On the Design of Power Adaptation for Free-Space Optical (FSO) – based Vertical Networks using Machine Learning Approach

Presenter: Tinh Nguyen

Computer Communications Lab.,
The University of Aizu

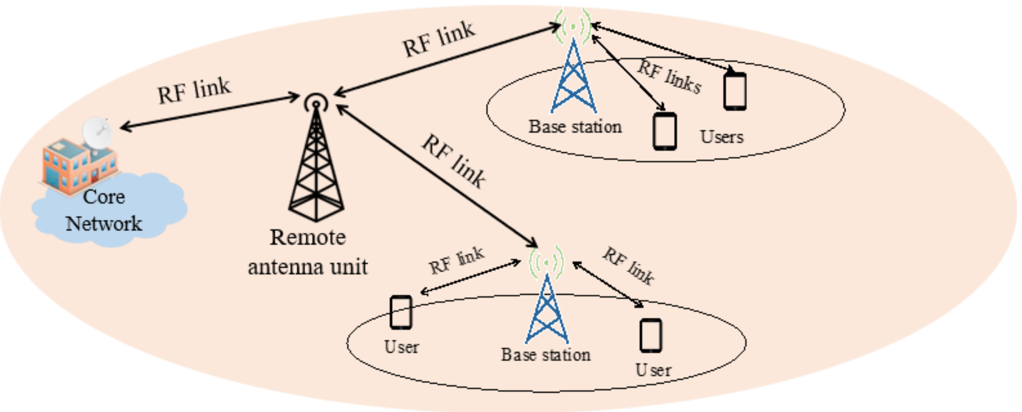
Outline

- Introduction
  - Free-Space Optics (FSO)-Based Vertical Network
  - Critical Issues and Challenges
  - Motivations
  - Goals of the Study
- Power Adaptation Design with Channel Prediction
  - System Description
  - Power and Transmission Mode Thresholds
  - Channel State Model
  - Assigning the Channel States to Transmission Modes
  - ESN Prediction Model
- Performance Analysis and Results
- Conclusions

Introduction

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



Terrestrial cellular mobile networks using RF transmission

- Two main limitations:

1) Restricted Coverage Areas

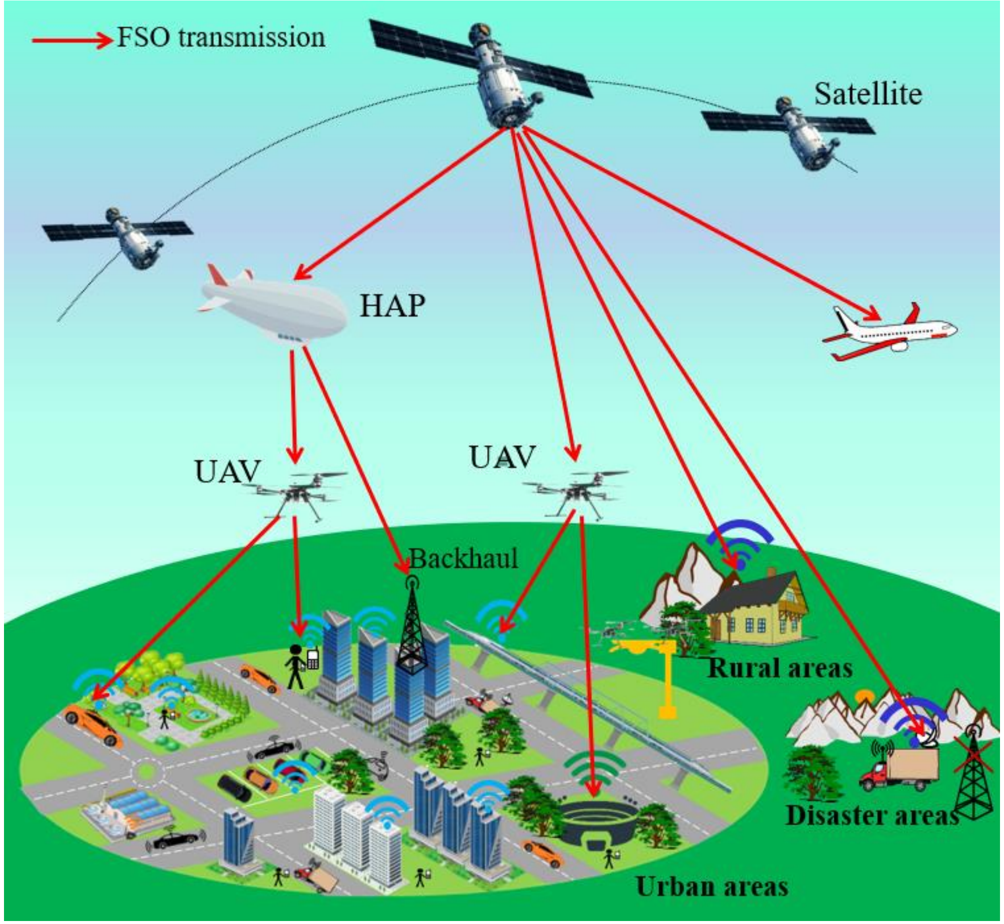
- Limit the support to rural/remote areas, cannot guarantee global coverage

2) Data-rate Limitation

- Can support Mbps data rate or lower → need higher data rates for future applications (~ Gbps or even Tbps)

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
  - Large bandwidth, high-speed connections (~ Gbps or even Tbps)
  - High level of security, immunity to electromagnetic interference



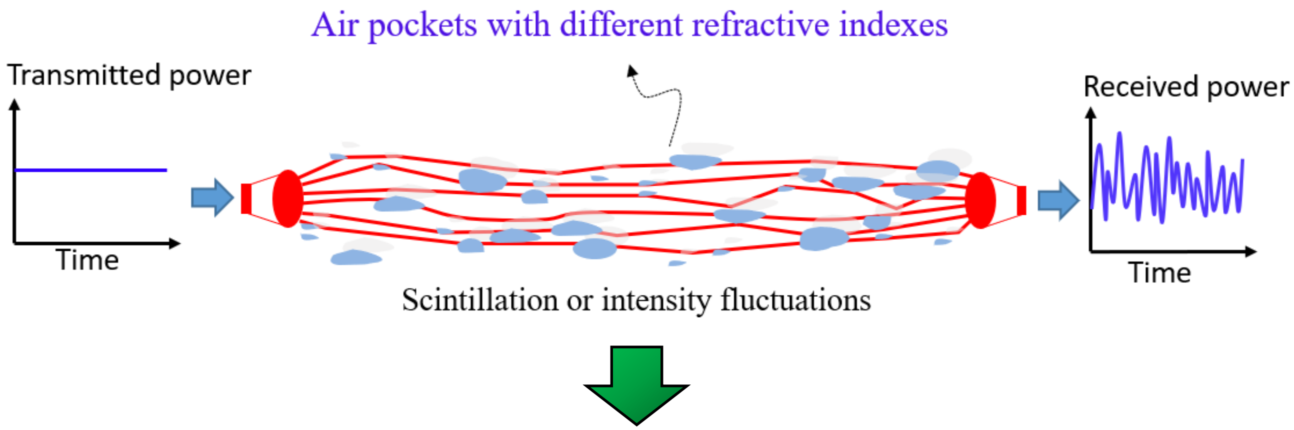
- Vertical/space network
  - By employing flying platforms, e.g., satellites, Unmanned Aerial Vehicle (UAV), and High-Altitude Platform (HAP) → Providing wide coverage and flexible deployment

→ 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:

- FSO link is sensitive to atmospheric turbulence, which causes the scintillation effect



power fluctuations at the receiver

→ Mitigation techniques such as adaptive rate/power/coding rate and hybrid FSO/RF schemes are crucial to maintaining reliable transmissions

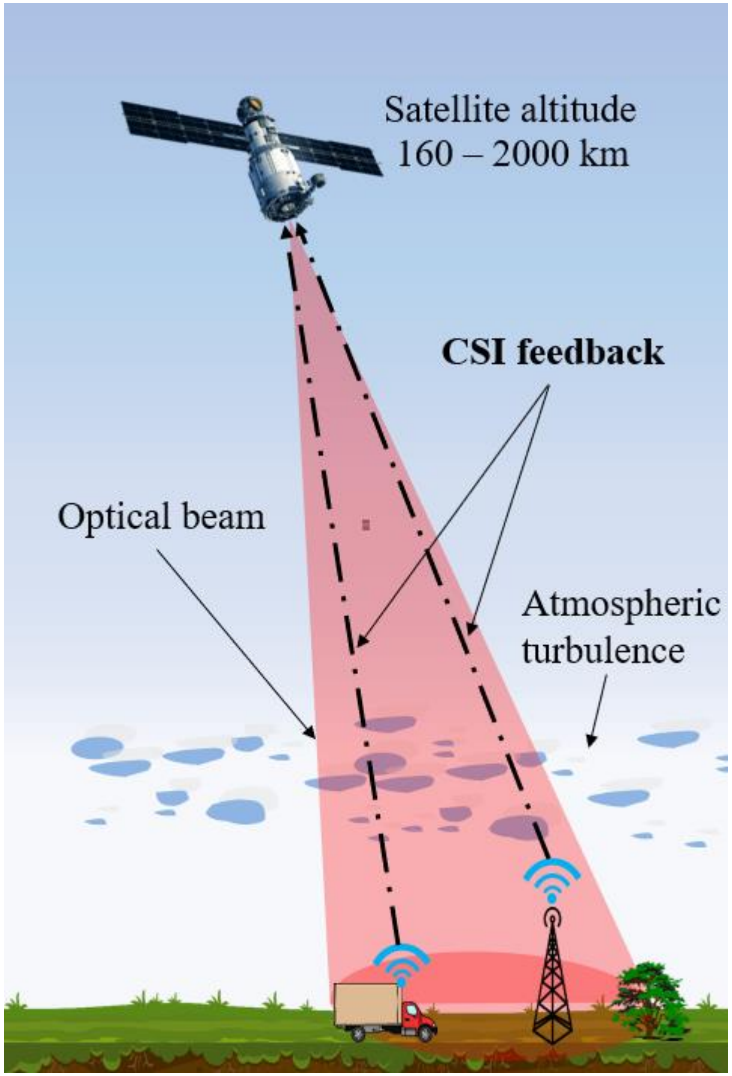
Critical Issues and Challenges (2)

- Challenges:
  - The system changes its parameters according to the feedback of the channel state information (CSI), a parameter that describes the current fading channel conditions

  → *The performance heavily depends on the accuracy of the CSI*

  - The CSI tends to be outdated due to long feedback distances (up to thousands of kilometers)

  → *An efficient channel prediction scheme for such FSO system is required*



Motivations

- The flying platforms (satellites, HAPs, UAVs) have limited power → not be able to operate for a long duration

  → *It is necessary to design an energy-efficient communication system that can reduce energy consumption and extend the battery life of wireless terminals.*

- The adaptive power schemes have been widely applied for radio frequency (RF) communications and FSO-based terrestrial systems

  → *They have not been studied FSO-based space networks, where the CSI tends to be outdated due to long transmission distance*

- Other mitigation techniques that are currently studied for FSO-based vertical networks, such as hybrid FSO/RF, adaptive rate/coding rate, often assume that the CSI is known and perfect for the transmitter

  → *It lacks practicality. Therefore, it's necessary to have an efficient channel prediction scheme for such networks*

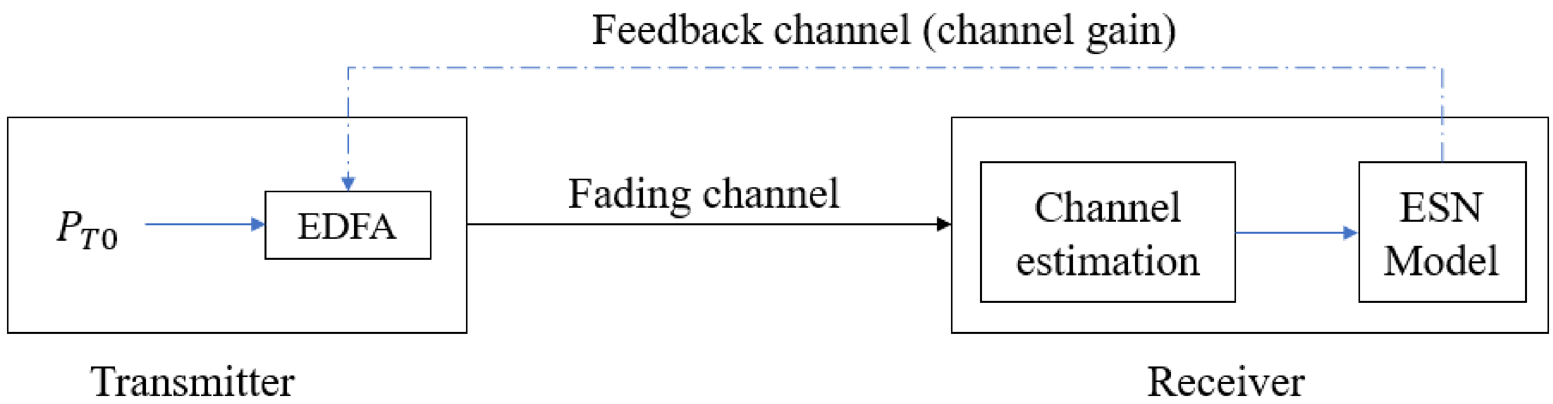
The adaptive power system with channel prediction is a promising candidate.

Goals of the Study

- We design an energy-efficient scheme for the FSO system, which adapts the transmitted power according to the current channel status
- The CSIs are predicted beforehand by using the machine learning (ML)-based echo state network (ESN) model thanks to its simple structure yet high efficiency
- We analyze the performance of the proposed system with different channel conditions

Power Adaptation Design with Channel Prediction

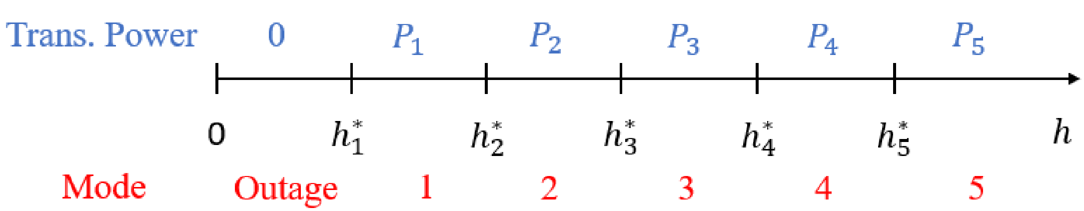
System Description (1)

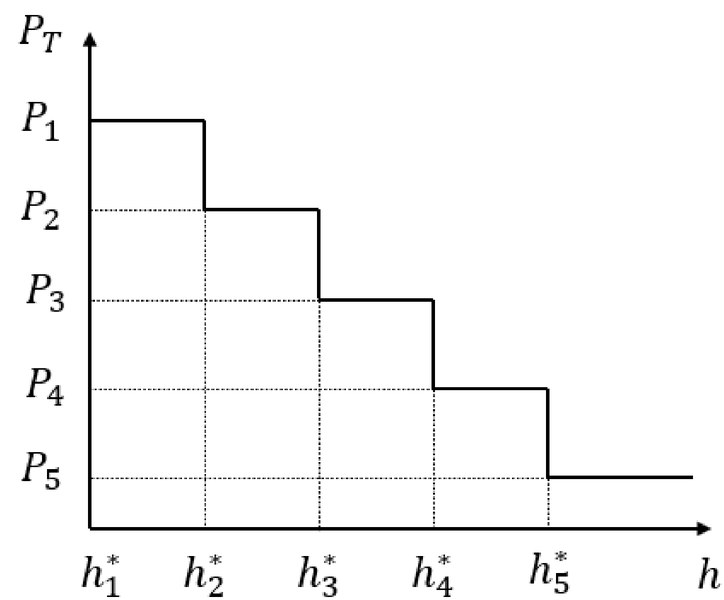


- Main idea:
  - We fix the power P_{T0} and change the gain G of the Erbium-doped fiber amplifier (EDFA) according to the current channel conditions (channel gain h) to meet the QoS, e.g., BER.
  - The transmitted power after being amplified by the EDFA is $P_T = GP_{T0}$
  - The system adapts the gain G according to the feedback CSIs, which are predicted in advance by the ESN model

System Description (2)

- Let $h_1^* < h_2^* < \ \ldots < h_M^*$ be the switching thresholds for M different transmission modes and h is the instantaneous channel gain. The transmission mode n is selected if $h_n^* \le h < h_{n+1}^*$. The transmitted power changes for each mode
- To avoid a high bit error rate, no transmission is allowed when $h < h_1^*$





A system illustration with $M = 5$

Power and Transmission Mode Thresholds

- Power thresholds:
  - The EDFA has its own range of gain: $[G_{\min}, G_{max}]$. Therefore, the transmitted power also falls into the range $[P_{T_{min}}, P_{T_{max}}]$
  - We divide the power range into $P_{T_{min}} \leq P_1 < P_2 < \cdots < P_M \leq P_{T_{max}}$ (1), such that each value satisfies the gain step of the EDFA

- Transmission Mode Thresholds
  - To maintain a predefined BER using a particular modulation scheme, e.g., K-QAM, we need a certain SNR, denoted as γ_{tar}
  - Meanwhile, based on the transmit power and the channel gain, the SNR can be computed as $\gamma_{tar} = \frac{P_i^2 {h_i^*}^2}{\sigma_{noise}^2}$ (2)
  - From (1) and (2), a set of transmitted power threshold P_i and transmission mode threshold h_i^* can be derived

Channel State Model

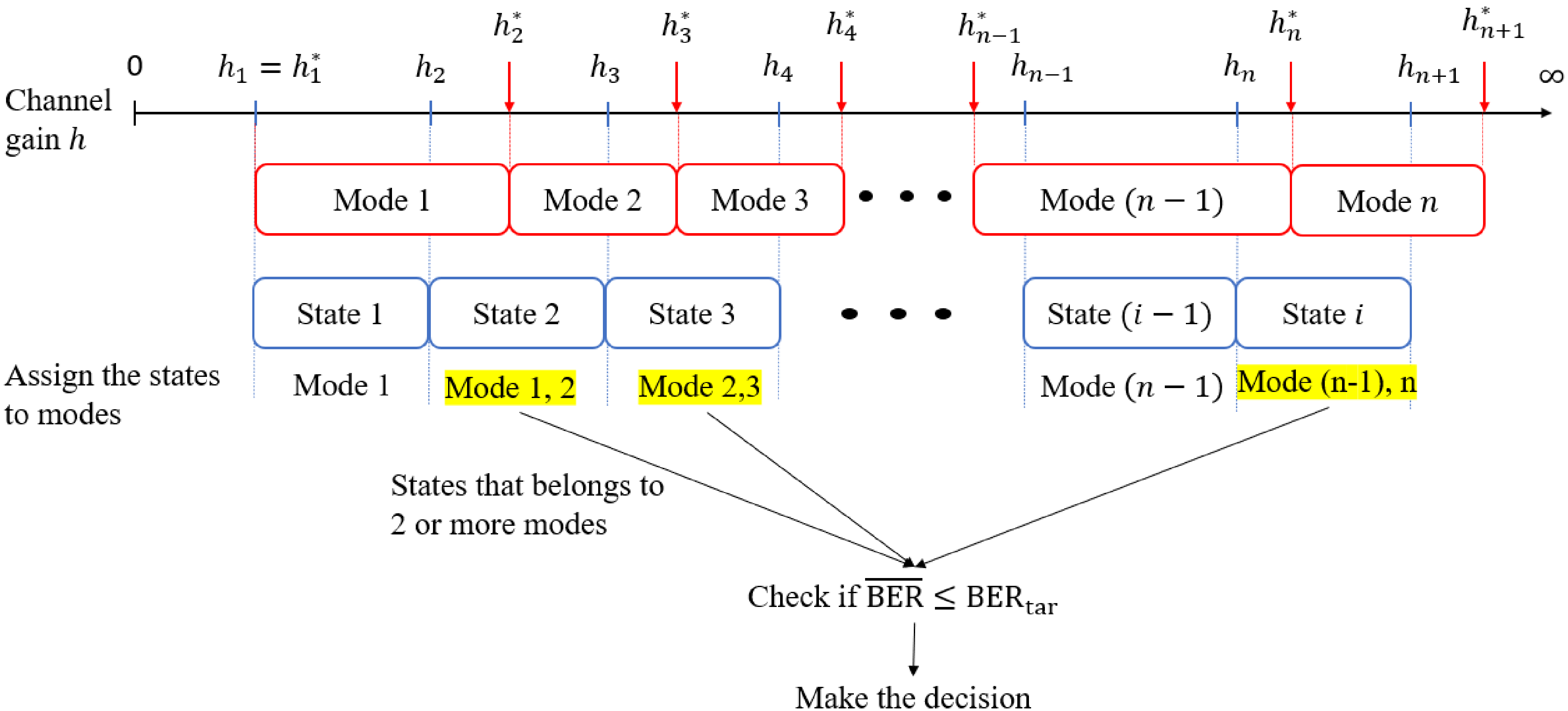
- We now design the channel-state model to effectively facilitate the operation of the system over turbulence fading channels
  - Data are transmitted in fixed-time bursts (T_{burst}) whose duration is shorter than the coherence time of the fading channel
  - We first divide the channel into states defined by a range of CSIs
  - The selection of the range of CSIs satisfies the condition that all channel states' intervals are equal to T_{burst}. The interval of the channel state i^{th}, $\overline{\tau}_i$, depends on the statistics of the channel and can be expressed as

$$\overline{\tau}_i = \frac{\mathrm{Pr}_i}{\mathrm{LCR}(h_i)+\mathrm{LCR}(h_{i+1})} = T_{burst} \quad (3)$$

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 the Channel States to Transmission Modes

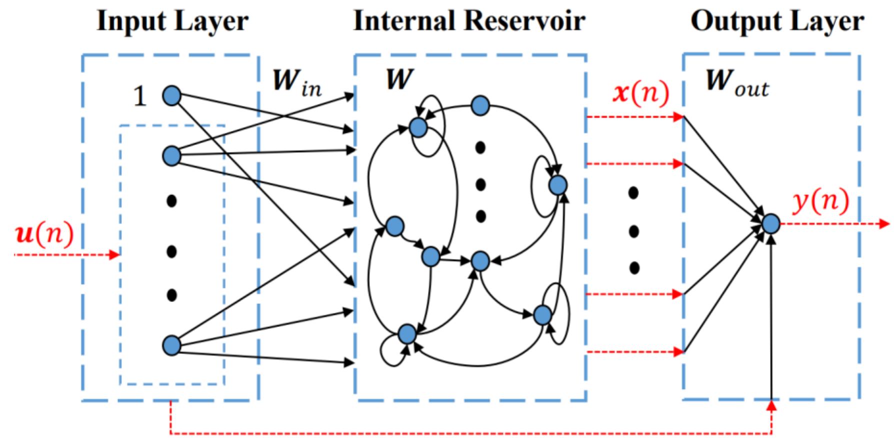
- When all the channel states and transmission modes have been determined, we assign the states to each mode as follows



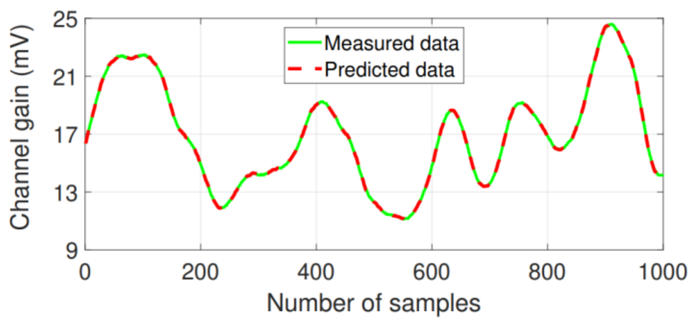
ESN Prediction Model

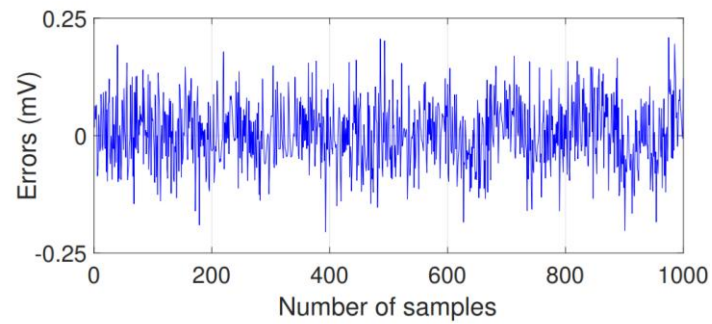
- ESN model has a simple structure
  - Feedforward neural network with three layers
  - There's an internal reservoir that can store the historical information

  → *ESN performs enormous potential in time-series prediction*



- Prediction accuracy: we evaluate the prediction performance of the ESN model



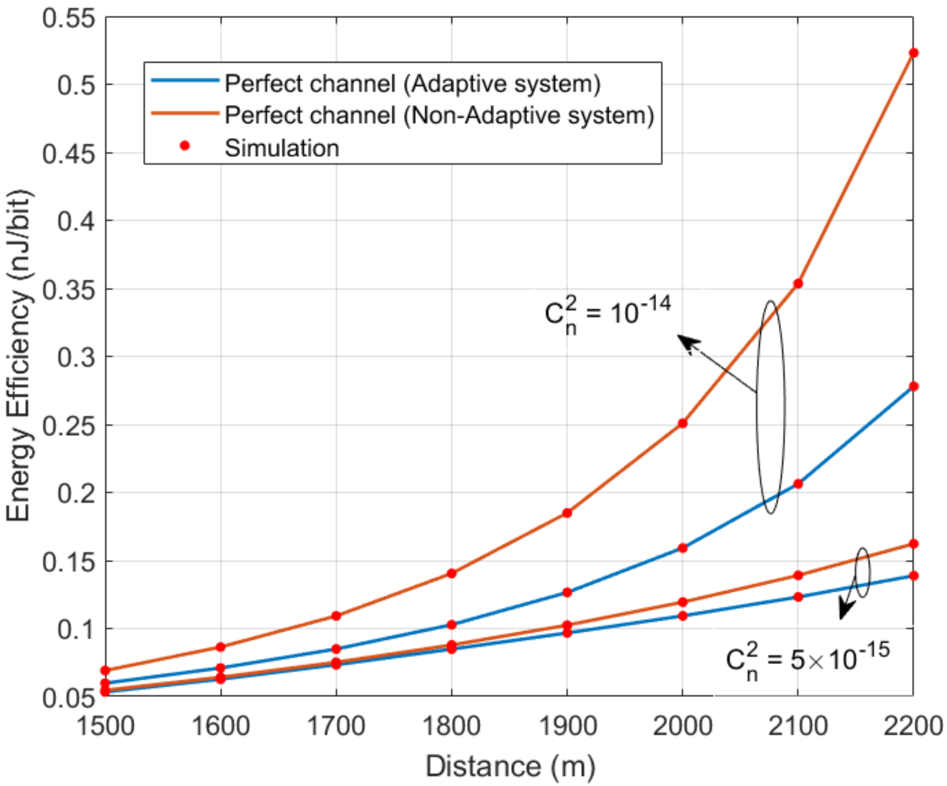


→ *The ESN model offers excellent prediction performance*

Performance Analysis and Results

Energy Efficiency: Adaptation vs. Non-Adaptation

- We first compare the energy efficiency in two cases: using the adaptive system and non-adaptive system
  - We assume that the channel is perfect (there's no delay and error in feedback CSI)
  - The power used for the non-adaptive mode is the power of mode 1 of the adaptive mode



We can see that

→ The adaptive system offers a much better energy efficiency than that of the non-adaptive system

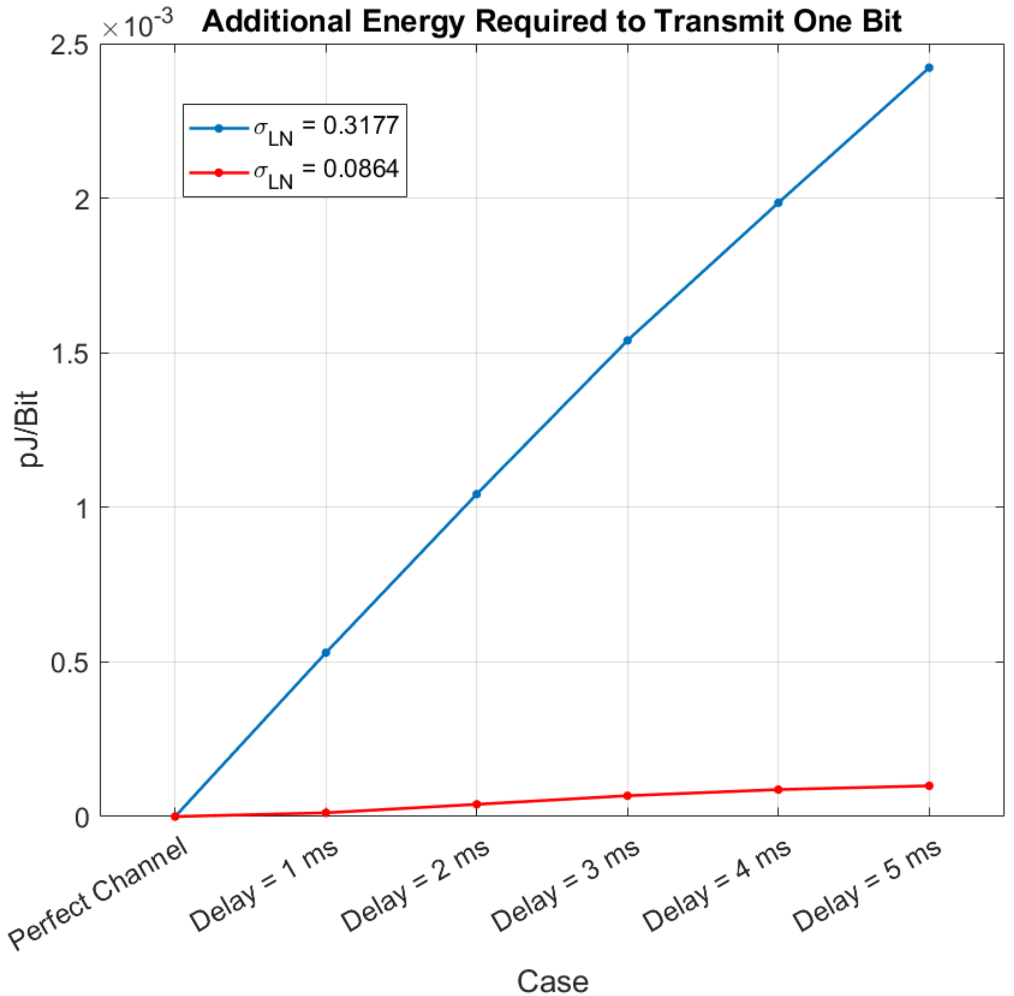
→ The gap is more considerable when the turbulence condition is stronger

Energy Efficiency: Perfect CSIs vs. Delayed CSIs

- Next, we use the real channel data to evaluate the EE in case of delayed CSIs

→ The additional energy required to transmit one bit in case of delayed CSIs compared to the perfect CSIs increases when the delay increases

→ When the fading condition is stronger, the effect of delayed CSI on the EE is more severe



Conclusions

- We presented the power adaptation design for FSO-based vertical networks with channel prediction
- Remarkable observations from the result
  - The EE of the adaptive system is much better than that of the non-adaptive system
  - The effect of delayed CSI on EE increases when the turbulence condition is stronger
- Future Work
  - Evaluate the EE in case of predicted CSI

Thank you for your listening!