Adaptive Rate/Power Control with ML-based Channel Prediction for Optical Satellite Systems

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Outline

I. Introduction

II. System Description and Transmission Schemes

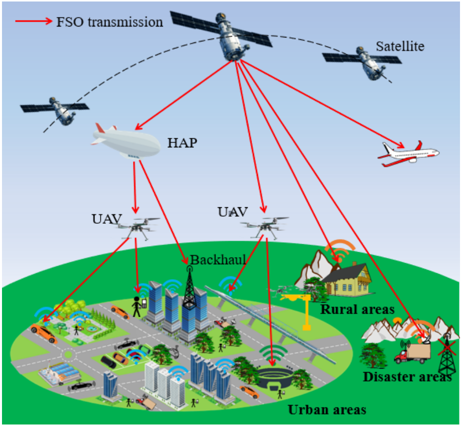
III. Performance Evaluation and Numerical Results

IV. Conclusion

Free-Space Optics (FSO)-Based Vertical Network

- FSO is a line-of-sight technology using infrared frequency bands (187 - 400 THz) for data transmission in free space
  $\Longrightarrow$ *Large bandwidth, high-speed connections ($\sim$ hundreds of Gbps or even Tbps)*

- Vertical/space network by employing flying platforms, e.g., satellites, Unmanned Aerial Vehicle (UAV), and High-Altitude Platform (HAP)
  $\Longrightarrow$ *Wide coverage and flexible deployment*



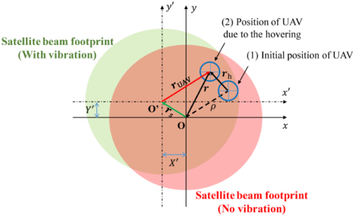
With global coverage and extremely high data rate, FSO-based vertical network is expected to be a key technology for the beyond-5G wireless networks

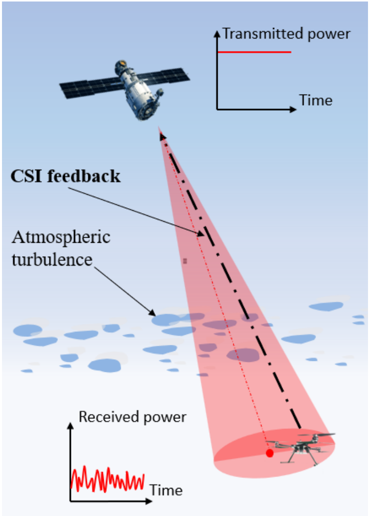
Critical Issues and Challenges (1)

Critical issues:

1. **Atmospheric turbulence:** air pockets with different refractive indexes cause the scintillation effect
2. **Pointing error:** misalignment between the center of the satellite beam footprint and that of the receiver detector

➡ *Power attenuation and power fluctuations at the receiver → Mitigation techniques are required*





Critical Issues and Challenges (2)

Challenges:

- For some PHY-layer mitigation techniques, such as adaptive rate/power/coding rate and hybrid FSO/RF schemes, the system changes its parameters according to the *feedback of the channel state information (CSI)*, which describes the current channel conditions

  $\Longrightarrow$ *The performance heavily depends on the accuracy of the CSI*

- *The CSI tends to be outdated* due to long feedback distance (up to 2000 kilometers for LEO satellite).
  For example:
  - Satellite's altitude: 500 km
  - Coherence time: $\sim$ 1 ms
  - Feedback time: $\sim$ 1.67 ms

  $\Longrightarrow$ *An efficient channel prediction scheme for such FSO systems is required*

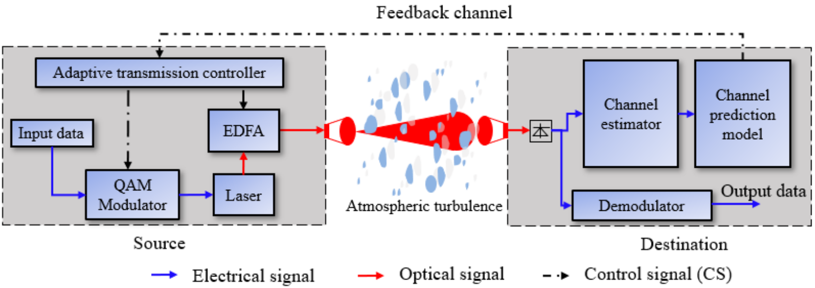
Motivations

1. Jointly adaptive power and modulation scheme is necessary for FSO-based vertical network
    - The flying platforms (satellites, HAPs, UAVs) have limited power → can not operate for a long duration → *an energy-efficient system is needed*
    - The existing studies focus on data rate adaptation with a fixed transmit power selected for the worst-case channel conditions → *low achievable energy efficiency (EE)*
    - Adaptive rate with power control can take advantage of favorable channel conditions → *highly enhance EE*
2. Channel prediction is needed to get the up-to-date CSI
    - Current adaptive schemes for FSO-based satellite systems assume that the CSI is known and perfect at the transmitter → *lacking practicality*

➡ *Adaptive modulation and power control with channel prediction is a promising candidate for FSO-based vertical network*

Outline

System Description



- The transmit power P_t and the order K of the K-QAM modulation scheme will be adaptively varied to attain minimum power consumption and also satisfy the required rate τ_{req} under the practical constraints, i.e., $\mathrm{Pr}_{\mathrm{out,tar}}$ (target outage probability), $\mathrm{BER}_{\mathrm{tar}}$ (target BER), and $P_{t,\max}$ (maximum transmit power)
- The system adapts its parameters according to the feedback CSI, which is predicted in advance by the ML-based prediction model

System Description (2)

- Let $\boldsymbol{h^*} = h_1^* < h_2^* < ... < h_M^*$ be the switching thresholds for M different transmission modes, $\boldsymbol{h} = h_1^* < h_2 < ... < h_N$ be the switching thresholds for N channel states, and h is the instantaneous channel gain
- The transmission mode i is selected if $h_i^* \leq h < h_{i+1}^*$ and the channel is said to be in state j if $h_j \leq h < h_{j+1}$. *The modulation scheme changes for each transmission mode and the transmit power changes for each channel state*
- To avoid a high bit error rate, no transmission is allowed when $h < h_1^*$

The Optimal AMP Scheme: Ideal Approach

The modulation scheme changes for each transmission mode, and *the transmit power continuously changes* according to the channel gain h: $P_t(h) = P_{r,i}/h$

- The optimization problem is to find the optimum vector of the transmission thresholds $\boldsymbol{h}^*$ and can be formulated as
- The Lagrange multiplier method is adopted to solve the optimization problem and get $\boldsymbol{h}^*$

$$\min_{\boldsymbol{h}^*} \overline{P_t} = \sum_{i=1}^{M} P_{r,i} \int_{h_i}^{h_{i+1}} \frac{f_h(h)}{h} \mathrm{d}h,$$

$$\text{s.t.} \quad \tau_{req} = R_s \sum_{i=1}^{M} \log_2 K_i \int_{h_i}^{h_{i+1}} f_h(h) \mathrm{d}h,$$

$$\mathrm{BER}(h) \leq \mathrm{BER}_{\mathrm{tar}},$$

$$\mathrm{Pr}_{\mathrm{out}} \leq \mathrm{Pr}_{\mathrm{out,tar}},$$

$$P_t(h) \leq P_{t,\max}$$

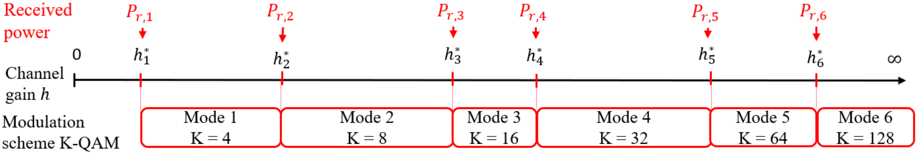


Figure: An example of AMP scheme with $M = 6$

The Sub-optimal AMP Scheme (SAMP): Our Approach

- **Problem with AMP scheme:** The power continuously changes over bit duration $\Longrightarrow$ *not feasible in practical systems due to delayed feedback and hardware limitation*
- **Our solution - SAMP scheme:** the modulation order changes for each transmission mode, and the transmit power changes for each burst duration
- **How to implement:** we need to
  1. Find the channel state thresholds $\boldsymbol{h}$
  2. Find the relation between $\boldsymbol{h}$ and $\boldsymbol{h}^*$

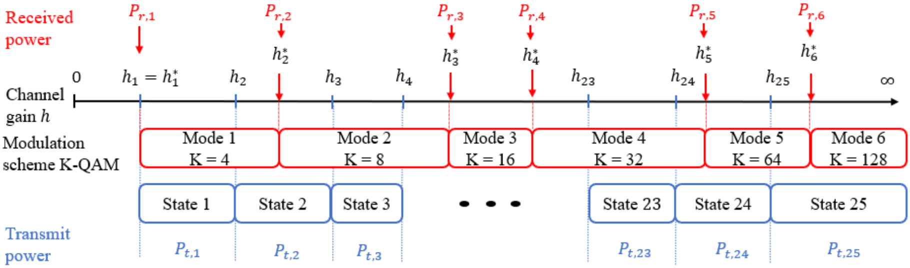


Figure: An example of SAMP scheme with $M = 6$ and $N = 25$

Channel State Model

We now design the channel-state model to effectively facilitate the operation of the system over fading channels

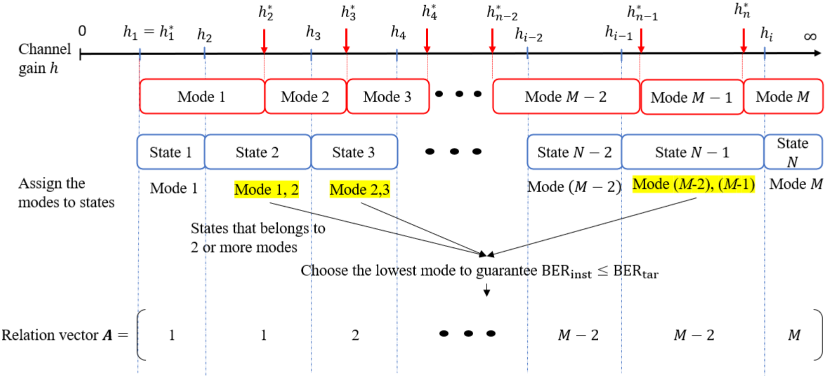
- Data are transmitted in fixed-time bursts (t_{burst})
- The interval of the channel state i^{th} satisfies the following conditions

$$\overline{t_i} = \frac{\mathrm{Pr}_i}{\mathrm{LCR}(h_i) + \mathrm{LCR}(h_{i+1})} = t_{\mathrm{burst}},$$

where $\mathrm{LCR}(h_{\mathrm{th}})$ is the level crossing rate at the certain threshold h_{th}, defined as the average number of times per second that the channel gain passes the threshold h_{th} [1], and Pr_i is the probability at channel state i^{th}

Assigning Transmission Modes to Channel States

When all the channel states and transmission modes have been determined, we assign the transmission modes to each channel state to find the relation vector $\boldsymbol{A}$ as follows



Finally, the transmitted power $P_{t,j}$ used for the j-th channel state is given as

$$P_{t,j} = \frac{P_{r,A_j}}{h_j}$$

Transmission Algorithm

Algorithm 1 Sub-optimal AMP Scheme

Input: τ_{req}, $\boldsymbol{P_r}$, $\boldsymbol{K}$, h
Output: $P_t(h)$, $K(h)$, $\boldsymbol{h^*}$, $\boldsymbol{h}$, $\boldsymbol{A}$
Step 1: Given $\mathrm{Pr}_{\mathrm{out,tar}}$, compute h_1^*
Step 2: Given τ_{req}, compute $\boldsymbol{h^*}$ by solving optimization problem.
Step 3: Compute $\boldsymbol{h}$ using channel state model
Step 4: Assign the transmission modes to channel states and get the vector $\boldsymbol{A}$.
Step 5:
if $h \geq h_1$ **and** $h_j \leq h < h_{j+1}$ **then**
  5.1: Choose transmit power $P_{t,j}$
  5.2: Choose modulation order $K_{\boldsymbol{A}_j}$
else
  Outage mode occurs, and the system is halted
end if

Outline

System Parameters

Name	Symbol	Value
LEO Satellite Parameters		
LEO satellite altitude	H_s	500 km
Zenith angle	ξ	$50°$
Divergence half-angle	θ	$223\ \mu$rad
Jitter angle	θ_jt	$11.15\ \mu$rad
UAV Parameters		
UAV's altitude	H_u	100 m
Aperture diameter	d_a	10 cm
Initial radial displacement	ρ	0 m
Other Parameters		
Symbol rate	R_s	250 Msps
Burst duration	t_burst	1 ms
Target BER	$\mathrm{BER}_{\mathrm{tar}}$	10^{-5}
Target outage probability	$\mathrm{Pr}_{\mathrm{out,tar}}$	1 %
Atmospheric altitude	H_a	20 km
Ground turbulence level	$C_n^2(0)$	10^{-14} m$^{-2/3}$

Evaluation Metrics

Average transmit power: The required transmit power needed to meet a requested rate and satisfy other constraints

Energy Efficiency: The successfully transmitted data bits per joule

$$\text{Energy Efficiency} = \frac{\#\ \text{successfully transmitted data bits per burst}}{\text{Avr transmit power} \times \text{burst duration}}$$

Avr Transmit Power vs. Requested Rate

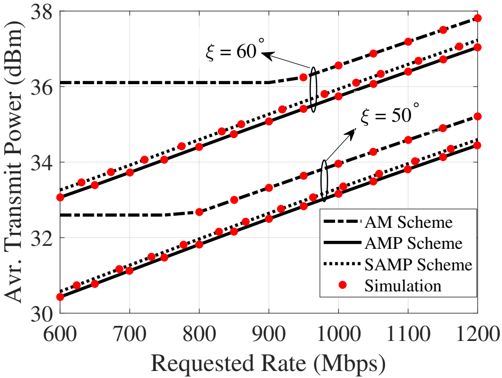


Figure: Average required transmit power vs. requested rate for various adaptive schemes.

$\Longrightarrow$ In both cases of zenith angle, the adaptive modulation (AM) scheme required more power (~ 0.9dB) than the other schemes

$\Longrightarrow$ The sub-optimal AMP scheme nearly has the same performance as the optimal one

Effects of Outdated CSI

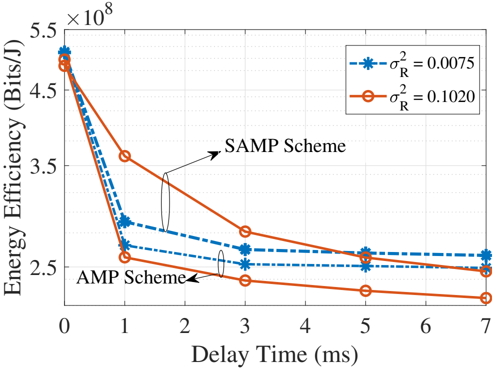


Figure: Energy efficiency in case of outdated CSI.

⟹ Outdated CSI severely degrades the system's performance

⟹ The AMP scheme is more sensitive to delayed CSI than the sub-optimal one

Energy Efficiency with Predicted CSI

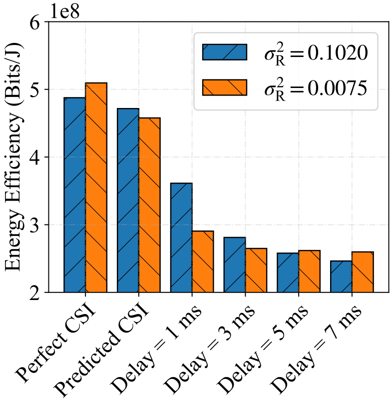


Figure: EE in case of predicted CSI and outdated CSI.

The echo state network (ESN), a simple yet efficient RNN model, is employed for channel prediction [2]

$\Longrightarrow$ By using the channel prediction scheme, the EE is considerably improved

Outline

Conclusion

1. The thesis presented an adaptive modulation and power control design for FSO-based vertical networks with channel prediction
2. Remarkable observations from the results:
   - The sub-optimal AMP scheme is less sensitive to delayed CSI than the optimal one. While in perfect channels, they offer nearly similar performance
   - The outdated CSI severely deteriorates the system's performance. By using channel prediction schemes, energy efficiency is considerably improved

References

[1] H. D. Le and A. T. Pham, "On the design of FSO-based satellite systems using incremental redundancy hybrid ARQ protocols with rate adaptation," *IEEE Trans. Veh. Technol.*, vol. 71, no. 1, pp. 463–477, Jan. 2022.

[2] T. V. Nguyen, H. D. Le, and A. T. Pham, "Echo state network for turbulence-induced fading channel prediction in free-space optical systems," in *Proc. IEEE World Symp. Commun. Eng.*, 2022, pp. 47–52.