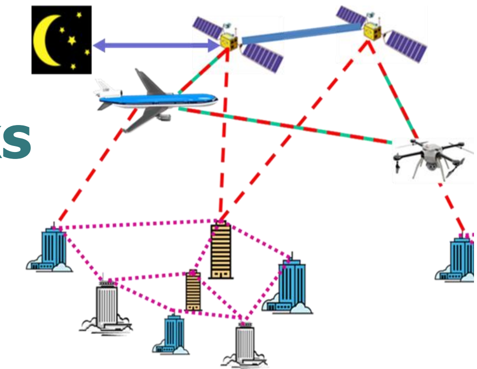
Claude E. Shannon Communication and Network Group

Optical Satellite Networks



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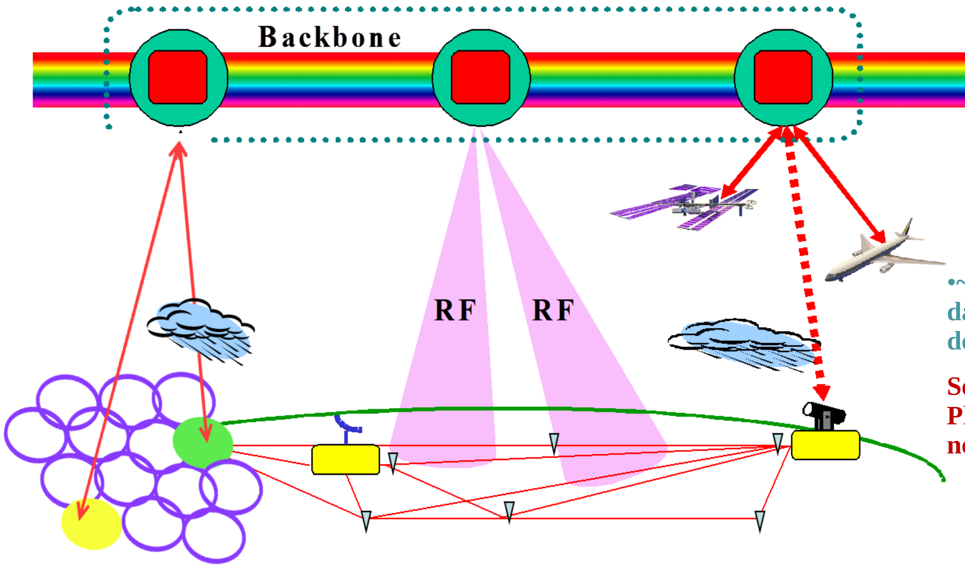
Massachusetts Institute of Technology
President IEEE Communications Society 2020-2021

Optical Satellite Networks

Abstract. We will explore the architecture of optical satellite networks at 100G-1Tbps. The challenge is to architect the system and the network protocols with large bandwidth-delay products and the presence of atmospheric turbulence and weather.

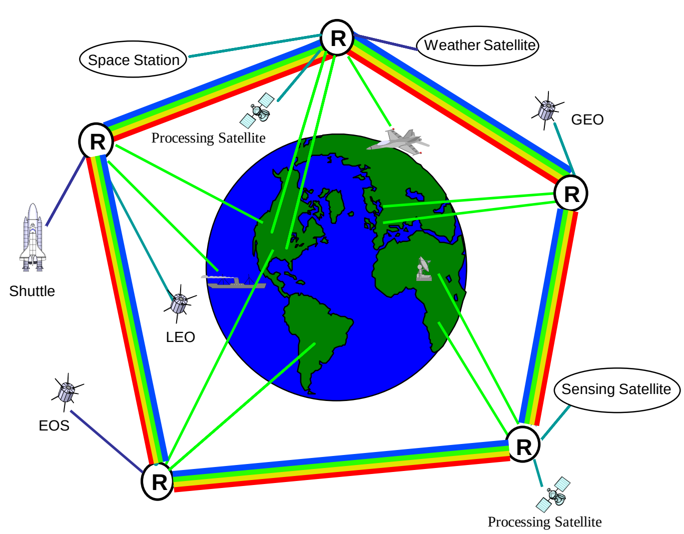
Disruptive changes in modern integrated global heterogeneous network:
satellites, fiber, wireless (multiple modalities) – **holistic networking**



•~3 orders increase in data rates, corresponding decrease in cost

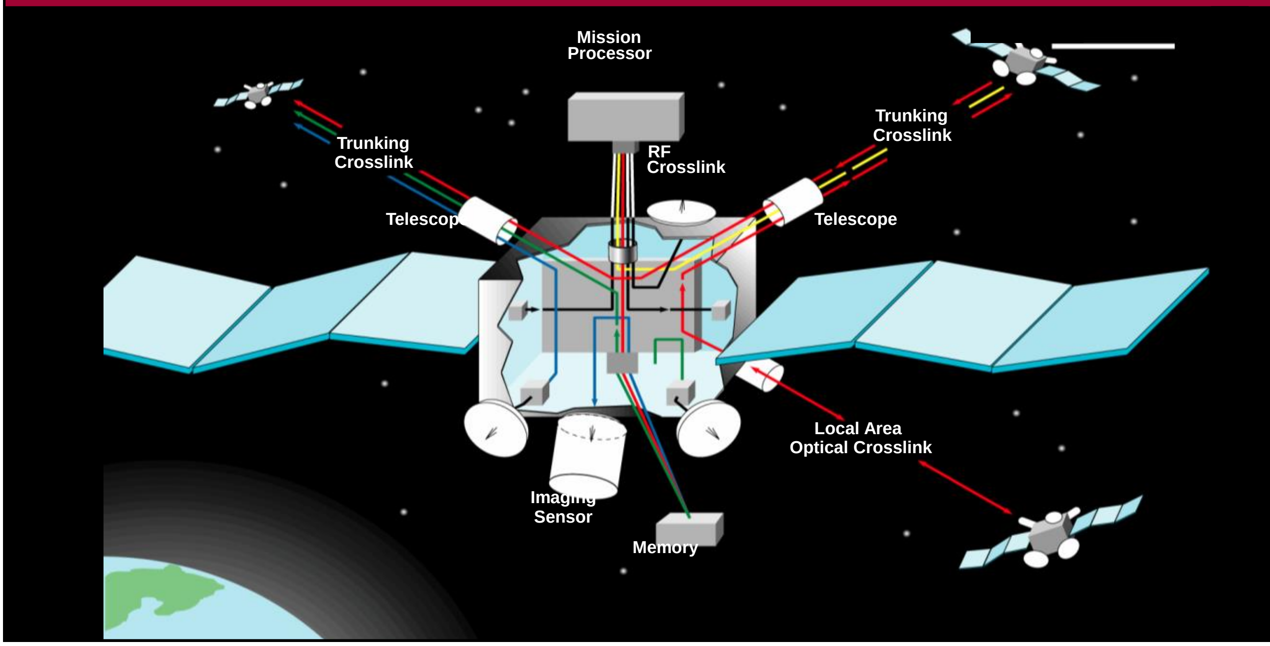
Serious challenges in Physical and higher network layers

Space-Based Information Network

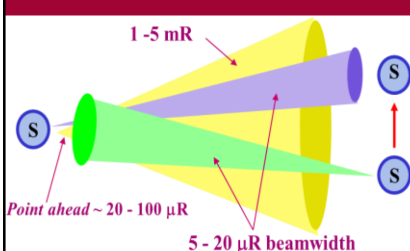


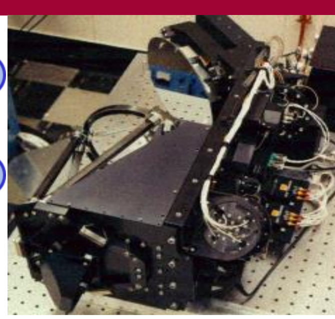
- De-Coupled, Shared, and Distributed Space-Borne Data Processing
- Backbone Constellation Design
  - - GEO, HEO, MEO, LEO
- Cost Modeling based on Traffic Patterns
- Assumptions
  1. GEO/HEO/MEO/LEO
  2. Streams & Packets
  3. WDM trunks
  4. RF & optical accesses
  5. Fixed/mobile users

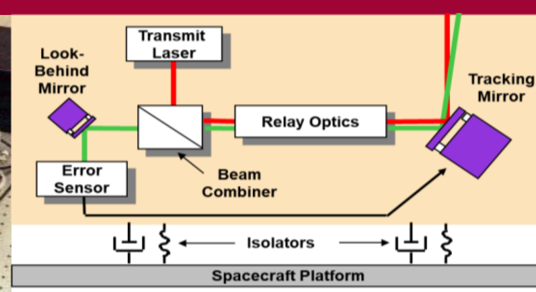
Spacecraft LAN and relay node concept

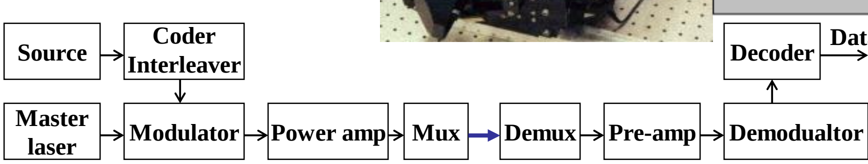


Optical Space Cross-Link

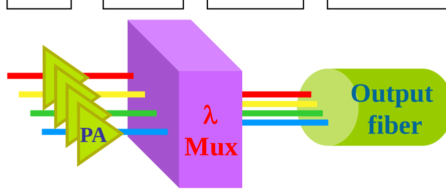


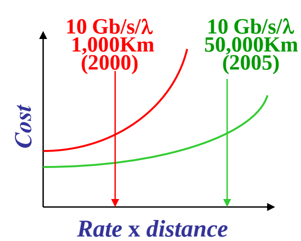


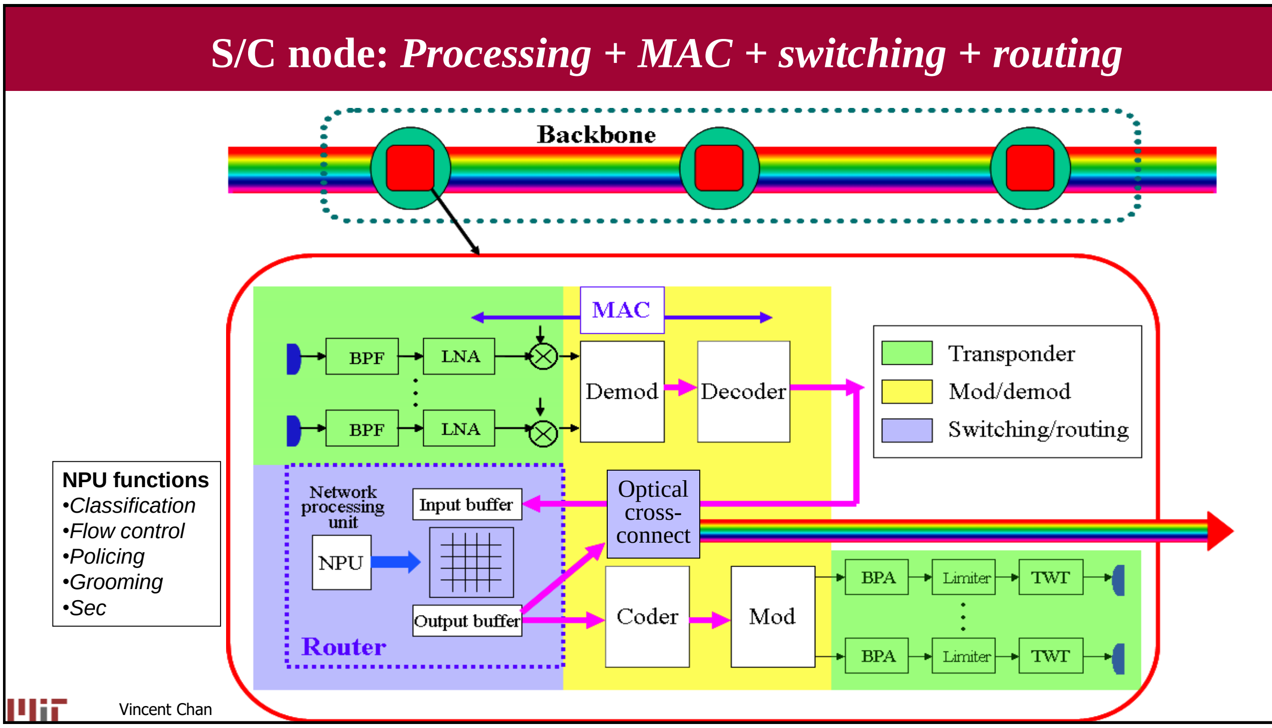


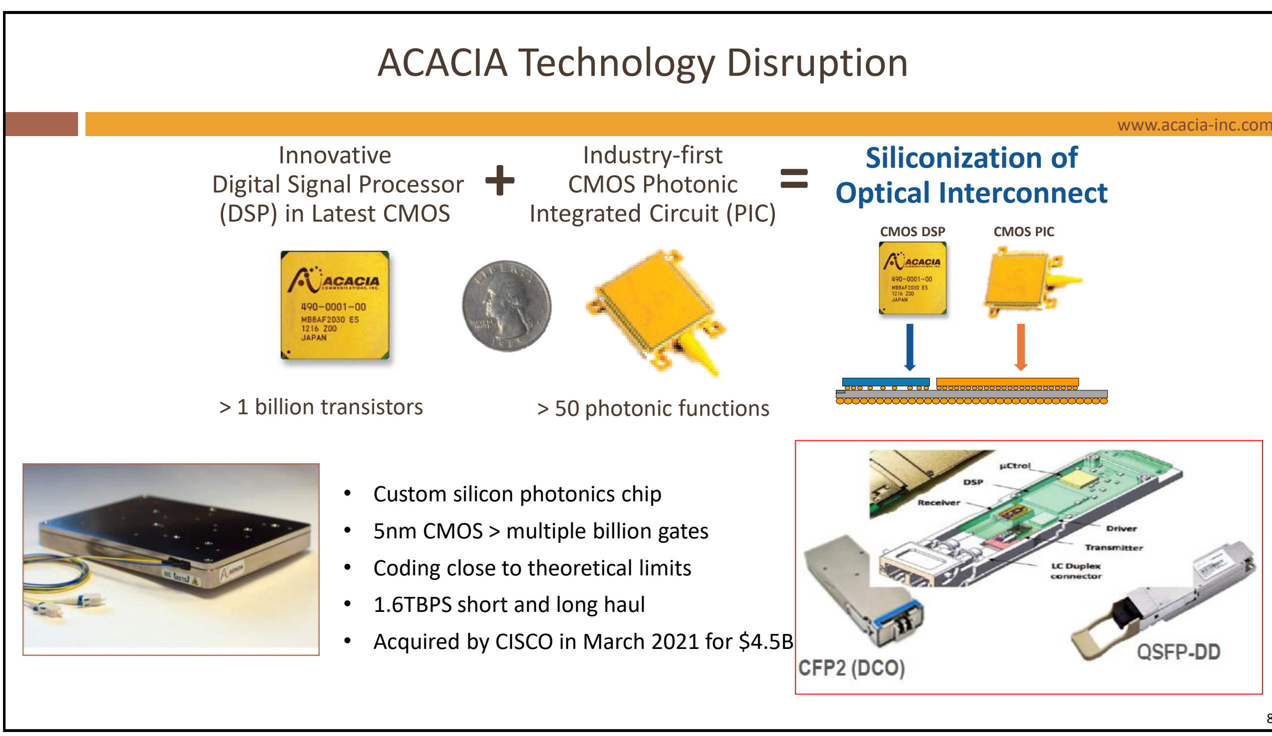


- Space backbone
- Digital or analog
- On-board demod
- Transponded
- E/O routed






S/C node: Processing + MAC + switching + routing
Backbone
MAC
BPF
LNA
BPF
LNA
Demod
Decoder
Transponder
Mod/demod
Switching/routing
NPU functions
•Classification
•Flow control
•Policing
•Grooming
•Sec
Network processing unit
Input buffer
NPU
Output buffer
Router
Optical cross-connect
Coder
Mod
BPA
Limiter
TWT
BPA
Limiter
TWT
Vincent Chan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+
Industry-first CMOS Photonic Integrated Circuit (PIC)
=
Siliconization of Optical Interconnect
CMOS DSP
CMOS PIC
> 1 billion transistors
> 50 photonic functions
Custom silicon photonics chip
5nm CMOS > multiple billion gates
Coding close to theoretical limits
1.6TBPS short and long haul
Acquired by CISCO in March 2021 for $4.5B
CFP2 (DCO)
QSFP-DD
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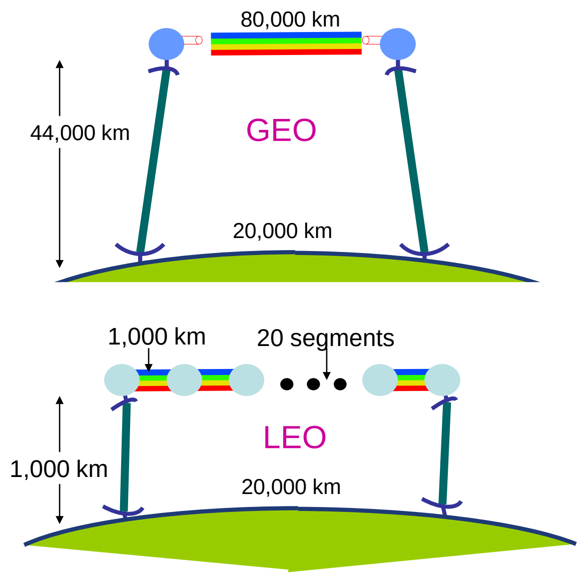
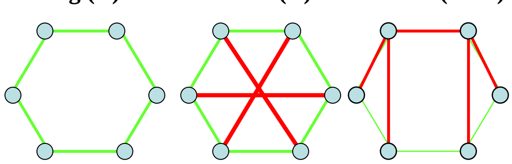
Business Case: 100 Gbps - 20,000 Km

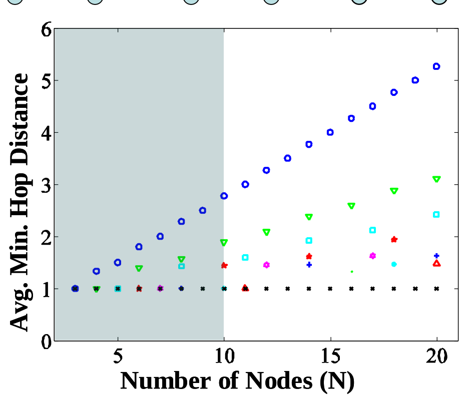


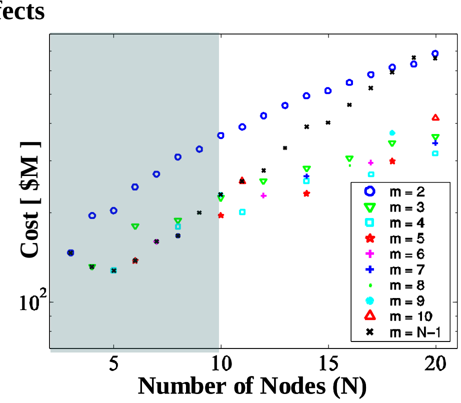
- •Assumptions:
  - •*End-to-end duplex system*
  - •*Includes bus, launch, O&M*
  - •*Conservative estimates*
- •GEO system:
  - •*RF U/L, D/L dominates*
  - •*~$1B/100Gbps/20yr*
  - •*0.6 s propagation delays*
- •LEO:
  - •*Optical X/L dominates*
  - •*~$1.5B/100Gbps/20yr*
  - •*0.06 s propagation delays*

Constellation connection topology in GEO

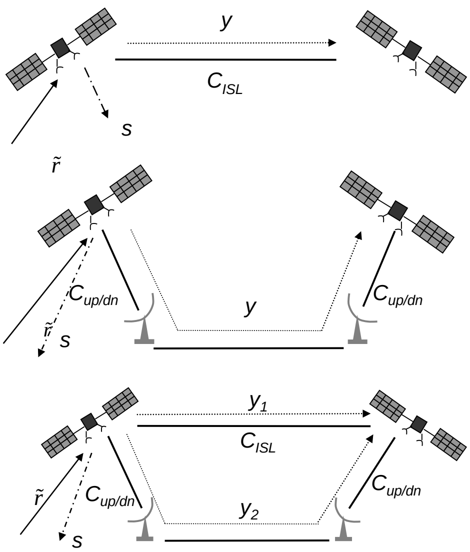


- •Uniform & Hub traffic
- •% pass-thru traffic increases with N
- •Degree 3, 4 seems best
- •Mesh is better: asymmetric traffic will have more dramatic effects

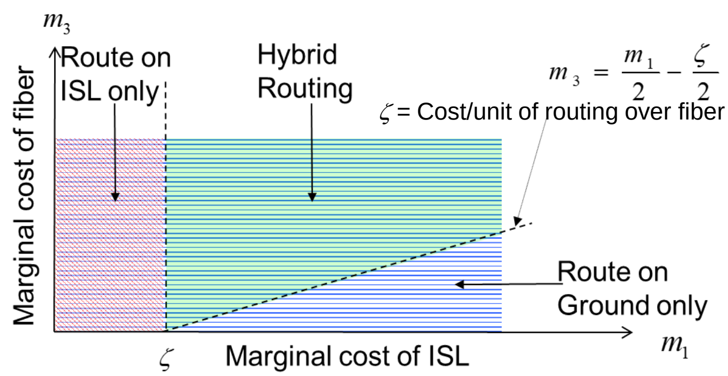




Stochastic programming for Topology Selection



- Uniform traffic demand and linear link cost functions
- Example only deal with average stochastic traffic
- Real business cases has service level agreements that have guarantees that involve at least second moments



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New affordable satellite technologies?

Low earth satellites: SpaceX, OneWeb, …

Amazon's Project Kuiper - 3,200 satellites

- Low-latency, broadband connectivity to unserved and underserved communities around the world > 4Billion
- Up to Gbps -$10/month?

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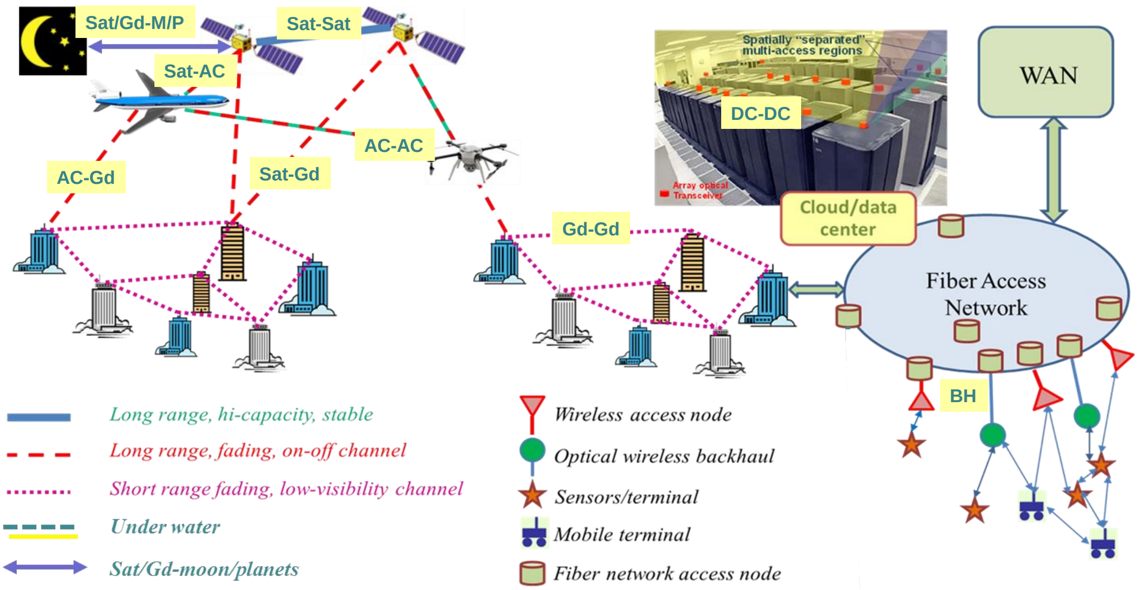
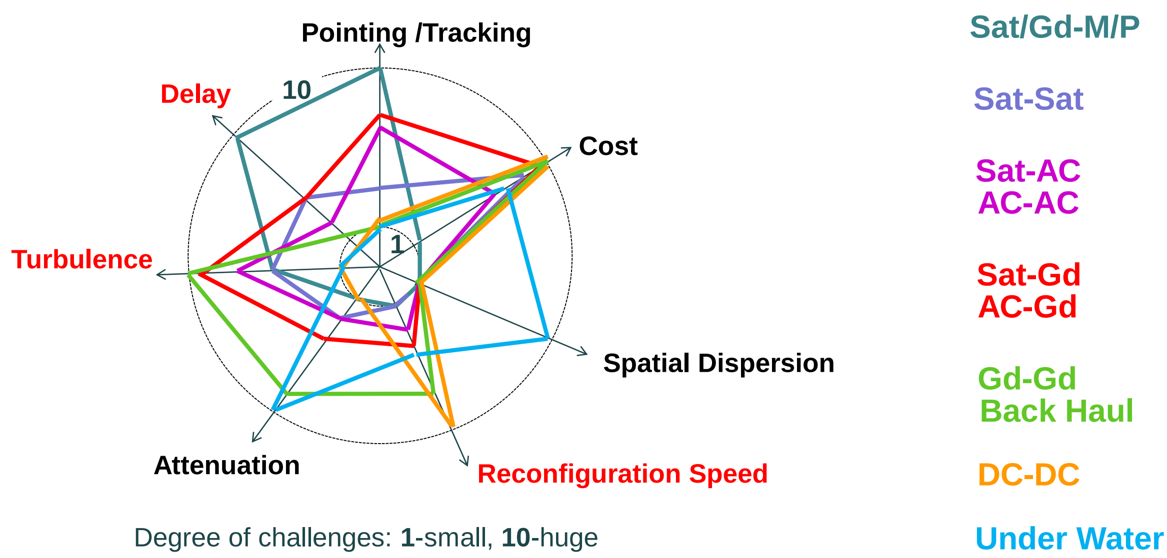
Types of links in optical wireless networks



What are the architecture problems?

1. **Constellation/Connection topology:** *Traffic model, dynamic physical reconfiguration, routing*
2. **Physical and Data Link Control Layers**
3. **Spaceborne processing**
4. **Cost:**, *life cycle planning*
5. **Network architecture**
   a. **Switching and routing**: *Line/circuit/packet/hybrid switching, load balancing, scheduling, congestion and flow control*
   b. **Transport Layer protocol**: *TCP/…/green-field-design, fading drop-outs, window closing, slow start, internetting with terrestrial networks (splitting, spoofing, …)*
   c. **Interconnection with ground and airborne networks**: *Diversity, Border Gateway protocol, splitting/spoofing/…etc, security, congestion and flow control, green-field design*
   d. **Applications**…

Types of channels and degrees of Physical Layer challenges



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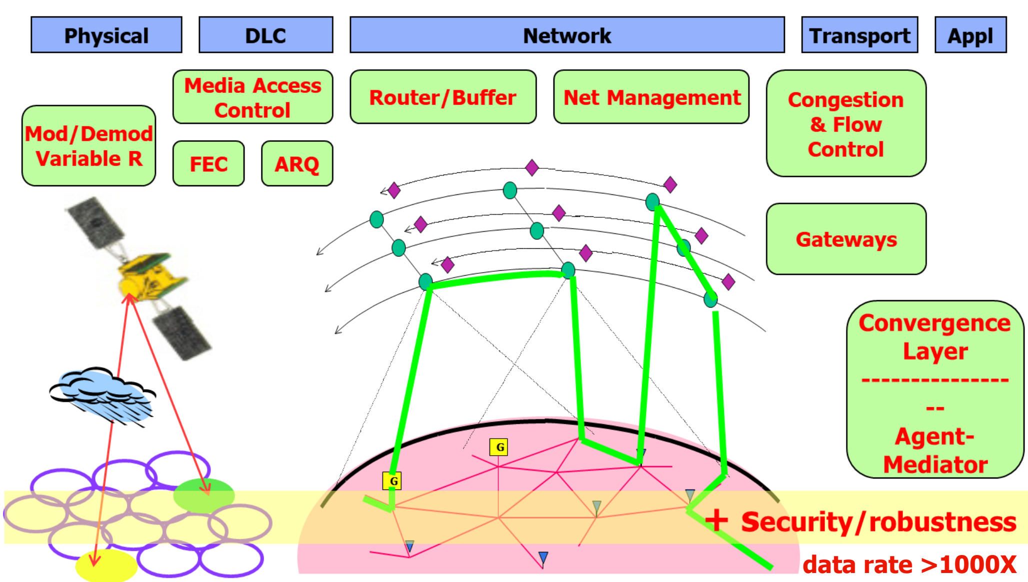
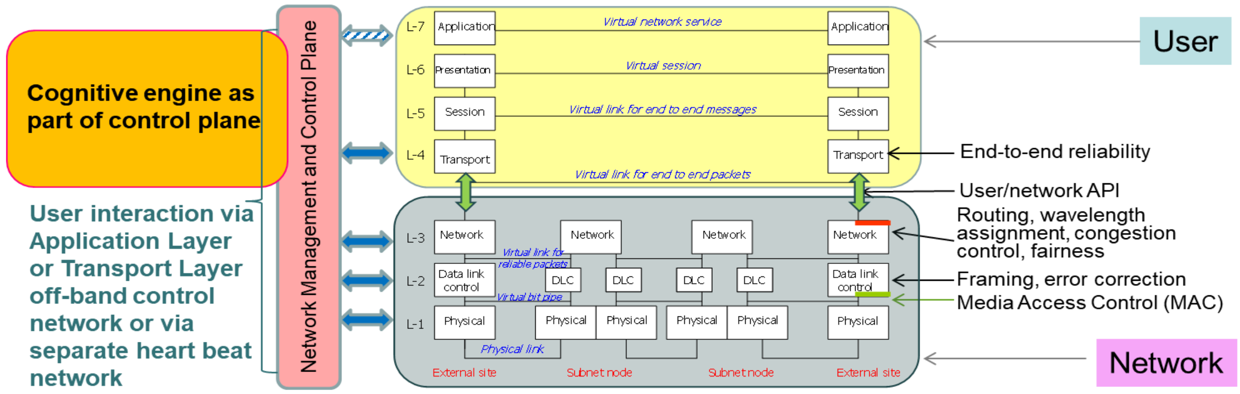
Dynamic 4-D Integrated Heterogeneous Network



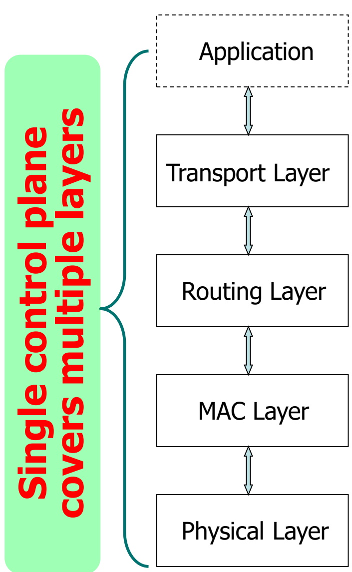
•Dynamic Capacity
•Agile beams
•MAC
•Fading
•Dynamic routing: deterministic & stochastic
•Heterogeneous network: Satcom, fiber, wireless
•Differentiated services: cost-based, time-deadline,

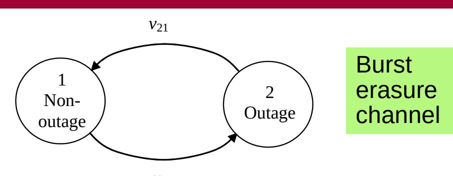
Control plane interactions with all layers of network



- A **cognitive network management and control system** ***senses*** network states (traffic, flow patterns) and ***decide*** how to ***adapt*** the network to satisfy/improve overall performance and provide ***quick responses*** to transaction requests.
- **Control plane** never used to interact with user part of the network protocol stack - Interactions necessitated by **elephants**
- **Cognitive engine allows:**
  1. Fast recognition of traffic changes
  2. Adapt quickly

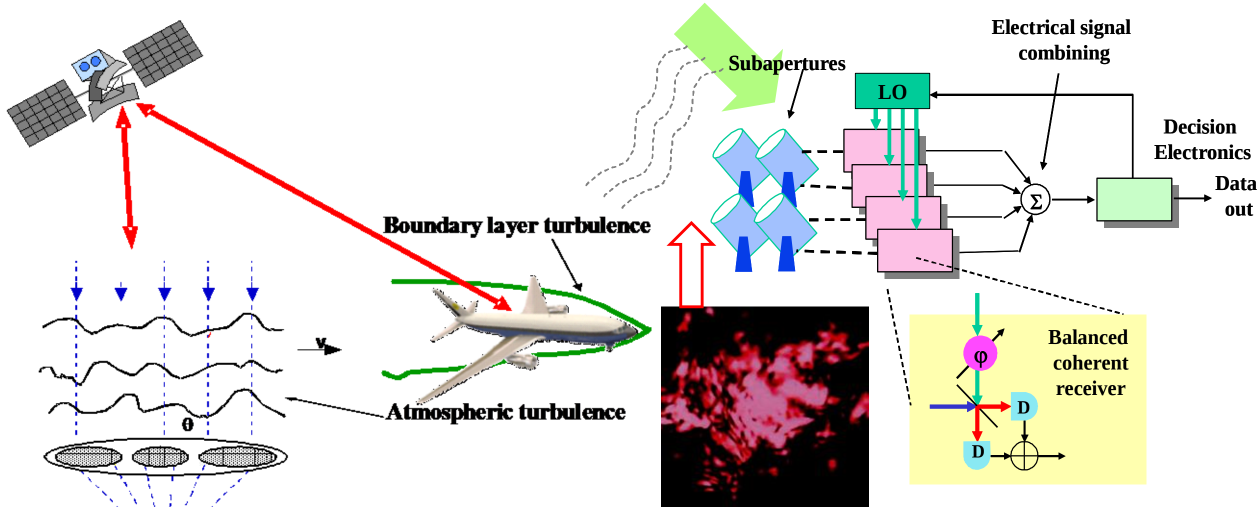
Protocol stack construct for optical-wireless networks





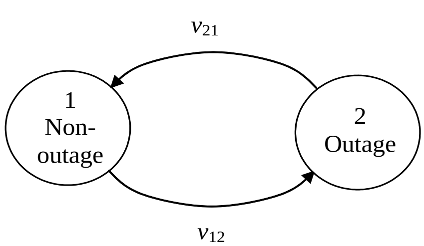
- New transport layer protocol for burst errors due to multi-path fading
- Very agile + multipath routing + bursty mobile users and multi-path evolutions
- Spatial mode multiple access (MAC) to discriminate unique user signature for processing
- Diversity coherent receivers with low rate feedback: tracks user and multi-path migrations

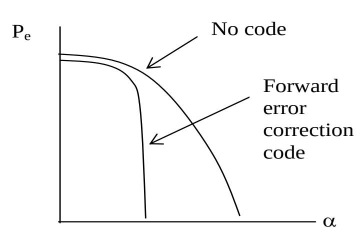
Multi-aperture Coherent Receiver

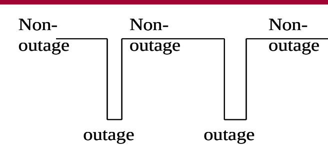


- Coherent receiver array
- Each element more than coherence length apart

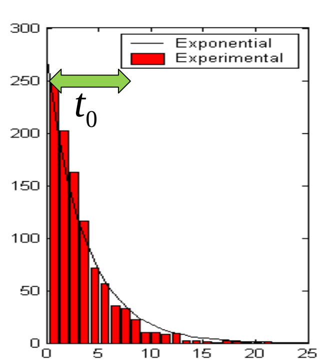
Markov Channel Model

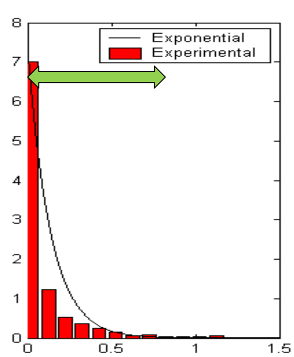


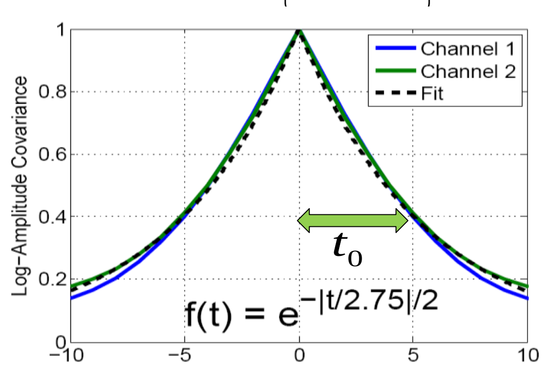




$$R_{hh}(t) = \exp\left\{ -\frac{1}{2}\left(\frac{v_{\perp} t}{\rho_0}\right)^{\frac{5}{3}} \right\} \sim \exp\left\{ -\frac{t}{t_0} \right\}$$



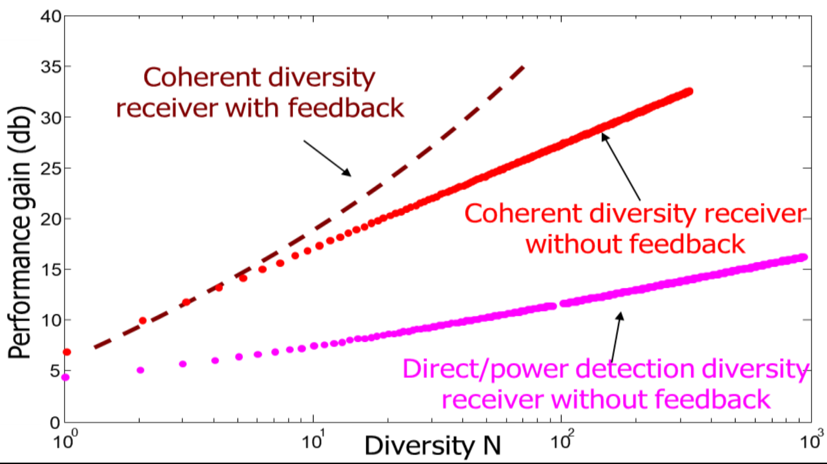


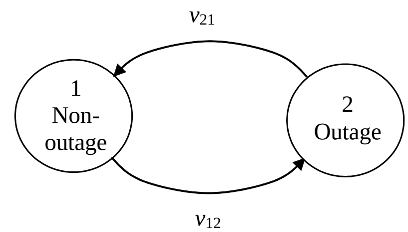


Power Gain of Diversity Receivers

$P_{outage} \sim c_3 \exp\left\{-c_2 N (\ln m)^2\right\}$ **for diversity N and margin m**

$E[outage\ length] \sim c_1 \frac{t_0}{\sqrt{n_{tx} n_{rx}}} = c_1 \frac{t_0}{N}$ < 1 mS





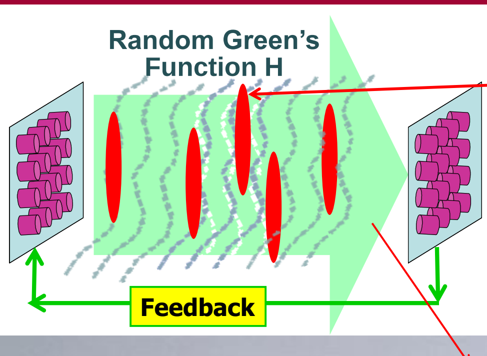
σ_χ=0.3, moderate turbulence

P_e^{thresh}=0.1

P_{outage}=0.1

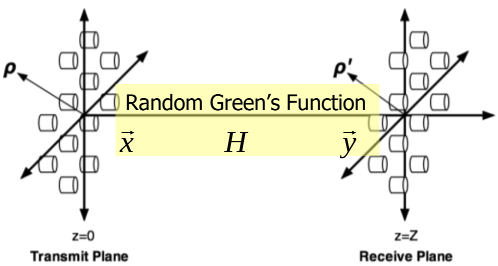
Background noise N_n=1

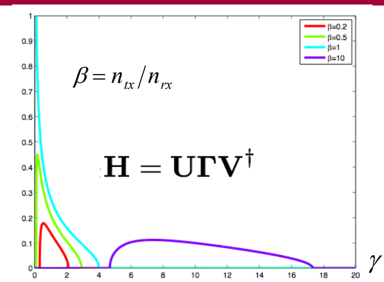
Communication using Mirages: Atmospheric Turbulence Mitigation



- Turbulence is acting as relay lenses
- Since turbulence can be closer to the receiver, power received can be greater than diffraction limited transmission in vacuum
- Similar to "ducting" in mirages, except we exploit it actively

Near field communication over turbulent atmosphere





•Eigenvalue distribution, f(γ), determines performance → Marcencko-Pastur density for large N

•Modulate mode with largest eigenvalue γ_{max}

$$\vec{y} = H\vec{x} + \vec{w}$$

$$H = U\Gamma V^{+}$$

$$\Gamma = \begin{bmatrix} \gamma_1 & 0 & \cdots & 0 \\ 0 & \gamma_2 & & \vdots \\ \vdots & & \ddots & \\ 0 & \cdots & & \gamma_m \end{bmatrix}$$

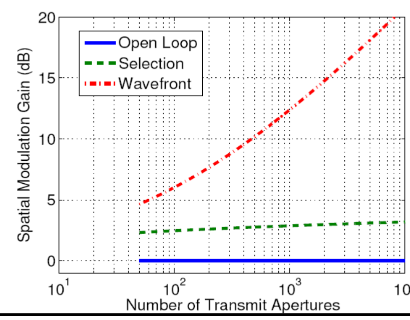
$$\vec{x}^* = a\vec{v}_{\max}$$

$$\phi = \mathrm{Re}\left\{ \vec{u}^{+}_{\max}\vec{y} \right\}$$

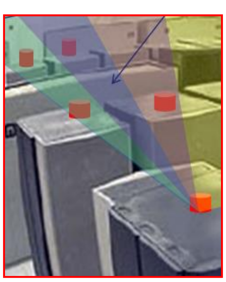
Gain over no feedback

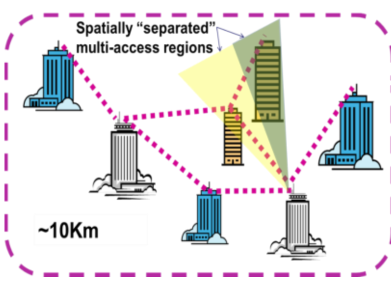
$$\sim \left(1 + \sqrt{\beta}\right)^2$$

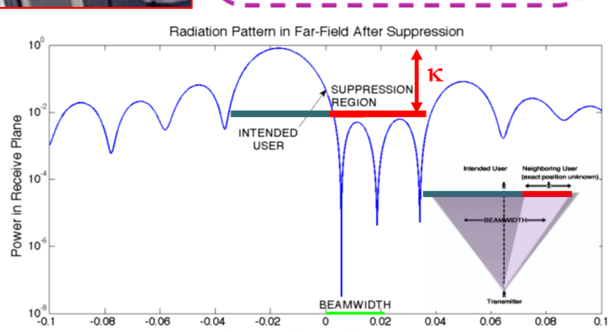
$$\beta = \frac{n_{tx}}{n_{rx}}$$



Narrow-cast Multiple Access technique and algorithm







Parallel multi-thread MAC processing

Identify user signature:

- Suppress in-beam spatial regions: κ
- Significant gain on intended user

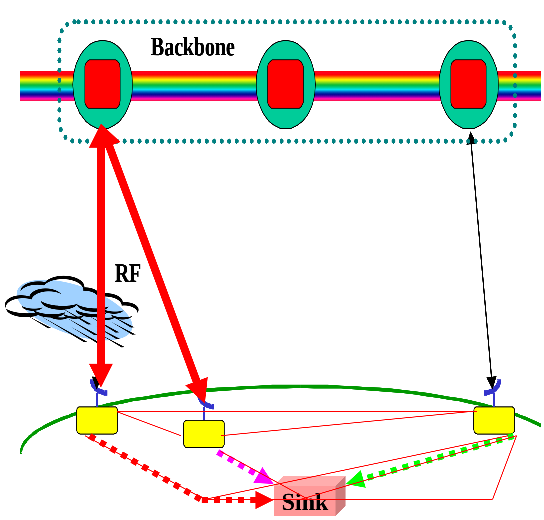
Algorithm types:

1. Descent types:
   a. Gradient (slow as snail)
   b. Conjugate gradient (faster in N steps = # elements)
2. Digital Block processor:
   a. process a block of signal shorter than coherence time
   b. Each user processed in parallel separate threads
3. Genetic algorithms combining features of both 1 and 2, ideal for parallel processing

Architecture construct for optical wireless networks

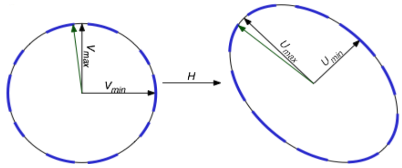
Layer	
Application	
Transport Layer	•New transport layer protocol
Routing Layer	•Very agile + multipath routing
MAC Layer	•Spatial mode multiple access
Physical Layer	•Diversity coherent receivers with low rate feedback: excite "mirages"

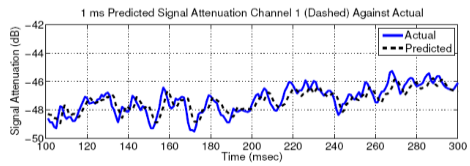
Network routing at Layer 3

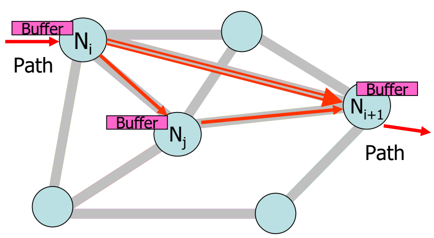


1. **Dynamic adaptation based on channel states** - *variable link capacities and qualities; fast adaptations may lead to oscillations*
2. **Maximizes downlink capacity and/or delay via optimum routing/scheduling**
3. **End-to-end routing including terrestrial subnets**
4. **Time deadline QoS**
5. **Routing algorithm -OSPF ?, ..., Internetworking - BGP?, ..**
6. **Diversity routing for reliability and time-deadline delivery - trade capacity for reliability, only way to provide < 1 S deadlines with assurance**
7. **Stability**

Routing Layer based on prediction, diversity combining, dynamic route switching and retransmission of small buffered data







- Channel state is N-dimensional ellipsoid
- Receiver tracks eigen-states
- Predict 3mS ahead to ~ 3 db, except dropouts (~50μS), tracks γ' and γ''
- Transmit largest eigenvalue state + next largest eigenvalue state with γ' >0
- Also send on alternative path with no common link
- Buffer retransmission upon notification of fade (~1mS)
- Congestion control via access rate control and speed-up of transmitters at nodes
- Diversity/retransmission results in almost no drops - retransmission of buffer cover losses

$$\vec{x}^* = \begin{bmatrix} \vec{x}_1^* \\ \vec{x}_1' \\ \vec{x}_2^* \end{bmatrix} = \begin{bmatrix} a_1^*\vec{v}_1^* \\ a_1'\vec{v}_1' \\ a_2^*\vec{v}_2^* \end{bmatrix}$$

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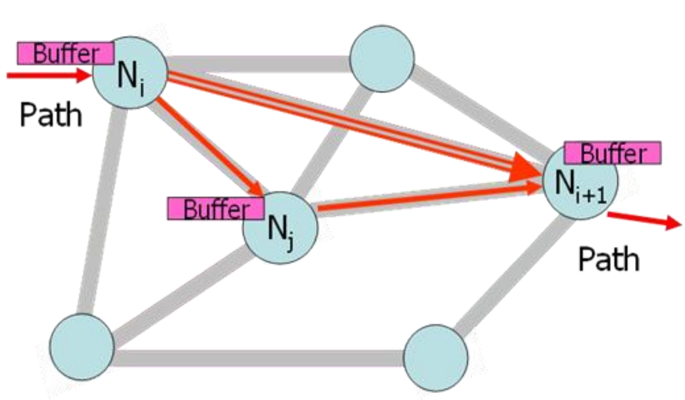
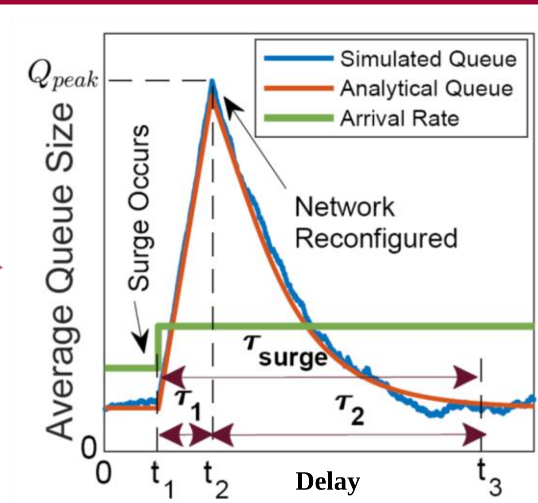
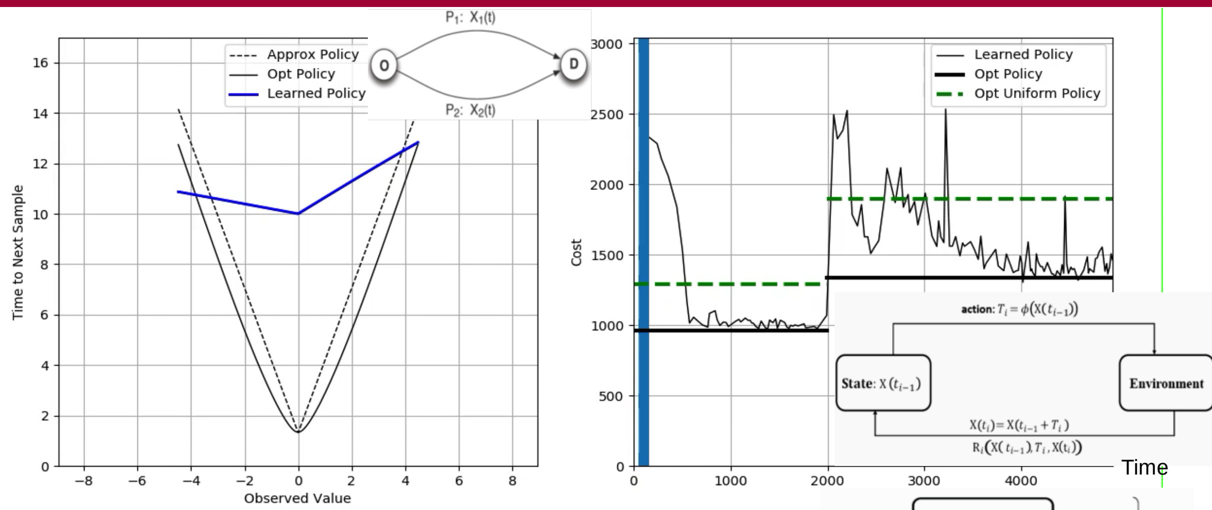
Stopping trial sequential decision algorithm for reconfiguration



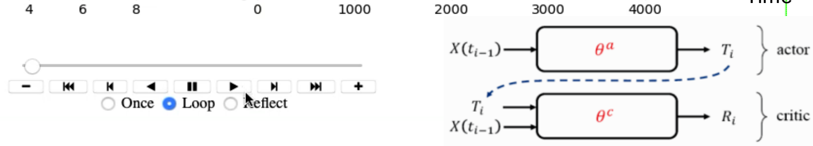


- **Need quick response to prevent congestion**
- **"Stopping Trial" trigger path reconfiguration - Provably fastest reconfiguration algorithm**

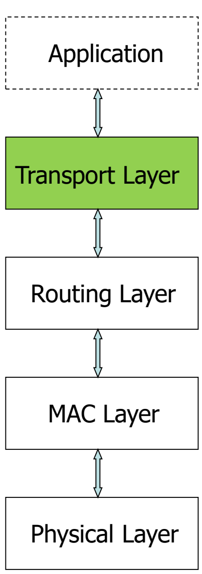
Handling non-stationary routing environments



Convergence speed? Stability?

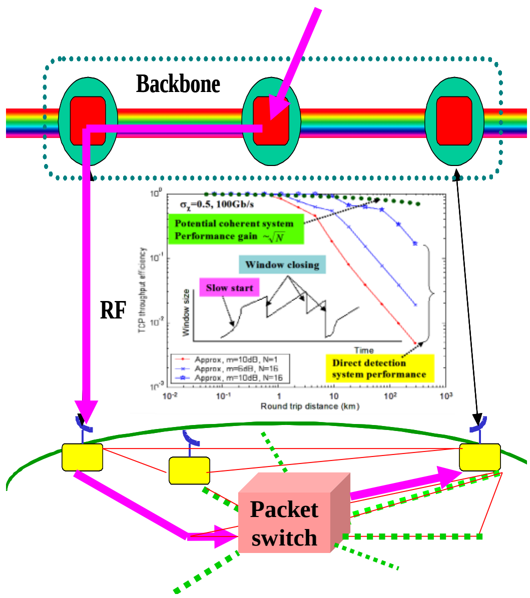


Architecture construct for optical wireless networks



- New transport layer protocol
- Very agile + multipath routing
- Spatial mode multiple access
- Diversity coherent receivers with low rate feedback: excite "mirages"

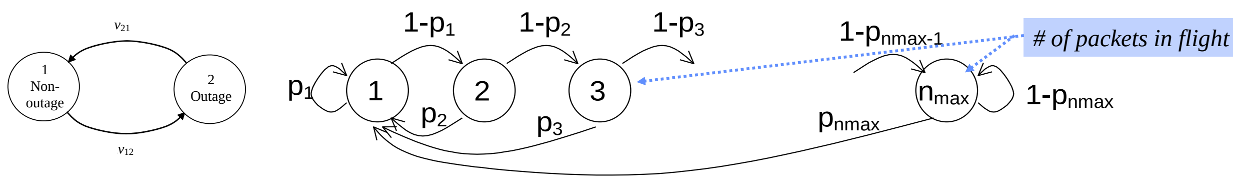
Transport Layer Protocol – Beyond TCP, …

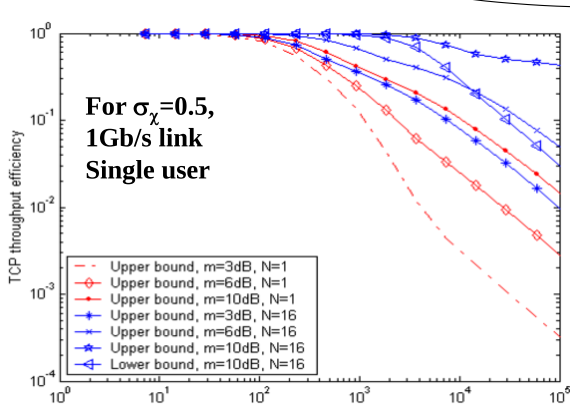


1. **TCP: end-to-end reliable delivery**
2. **Long delay link and window options can allocate unfair amount of resources**
3. **If long delay links have outages, then window flow control may prevent full rate transmissions, leading to high inefficiencies**
4. **Proxy service decouples Layer 3 communication – hard to provide QoS such as time deadlines**
5. **UDP plus add on protocol? Others? Congestion control?**
6. ***New Transport Layer Protocol – must feedback channel states, fair allocation with priority pre-emption***

TCP Throughput with Diversity

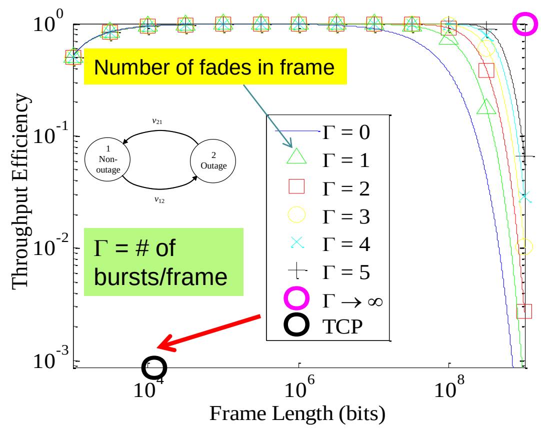
TCP's retransmission timeout value equals RTT so that outages trigger timeout (window goes to 1)

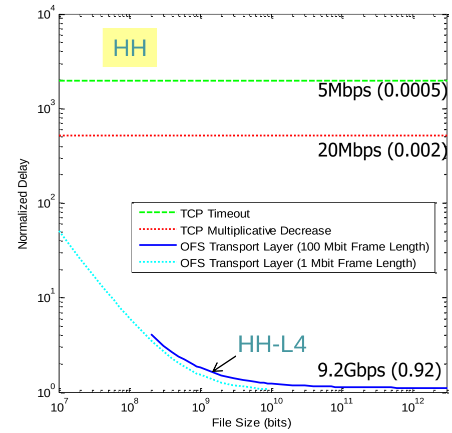




- *Max window size set to RTT*
- *Upperbound: exponential build-up*
- *Lowerbound: linear build-up*
- *Even upperbound looks bad for GEO distances*
- *Modification of TCP possible but create problems when internetted with ground networks*

High speed data transfer performance: TCP/IP vs HH-L4



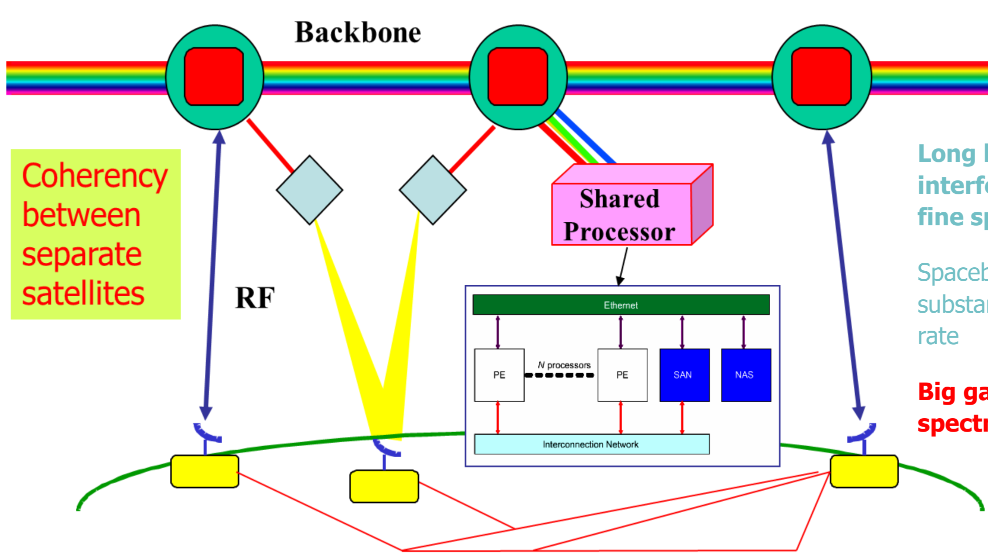


TCP/IP problems for large transactions: Slow start, window closing upon loss packets

HH-L4 uses large frame structures ~ 100 MB, with much higher thruput

Replaces TCP no need for: Rate matching, Congestion control

Coherent distributed satellites for ultra fine spatial resolution



Long baseline interferometry for ultra fine spatial user resolution

Spaceborne processing substantially reduces D/L data rate

Big gain in revenue for spectrum lease

Looking forward

Exciting future in satellite communication and networking – lots of uncertainties

Serious problem with the communication and network protocols to be addressed:

1. **Links will present data to upper layers with some errors and high rate variations**
2. **Non-zero delay in data delivery, sometimes long and unpredictable delays**
3. **Intermittent and changing connectivity**
4. **Must tell upper layer link states to tune, ML/AI cannot perform fast adaptation to new situations**
5. **Security**
6. **Serious issues with internetworking:**
   a. **Routing layer (e.g. Border Gateway Protocol)**
   b. **Layer 4 (Transport) and Application Layer (PEP)**