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Hoang D. Le, 2nd Year Ph.D. Student
Computer Communications Lab., The University of Aizu

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Error Control Protocols for Free-Space Optical Satellite Communication Systems

1. General Background

1.1. Free-space Optics (FSO)

- **FSO**: is a line-of-sight technology for data transmission using light in free space.
- **Benefits**: high-speed connections, low power consumptions, and flexible deployment.

1.2. Low earth orbit (LEO) Satellite

- **LEO satellite**: operates from 500 km to 2000 km
- **Benefits**: wide coverage areas, low power. consumptions and cost-effectiveness, low propagation delay compared to other types of satellite.

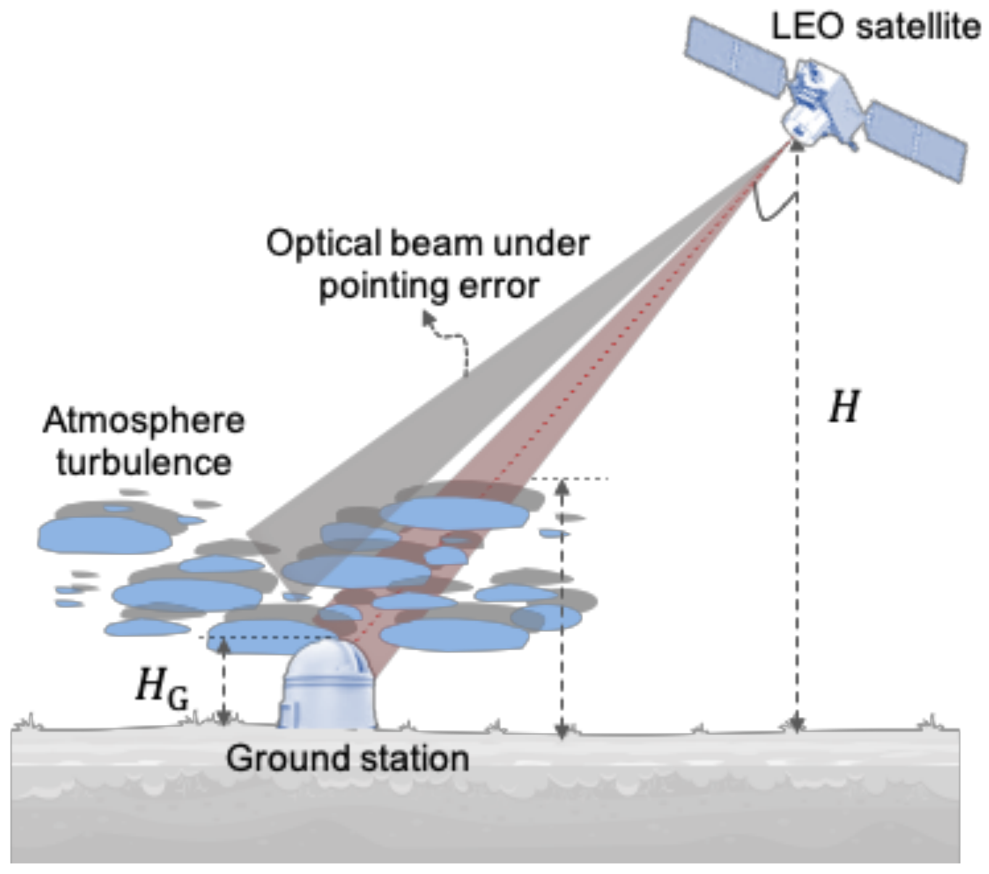

Fig. 1. FSO-based satellite system

1.3. Challenges

- ***Atmospheric turbulence***: causes the scintillation effect, which results in signal fluctuations at the receiver on the ground.
- ***Pointing errors***: are due to the misalignment between the beam center and the detector of receiver.

These issues pose various challenges in the design of FSO-based satellite systems.

2. Solution and Motivation

2.1. Existing Solutions

Error Control Protocols

Link-layer solutions

- Automatic repeat request (ARQ)
  + *Stop-and-wait (SW)*
  + *Sliding widow*
- Hybrid ARQ
  + *Chase combining (CC)*
  + *Incremental redundancy (IR)*
- Error Correction Code (ECC)

…

Physical-layer solutions

- Forward Error Correction (FEC) codes
- Adaptive Rate Transmission
- Modulation/Coding signal processing
- Cooperative/Multi-hop transmissions

…

2.2. Motivation

- **Link layer:** sliding window ARQ and ECC are the most popular error-control protocols in FSO-based satellite systems
  - ECC often requires excessive redundancy to guarantee transmission reliability and usually leads to inefficiencies in terms of throughput performance
  - ARQ often fail to provide satisfactory delay and throughput performance in satellite systems, as they require many retransmissions for erroneous frames.

Incremental redundancy Hybrid ARQ/ECC (IR-HARQ), which combines sliding window ARQ and ECC, is the promising candidate.

- **Physical layer:** adaptive rate transmission is well-known technique

⇨ *We focus on the cross-layer design of link-layer IR-HARQ and adaptive rate transmission for FSO-based satellite systems*

3. Approach and Results

3.1. System Model

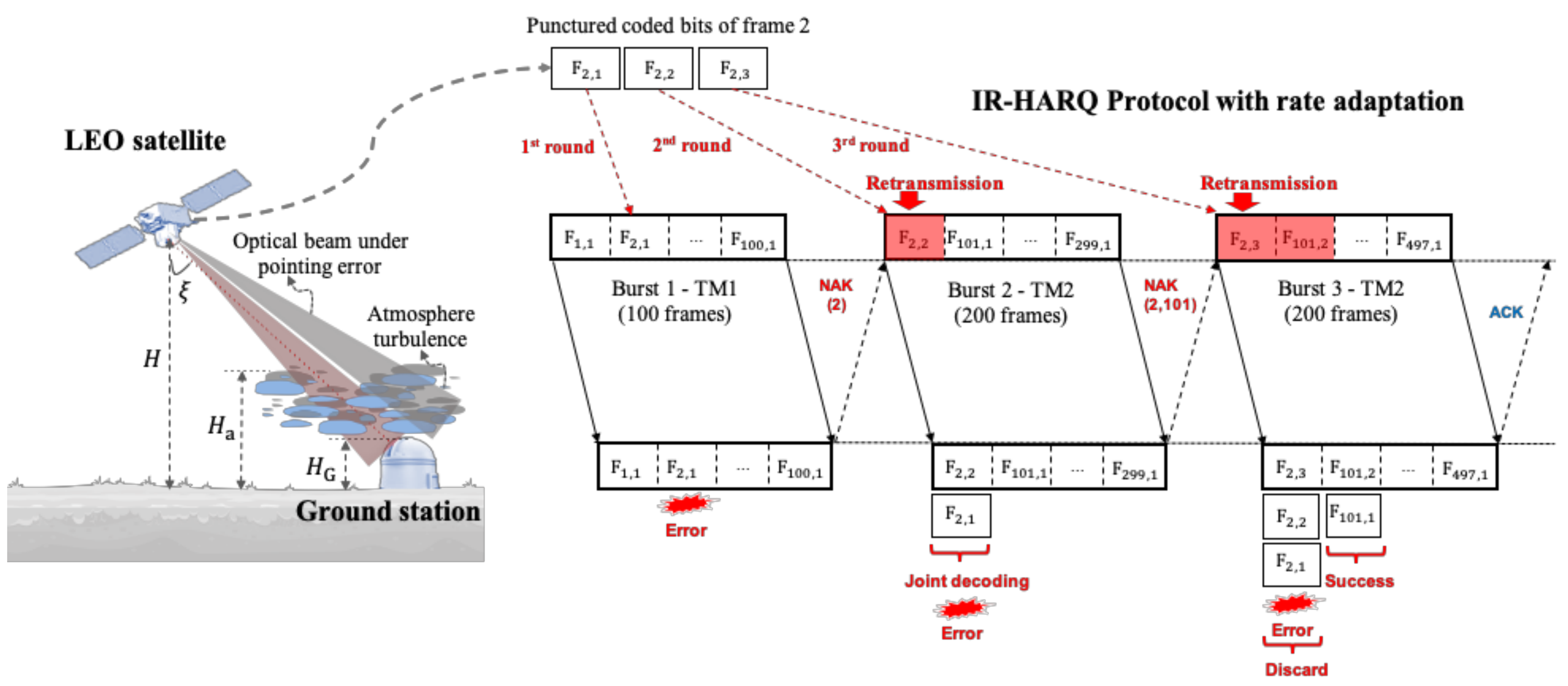

Fig. 2. FSO-based LEO satellite system using IR-HARQ with adaptive rate transmission

3.2. Approach

Markov Chain for system performance analysis

+ A Finite-state Markov chain is used to develop the channel-state model (Fig. 3)
+ Then, the channel-state model is used to develop the transmission loss model (two states: loss and non-loss) for analytically deriving the system performance (Fig. 4)

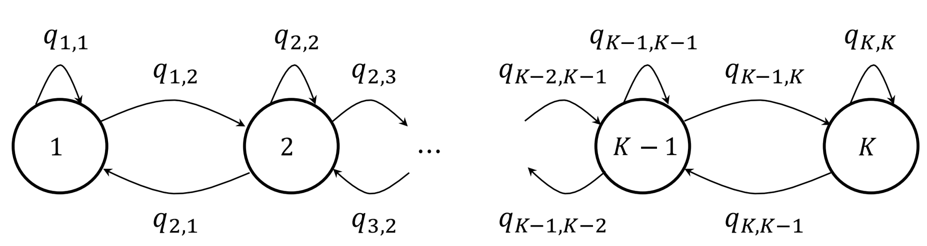

Fig. 3. Finite-state Markov channel model

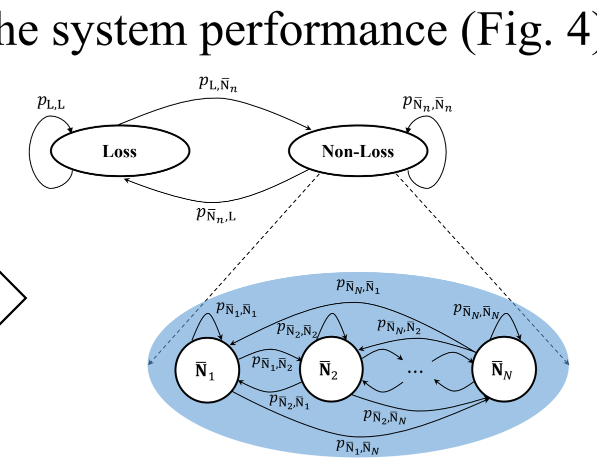

Fig. 4. Transmission Loss Model

3.3. Simulation Results

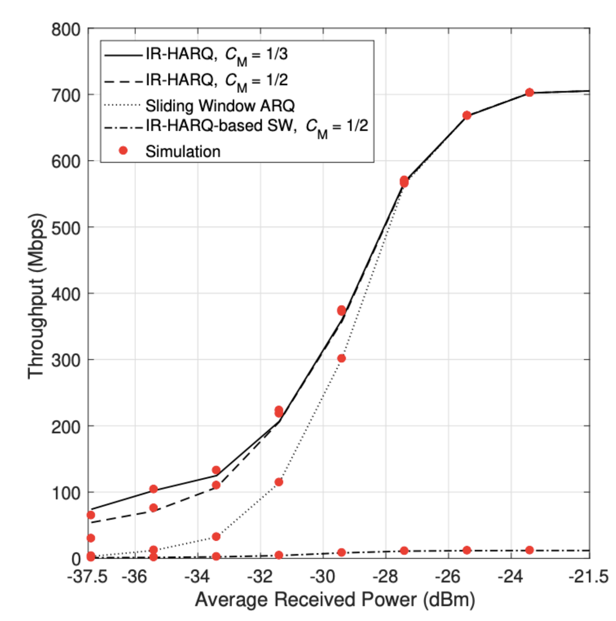

Fig. 5. Throughput comparison

IR-HARQ using sliding window mechanism achieves better throughput performance than the other protocols.

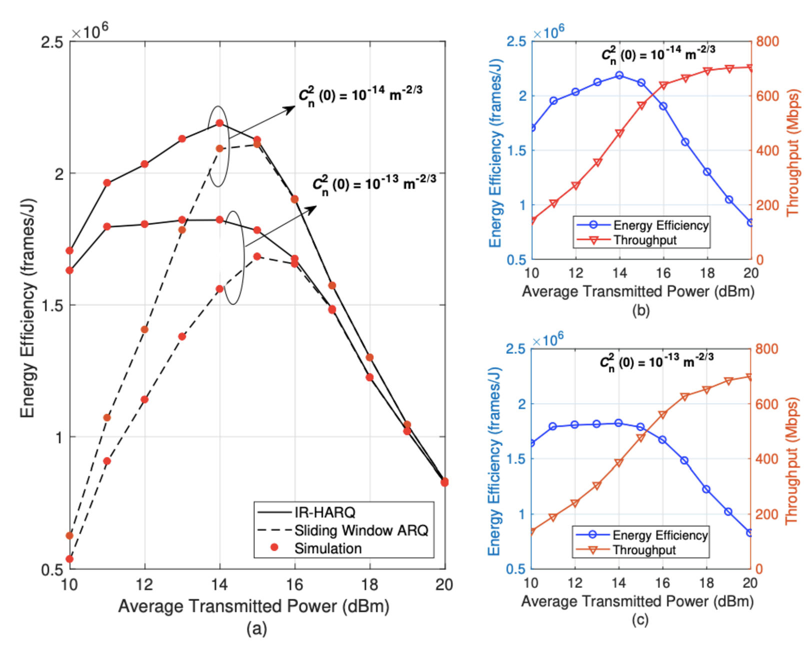

Fig. 6. Energy efficiency comparison

IR-HARQ outperforms than the pure sliding window ARQ in terms of energy efficiency

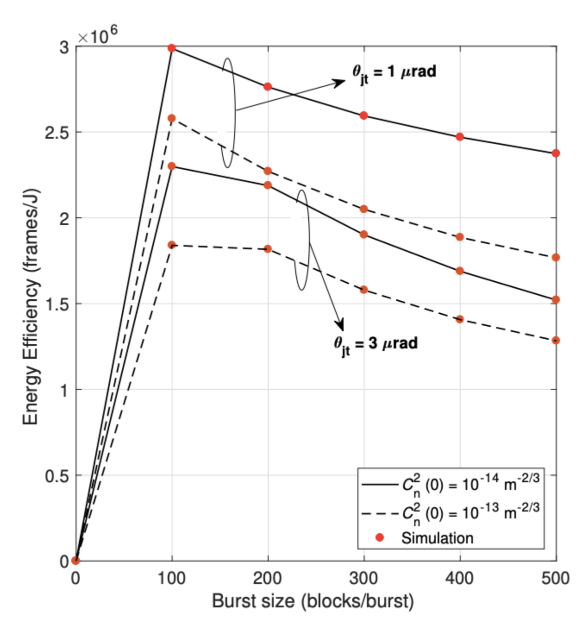

Fig. 7. Impact of both turbulence and pointing errors on system performance

Impact of both turbulence and pointing error are severe

3.4. Concluding Remarks

- The impact of both atmospheric turbulence and pointing error on the system performance is severe.
- The performance of IR-HARQ using sliding window outperforms that of IR-HARQ based stop-and-wait ARQ mechanism and pure sliding window ARQ in FSO-based satellite communication systems.