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

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Outline

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

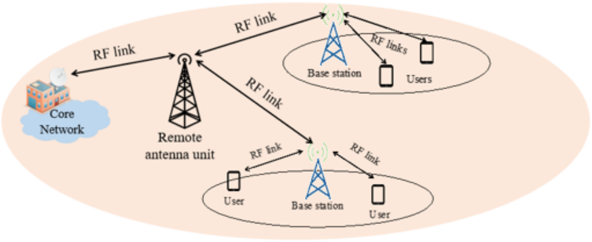


Figure: Terrestrial cellular mobile networks using RF transmission

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 ($\sim$ 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:**
   The use of unmanned aerial vehicles (UAVs) has 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

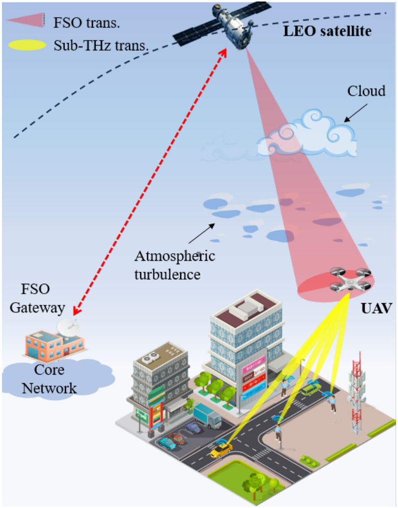
We consider an end-to-end network scenario that includes two main transmission links

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

   $\Longrightarrow$ *FSO transmission is considered*

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

   $\Longrightarrow$ *Sub-THz transmission is considered*



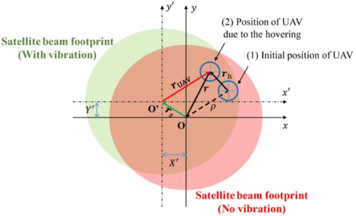
Outline

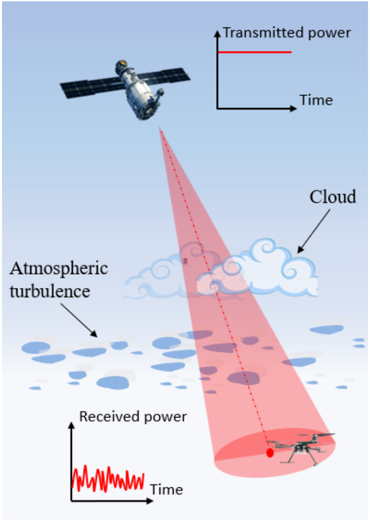
Critical Issues (1)

Backhaul link:

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

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





Critical Issues (2)

Access link:

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

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?

⟹ *Adopt mitigation techniques for backhaul link and find the optimal UAV's trajectory for access link*

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 **keep the QoS** (outage probability/BER) under the **constraints of the backhaul link** and **dynamic network** of the access link

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* in advance to support the optimization process of the UAV trajectory design

Goals of the Study (2)

2. **Access link:**

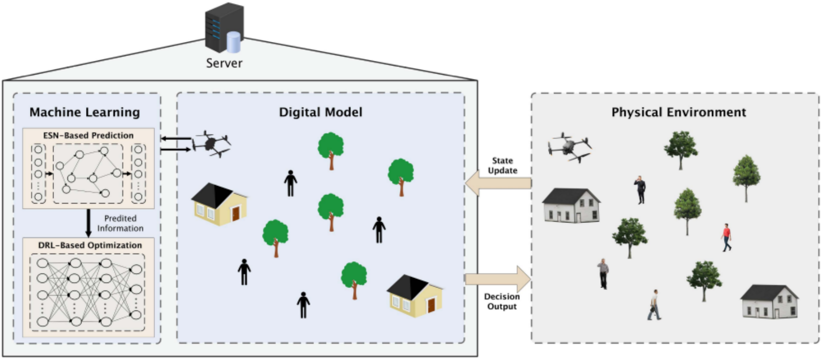
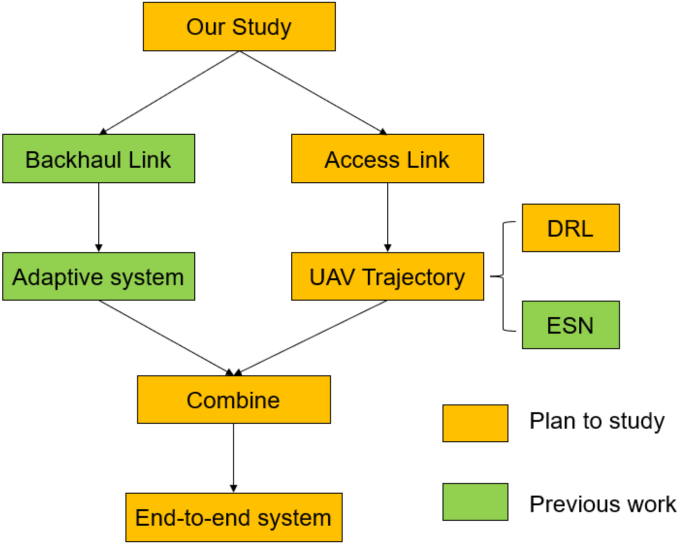


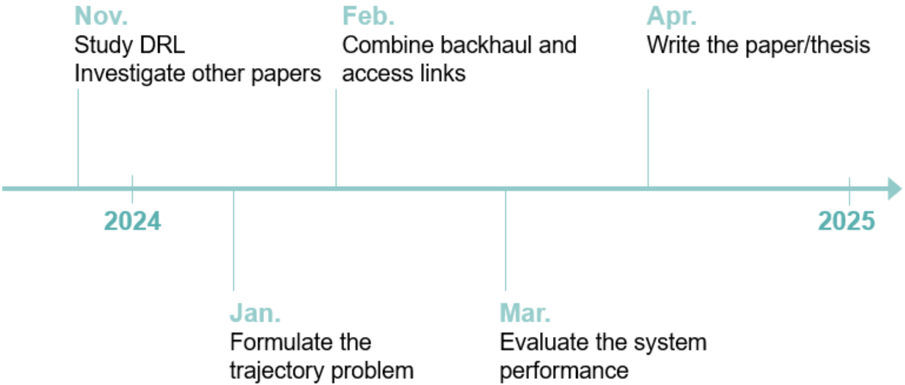
Figure: The access-link system model

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

Research Summary



Research Schedule



Thank you for your attention!