End-to-end Performance Optimization for Mixed FSO/sub-THz-aided Vertical Networks: A ML Aproach

NGUYEN Van Tinh - m5272016
Supervisor: Prof. LE Doan Hoang

Computer Communication Lab.,
The University of Aizu, Japan

Nov. 15^{th}, 2023

Outline

I. Network Scenario

II. Critical Issues

III. Research Goal and Tentative Schedule

Current 5G Network and Its Limitations

5G is mostly based on terrestrial infrastructure using radio frequency (RF) transmission

Main limitations:

1. **Data-rate Limitation:** 5G can support Gbps data rate or lower → need higher data rates for future applications
2. **Coverage Limitation:** limit the support to rural/remote areas, cannot guarantee global coverage
3. **Flexibility Limitation:** limit to provide flexible deployment for emergency communications and temporary events

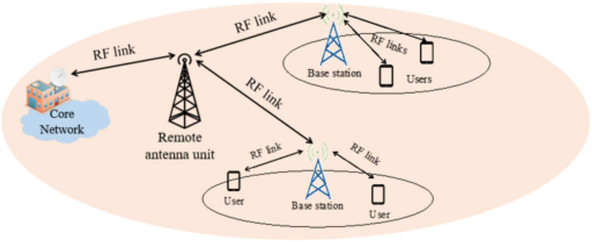


Figure: Terrestrial cellular mobile networks using RF transmission

Research Motivations

1. **Data-rate Limitation:**
   Free-space optics (FSO) (187-400 THz) and **sub-THz (90-300 GHz)** technologies can offer much larger bandwidth than the current **5G mmWave (24-100 GHz)**
   $\Longrightarrow$ *Higher speed connections (∼ hundreds of Gbps or even Tbps)*
2. **Coverage Limitation:**
   Low-earth orbit (LEO) satellites (160-1500 km) forming constellation networks can be deployed to provide the Internet from space (e.g., Starlink-SpaceX, Project Kuiper-Amazon,...)
   $\Longrightarrow$ *Global coverage and lower latency than other types of satellite*
3. **Flexibility Limitation:**
   Unmanned aerial vehicles (UAVs) have recently emerged as an efficient solution for a wide range of applications, e.g., delivery services, search and rescue in emergency operations, smart agriculture, and military missions
   $\Longrightarrow$ *Low-cost and flexible deployment*

Considered Network Scenario

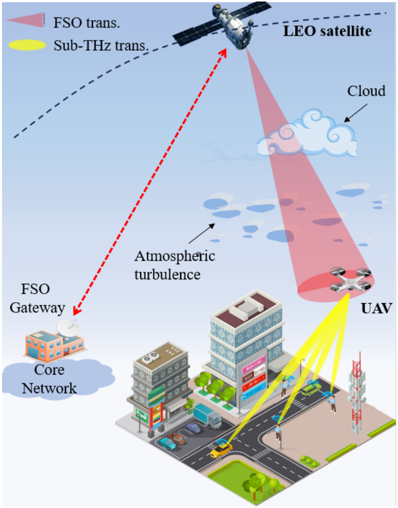
We consider an end-to-end network scenario that includes two main transmission links

1. **Backhaul Link:** from LEO satellite to UAV
   - Long distance (hundreds of km)
   - High speed needed

   ⟹ *FSO transmission is considered*

2. **Access Link:** from UAV to ground users (GU)
   - Short distance (hundreds of meters)
   - Dynamic network (the mobility of GUs)

   ⟹ *Sub-THz transmission is considered*



Outline

Critical Issues

Backhaul link:

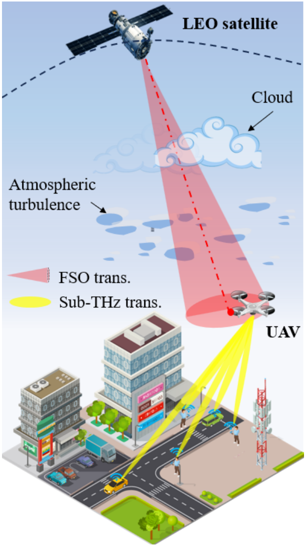
- **Cloud attenuation:** the liquid water particles in clouds cause the scattering phenomenon
- **Atmospheric turbulence:** air pockets with different refractive indexes cause the scintillation effect
- **Pointing error:** misalignment between the center of satellite beam footprint and that of the UAV detector

➡ *Unstable channel → Limited capacity of the backhaul link*

Access link:

- **Dynamic network:** the GUs move over time → time-varying network topology

➡ *Difficulty in maintaining the quality of service (QoS) for all GUs*



Research Question

How to optimize the end-to-end performance/keep the quality of service/experience (QoS/QoE) under the constraints of backhaul link and dynamic network of access link?

$\Longrightarrow$ *Find the optimal UAV trajectory to optimize the end-to-end performance*

New challenges:

- Moving UAV: more uncertainty of the backhaul channel
- End-to-end dynamic network: satellite orbit, UAV trajectory, GU mobility

$\Longrightarrow$ *Must be considered carefully*

Outline

Literature Review

Survey of major studies related to UAV trajectory for access links

Reference	Summary
[1] – 2021	A novel mechanism for link optimization for a LEO satellite-UAV-GU network. MmWave is employed for the backhaul link.
[2] – 2021	A trajectory algorithm and collision avoidance schemes for multiple UAVs for access link. FSO transmission is adopted. *→ No backhaul-link consideration. BS positions are fixed*
[3] – 2023	Algorithms for UAV trajectory for UAV-to-BS (access) link. Random position of BSs and THz transmission are considered. *→ No backhaul-link consideration*

⇒ The UAV-trajectory algorithm considering FSO-based satellite-to-UAV backhaul link is not studied yet.

[1] A. H. Arani, P. Hu and Y. Zhu, "Fairness-Aware Link Optimization for Space-Terrestrial Integrated Networks: A Reinforcement Learning Framework," in IEEE Access, vol. 9, pp. 77624-77636, 2021.
[2] S. Song, M. Choi, D. -E. Ko, and J. -M. Chung, "Multi-UAV Trajectory Optimization Considering Collisions in FSO Communication Networks," in IEEE Journal on Selected Areas in Communications, vol. 39, no. 11, pp. 3378-3394, Nov. 2021.
[3] M. T. Dabiri, M. Hasna, N. Zorbaand T. Khattab, "Optimal Trajectory and Positioning of UAVs for Small Cell HetNets: Geometrical Analysis and Deep Reinforcement Learning Approach," IEEE Open Journal of the Communication Society, 2023.

Goals of the Study (1)

GOAL: to optimize the **end-to-end throughput performance** and **maintain the QoS** (outage probability/BER) under the **constraints of (1) satellite/UAV energy consumption, (2) the unstable channels of the backhaul links** and **(3) the dynamic network** of the access links

1. **Backhaul link:**
   - We design an adaptive power/rate scheme to keep the QoS of the backhaul link (our previous work)
2. **Access link:**
   - Optimization problem for UAV trajectory is usually NP-hard (non-convex, non-linear combination problem) → *Apply deep reinforcement learning (DRL)*
   - UAV has limited energy and weak computing power → *Employ digital twin (DT) technology to provide a virtual training environment*
   - We also employ *a ML-based echo state network (ESN) to predict the GU positions* in advance to support the optimization process of the UAV trajectory design

Goals of the Study (2)

2. **Access link:**

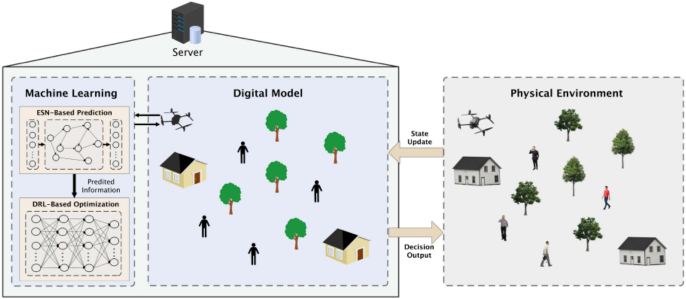
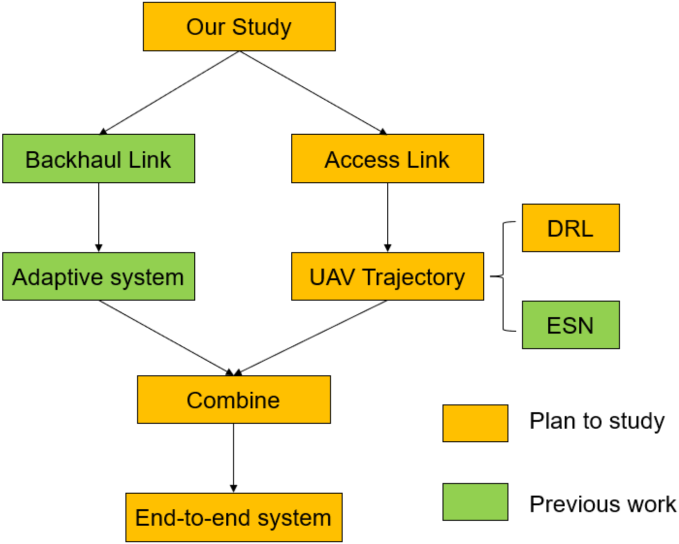


Figure: The access-link system model

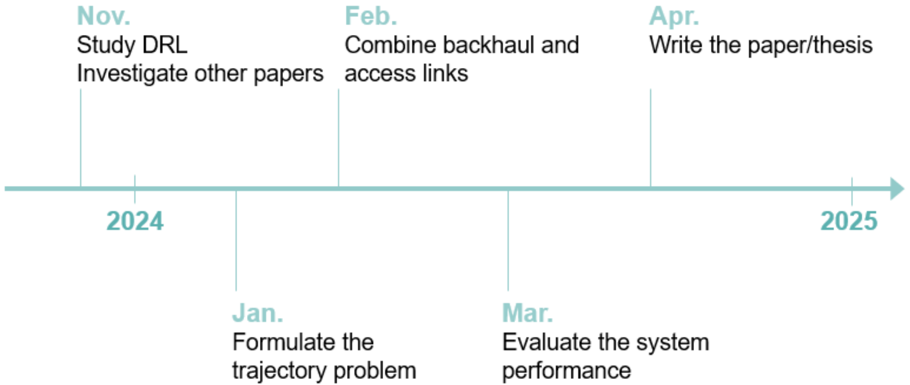
⟹ The processing delay of the DT may affect the end-to-end performance → need to be considered

3. We investigate the end-to-end performance of the system

Research Summary



Research Schedule



Thank you for your attention!