4-D-Networks
Architectures for Efficient Networking of Satellite and Terrestrial Networks

by

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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

Source → Coder Interleaver → Master laser → Modulator → Power amp → Mux → Demux → Pre-amp → Demodulator → Decoder → Data

![Graph showing cost vs. rate x distance]

- 10 Gb/s/λ 1,000Km (2000)
- 10 Gb/s/λ 50,000Km (2005)

![Power Amplifier graph]

- Power Amplifier
- Pump Power (W)
- Output fiber
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

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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

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

- **Satellite resources** extremely precious

**Layers:**
- **Physical**
- **DLC**
- **Network**
- **Transport**
- **Appl**

**Components:**
- Mod/Demod
- Variable R
- Media Access Control
- FEC
- ARQ
- Router/Buffer
- Net Management
- Congestion & Flow Control
- Gateways

**Agent-Mediator**

**Convergence Layer**

- LIDS

**Key Points:**

- Satellite resources extremely precious

**Network Features:**

- Dynamic Capacity
- Agile beams
- MAC

**Routing:**

- Dynamic routing: deterministic & stochastic

**Network Types:**

- Heterogeneous network: Satcom, fiber, wireless

**Services:**

- Differentiated services: cost-based, time-deadline, ...
Dynamic 4 - D Network
Physical & Data Link Control Layers

- 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

MBA

φ-array

PA

IF

Mod

Coder

Router

Filter

IF

Demod

Decoder

Vector Processor

Demod

Decoder
Variable Rate Modulation

BPSK

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

QPSK

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

M-PSK

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

4-QAM

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

16-QAM

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

$E_s = 3E_{av}$

64/256/M…-QAM

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

$\log_2 M$ bits
Atmospheric Model

0-3 db → Light rain → Moderate rain → Heavy rain

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

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

- Heterogeneous network
  - Routing
    - Faster time scales
    - Multiple modalities
    - Internetworking
    - QoS dependent
    - Profit maximization

- Differentiated services
  - Cost-based
  - Time-deadline, jitter, ...
Dynamic 4 - D Network
Congestion/Flow Control, Transport/Applic Layer

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

\( f = \) carrier frequency
\( W = \) available bandwidth
\( P = \text{max power/user} \)
\( M = \# \text{ of users} \)
\( N = \# \text{ of antennas} \)
\( \{x\} = \text{user locations} \)
\( \{y\} = \text{receiver locations} \)