Adaptive Modulation and Power Control for FSO–based Vertical Networks with Channel Prediction

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Outline

Current 5G Network and Its Limitations

We are now witnessing the explosion of the 5G technology

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

Two main limitations:

1. **Restricted Coverage Areas:** Limit the support to rural/remote areas, cannot guarantee global coverage
2. **Data-rate Limitation:** 5G can support Mbps data rate or lower → need higher data rates for future applications (∼ Gbps or even Tbps)

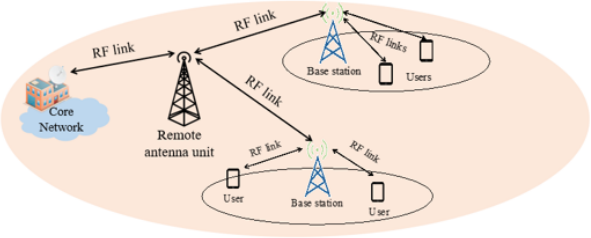
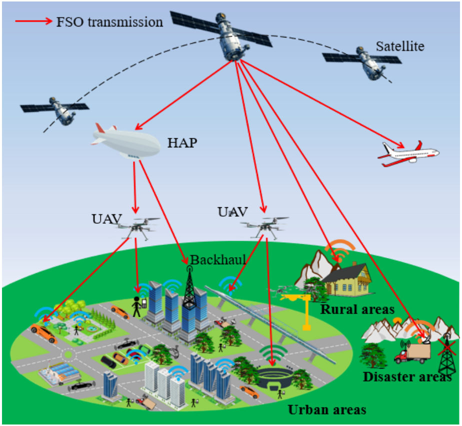


Figure: Terrestrial cellular mobile networks using RF transmission

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 (∼ 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*



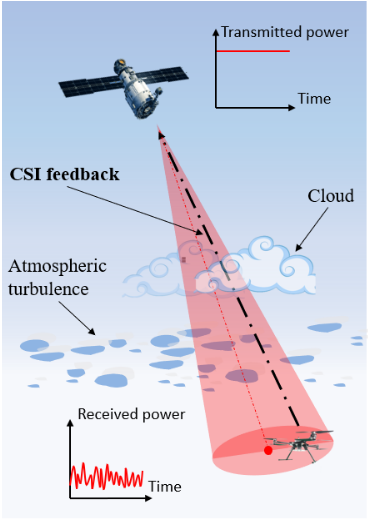
With global coverage and extremely high data rate, FSO-based vertical network is expected to be a key technology for the beyond-5G wireless networks

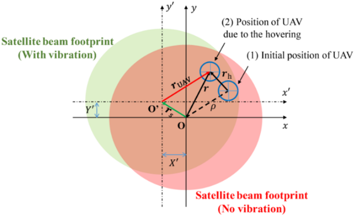
Critical Issues and Challenges (1)

Critical issues:

1. **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

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





Critical Issues and Challenges (2)

Challenges:

- For some 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)*, a parameter that 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 adaptive power scheme has not been studied for FSO-based vertical networks, where the CSI tends to be outdated
   - The adaptive modulation scheme has been proven to offer better rate/throughput performance
2. Channel prediction is needed to get the up-to-date CSI
   - The performance of adaptive techniques highly depends on the accuracy of the CSI
   - Some techniques that are currently studied for FSO-based vertical networks, such as hybrid FSO/RF, and adaptive rate/coding rate, often assume that the CSI is perfect for the transmitter → *lacking practicality*

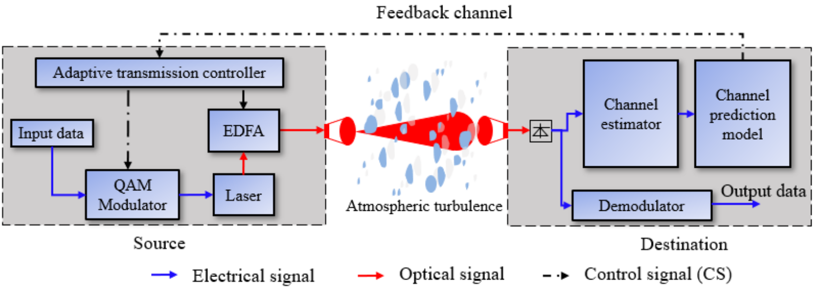
➡ *Adaptive modulation and power control with channel prediction is a promising candidate for FSO-based vertical network*

Goals of the Study

1. We design an energy-efficient scheme for the FSO system, which adapts the transmit power and modulation scheme according to the current channel status
2. We adopt the machine learning (ML)-based prediction model to accurately get the up-to-date CSI
3. We then analyze the performance of the proposed system with different channel conditions

Outline

System Description (1)



- 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., $\mathrm{Pr}_{out,tar}$ (target outage probability), $\mathrm{Pr}_{e,tar}$ (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 $h < h_1^*$

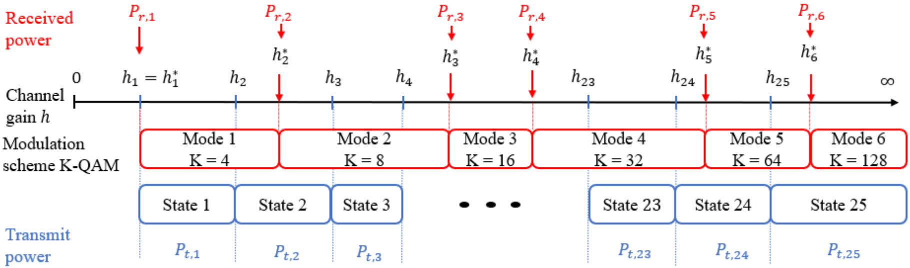


Figure: A system illustration with $M = 6$ and $N = 25$

The Optimal AMP Scheme: Ideal Approach

- We first consider the optimal adaptive modulation and power control (AMP) scheme
- The modulation scheme changes for each transmission mode, and *the transmit power continuously changes* according to the channel gain h (not depend on the channel state): $P_t(h) = P_{r,i}/h$
- The optimization problem is to find the optimum vector of the transmission thresholds $\boldsymbol{h}^*$ and can be formulated as

$$\begin{aligned} \min_{\boldsymbol{h}^*} \overline{P_t} &= \sum_{i=1}^{M} P_{r,i} \int_{h_i}^{h_{i+1}} \frac{f_h(h)}{h} \mathrm{d}h, \\ \text{s.t.} \qquad \tau_{req} &= R_s \sum_{i=1}^{M} \log_2 K_i \int_{h_i}^{h_{i+1}} f_h(h) \mathrm{d}h, \\ \mathrm{Pr}_e &\leq \mathrm{Pr}_{e,tar}, \\ \mathrm{Pr}_{out} &\leq \mathrm{Pr}_{out,tar}, \\ P_t(h) &\leq P_{t,max} \end{aligned}$$

- The Lagrange multiplier method is adopted to solve the optimization problem and get $\boldsymbol{h}^*$

The Sub-optimal AMP Scheme: 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 - sub-optimal AMP scheme:** the modulation scheme changes for each transmission mode, and the transmit power changes for each burst duration (channel state)
- **How to implement:** we need to
  1. Find the channel state thresholds $\boldsymbol{h}$
  2. Find the relation between the channel state thresholds $\boldsymbol{h}$ and transmission mode thresholds $\boldsymbol{h}^*$

Channel State Model

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

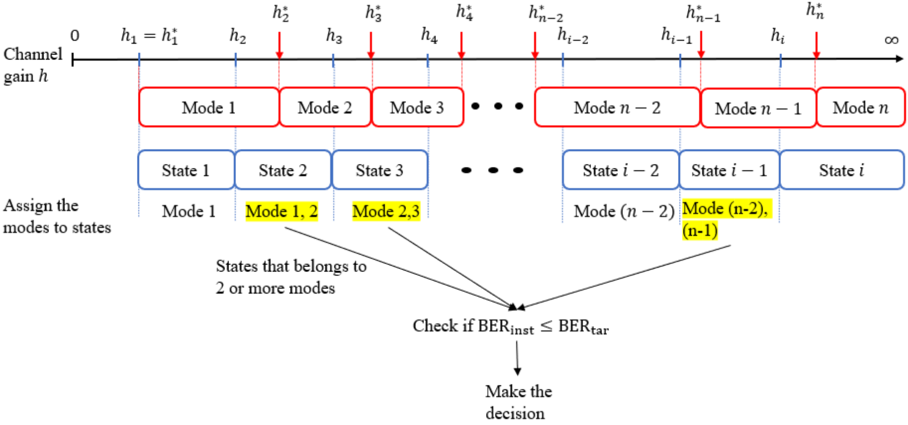
- Data are transmitted in fixed-time bursts (t_{burst})
- The selection of $\boldsymbol{h}$ satisfies the condition that all channel states' intervals are equal to t_{burst}. The interval of the channel state i^{th} can be expressed as

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

where $\mathrm{LCR}(h_{th})$ 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}, 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 as follows



Transmission Algorithm

Algorithm 1 AMP Scheme

Input: τ_{req}, $\boldsymbol{P_r}$, $\boldsymbol{K}$, h
Output: $P_t(h)$, $\boldsymbol{h}^*$, $K(h)$
Step 1: Given τ_{req}, compute h_1^* and $\boldsymbol{h}^*$ by solving optimization problem
Step 2:
if $h \geq h_1^*$ **and** $h_i^* \leq h < h_{i+1}^*$ **then**
  2.1: Allocate optimal transmit power $P_t(h) = \frac{P_{r,i}}{h}$
  2.2: Choose modulation order K_i
else
  With the $\Pr_{e,tar}$ and $\Pr_{out,tar}$, τ_{req} can not be delivered
end if

Algorithm 2 Sub-optimal AMP Scheme

Input: τ_{req}, $\boldsymbol{P_r}$, $\boldsymbol{K}$, h
Output: $P_t(h)$, $K(h)$, $\boldsymbol{h}^*$, $\boldsymbol{h}$, $\boldsymbol{St}_{asg}$
Step 1: Given τ_{req}, compute h_1^* and $\boldsymbol{h}^*$ by solving optimization problem.
Step 2: Compute $\boldsymbol{h}$ using channel state model
Step 3: Assign the transmission modes to channel states and get the array $\boldsymbol{St}_{asg}$.
Step 4:
if $h \geq h_1$ **and** $h_j \leq h < h_{j+1}$ **then**
  4.1: Choose transmit power $P_{t,j}$
  4.2: Choose modulation order $K_{\boldsymbol{St}_{asg,j}}$
else
  With the $\Pr_{e,tar}$ and $\Pr_{out,tar}$, τ_{req} can not be delivered
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 μrad
Jitter angle	θ_jt	11.15 μrad
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	$\mathrm{Pr}_{e,tar}$	10^{-5}
Target outage probability	$\mathrm{Pr}_{out,tar}$	1 %
Atmospheric altitude	H_a	20 km
Ground turbulence level	$C_n^2\left(0\right)$	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

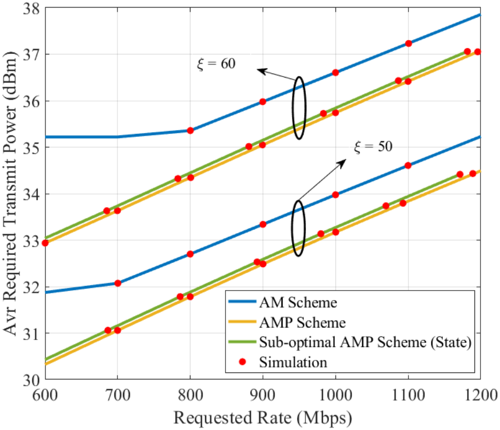


Figure: Average required transmit power vs. requested rate for various adaptive schemes.

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

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

Energy Efficiency vs. Radial Displacement

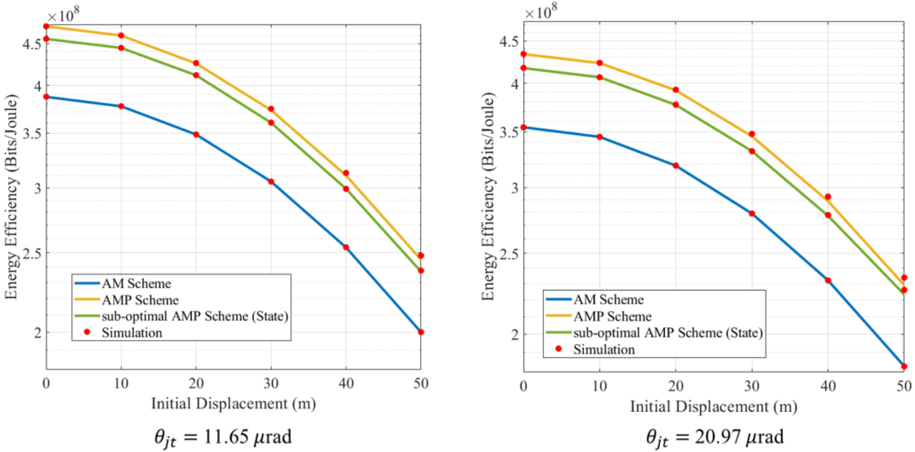


Figure: Energy efficiency vs. UAV's initial displacement for various adaptive schemes.

$\Longrightarrow$ The pointing error has a considerable effect on the system's performance

Effects of Outdated CSIs

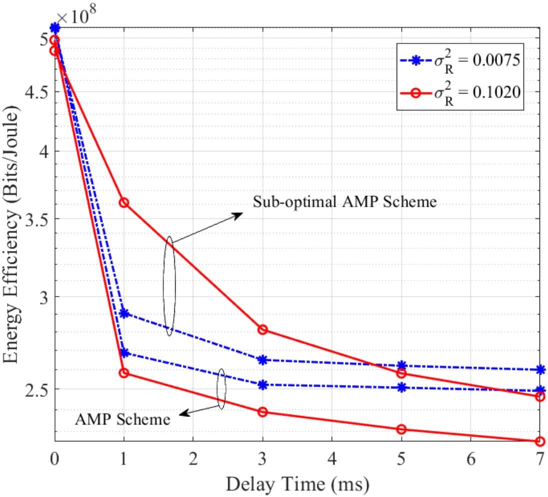


Figure: Energy efficiency in case of outdated CSIs.

⟹ Outdated CSIs severely degrade the system's performance

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

Energy Efficiency with Predicted CSI

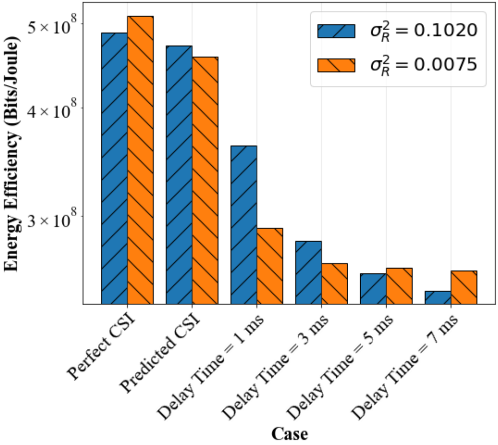


Figure: EE in case of predicted CSIs and outdated CSIs.

We use the sub-optimal AMP scheme and employ the echo state network (ESN), a simple yet efficient RNN model, for channel prediction

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

Outline

Conclusion

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