Intelligent Free-Space Optical Communications

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Outline

I. Background of FSO Communications

II. Challenges of FSO Communications

III. Intelligent FSO Communication

IV. Use Cases

V. Conclusion

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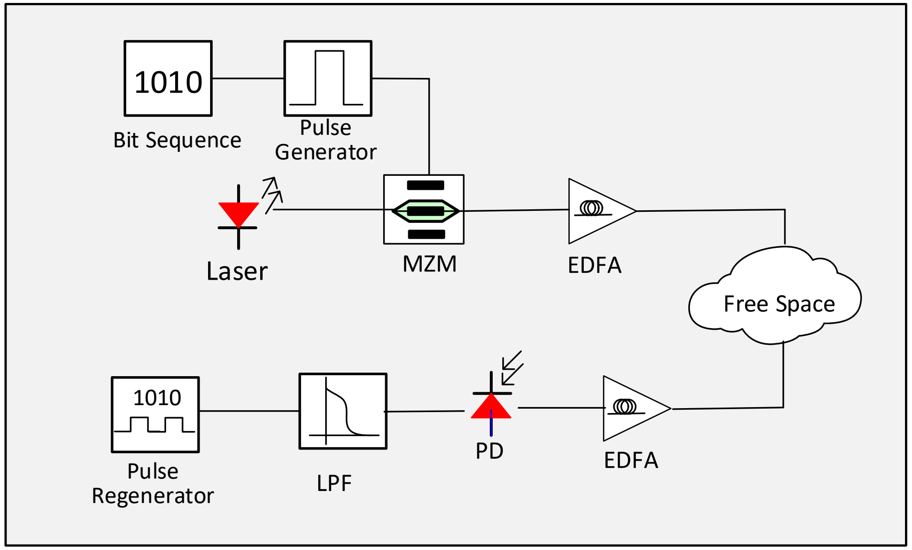
Background of Free Space Optical Communication

- Free Space Optical (FSO) communication uses laser as carrier to transmit data in free space.
- Combining advantages of wireless and optical communications.
- Applied in space, aerial, terrestrial and underwater scenarios.

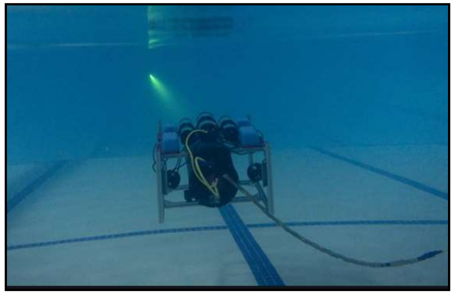


General FSO system model

Mobile Fronthaul

Satellite Communication

UAV Communication

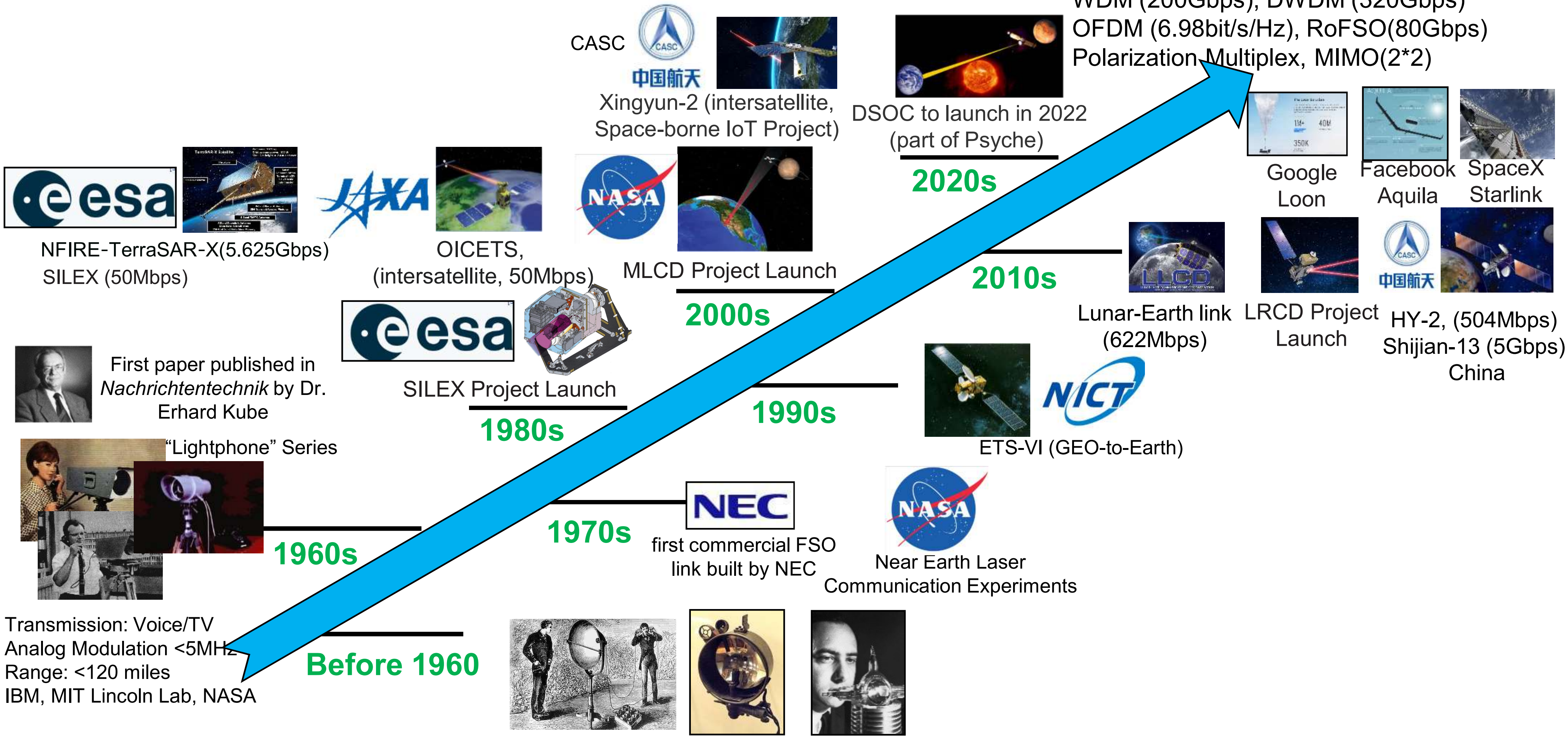


Underwater Communication

Background of Free Space Optical Communication

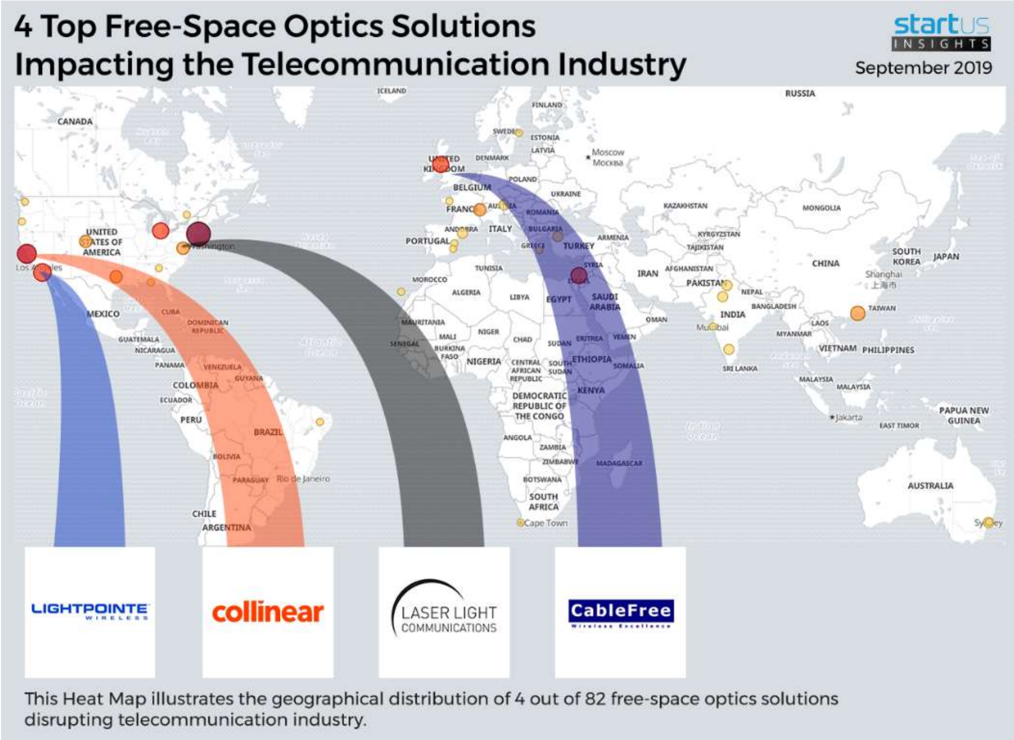
- FSO has a long history…

Experimental Demonstration
PAM4,PAM8,4096-QAM, Coherent
WDM (200Gbps), DWDM (320Gbps)
OFDM (6.98bit/s/Hz), RoFSO(80Gbps)
Polarization Multiplex, MIMO(2*2)



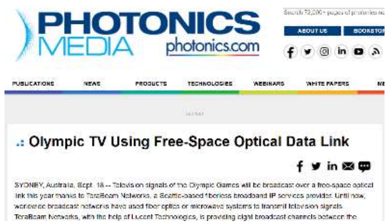
Background of Free Space Optical Communication

- Part of Terrestrial Deployment of FSO Communication



FSO products are installed for customers in over **90 countries** worldwide.

FSO link used in emergency communication



London 2012 Olympic

Sydney 2000 Olympic

EL-1G(15km)

EL-10Gex(30Gbps)

Commercial products for terrestrial FSO up to **30Gbps** and **15km** are available！

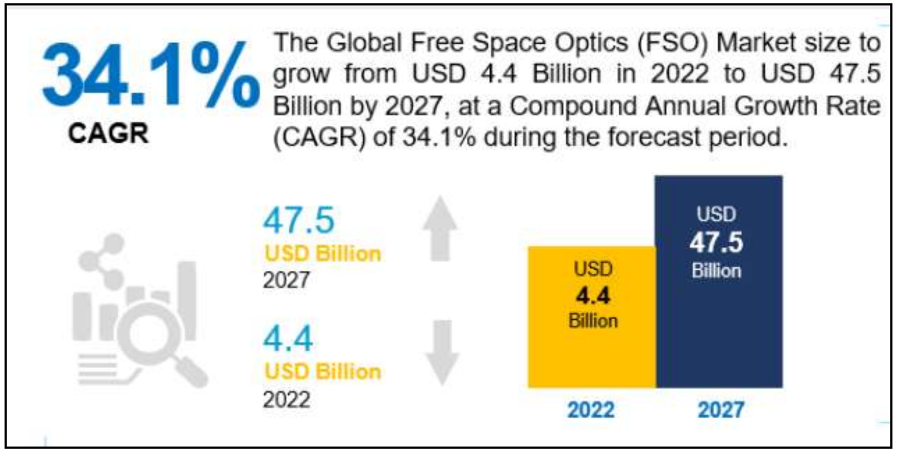
Background of Free Space Optical Communication

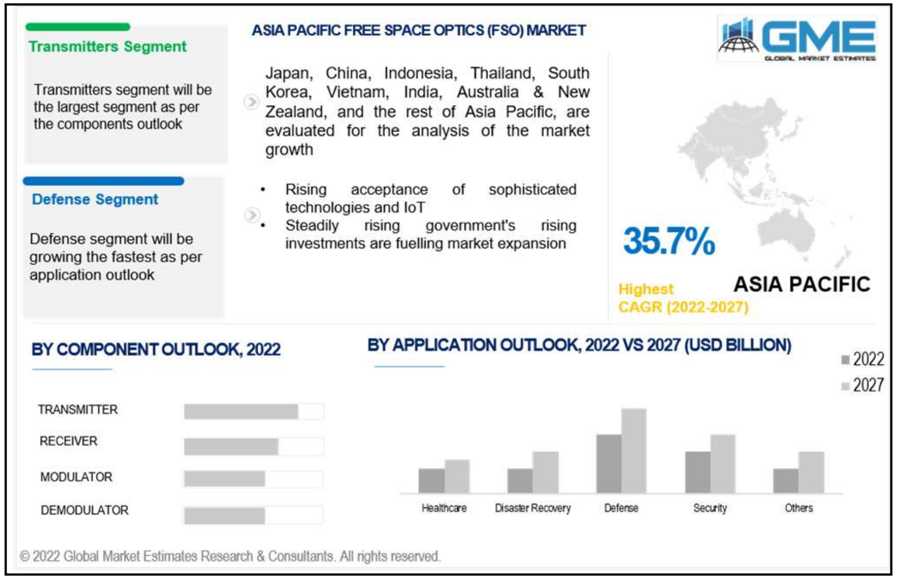
- FSO market estimation

"Global FSO is projected to grow from USD 4.4 billion in 2022 to USD 47.5 billion by 2027 at a CAGR value of **34.1%** from 2022 to 2027."

"North America will have a **dominant share** in the FSO market from 2022 to 2027. "

"Asia-Pacific region is expected to be the **fastest-growing** segment in the FSO market during the forecast period. "





https://www.globalmarketestimates.com

Outline

Challenge of Free Space Optical Communication

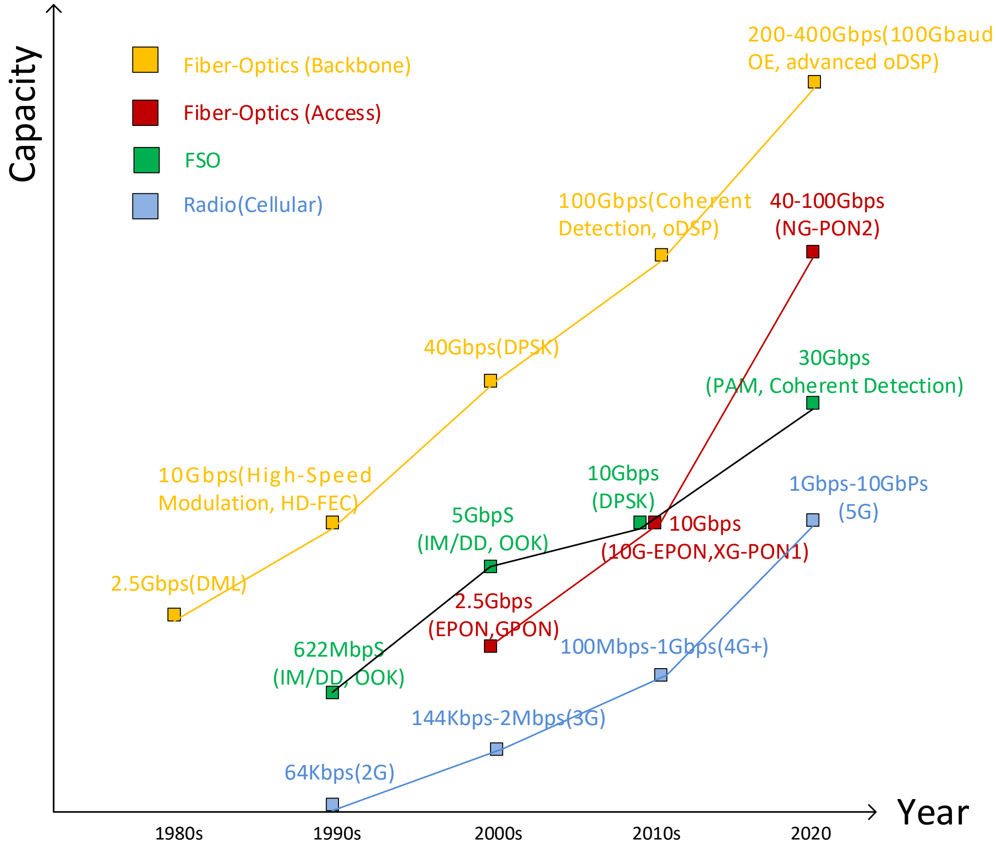
- FSO still has a long way to go…

In the past 50 years,

- Fiber-Optics (Backbone): 2.5Gbps-400Gbps
- Fiber-Optics (Access): 2.5Gbps-100Gbps
- FSO: 0.622Gbps-30Gbps
- Radio(Cellular): 64Kbps-10Gbps

✓ FSO capacity reaches at just **1/10** of backbone fiber and **1/3** of access fiber.

✓ FSO capacity increases at the speed of **1%** of cellular radio in recent 20 years.



Capacity over Years (Fiber-Optics, FSO, Radio)

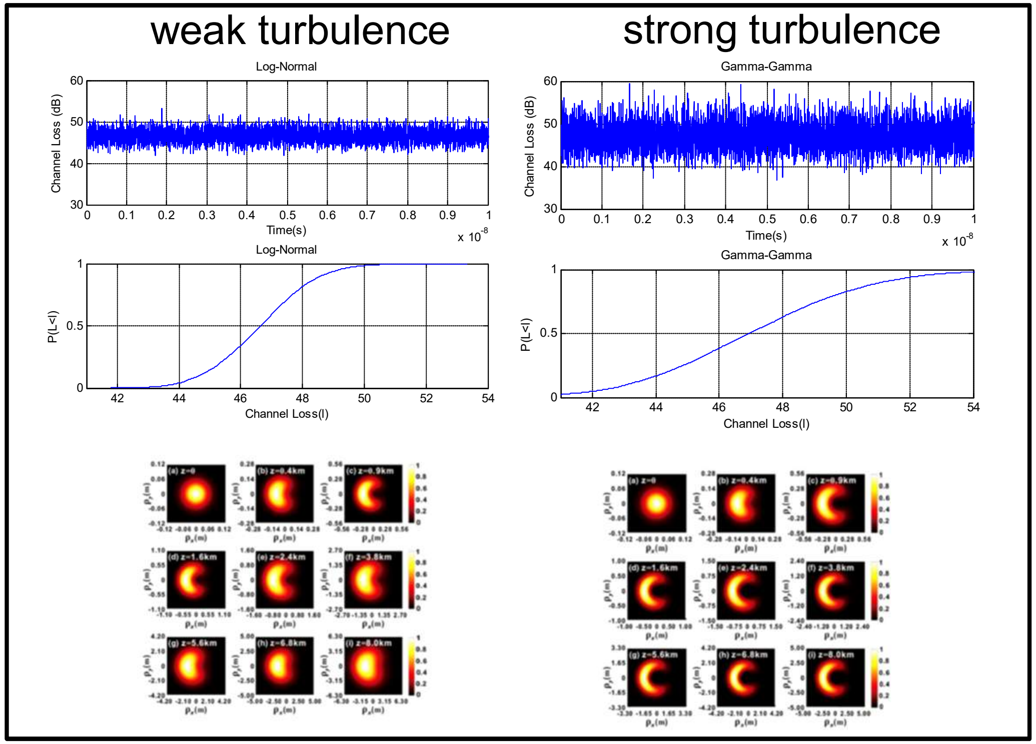
Challenge of Free Space Optical Communication

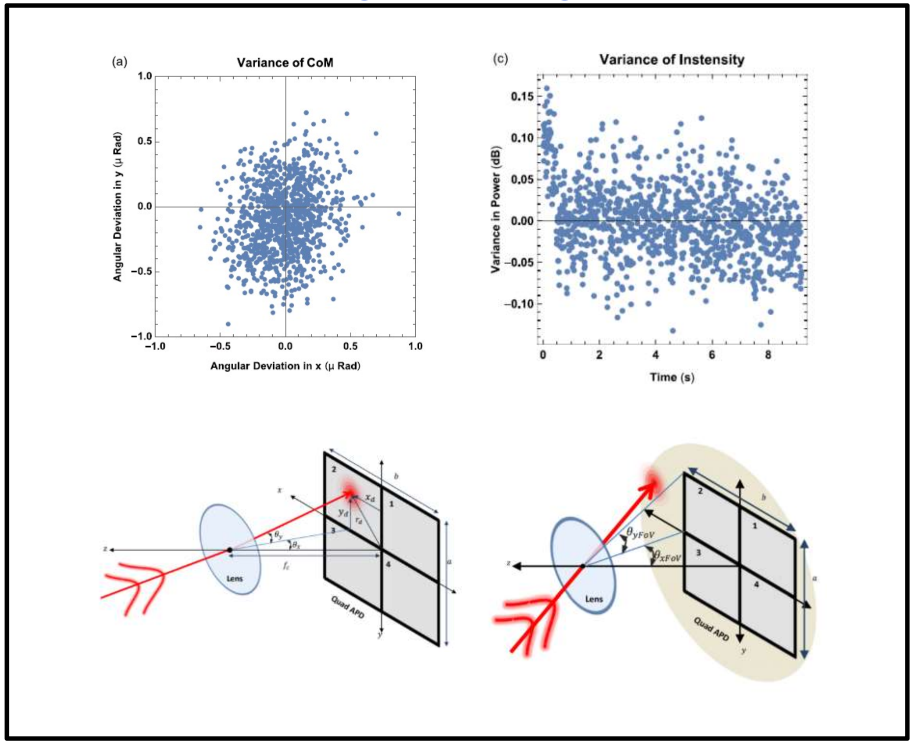
- FSO still has a long way to go…

Technological Challenges

Atmospheric Effects

Pointing Misalignment





How to keep a Rapid, Reliable, and Robust (3R) FSO transmission?

A Number of Methods against Challenges

- ✓ Structured Light

  Bessel beams, Partially coherent optical beam, Pin-Like optical beams, et al.

- ✓ Adaptive Optics

  Sensor & Wavefront correction.

- ✓ Acquisition Tracking and Pointing(ATP)

  Gimbal-based, Mirror-based, Hybrid gimbal-mirror, Adaptive optics, Liquid-crystal based, Hybrid FSO-RF, Rotating Head, Spheric node design

- ✓ Modulation and Coding

  PAM4, PAM8, QPSK, M-QAM, OFDM et al

  LDPC, Space-Time code, Raptor code, Polar code et al.

- ✓ Diversity

  Time diversity, Frequency diversity, Mode diversity, Spatial diversity et al.

A Number of Methods against Challenges

- ✓ Structured Light

- ✓ These methods are usually operated in **reactive mode**.
- ✓ **Channel Status Information (CSI)** is important for the intelligent operation of these methods in practice, especially when dynamic adjustment is required.
- ✓ **Feedback link** is required to monitor instantaneous channel state.

- ✓ Modulation and Coding

  PAM4, PAM8, QPSK, M-QAM, OFDM et al

  LDPC, Space-Time code, Raptor code, Polar code et al.

- ✓ Diversity

  Time diversity, Frequency diversity, Mode diversity, Spatial diversity et al.

Outline

Intelligence is Coming into FSO System

1. M. Wang, W. Guo, and X. Yuan, Single-shot wavefront sensing with deep neural networks for free-space optical communications, *Opt. Express* 29, 3465-3478, 2021
2. B. Gong, S. Cai, Z. Xiao, X. Wang, L. Li, and Z. Zhang, Recognition of OAM state using CNN based deep learning for OAM shift keying FSO system with pointing error and limited receiving aperture, in Proc. *CLEO*, 2021, JTu3A.169
3. H. Luan, D. Lin, K. Li, W. Meng, M. Gu, X. Fang, 768-ary Laguerre-Gaussian-mode shift keying free-space optical communication based on convolutional neural networks, *Opt. Express* 29, 19807-19818, 2021
4. W. Chen et al., Deep Learning-Based Channel Modeling for Free Space Optical Communications, *Journal of Lightwave Technology*, vol. 41, no. 1, pp. 183-198, 2023
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6. M. A. Esmail, W. S. Saif, A. M. Ragheb, S. A. Alshebeili, Free space optic channel monitoring using machine learning, *Opt. Express* 29, 10967-10981, 2021.
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8. Y. Qian, H. Chen, P. Huo, X. Wang, S. Gao, P. Zhang, H. Gao, R. Liu, and F. Li, Towards fine recognition of orbital angular momentum modes through smoke, *Opt. Express* 30, 15172-15183, 2022

Channel Attenuation Analysis

- Atmospheric Attenuation

1) Atmospheric Loss

Cause: atmospheric constituents, wavelength, link distance, aperture size, weather conditions, et al.

Results: absorption, scattering, beam divergence

2) Atmospheric Turbulence

Cause: irregular air motions due to wind and heating

Results: random scintillation of optical intensity

CSI unavailable from the existing channel models

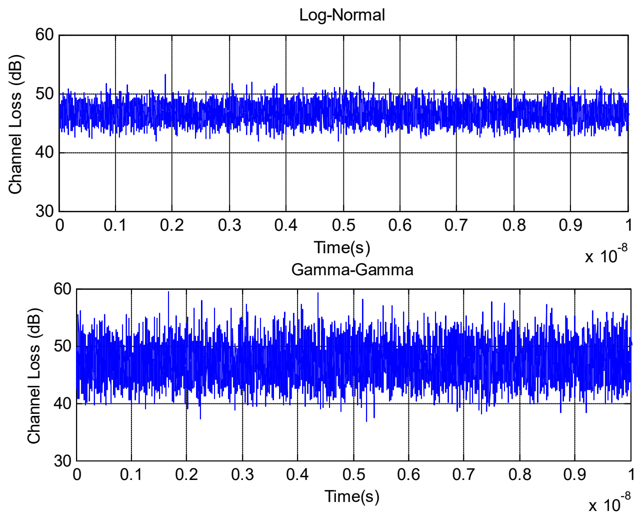
- Turbulence-induced channel model

Gamma-Gamma

$$f_I(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{((\alpha+\beta)/2)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), \quad I > 0,$$

Log-Normal

$$f(I) = \frac{1}{\sqrt{2\pi\sigma_I^2 I}} \exp\left[-\frac{(ln(I)-\mu)^2}{2\sigma_I^2}\right]$$



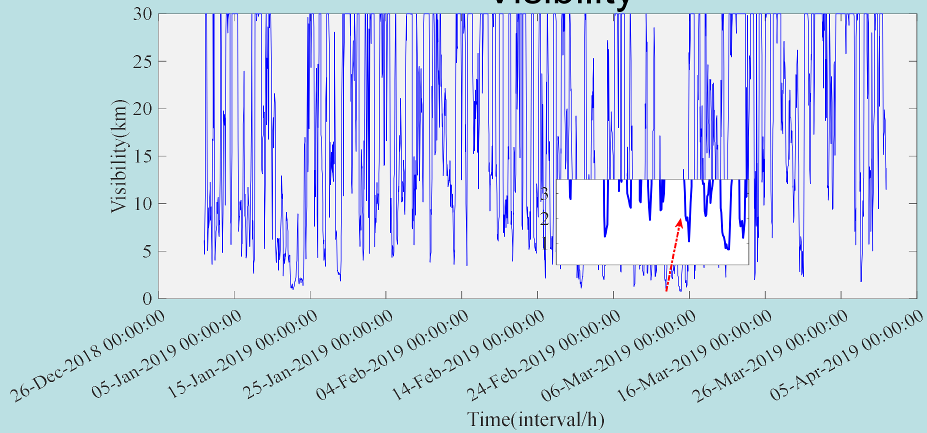
✓ Probabilistic characterization of turbulence-induced scintillation

✓ We can not read CSI directly from the models.

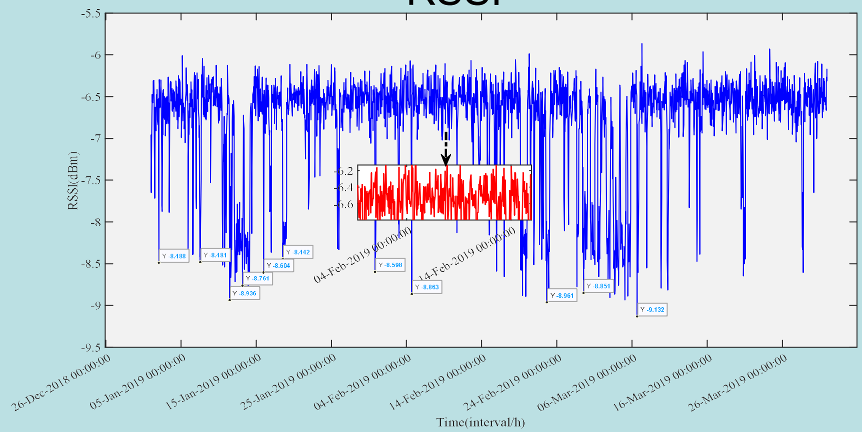
Correlation of Atmospheric Attenuation

Atmospheric attenuation is closely correlated with meteorological conditions.

Visibility

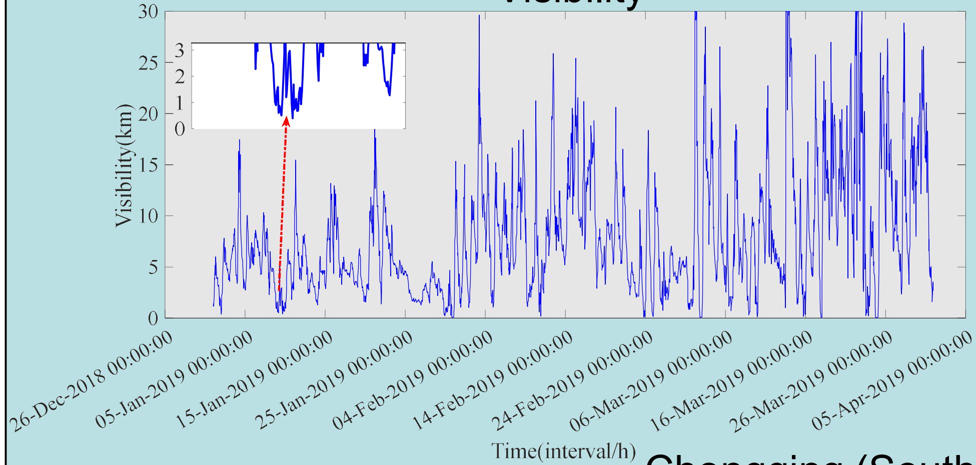


RSSI

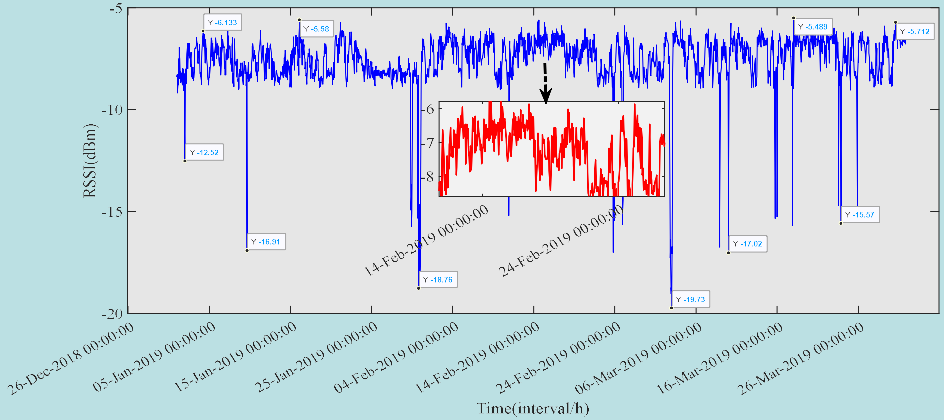


Shenyang (Northeastern China, Dec. 26, 2018-Mar. 31, 2019)

Visibility



RSSI



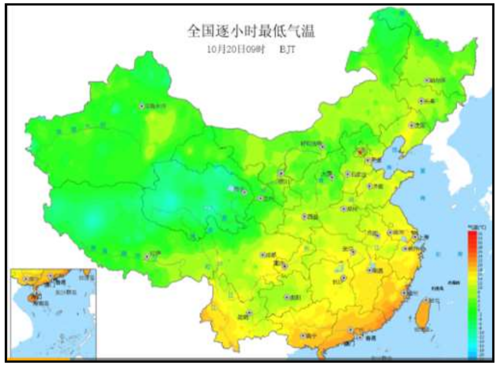
Chongqing (Southwestern China, Dec. 26, 2018-Mar. 31, 2019)

Main Idea

Can we predict FSO channel by the meteorological data?

- We have the meteorological dataset of **50+ years** in China.
- We have meteorological data **everywhere** internet is available with any additional monitoring device not required.
- We have **highly-accurate** meteorological prediction results (>90% in 72h).

National Meteorological Information Center, China



Meteorological Dataset

Selected **5 cities** in China:

- Beijing(39.9042° N, 116.4074° E)
- Shenyang(41.8057° N, 123.4315° E)
- Chongqing(29.4316° N, 106.9123° E)
- Shanghai(31.2304° N, 121.4737° E)
- Lhasa (29.6548° N, 91.1406° E)

Time duration: Jan. 1, 2010 to Dec. 31, 2019 (10 years)

The data is collected per hour.

Each data entry includes 9 items:

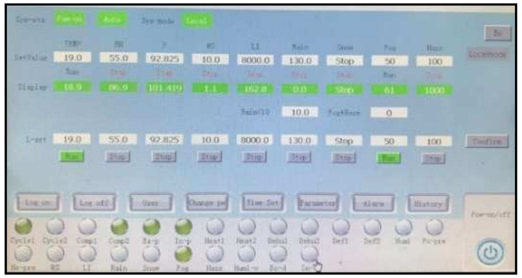
geographical location	altitude	temperature	humidity	pressure	precipitation	wind speed	wind direction	visibility

A total of 6,071,160 entries and 115,352,040 data values.

Emulated Atmosphere Chamber

4500mm*2000mm*3000mm
(Length*Width*Height)

Indicator	value	unit
Temperature	-20～60	℃
Humidity	30～95%	RH
Wind speed	0~18(± 0.5)	m/s
Wind direction	360	degree
Lumination	8000～50000	lux
Rainfall	0～130(±0.2)	mm/h
Snowfall	0～10 (± 0.2)	mm/h
Visibility	0～10	km



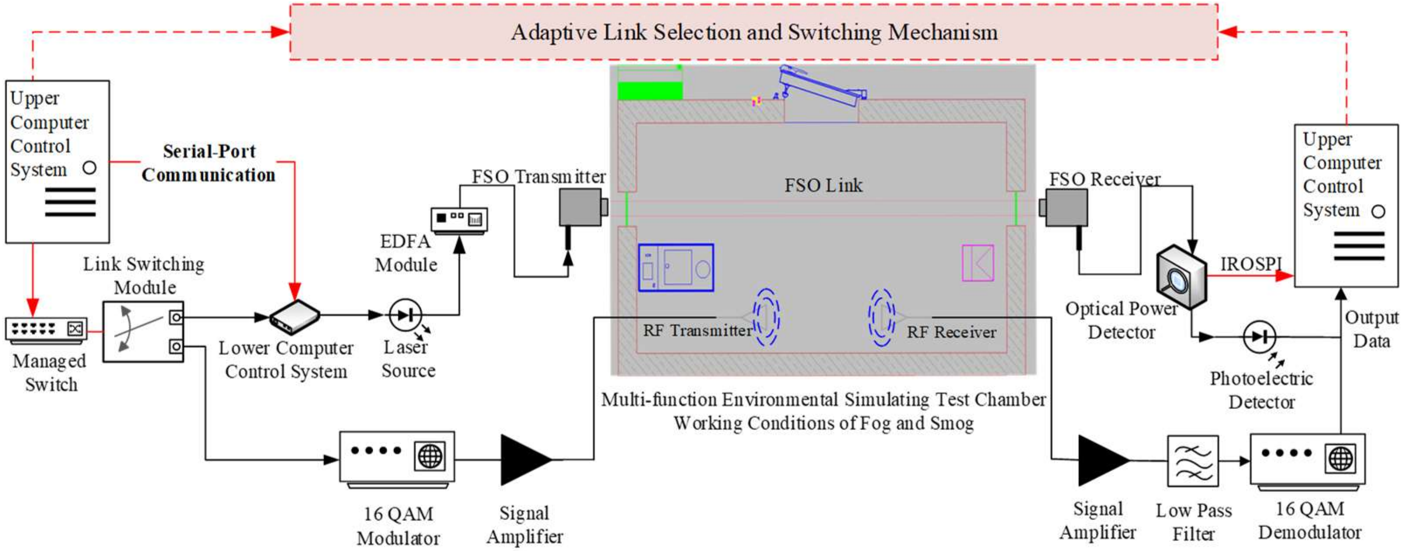
Control Panel

300*300mm coated glass
(Transmittance ≥95% for 900-1600nm laser)

Inside chamber
(full of heavy fog)

FSO Link Prototype

External view of #1 terminal



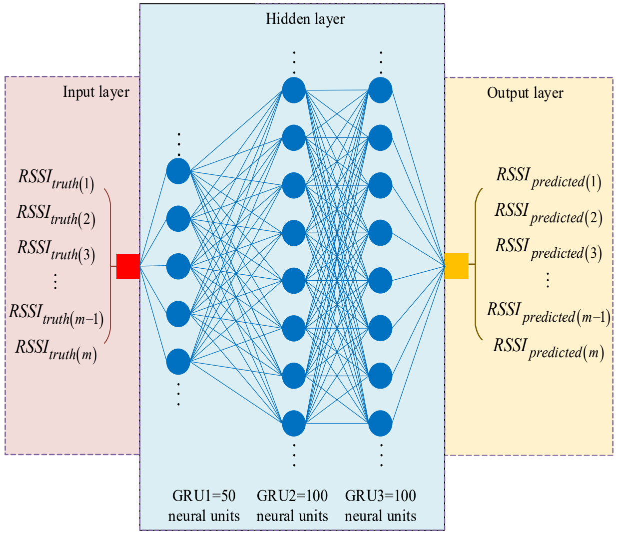
External view of #1 terminal

Schematic diagram of FSO link prototype

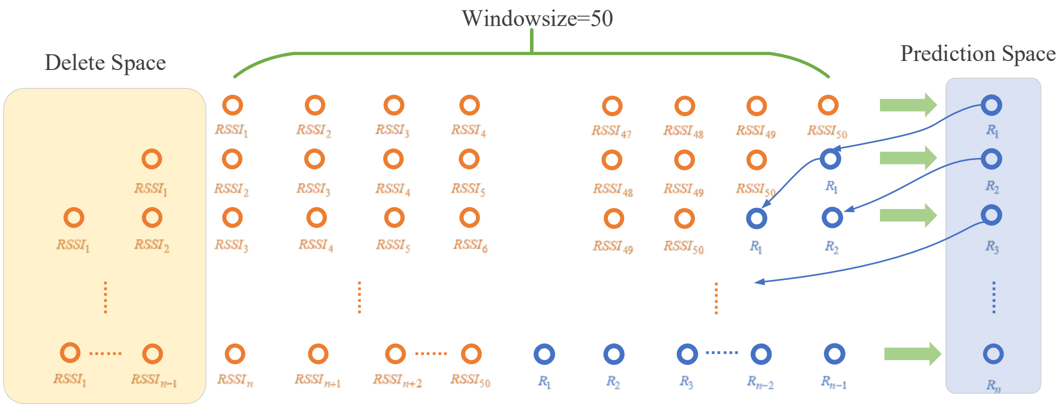
Parameters	Values
Data rate	10Gbps
Transmission range	5m～1km
Launch power	-6dBm
Receiver sensitivity	-15dBm
Modulation	IM/DD
Laser beam divergence	0.8 mrad
Laser wavelength	1550nm

AI-Assisted FSO Channel Prediction

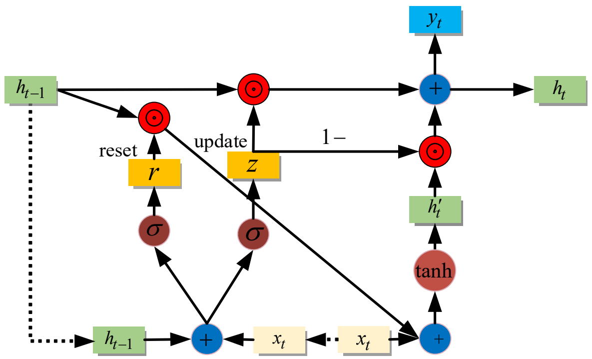
RSSI: Received Signal Strength Indicator



GRU model used in prediction



Rolling prediction scheme



Neural unit in GRU

Reset gate: $r_t = \sigma\left(x_t W_{xr} + h_{t-1} W_{hr} + b_r\right)$

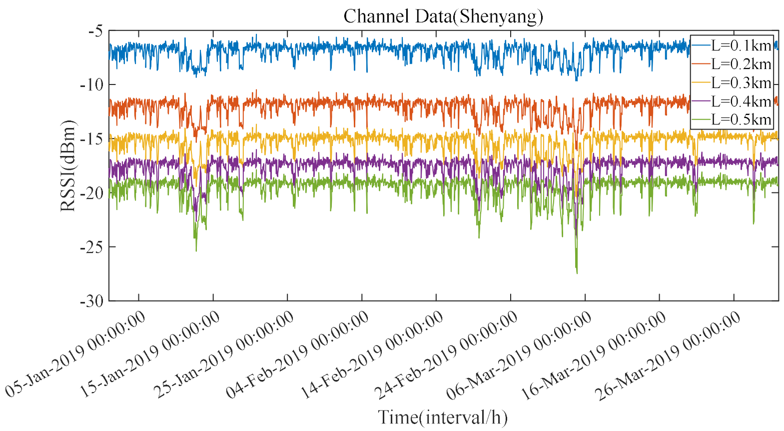
Update gate: $z_t = \sigma\left(x_t W_{xz} + h_{t-1} W_{hz} + b_z\right)$

New memory: $h_t' = \tanh\left[x_t W_{xh} + \left(r_t \cdot h_{t-1}\right) W_{hh} + b_h\right]$

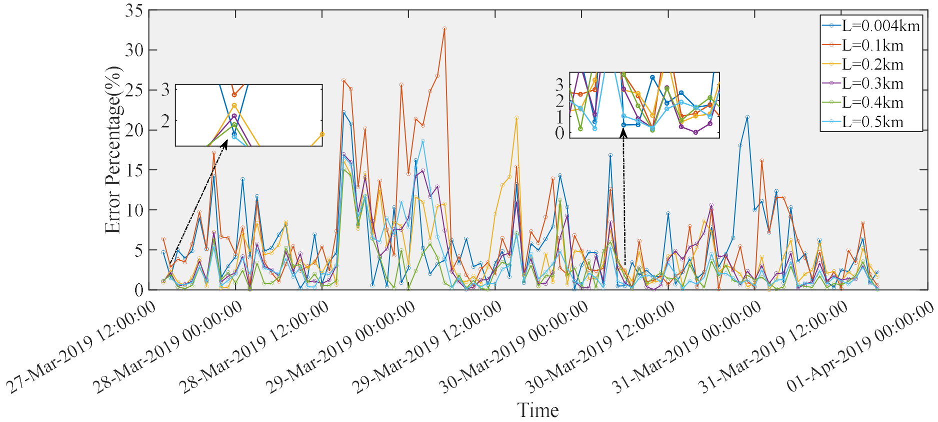
Hidden state: $h_t = z_t h_t' + \left(1 - z_t\right) h_{t-1}$

Loss function: MSE

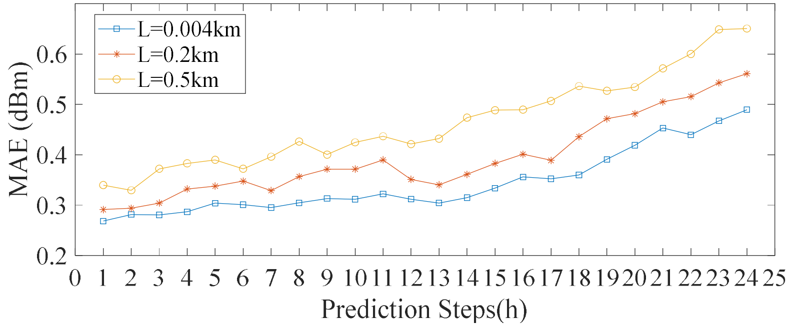
AI-Assisted FSO Channel Prediction



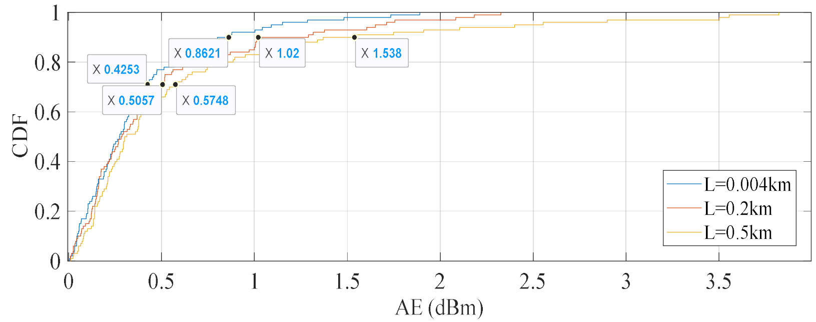
RSSI data with different link distances



RSSI Prediction error percentage

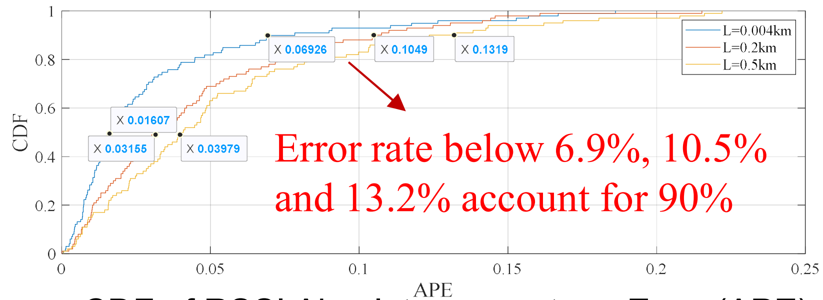


RSSI data with different prediction steps



CDF of RSSI Absolute Error (AE)

$$AE = \left|RSSI_P - RSSI_R\right| \qquad APE = \frac{\left|RSSI_P - RSSI_R\right|}{RSSI_R}$$



CDF of RSSI Absolute percentage Error (APE)

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I. Background of FSO Communications

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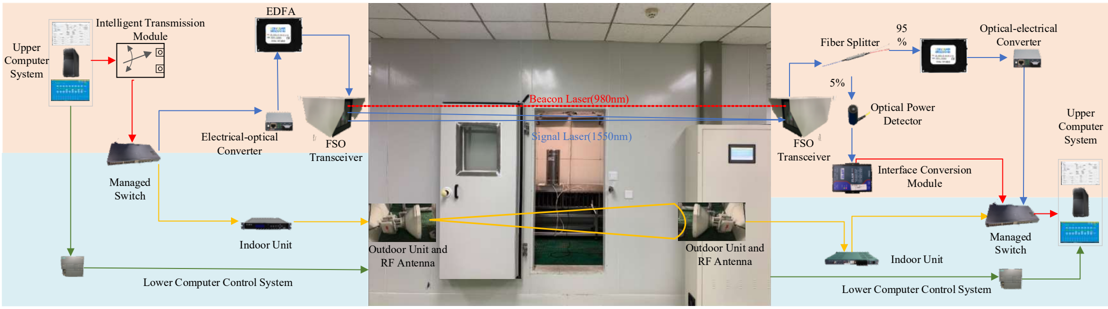
Use Case I：Intelligent Link Switching for Hybrid FSO/RF system

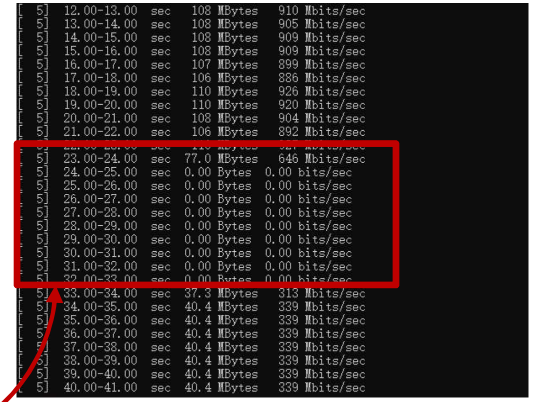
Issues in traditional switching：

- Invalid switching in periodic scheme
- Over switching in threshold-based scheme

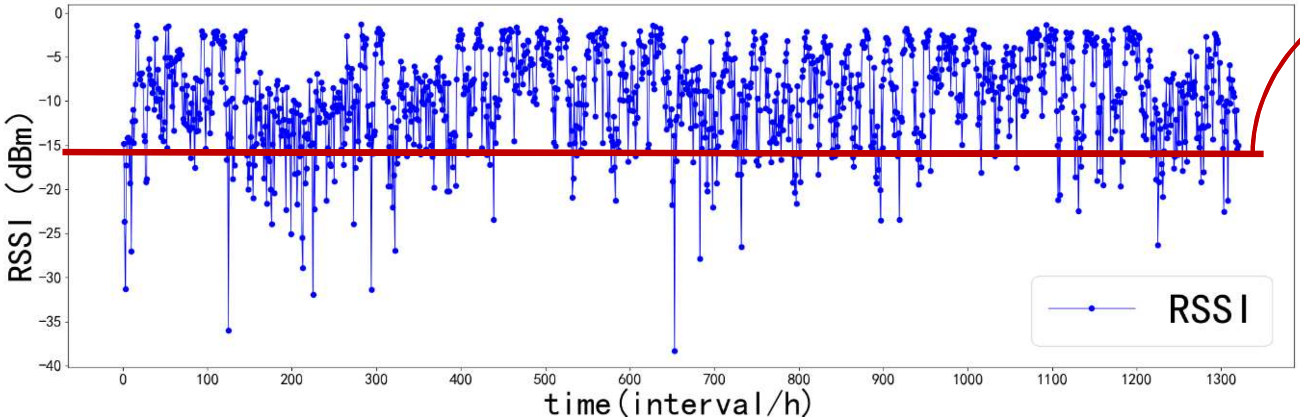


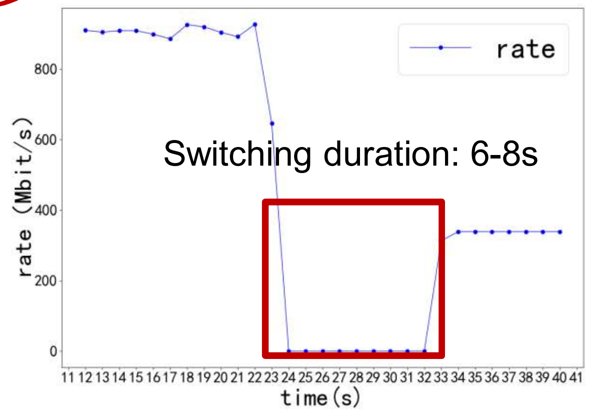
Hybrid FSO/RF system
(10Gbps at 1550nm, 0.9Gbps at 13GHz)

FSO link to RF link


[5] 12.00-13.00 sec 108 MBytes 910 Mbits/sec
[5] 13.00-14.00 sec 108 MBytes 905 Mbits/sec
[5] 14.00-15.00 sec 108 MBytes 909 Mbits/sec
[5] 15.00-16.00 sec 108 MBytes 909 Mbits/sec
[5] 16.00-17.00 sec 107 MBytes 899 Mbits/sec
[5] 17.00-18.00 sec 106 MBytes 886 Mbits/sec
[5] 18.00-19.00 sec 110 MBytes 926 Mbits/sec
[5] 19.00-20.00 sec 110 MBytes 920 Mbits/sec
[5] 20.00-21.00 sec 108 MBytes 904 Mbits/sec
[5] 21.00-22.00 sec 106 MBytes 892 Mbits/sec
[illegible]
[5] 23.00-24.00 sec 77.0 MBytes 646 Mbits/sec
[5] 24.00-25.00 sec 0.00 Bytes 0.00 bits/sec
[5] 25.00-26.00 sec 0.00 Bytes 0.00 bits/sec
[5] 26.00-27.00 sec 0.00 Bytes 0.00 bits/sec
[5] 27.00-28.00 sec 0.00 Bytes 0.00 bits/sec
[5] 28.00-29.00 sec 0.00 Bytes 0.00 bits/sec
[5] 29.00-30.00 sec 0.00 Bytes 0.00 bits/sec
[5] 30.00-31.00 sec 0.00 Bytes 0.00 bits/sec
[5] 31.00-32.00 sec 0.00 Bytes 0.00 bits/sec
[5] 32.00-33.00 sec 0.00 Bytes 0.00 bits/sec
[5] 33.00-34.00 sec 37.3 MBytes 313 Mbits/sec
[5] 34.00-35.00 sec 40.4 MBytes 339 Mbits/sec
[5] 35.00-36.00 sec 40.4 MBytes 339 Mbits/sec
[5] 36.00-37.00 sec 40.4 MBytes 339 Mbits/sec
[5] 37.00-38.00 sec 40.4 MBytes 339 Mbits/sec
[5] 38.00-39.00 sec 40.4 MBytes 339 Mbits/sec
[5] 39.00-40.00 sec 40.4 MBytes 339 Mbits/sec
[5] 40.00-41.00 sec 40.4 MBytes 339 Mbits/sec

Ping-Pong effect：frequent switching and interruption caused by strong turbulence



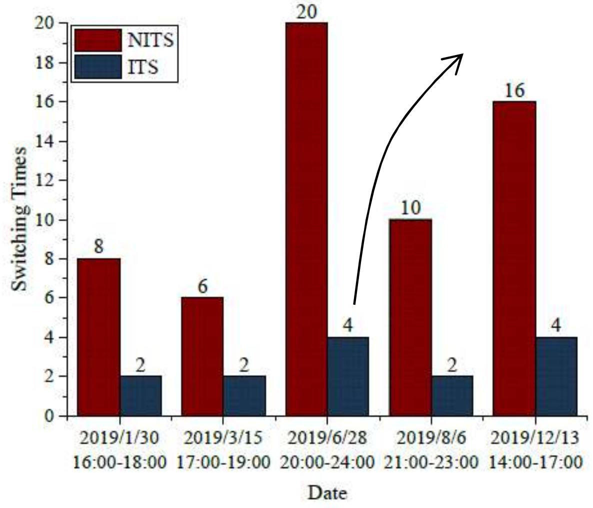


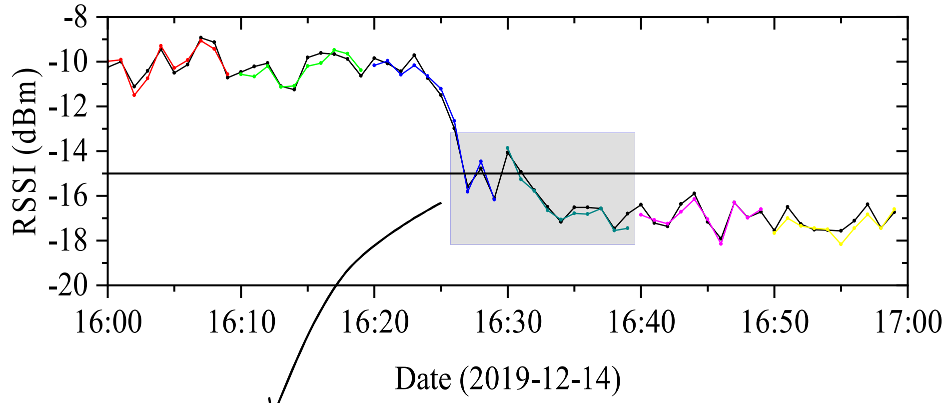
Use Case I：Intelligent Link Switching for Hybrid FSO/RF system

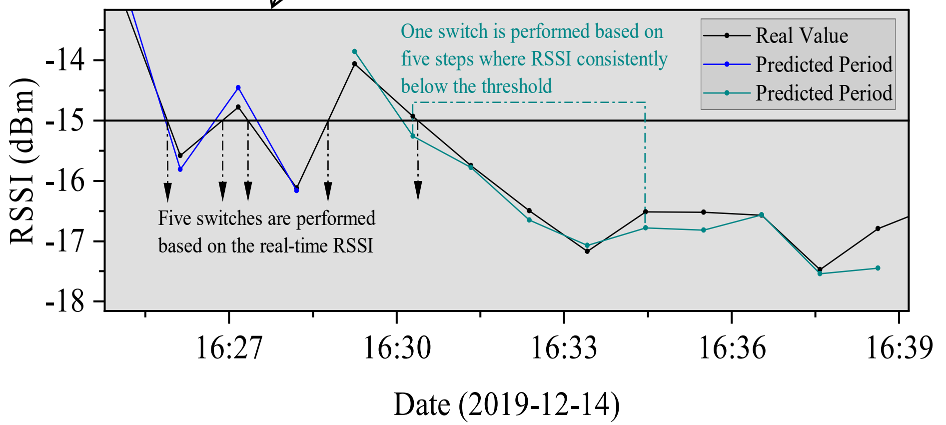
Intelligent switching:

Link is switched only when the predicted RSSI keeps lower than threshold for *m* continuous time points.

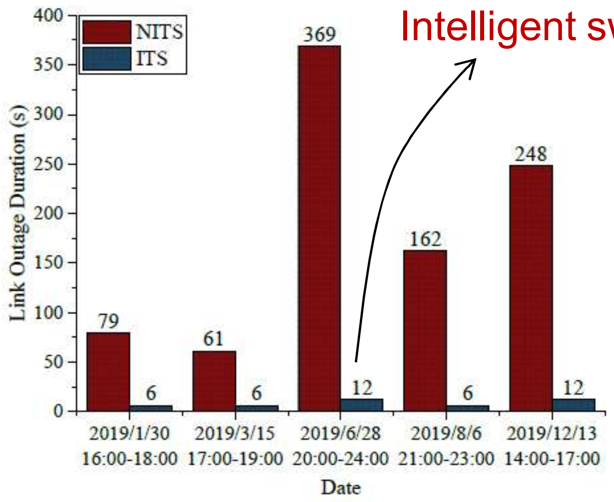
Intelligent switching





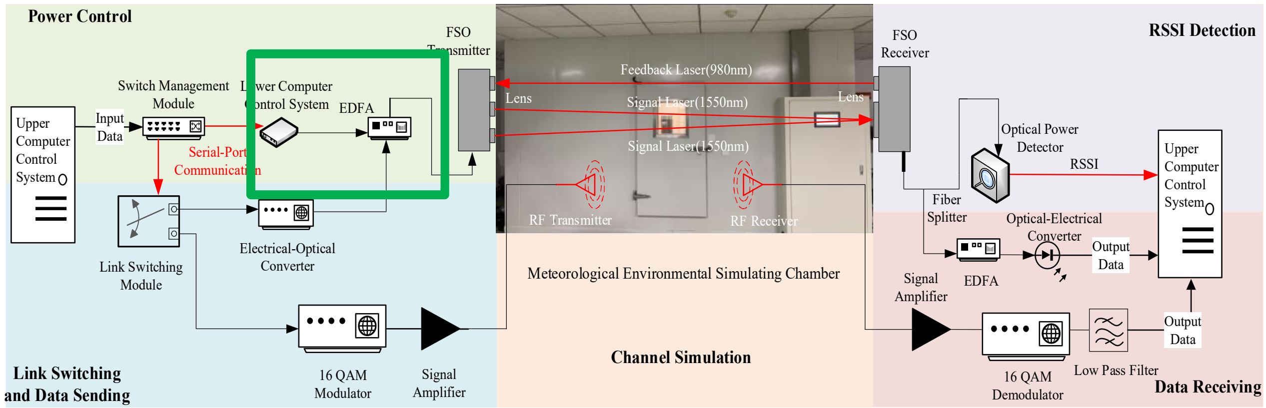


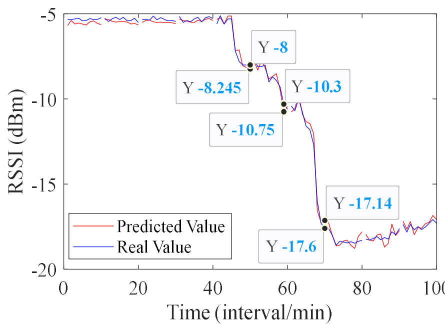
Intelligent switching



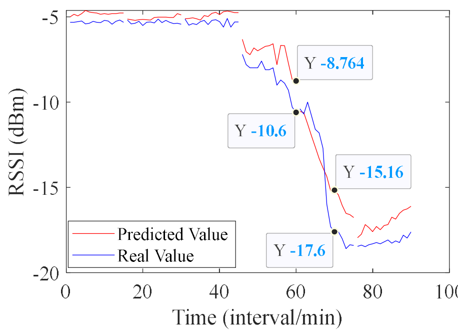
Use Case II：Intelligent optical power control

To increase transmit power when the RSSI is predicted to be lower than the threshold instead of link switching.

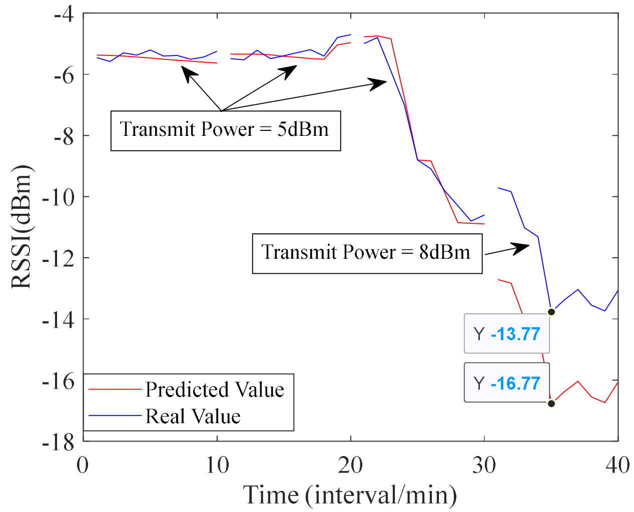


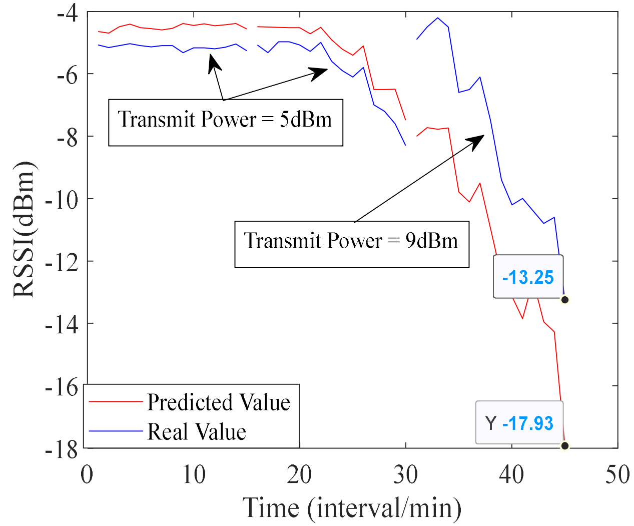


RSSI (prediction step=10)



RSSI (prediction step=15)





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Outline

Conclusion

- ✓ FSO communication has made significant progress, although some issues remain challenging.
- ✓ Intelligentization may be a feasible way to further progress for FSO communication.
- ✓ The channel predictability enables the possibility of intelligent FSO communication system.
- ✓ To address the demanding requirements and complex application, intelligent FSO communication system is worth of more research attentions.

Thank You for Attention

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