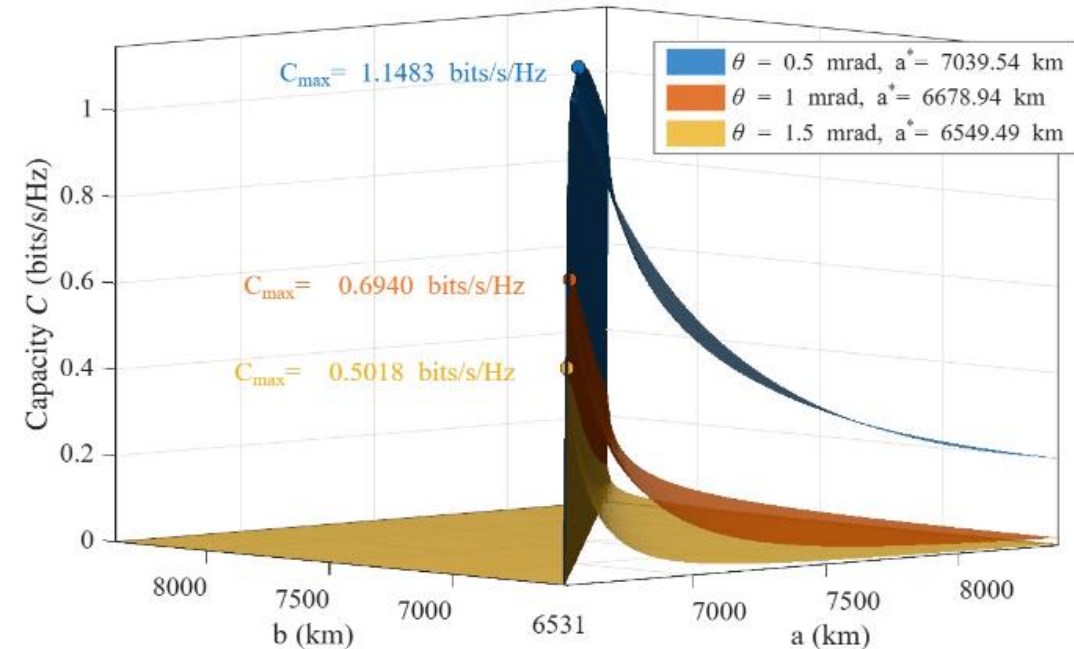
Fig.5 Ergodic capacity in an elliptical orbit.

[5] Mouhammad, C. S., Bashir, M. S., Alouini, M.-S. Optimal LEO Satellite Orbit for Delay-Tolerant Networks." IEEE Internet of Things Journal,2025,submitted.

Circular Orbits

Optimization Problems

3) $\mathcal{P}_2$
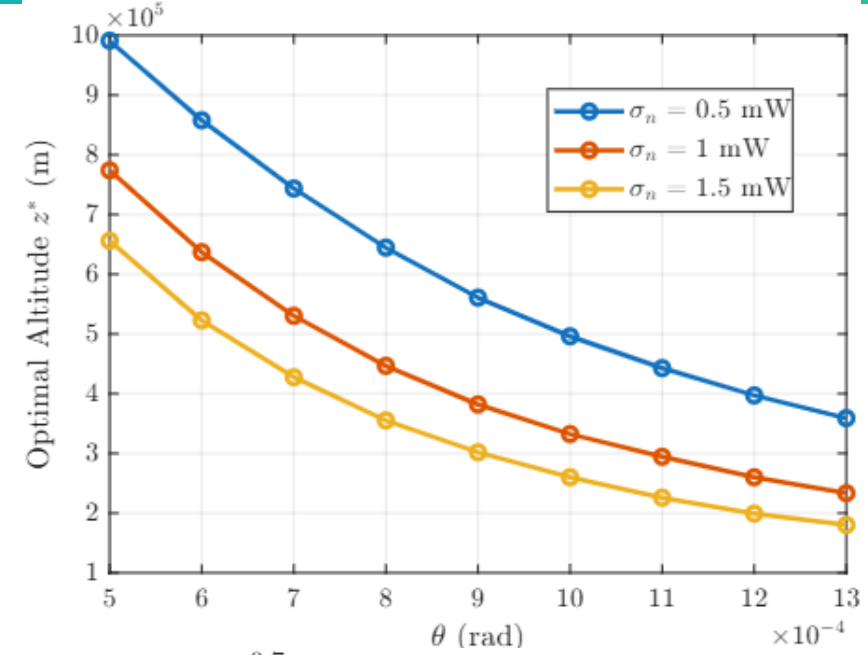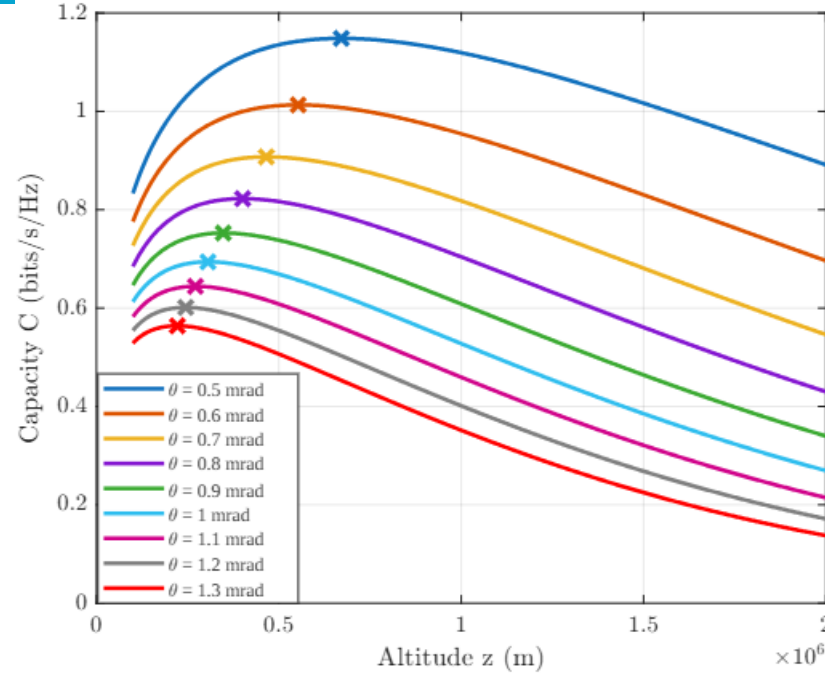
$$\max_z \quad C(z)$$

$$\text{s.t.} \quad z > z_0.$$

Thank You

> A telephone subscriber here may call up and talk to any other subscriber on the *Globe*. An *inexpensive* receiver, not bigger than a watch, will enable him to listen *anywhere*, on *land* or *sea*, to a speech delivered or music played in some other place, however *distant*.
>
> — **Nikola Tesla 1919**

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