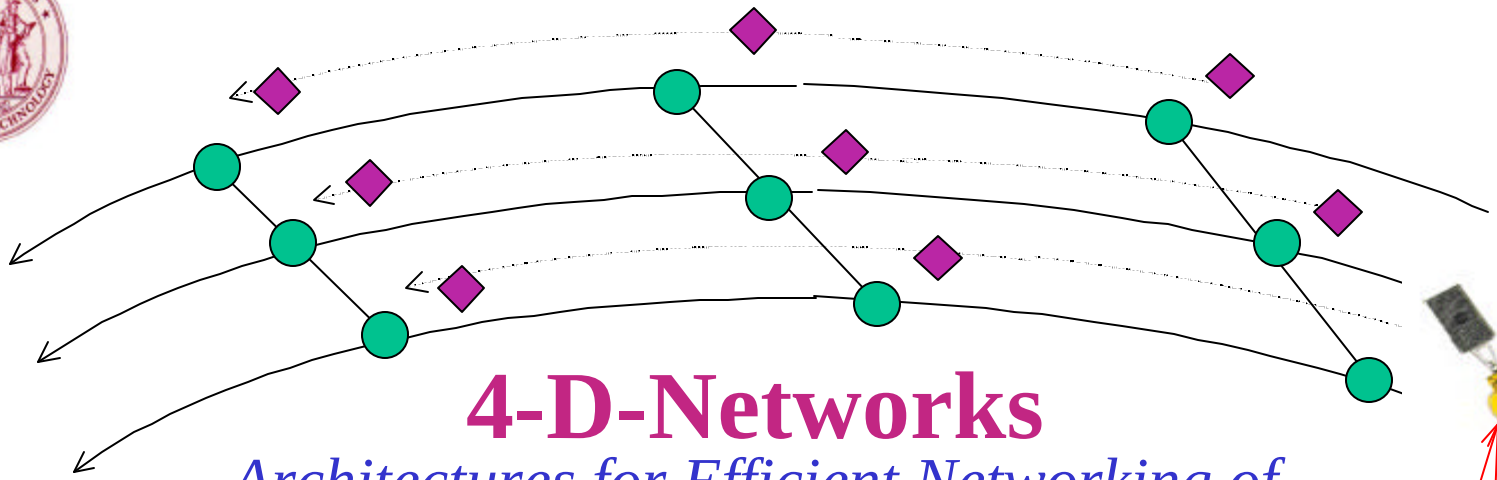


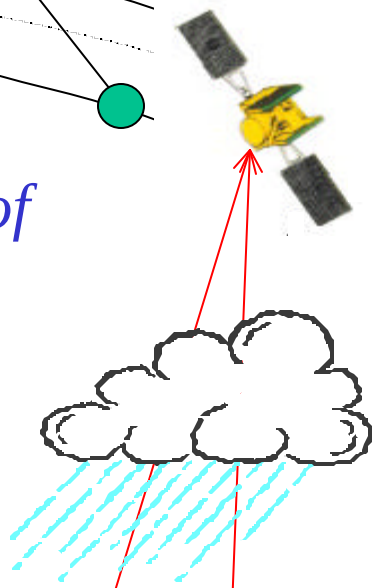
4-D-Networks

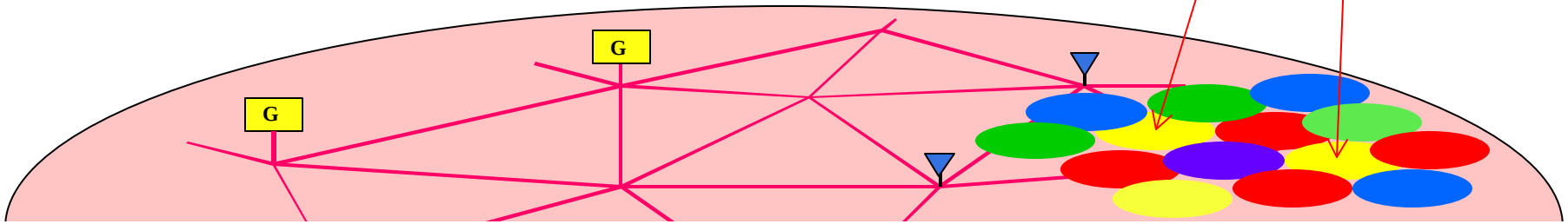
Architectures for Efficient Networking of Satellite and Terrestrial Networks

by

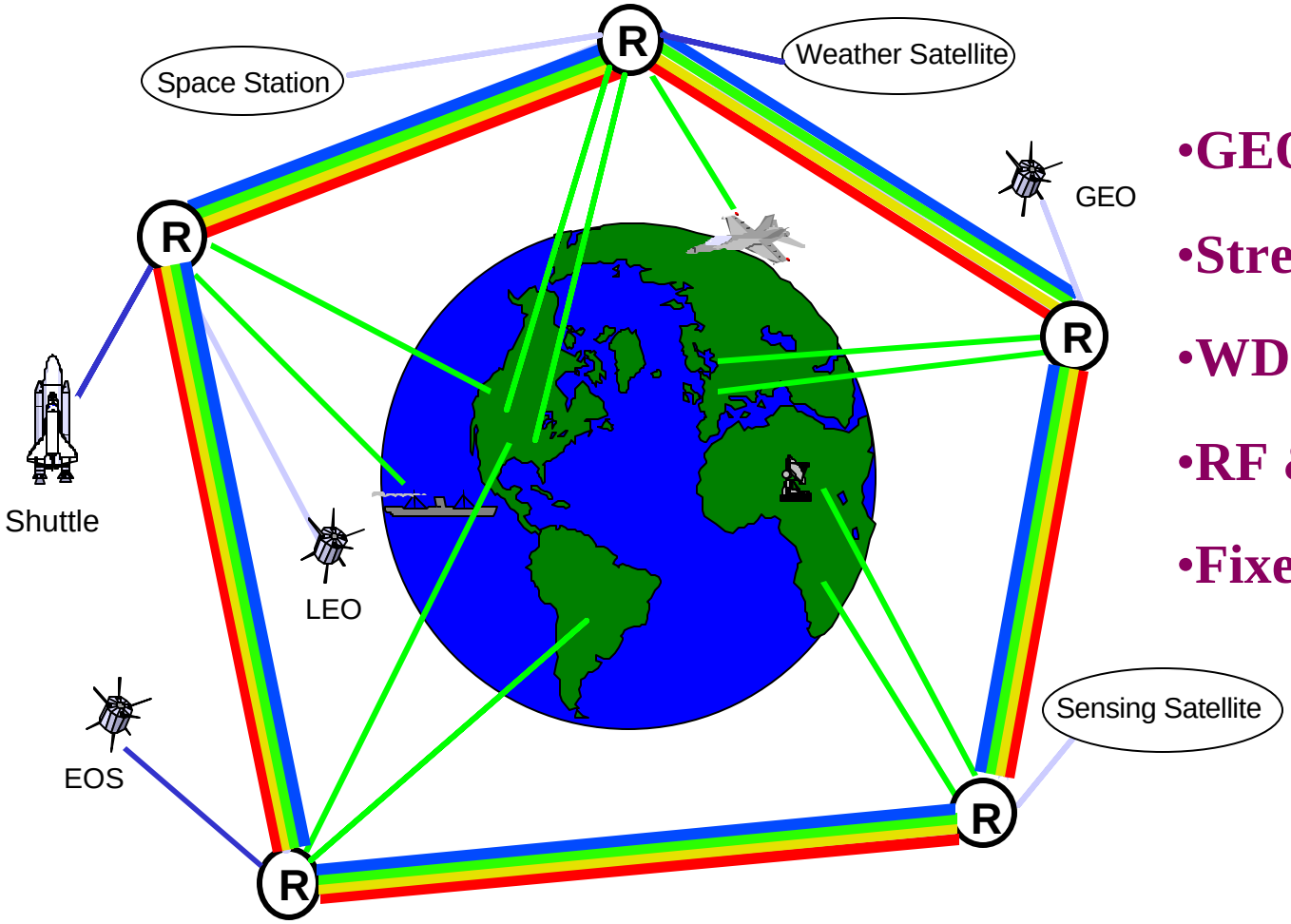
Vincent W. S. Chan

Department of Aeronautics & Astronautics
Department of Electrical Engineering & Computer Science
Laboratory for Information and Decision Systems (LIDS)
MIT





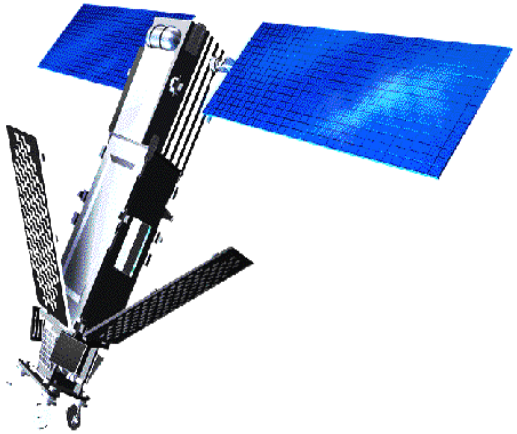
WDM Wide Area Network in Space

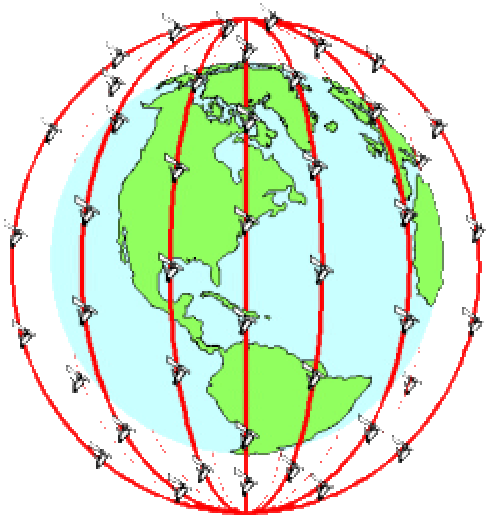


- GEO/MEO/LEO
- Streams & Packets
- WDM trunks
- RF & optical accesses
- Fixed/mobile users

Space Communication Networks

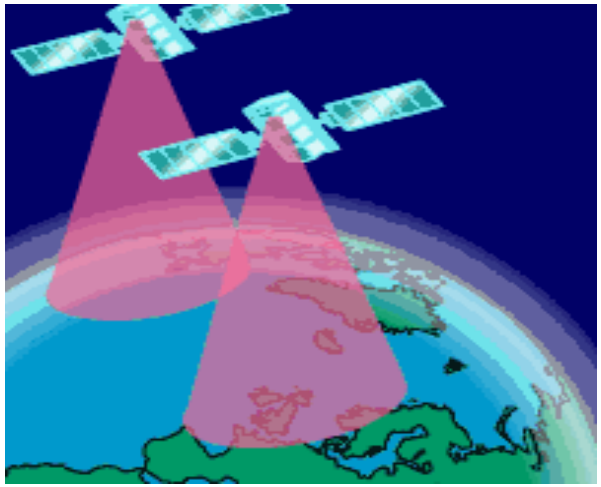
Iridium



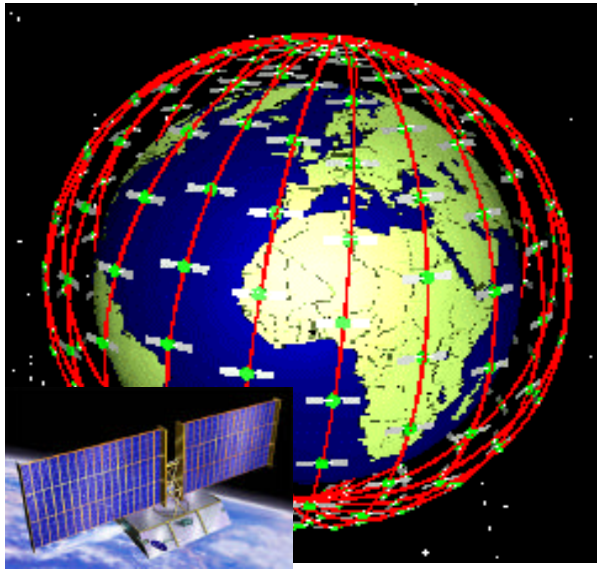


Globalstar

SkyBridge

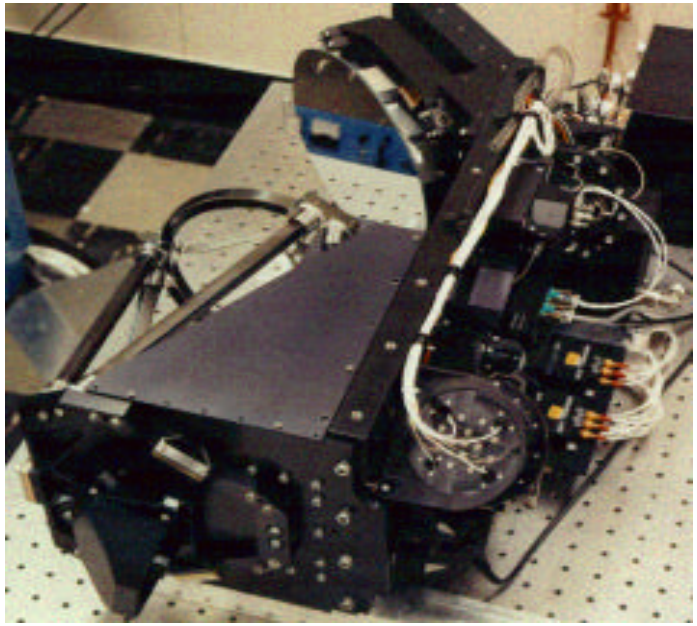


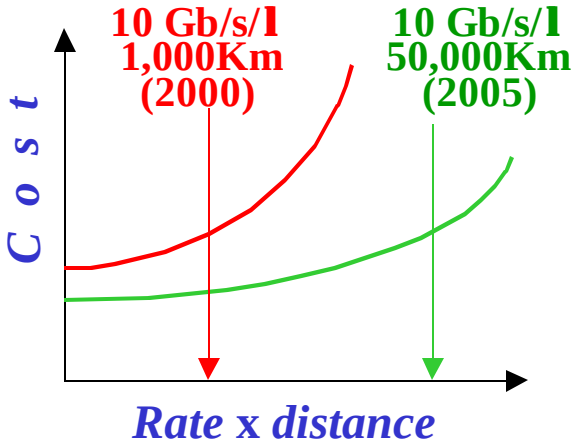
Teledesic

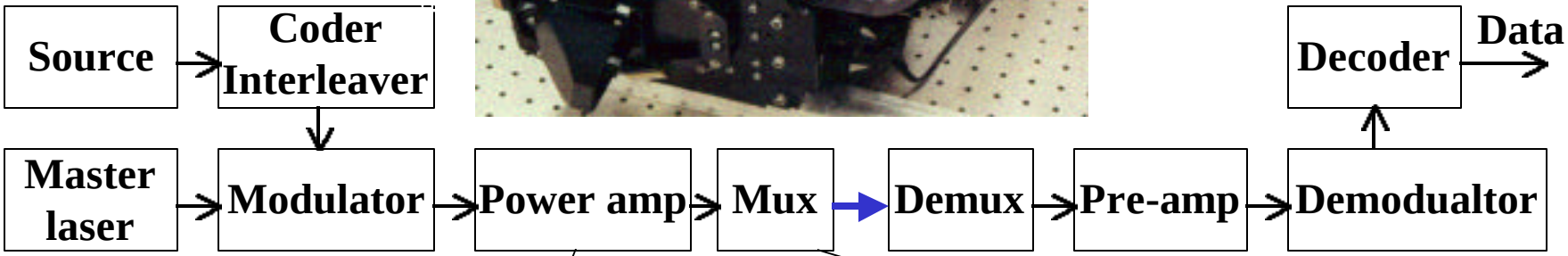


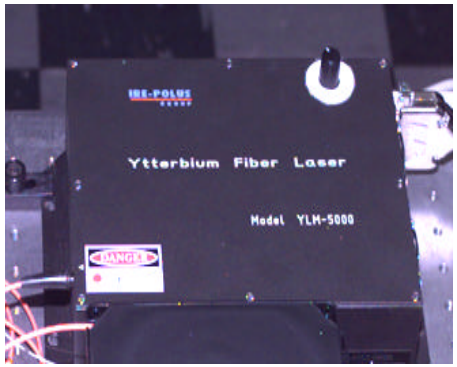
Optical Space Cross-Link

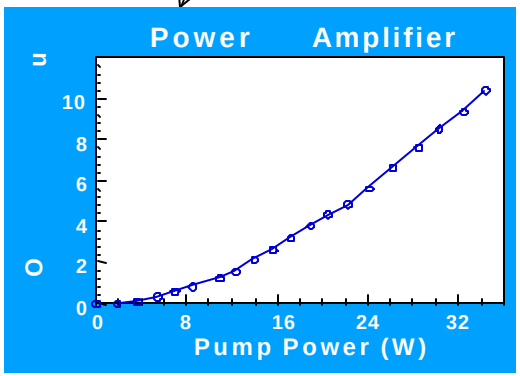
- Space backbone
- Digital or analog
- On-board demod
- Transponded
- E/O routed

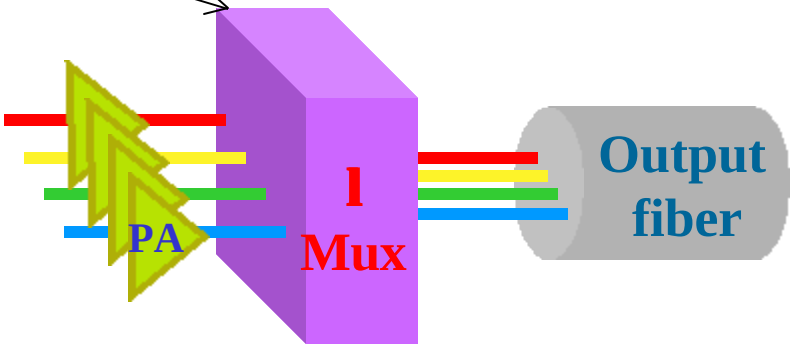




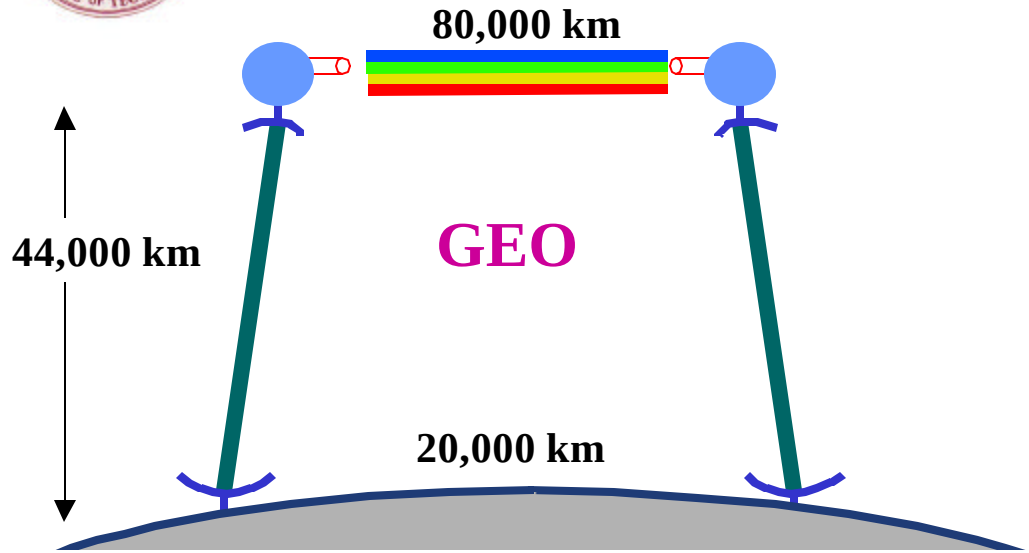


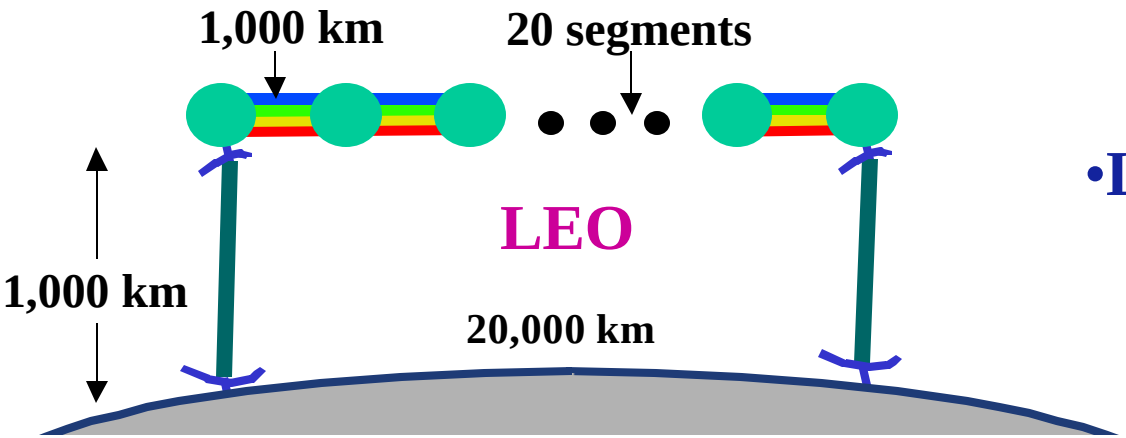






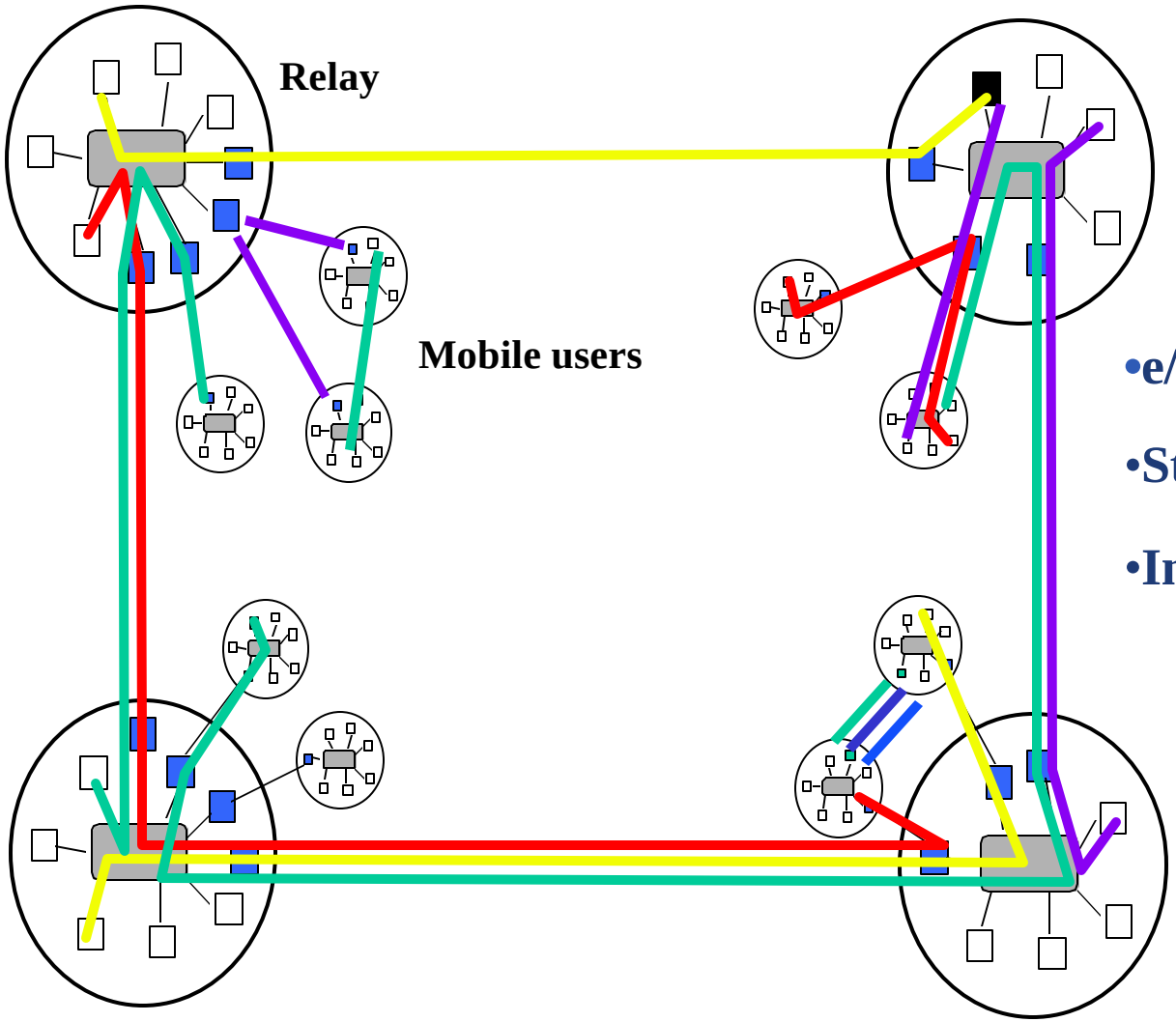
Business Case: 100 Gbps - 20,000 Km





- **Assumptions:**
  - *End-to-end duplex system*
  - *Includes bus, launch, O&M*
  - *Y2K$*
  - *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*

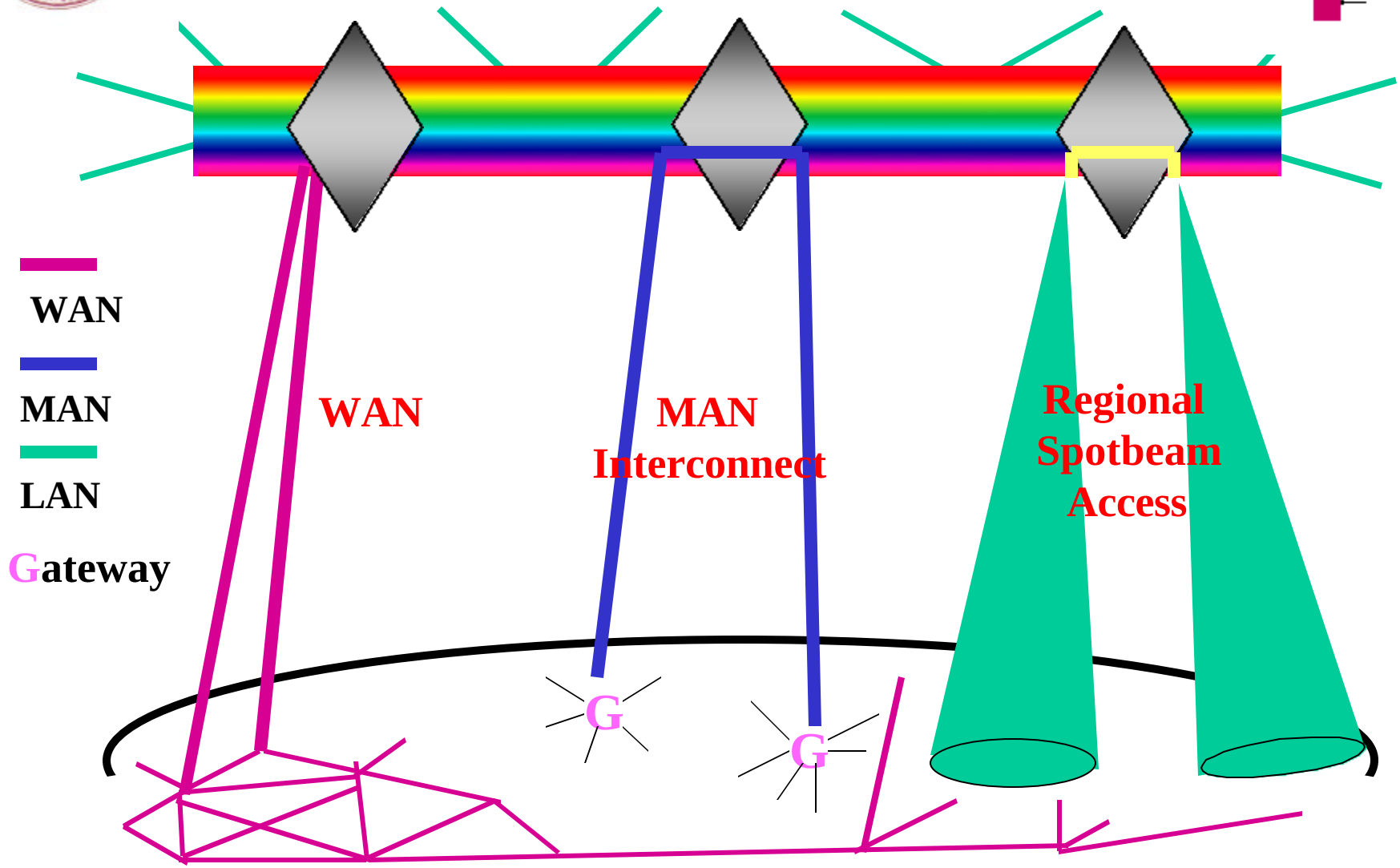
Node Concepts



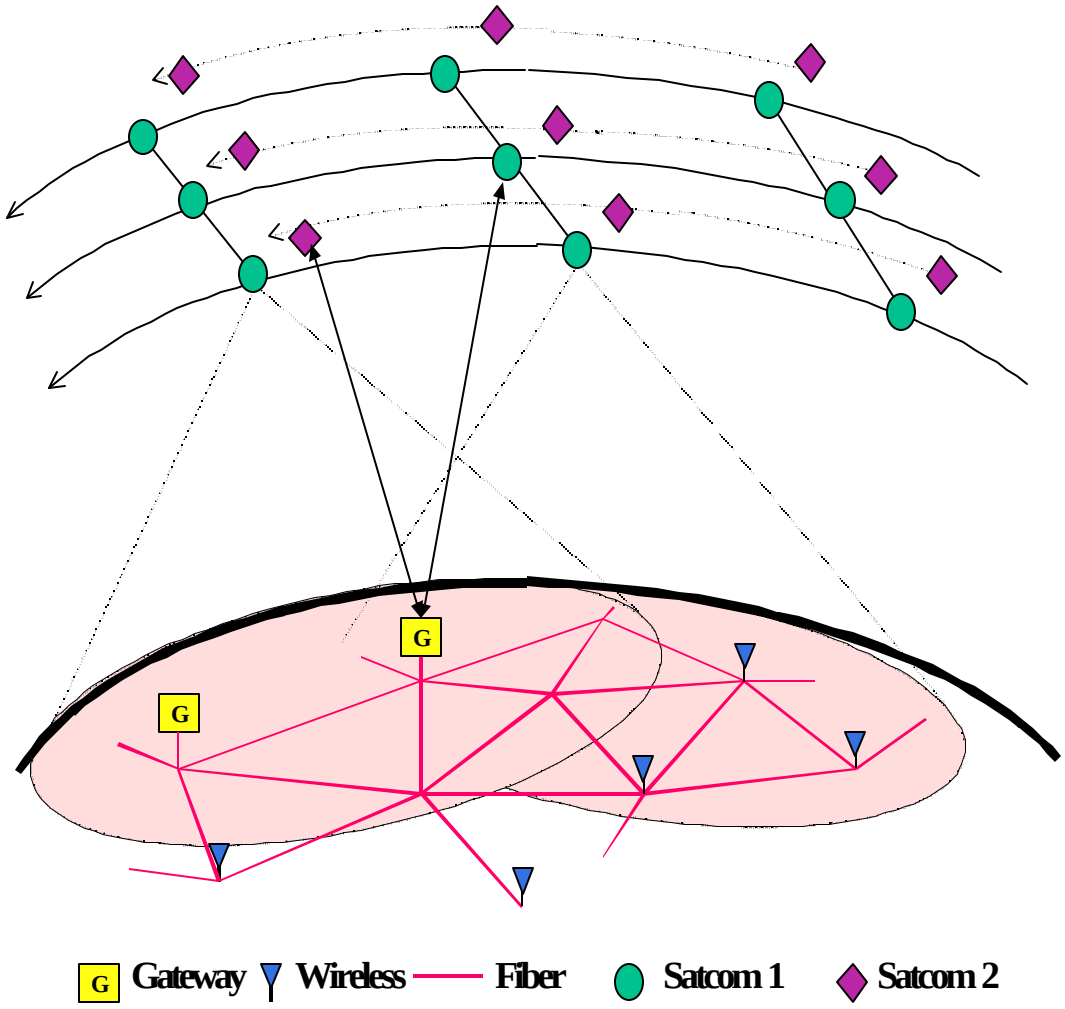
- e/o switching/routing
- Streams/packets
- Interconnect with RF

= S/C LAN

4-D Global Network



Future 4-D Network



- **Market**
  - *Long-haul*
  - *MAN/LAN interconnect*
  - *Mobile/portable users*
- **Technical Challenges**
  - *High-power/low-loss WDM*
  - *Efficient modulation/coding*
  - *High sensitivity receivers*
  - *Power efficient systems*
  - *Spacecraft LAN*
  - *BEM/coding RF links*
  - *Dynamic resource allocation*
  - *Internetworking protocols*

Dynamic 4 - D Network

Physical	DLC	Network	Transport	Appl

Mod/Demod Variable R

Media Access Control

FEC

ARQ

Router/Buffer

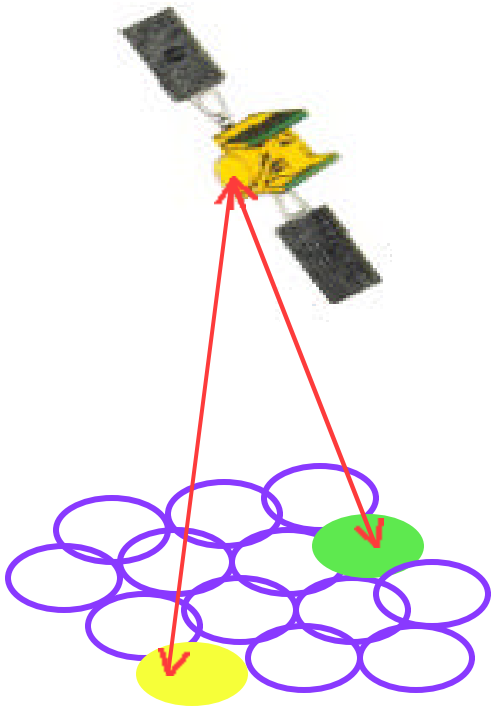
Net Management

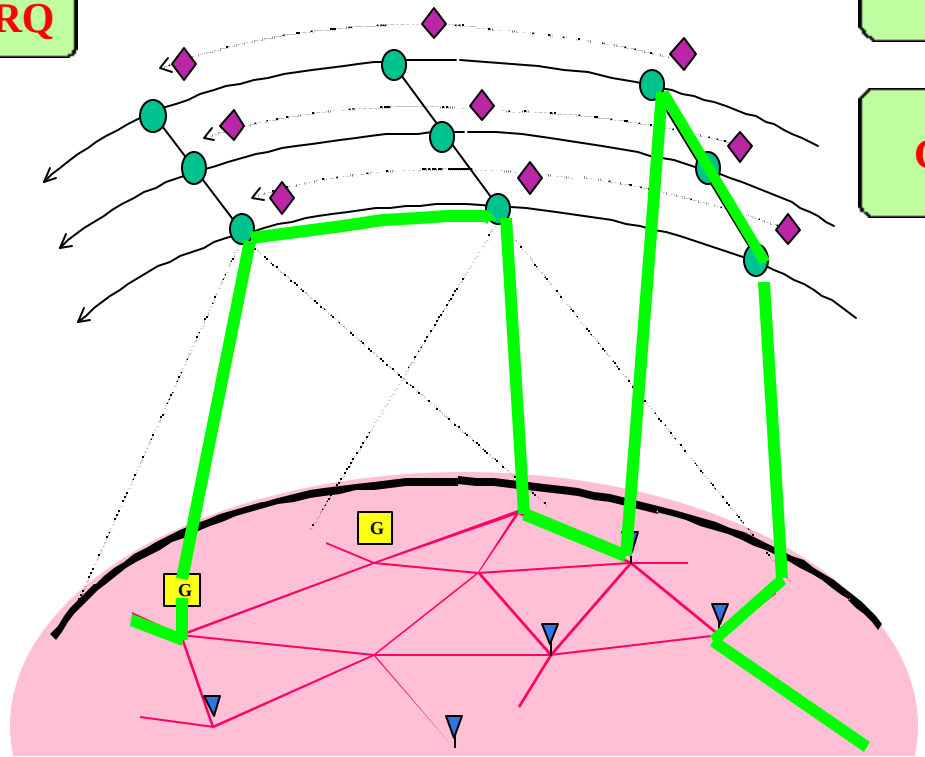
Congestion & Flow Control

Gateways

Convergence Layer

Agent-Mediator





- *Dynamic Capacity*
- *Agile beams*
- *MAC*

- ***Dynamic routing:*** *deterministic & stochastic*
- ***Heterogeneous network:*** *Satcom, fiber, wireless*
- ***Differentiated services:*** *cost-based, time-deadline, ...*

- ***Satellite resources extremely precious***

Dynamic 4 - D Network

Physical & Data Link Control Layers

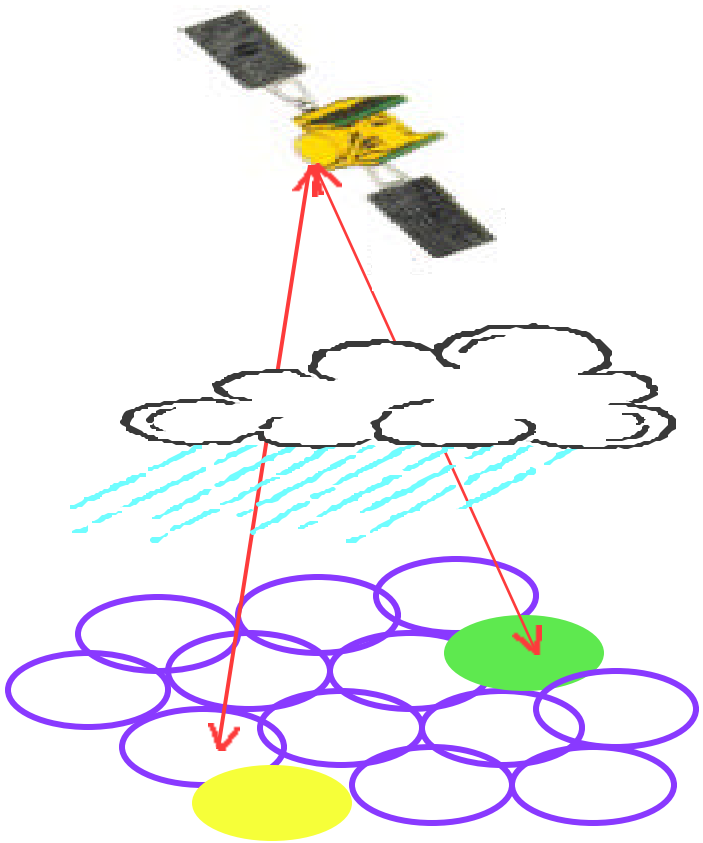
Physical	DLC	Network	Transport	Appl

Mod/Demod Variable R

Media Access Control

FEC

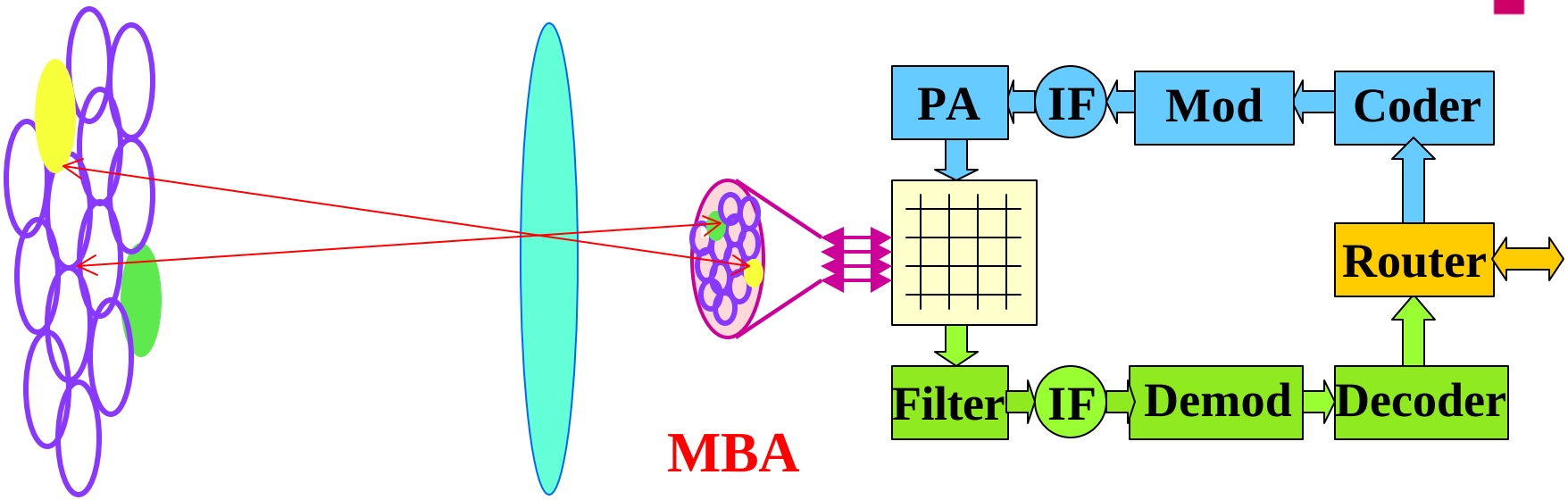
ARQ

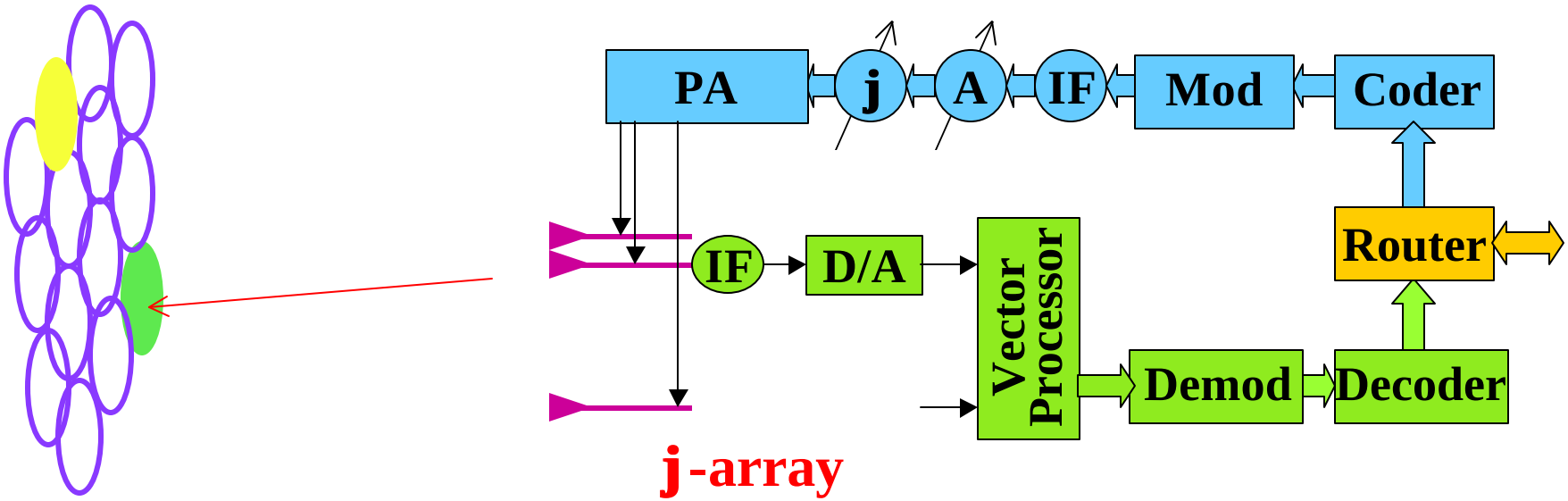


- **Weather induced variable capacity channel**
  - ***Channel measurements:***
    - *Direct/indirect power measurements*
    - *Via DLC BER*
    - *Via ARQ*
  - ***Adaptation:***
    - *Power management*
    - *Variable rate mod/demod*
    - *Variable rate coding*
    - *Cost advertisement*

- **Media access control of agile antenna beams**
  - ***MAC protocol for efficient access:***
    - *Random access*
    - *Reservation/scheduling*
    - *Differentiated services and pre-emption*
  - ***Beam pattern design for efficient:***
    - *Multicast*
    - *Power management*

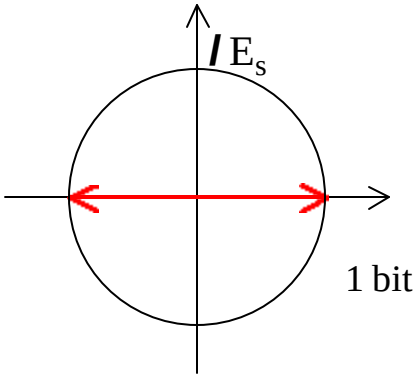
Multiple Beam (MBA) and Phase Array Antenna





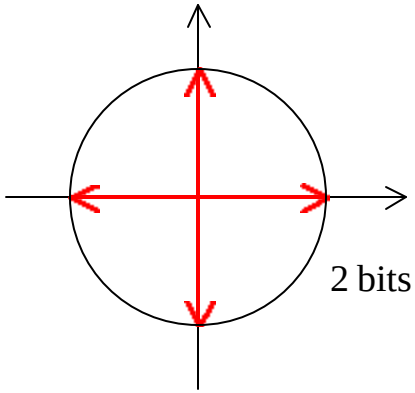
Variable Rate Modulation

BPSK



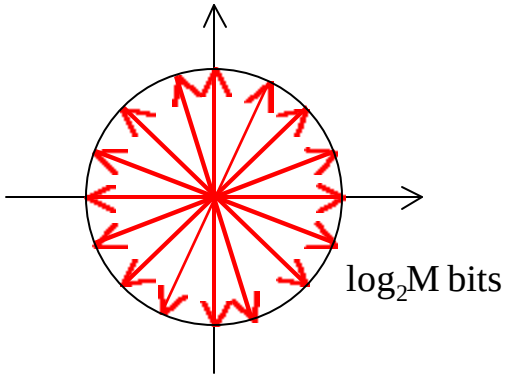
$P[\varepsilon] \sim \exp - \{E_s/N_0\}$

QPSK



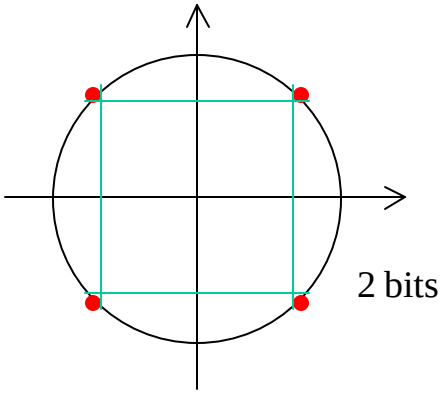
$P[\varepsilon] \sim \exp - \{E_s/2N_0\}$

M-PSK



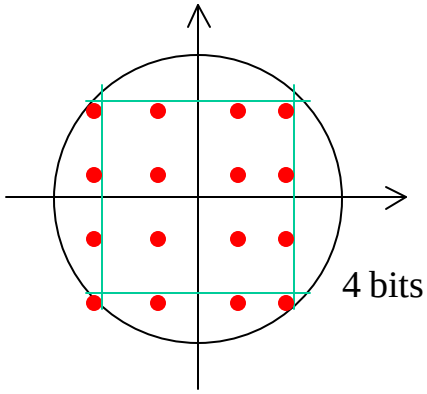
$P[\varepsilon] \sim \exp - \{(E_s/N_0)(\pi/M)^2\}$

4-QAM



$P[\varepsilon] \sim \exp - \{E_s/2N_0\}$

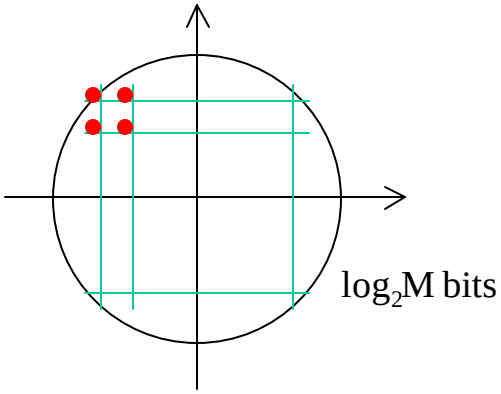
16-QAM



$P[\varepsilon] \sim \exp - \{E_s/18N_0\}$

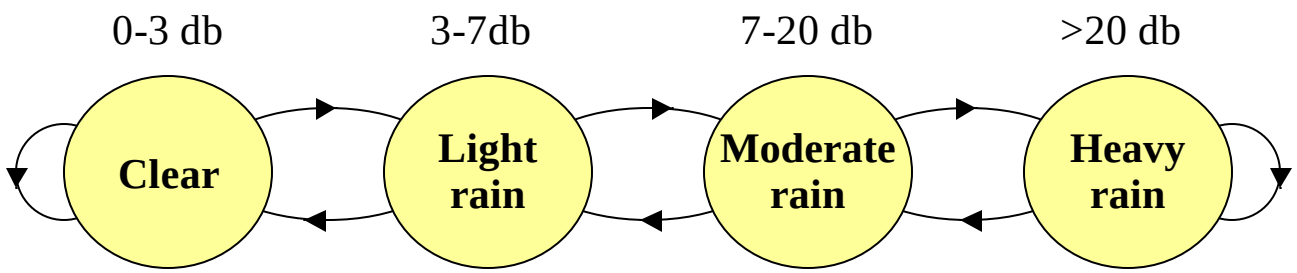
$E_s = 3E_{av}$

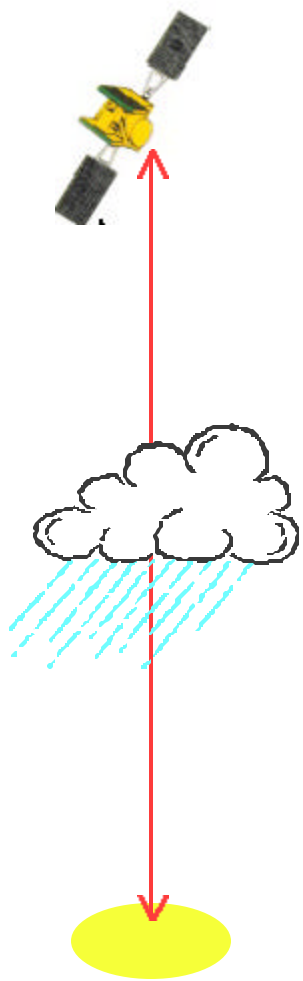
64/256/M…-QAM



$P[\varepsilon] \sim \exp - \{(E_s/N_0)/2M\}$

Atmospheric Model





- Scintillation: $f^{-2.3} \sim f^{-3.7}$, *corner frequency 0.1 Hz ~ 1 or 2pole model*
- Rain attenuation: f^{-2}, *corner frequency* $10^{-3}, 10^{-4}$ *Hz ~ 1 pole model*
- $u[k] = a.u[k-1] + b.u[k-2] + w[k]$
- Measurement via: *(1) power monitoring, (2)BER, (3) ARQ*

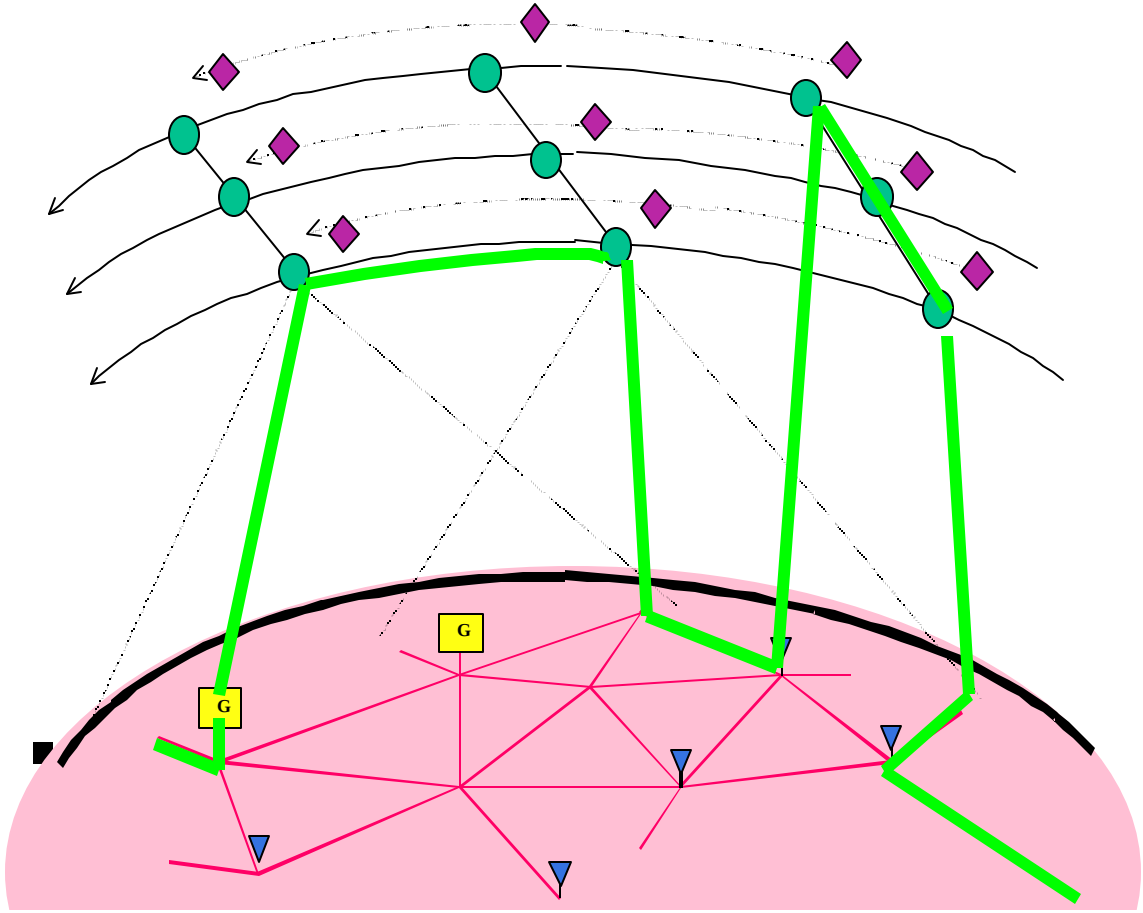
Dynamic 4 - D Network
Routing

Physical	DLC	**Network**	Transport	Appl

Router/Buffer | **Net Management**

- **Dynamic routing**
  - ***Deterministic***
    - *Satellite topology*
    - *Scheduled services*
  - ***Stochastic***
    - *Time-varying capacities*
    - *Unscheduled traffic*

- **Heterogeneous network**
  - ***Routing***
    - *Faster time scales*
    - *Multiple modalties*
    - *Internetworking*
    - *QoS dependent*
    - *Profit maximization*
  - ***Differentiated services***
    - *Cost-based*
    - *Time-deadline, jitter, ...*



Dynamic 4 - D Network

Congestion/Flow Control, Transport/Appl Layer

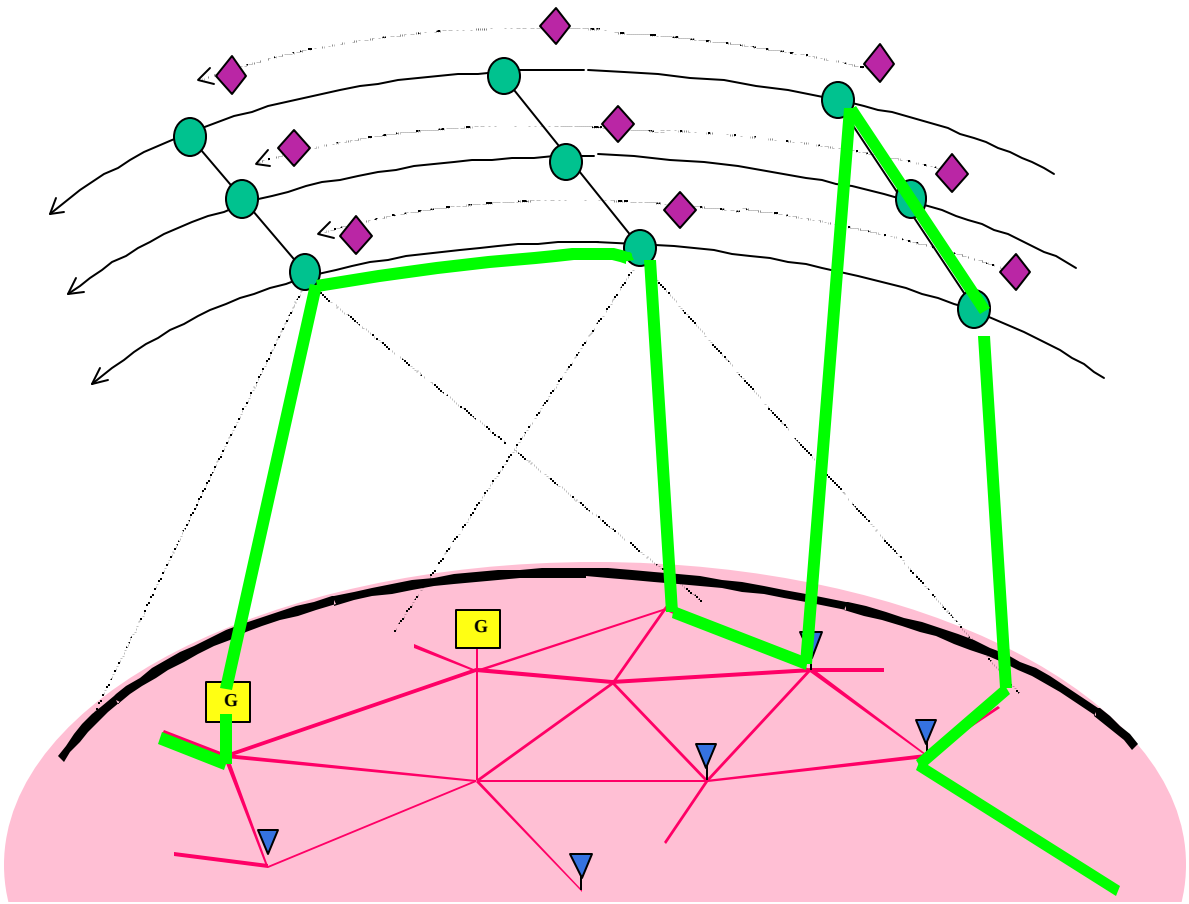
Physical	DLC	Network	Transport	Appl

Router/Buffer

Net Management

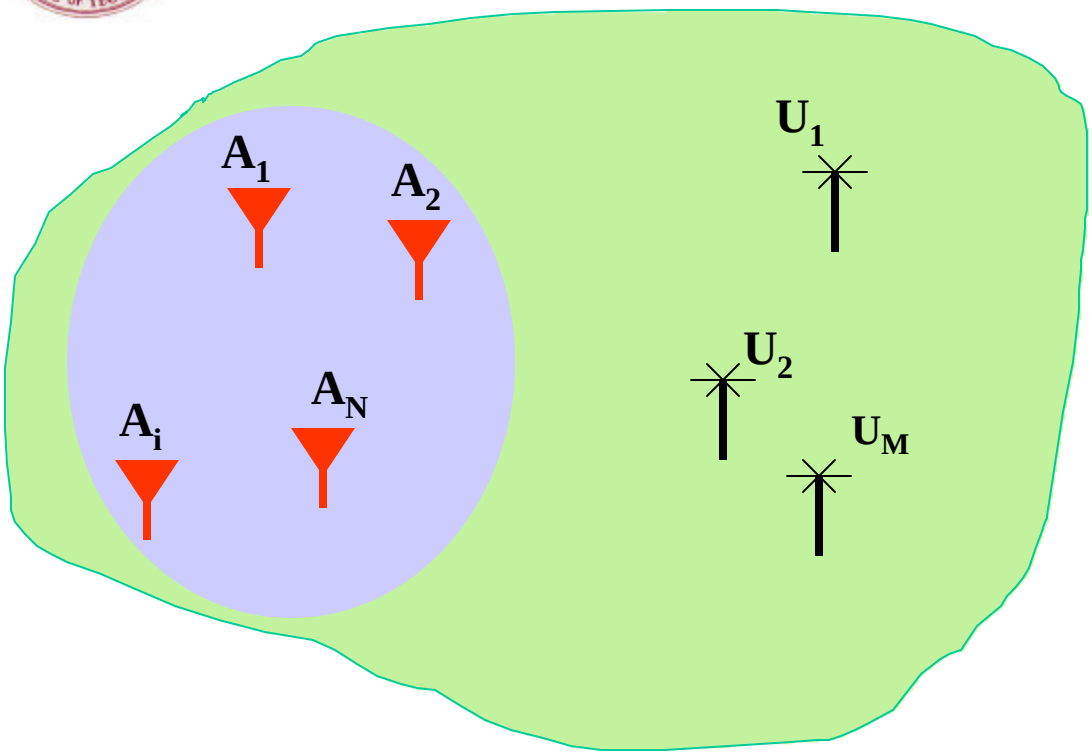
Congestion & Flow Control

Gateways



- **Convergence layer**
  - *QoS negotiation*
  - *Cost minimization*
- **End-to-end reliability/ Congestion/flow control**
  - *TCP modifications*
  - *Gateway/proxies*

Fundamental Limits of Radio Channels



f = *carrier frequency*

W = *available bandwidth*

P = *max power/user*

M = *# of users*

N= *# of antennas*

{x} = user locations

{y} = receiver locations

- Fading dispersive multi-path channel
- Multi-access/multi-user information theory
- Robust communications over unpredictable random channels
- Antenna and signal processing technology
- Multi-layer network design and optimization