Progress in
Free Space Optical Networks

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Overview

- Status of Lasercom/Free Space Optics Technology
- Opportunities to advance FSO Networks

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Free-Space Optical Communications

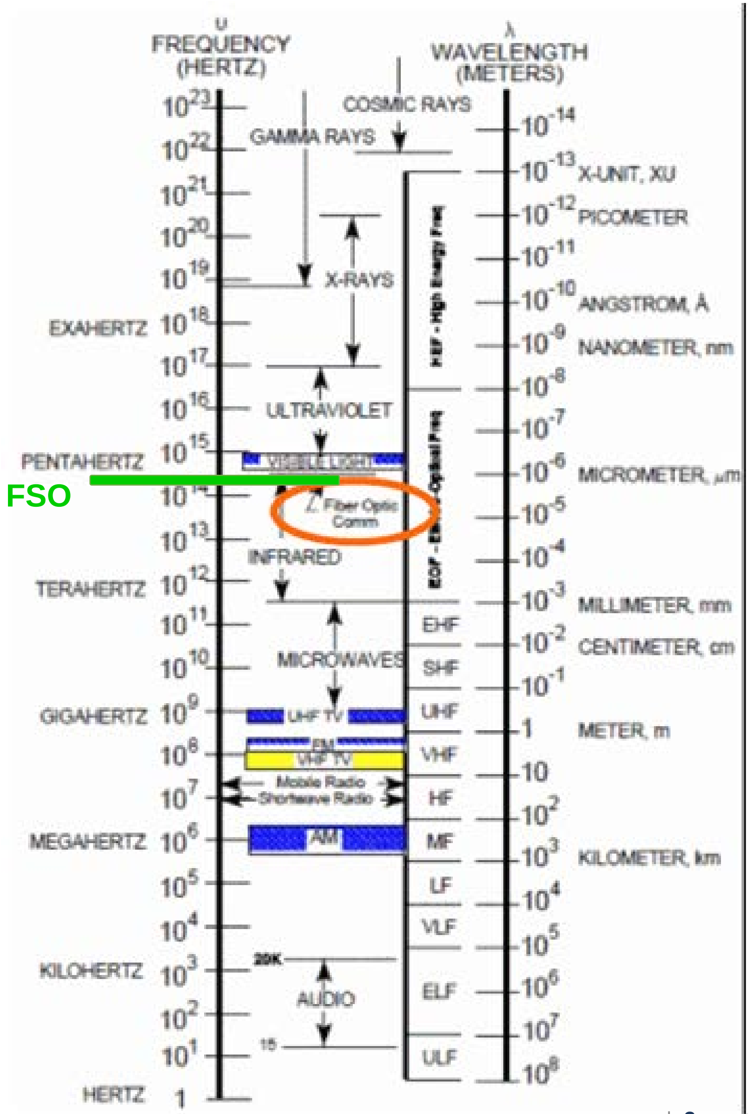
- **Operate outside traditional RF frequency bands in optical spectrum**
  - Leverage COTS telecom components
  - Frequency allocation requests not required above 3000 GHz at this time CONUS

- **Augment RF Communications**
  - Maintain high joint RF/FSO availability and throughput

- **Provide fiber-like data rates**
  - 10M/100M/1G/10G/100G+

- **Directional Beams**
  - Avoid cosite interference; no sidelobes
  - LPI/LPD

- **Compact form factors achievable**



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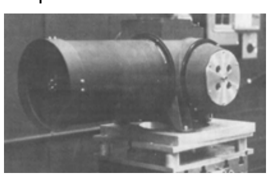
Where have we been?
Selected S&T Investments in Free Space Optical Comms

Pre-1990

- **Hughes** Ship Lasercom, 1984
- **AFRL HAVE LACE,** airborne lasercom using COTS, 1983-1986



- **AF 405B** – space laser communication, Nd:YAG 1Gbps downlink at 532nm, 1064nm 20kbps uplink; 1970s
- **NRL** 10um experiment

1990-1999

- **Commercial & SBIR FSO** for short range connectivity, 1995-2004 to Present
- **AFRL RICE,** airborne near-IR FSO, 1995-2005

- **NRL MRR,** 1999-Present
- **DARPA TALC,** assess utility of submarine lasercom, 1989-1991

- Commercial Lasercom challenged in Telecom Bubble. DoD efforts leverage fiber telecom advances.

2000-2009

- **AFRL Falcon,** airborne 2.5Gbps FSO, 120km A-A 2003-2010
- **ONR/NRL Maritime Lasercom Testbed** 2004-2007
- **NRL Trident Warrior** ship-to-ship 2006

- **NRL Empire Challenge Network,** 2010
- **MDA/TESAT/ DLR NFIRE,** 2007 -15

- Defense Contractors developed optical payloads for **Airborne Lasercom Terminal**, AF ESC, 2004-2006
- **DARPA ORCA** Develop a TRL6 hybrid Optical/RF network solution, 2008-2010

- **AFRL Iron T**2 Hybrid Program – Hawaii 150 Km Gnd Tests, Hybrid Optical/RF

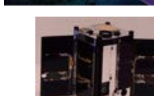
2010-Today

- **MIT/LL FOCAL** Airborne FSO, 2008-10

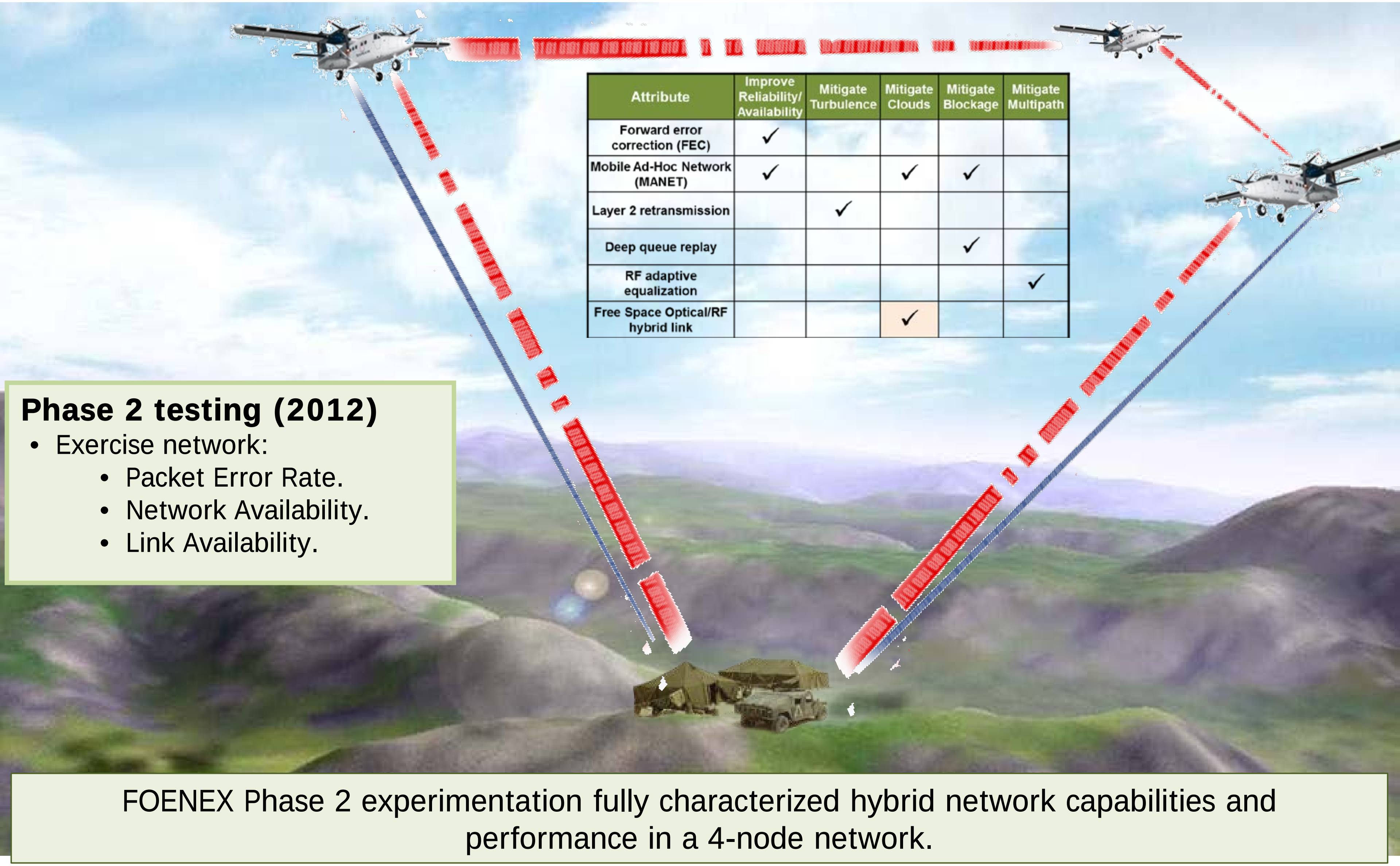
- **ONR TALON** Tactical FSO, 50km G-G 2010-2015; **OSD ATOLL for USMC** 2016-9
- **ONR Blue Green S&T**, 2008-Present
- **Google**
- **Facebook**

- **Commercial & NASA Space FSO,** ongoing

- **DARPA FOENEX** Demonstrate Air to Air and Gnd, hybrid optical/RF four node network to 10.3Gbps @200km, 2010-12



FOENEX Phase 2 experiment and demonstration



Attribute	Improve Reliability/ Availability	Mitigate Turbulence	Mitigate Clouds	Mitigate Blockage	Mitigate Multipath
Forward error correction (FEC)	✓				
Mobile Ad-Hoc Network (MANET)	✓		✓	✓	
Layer 2 retransmission		✓			
Deep queue replay				✓	
RF adaptive equalization					✓
Free Space Optical/RF hybrid link			✓		

Phase 2 testing (2012)

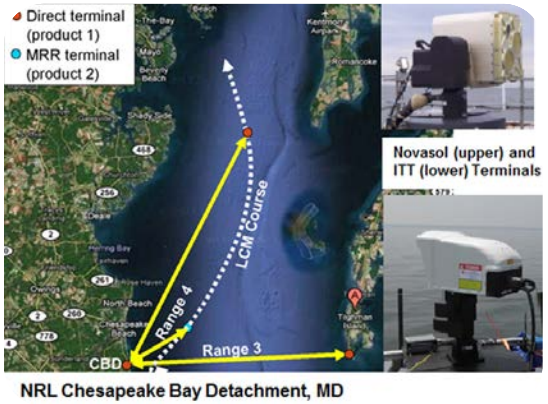
- Exercise network:
  - Packet Error Rate.
  - Network Availability.
  - Link Availability.

FOENEX Phase 2 experimentation fully characterized hybrid network capabilities and performance in a 4-node network.

Ongoing NRL FSO Developments

- OSD/DoD CIO Spectrum Access R&D Project: **Automated Tactical Optical Line of sight Links**
  - **Emphasis on tactical network integration with FSO as an augmentation to existing RF links**
  - **Spiral development of the TALON FSO system**
- OSD/DoD CIO Spectrum Access R&D Project: **Free Space Terabyte Offload**
  - **High rate offload from air platforms**
  - **Requires assured data delivery**
- ONR **Lasercom for Fractionated Small Satellite Architectures**
  - **Understand trades between closing links to SWaP-challenged, dynamic platforms**
- NRL, AFRL, ARL & SMDC awarded Applied Research for the Advancement of S&T Priorities (ARAP) for the **Defense Optical Channel Program**
  - **Emphasis on advanced lasercom waveforms and networking**

NRL compact ship FSO, 2008

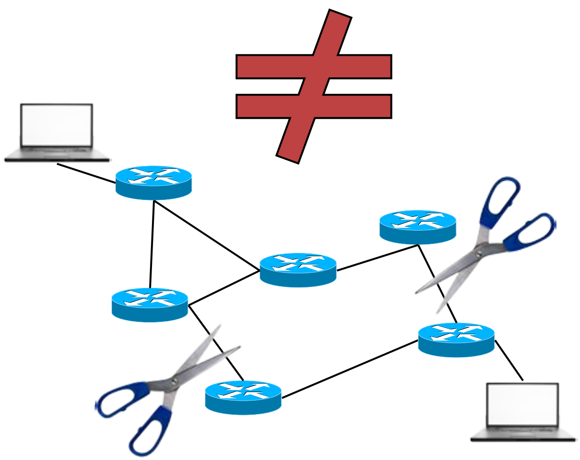


NRL Lasercom Test Facility: Shore and ship testing

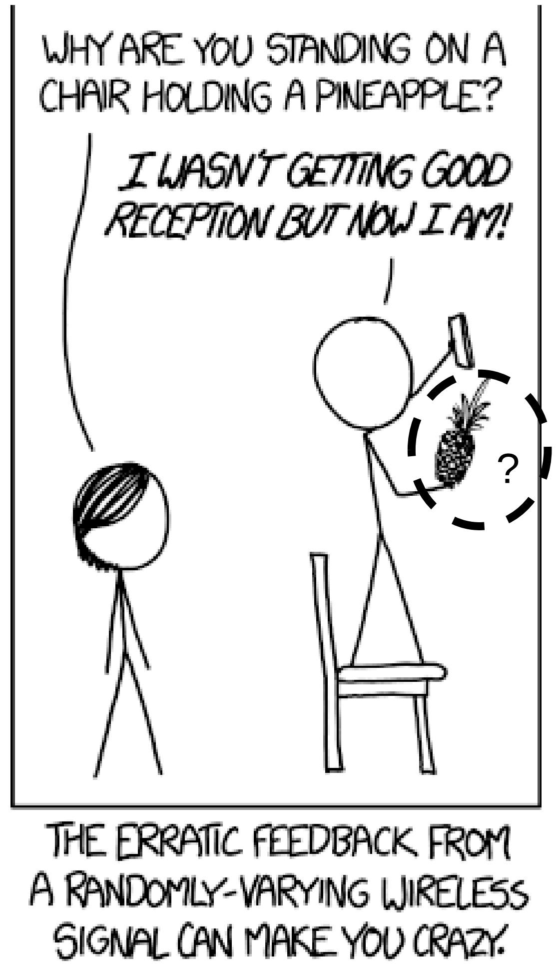
A General Challenge of Networked Wireless Systems

Networked Battlespace on the Move

Building Wireless Networks for This



Just Cutting The Wires



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Specific Theoretical Challenges of Networked Wireless Systems

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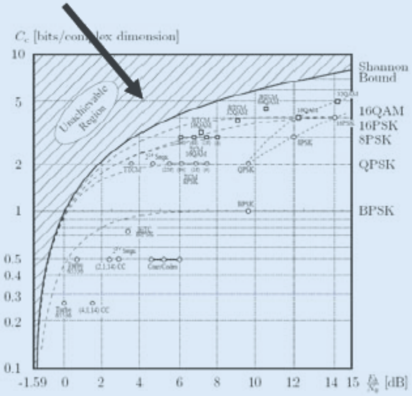
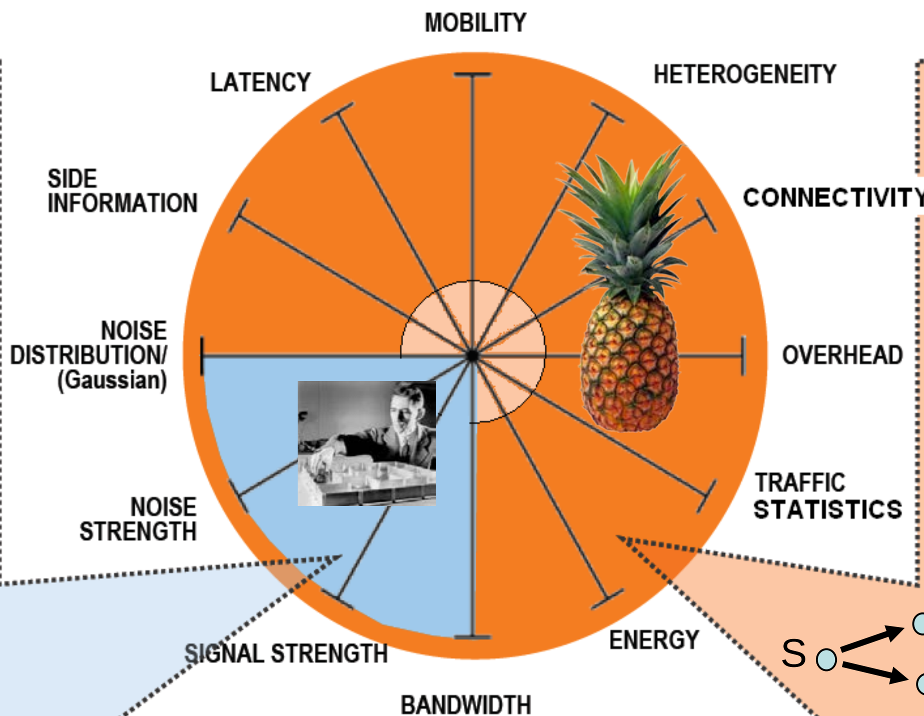
Point-to-point communications:

For AWGN channels, capacity is known (achievable in practice)



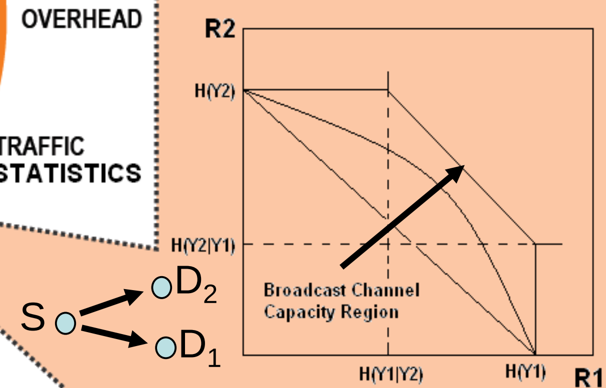
$C = W \log_2 (1 + S/N)$ [bits/second]



(blue)	Dimensions considered in Shannon formulation
(orange)	Dimensions that need to be considered for wireless networks

Wireless "network" communications:

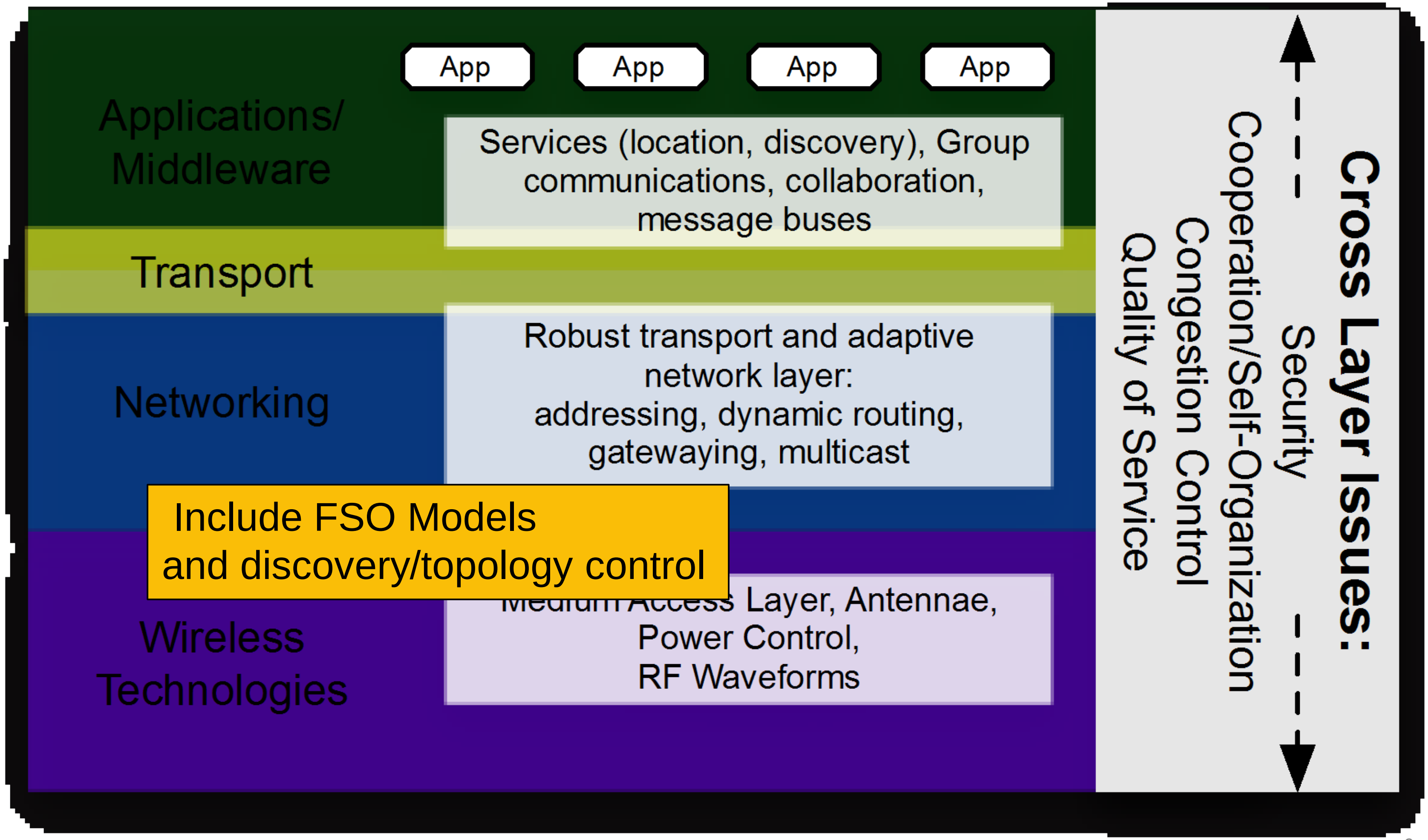
Capacity region is not known except for simple topologies e.g. multiaccess, broadcast



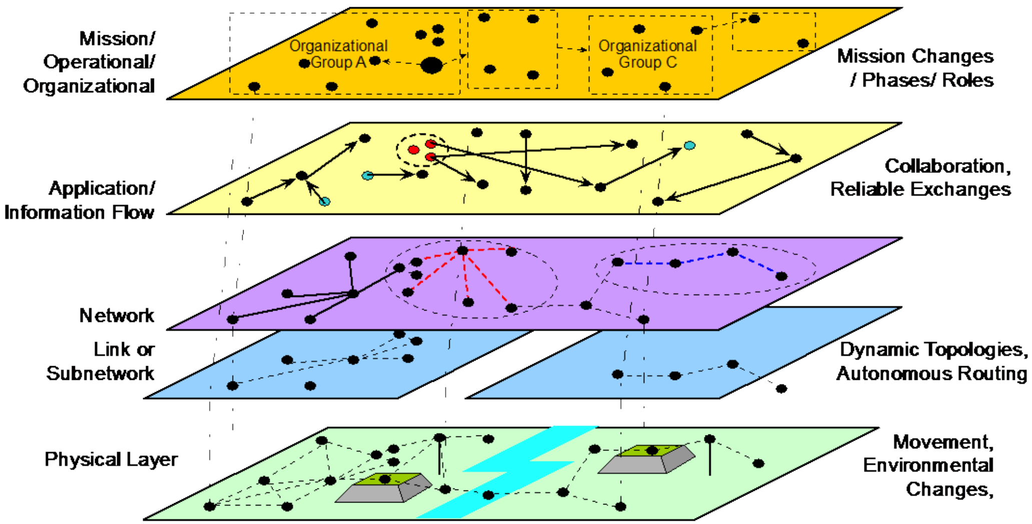
$C = ?$

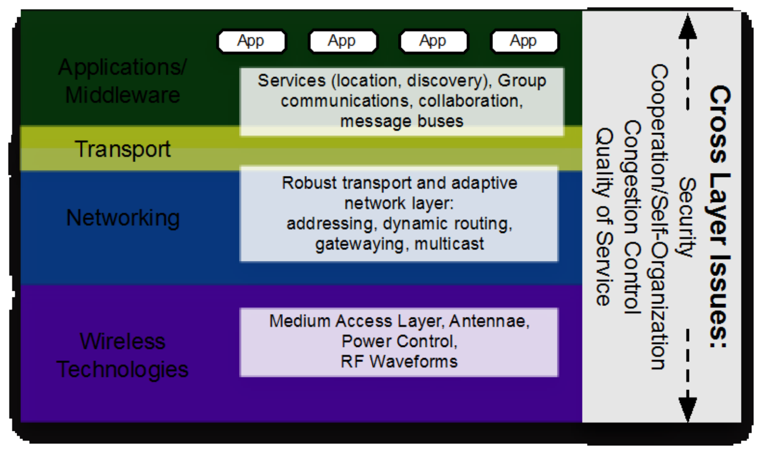
Classic Communication Capacity Theory → **Wireless Networked Communications**

A Layered View of Collaborative Mobile Network Systems



Layered Wireless Network System and Modeling Challenges





In a wireless network, none of these functions/layers are independent

Ongoing Applied Research Areas

- **Distributed control and self-organization mechanisms** to support autonomous/semi-autonomous wireless network systems
  - **FSO requires a robust discovery subsystem**

- **Resilient applications, middleware, and data transport protocols** in the context of challenging tactical edge communication networks and missions
  - **Elastic and resilient data transport appropriate for hybrid FSO network use**
  - **Tighter network-link layer designs (e.g., DLEP) for dynamic router response to intermittent connectivity (e.g., optical fades) and dynamic and heterogeneous data rates**

- **Scenario-driven modeling and cross-layered dynamic network experimentation** to aid analyses and performance assurance in realistic environments
  - **Hybrid architectures where FSO augments RF links with traffic prioritization. Need to model this early on in more realistic heterogeneous and dynamic environments**
  - **Dynamic physical topology management with FSO capabilities**

- **Evolving applications of recent theoretical advances** (e.g., complex network theory, control theory, network science) for analysis, optimization, and design of dynamic wireless network systems.
  - **Unique FSO characteristics are dramatically different from standard RF networks**
  - **New opportunities for research in dynamic topology control and network management**

IETF MANET Standards Evolution: "Building Block" Components

MANET Start ~1997-2007
- 2 Experimental Proactive Protocols
- 2 Exp Reactive

MANET Reboot

2005-2016
- 1 standard Proactive
- 1 standard Reactive

Building Block Approach

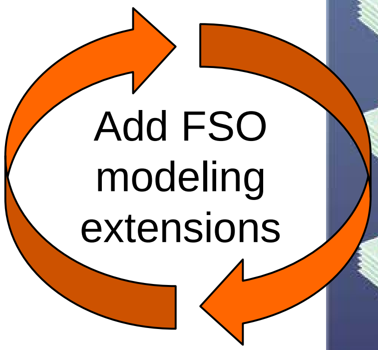
2006-2011
- Packet format
- Neighbor discovery
- Protocols
- Generalized multicast

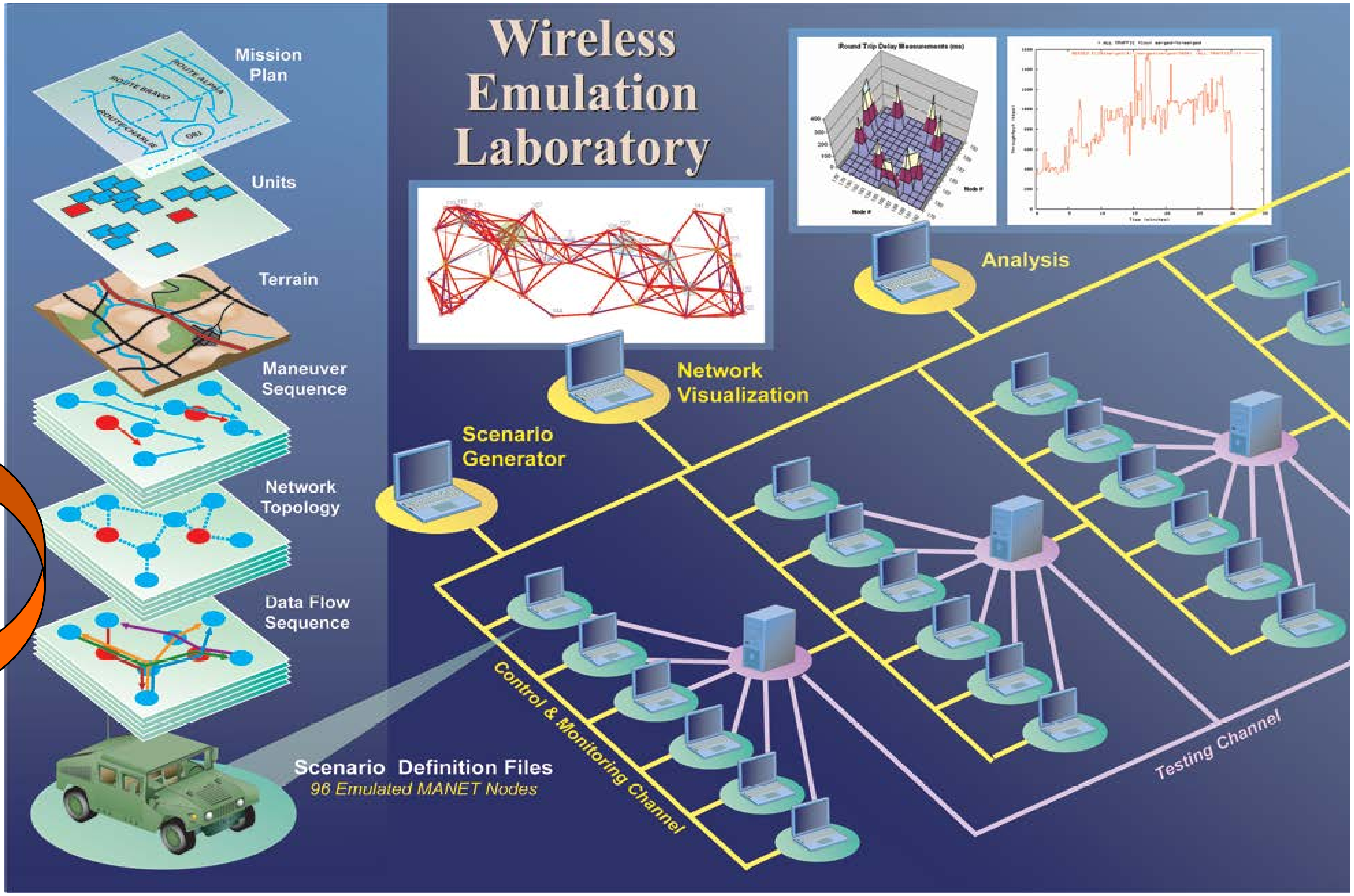
Extensions
2007-current
- Time
- Security
- Protocol Improvements

Today
2010-current
- Radio/Router Interface
- Multicast building block approach

These building blocks can be adapted and applied to new links (e.g., FSO) and environments (e.g., air, ground, space)

Cross-Layer Mobile Wireless Network Modeling Capability

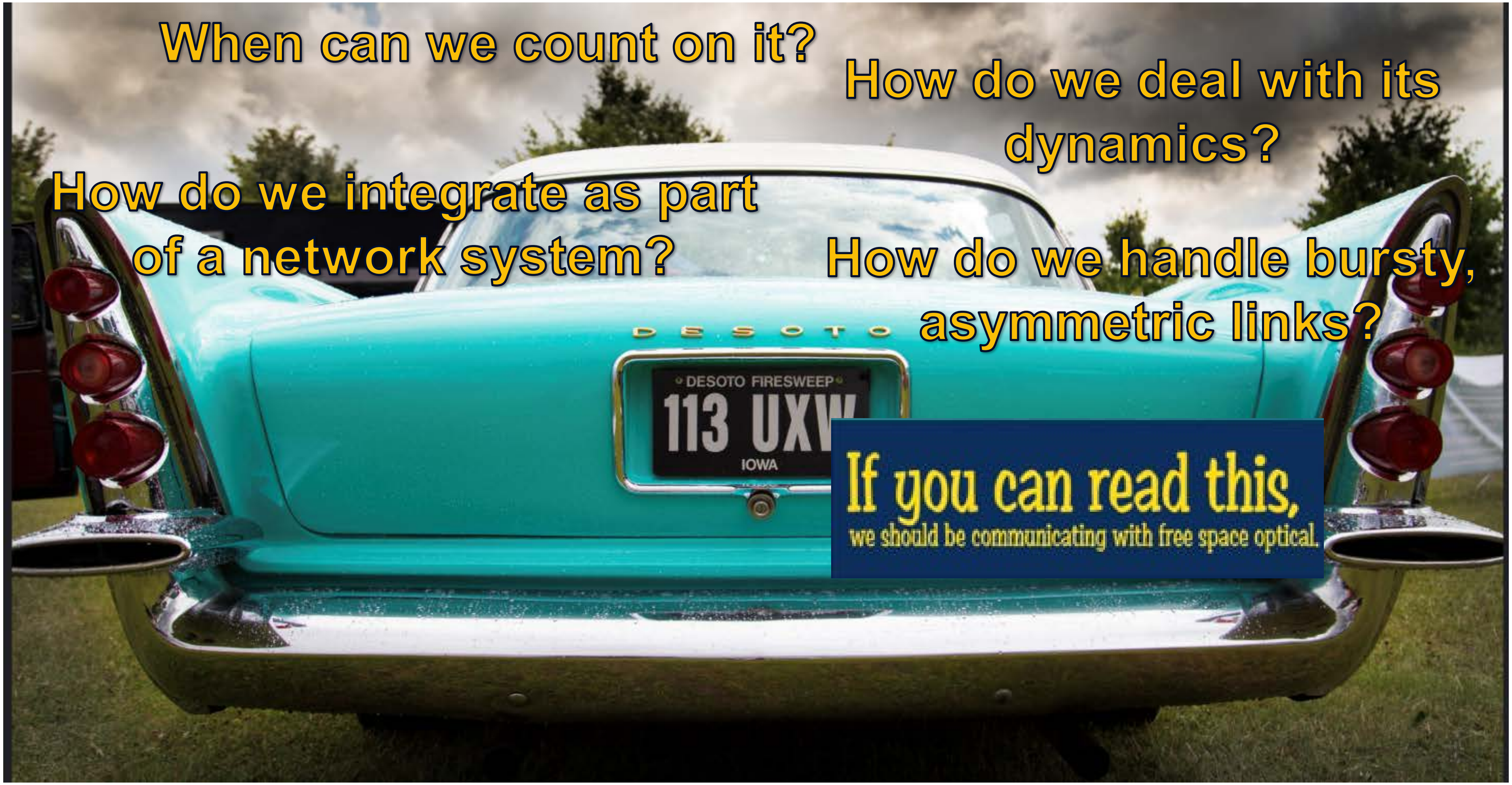




Free Space Optical Network Challenges

- Adapt FSO physical layer behavior for the network
  - Burst fades
  - Scintillation & turbulence
  - Beam wander
- Latency
  - Meet mission-level requirements
- Discovery
  - Dynamic networks (space, mobile, etc)
- Topology management
- Network Emulation
  - Tools for end-to-end emulation
  - Consider interactions from physical later to transport layer
  - Heterogeneous networks with RF
- Enable modularity with standardized interfaces
  - Leverage IETF network standards, among others
- Enable Interoperability
  - Commonality
  - Interchangeability
  - Compatibility

FSO Challenges drive many research opportunities



Thank you!

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Some of the Present Emulation Modeling Subsystems in Use

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Common Open Research Emulator (CORE):

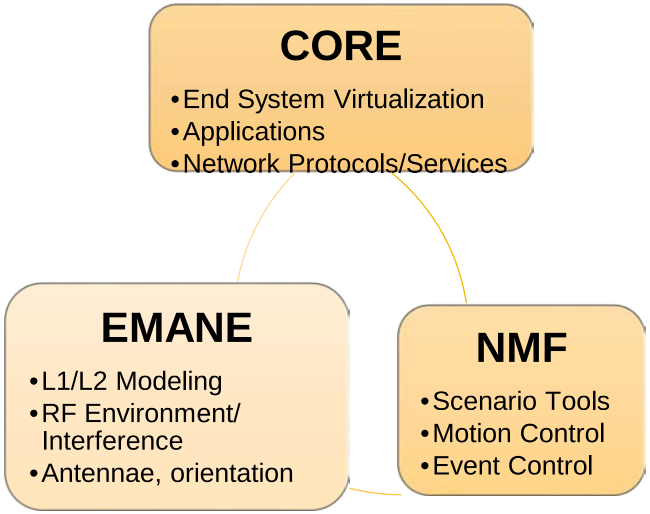
- Instantiates and orchestrates node virtualization
- Manages network and application services
- Provides real software stacks for app and network layers

NRL Network Modeling Framework (NMF):

- Construction and execution of complex scenarios
- Standard network description capability
- Mobility definition and control
- Supports event-based control and status to other processes
- Related toolsets (e.g., terrain modeling, externalities).

Extendable Mobile Ad-hoc Network Emulator (EMANE):

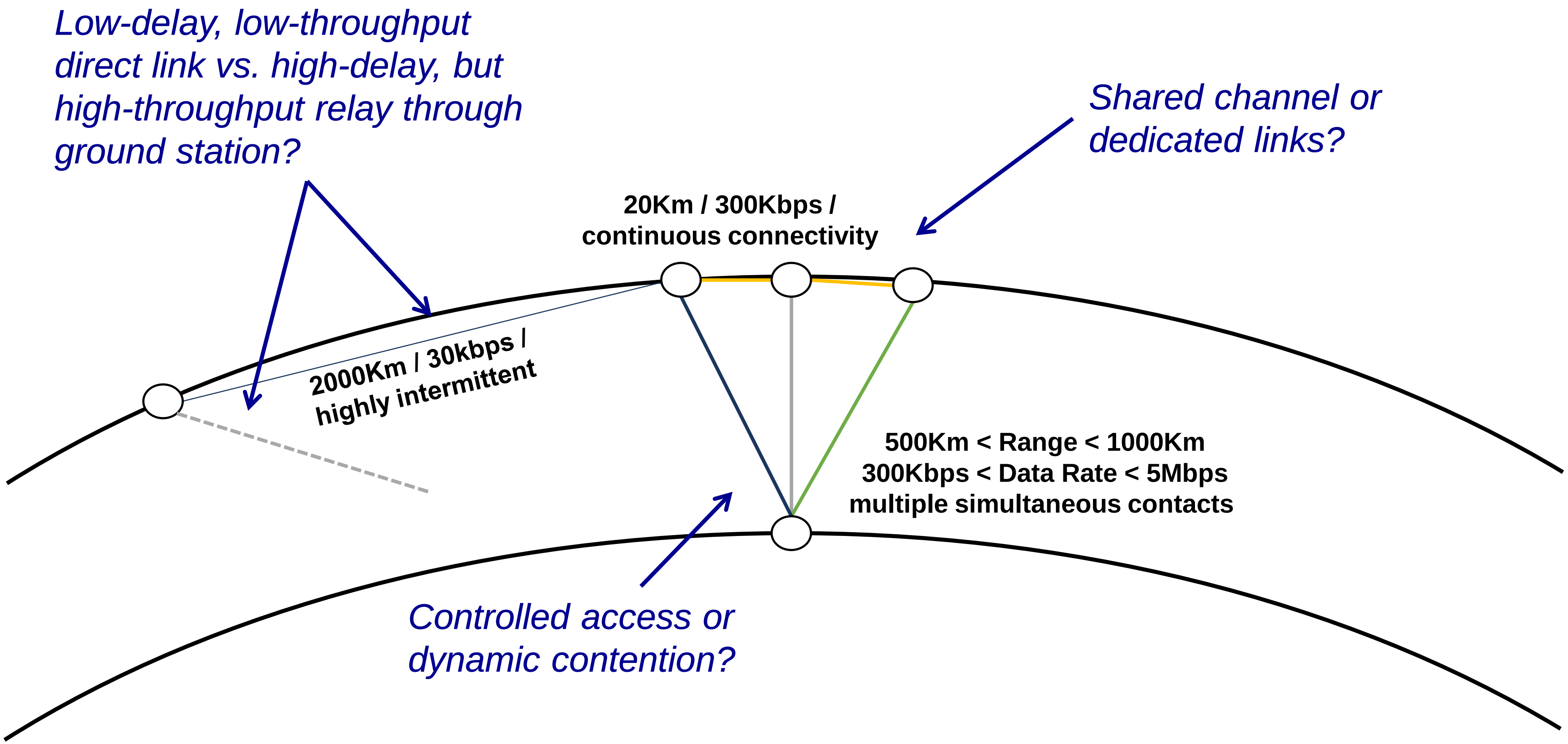
- Supports lower layer modeling MAC/PHY
- Canonical (CSMA, RFpipe) and actual DoD radio models
- Works with CORE and NMF in real-time via interface APIs and common module support developed



Can be used at multiple scales and fidelity:

- multi-core laptop
- high-end, multiple CPU systems
- distributed computing lab
- hybrid virtualization/real system testbeds (e.g., Android, UASes)
- Simplified RF models for scaling

Example Connectivity Tradeoffs



System modeling can help answer these and other questions.