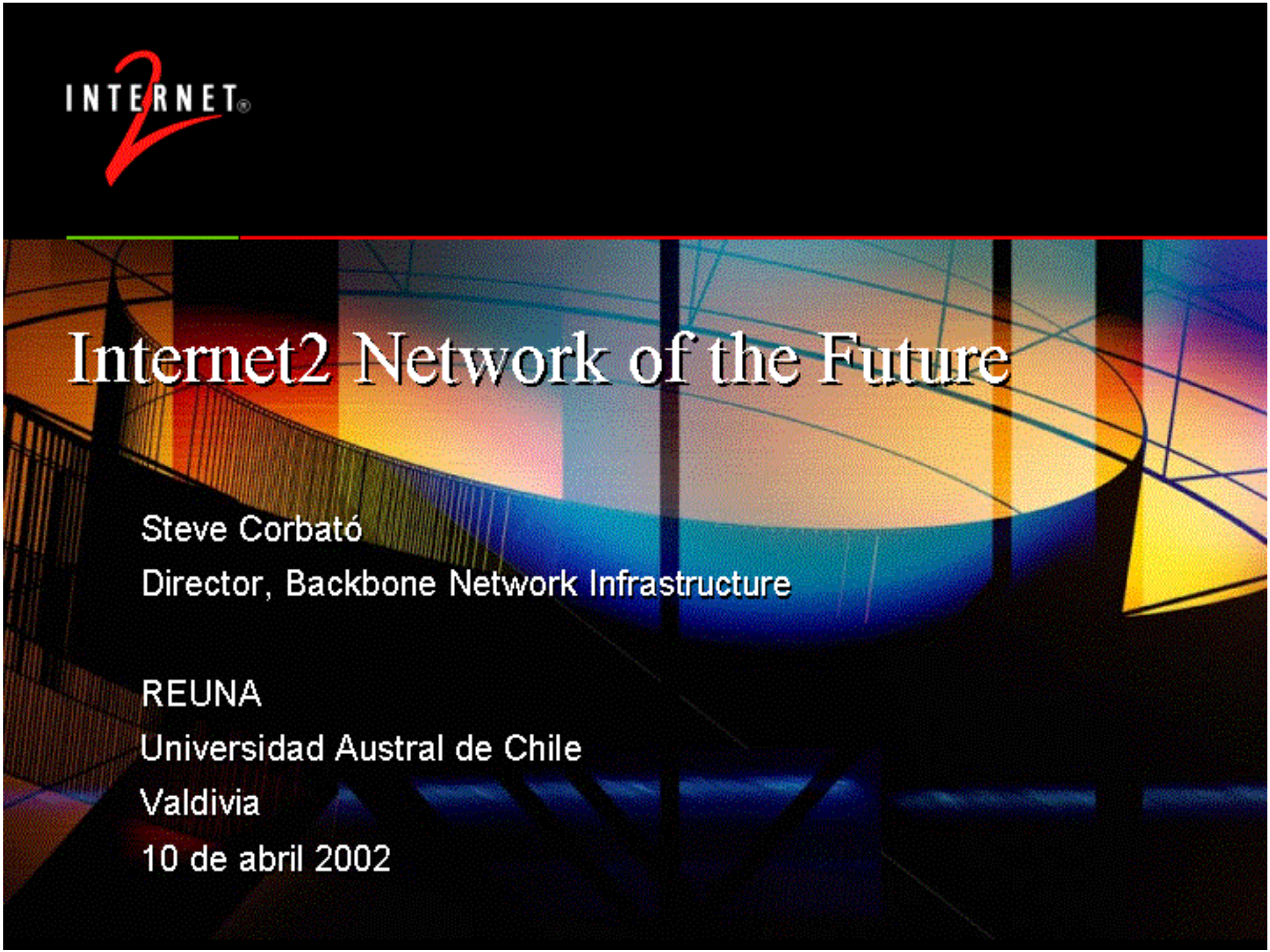

INTERNET2
Internet2 Network of the Future
Steve Corbató
Director, Backbone Network Infrastructure
REUNA
Universidad Austral de Chile
Valdivia
10 de abril 2002

Why Internet2?

The U.S. R&E network – NSFNet – was decommissioned by 1995

Commercial focus shifted to scale the Internet to the general populace

Advanced requirements of U.S. higher education – research, education, and medicine – were not being being prioritized

The U.S. research universities (35 at the start) created Internet2 to insure a collective effort to maintain and to develop advanced Internet capabilities

This presentation

- Abilene Network today
- Emergence and evolution of optical networking
- Next phase of Abilene

Networking hierarchy

Internet2 networking is a fundamentally hierarchical and collaborative activity

- International networking
  - Ad hoc → Global Terabit Research Network (GTRN)
- National backbones
- Regional networks
  - GigaPoPs → advanced regional networks
- Campus networks

Much activity now at the metropolitan and regional scales

Abilene focus

Goals

- Enabling innovative applications and advanced services not possible over the commercial Internet
- Backbone & regional infrastructure provides a vital substrate for the continuing culture of Internet advancement in the university/corporate research sector

Advanced service efforts

- Multicast
- IPv6
- QoS
- Measurement
  - an open, collaborative approach
- Security

Abilene background & milestones

Abilene is a UCAID project in partnership with

- Qwest Communications (SONET & DWDM service)
- Nortel Networks (SONET kit)
- Cisco Systems (routers)
- Indiana University (network operations)
- ITECs in North Carolina and Ohio (test and evaluation)

Timeline

- Apr 1998: Project announced at White House
- Jan 1999: Production status for network
- Oct 1999: IP version of HDTV (215 Mbps) over Abilene
- Apr 2001: First state education network added
- Jun 2001: Participation reaches all 50 states & D.C.
- Nov 2001: Raw HDTV/IP (1.5 Gbps) over Abilene

Abilene – April, 2002

IP-over-SONET backbone (OC-48c, 2.5 Gbps)

53 direct connections (MREN, NCSA in IL)

- 4 OC-48c connections
- *1 Gigabit Ethernet trial*
- 23 will connect via at least OC-12c (622 Mbps) by 1Q02
- Number of ATM connections *decreasing*

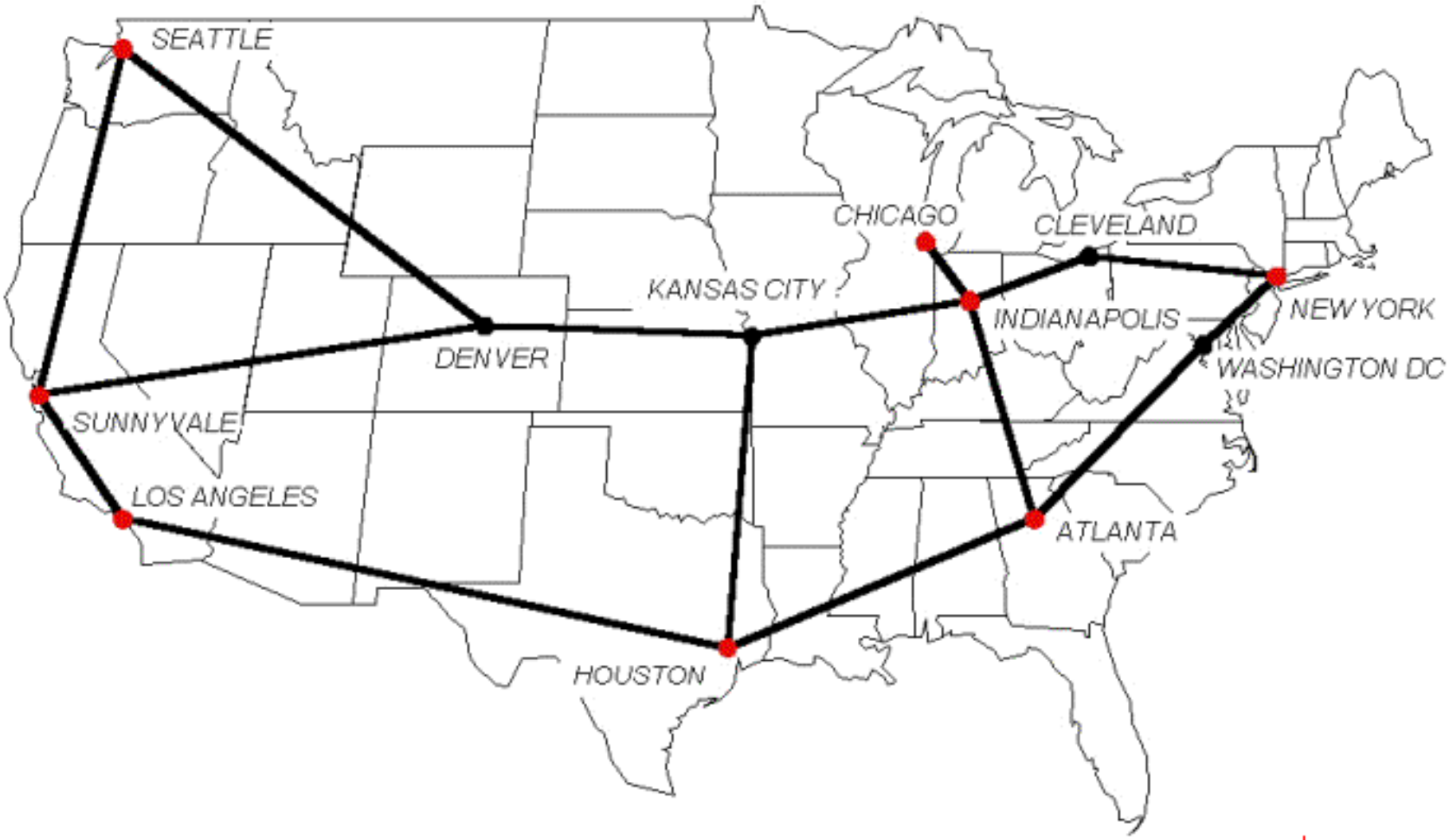
211 participants – research universities & labs

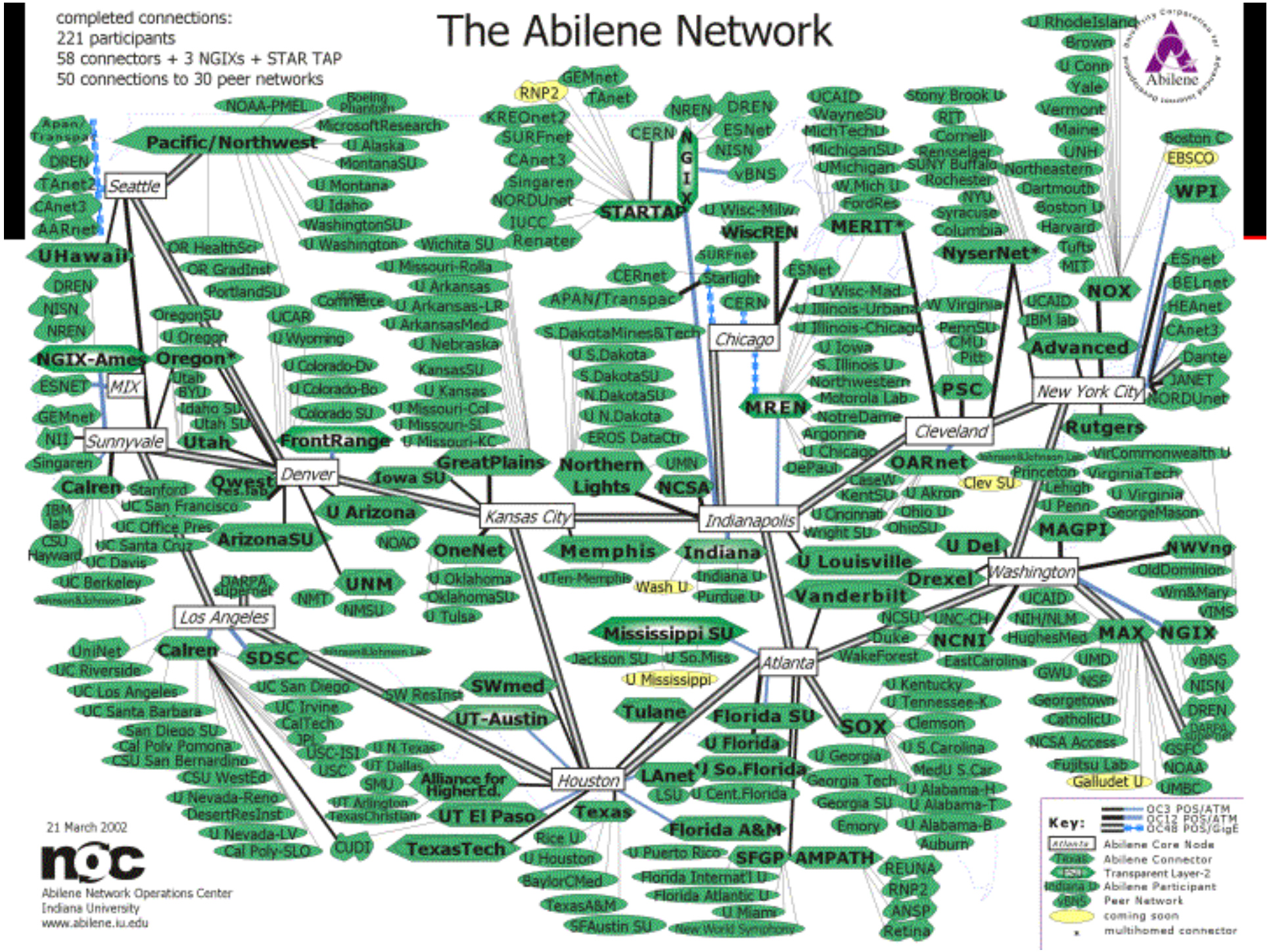
- All 50 states, District of Columbia, & Puerto Rico
- 15 regional GigaPoPs support ~70% of participants

Expanded access

- 46 sponsored participants
- *21 state education networks (SEGPs)*

ABILENE NETWORK - OCTOBER, 2001




The Abilene Network
completed connections:
221 participants
58 connectors + 3 NGIXs + STAR TAP
50 connections to 30 peer networks
Abilene
Pacific/Northwest
Seattle
Sunnyvale
Denver
Kansas City
Chicago
Indianapolis
New York City
Cleveland
Washington
Atlanta
Houston
Los Angeles
STARTAP
NGIX-Ames
MIX
Oregon*
Utah
FrontRange
GreatPlains
Northern Lights
Iowa SU
NCSA
OneNet
Memphis
Indiana
U Louisville
Drexel
Vanderbilt
MERIT*
MREN
WiscREN
NyserNet*
PSC
OARNet
Advanced
NOX
MAGPI
U Del
Rutgers
NWVng
MAX
NGIX
NCNI
SOX
Florida SU
U Florida
U So.Florida
LAnet
Florida A&M
SFGP
AMPATH
Texas
Tulane
UT-Austin
UT El Paso
TexasTech
Alliance for HigherEd.
SDSC
Calren
ArizonaSU
U Arizona
UNM
Qwest
SWmed
Mississippi SU
U Mississippi
Jackson SU
U So.Miss
Wash U
Purdue U
Indiana U
U Ten-Memphis
OklahomaSU
U Oklahoma
U Tulsa
NOAO
NMSU
NMT
DARPA supernet
Stanford
UC San Francisco
UC Office Pres
UC Santa Cruz
UC Davis
UC Berkeley
CSU Hayward
IBM lab
UniNet
UC Riverside
UC Los Angeles
UC Santa Barbara
San Diego SU
Cal Poly Pomona
CSU San Bernardino
CSU WestEd
U Nevada-Reno
DesertResInst
U Nevada-LV
Cal Poly-SLO
CUDI
UC San Diego
UC Irvine
CalTech
JPL
USC-ISI
USC
SW ResInst
U N.Texas
UT Dallas
SMU
UT Arlington
TexasChristian
Rice U
U Houston
BaylorCMed
TexasA&M
SFAustin SU
U Puerto Rico
Florida Internat'l U
Florida Atlantic U
U Miami
New World Symphony
Clemson
U S.Carolina
MedU S.Car
U Alabama-H
U Alabama-T
U Alabama-B
Auburn
Emory
Georgia Tech
Georgia SU
U Georgia
U Kentucky
U Tennessee-K
U Cent.Florida
LSU
REUNA
RNP2
ANSP
Retina
Duke
WakeForest
NCSU
UNC-CH
EastCarolina
NIH/NLM
HughesMed
UCAID
GWU
NSF
UMD
Georgetown
CatholicU
NCSA Access
Fujitsu Lab
Galludet U
GSFC
NOAA
UMBC
vBNS
NISN
DREN
DARPA support
Princeton
Lehigh
U Penn
Clev SU
CaseW
KentSU
U Akron
Ohio U
OhioSU
U Cincinnati
Wright SU
U Chicago
Argonne
NotreDame
Motorola Lab
DePaul
Johnson&Johnson Lab
VirCommonwealth U
VirginiaTech
U Virginia
GeorgeMason
OldDominion
Wm&Mary
VIMS
U Wisc-Milw
U Wisc-Mad
U Illinois-Urbana
U Illinois-Chicago
U Iowa
S. Illinois U
Northwestern
W.Mich U
FordRes
MichTechU
MichiganSU
UMichigan
WayneSU
UCAID
Stony Brook U
RIT
Cornell
Rensselaer
SUNY Buffalo
Rochester
NYU
Syracuse
Columbia
W Virginia
PennSU
CMU
Pitt
IBM lab
Northeastern
Dartmouth
Boston U
Harvard
Tufts
MIT
U Rhode Island
Brown
U Conn
Yale
Vermont
Maine
UNH
Boston C
EBSCO
WPI
ESnet
BELnet
HEAnet
CAnet3
Dante
JANET
NORDUnet
U Wyoming
U Colorado-Dv
U Colorado-Bo
Colorado SU
KansasSU
U Kansas
U Missouri-Col
U Missouri-St
U Missouri-KC
U Nebraska
U ArkansasMed
U Arkansas-LR
U Arkansas
U Missouri-Rolla
Wichita SU
U Montana
U Idaho
WashingtonSU
U Washington
MontanaSU
U Alaska
MicrosoftResearch
Boeing Phantom
NOAA-PMEL
OR HealthSci
OR GradInst
PortlandSU
OregonSU
U Oregon
Utah
BYU
Idaho SU
Utah SU
Commerce
S.DakotaMines&Tech
U S.Dakota
S.DakotaSU
N.DakotaSU
U N.Dakota
EROS DataCtr
UMN
Qwest res.lab
Johnson&Johnson Lab
Aban/Transpac
DREN
TAnet2
CAnet3
AARnet
UHawaii
NISN
NREN
ESNET
GEMnet
NII
Singaren
RNP2
GEMnet
TAnet
KREOnet2
SURFnet
CAnet3
Singaren
NORDUnet
IUCC
Renater
CERN
NREN
DREN
ESNet
NISN
vBNS
SURFnet
Starlight
CERN
CERNet
APAN/Transpac
ESNet
21 March 2002
noc
Abilene Network Operations Center
Indiana University
www.abilene.iu.edu
Key:
OC3 POS/ATM
OC12 POS/ATM
OC48 POS/GigE
Abilene Core Node
Abilene Connector
Transparent Layer-2
Abilene Participant
Peer Network
coming soon
multihomed connector

Abilene international connectivity

Transoceanic R&E bandwidths growing!

- GÉANT – 5 Gbps between Europe and New York City

Key international exchange points facilitated by Internet2 membership and the U.S. scientific community

- STARTAP & STAR LIGHT – Chicago (GigE)
- AMPATH – Miami (OC-3c → OC-12c)
- Pacific Wave – Seattle (GigE)
- MAN LAN - New York City – GigE/10GigE EP soon
- CA*NET3: Seattle, Chicago, and New York
- CUDI: CENIC and Univ. of Texas at El Paso

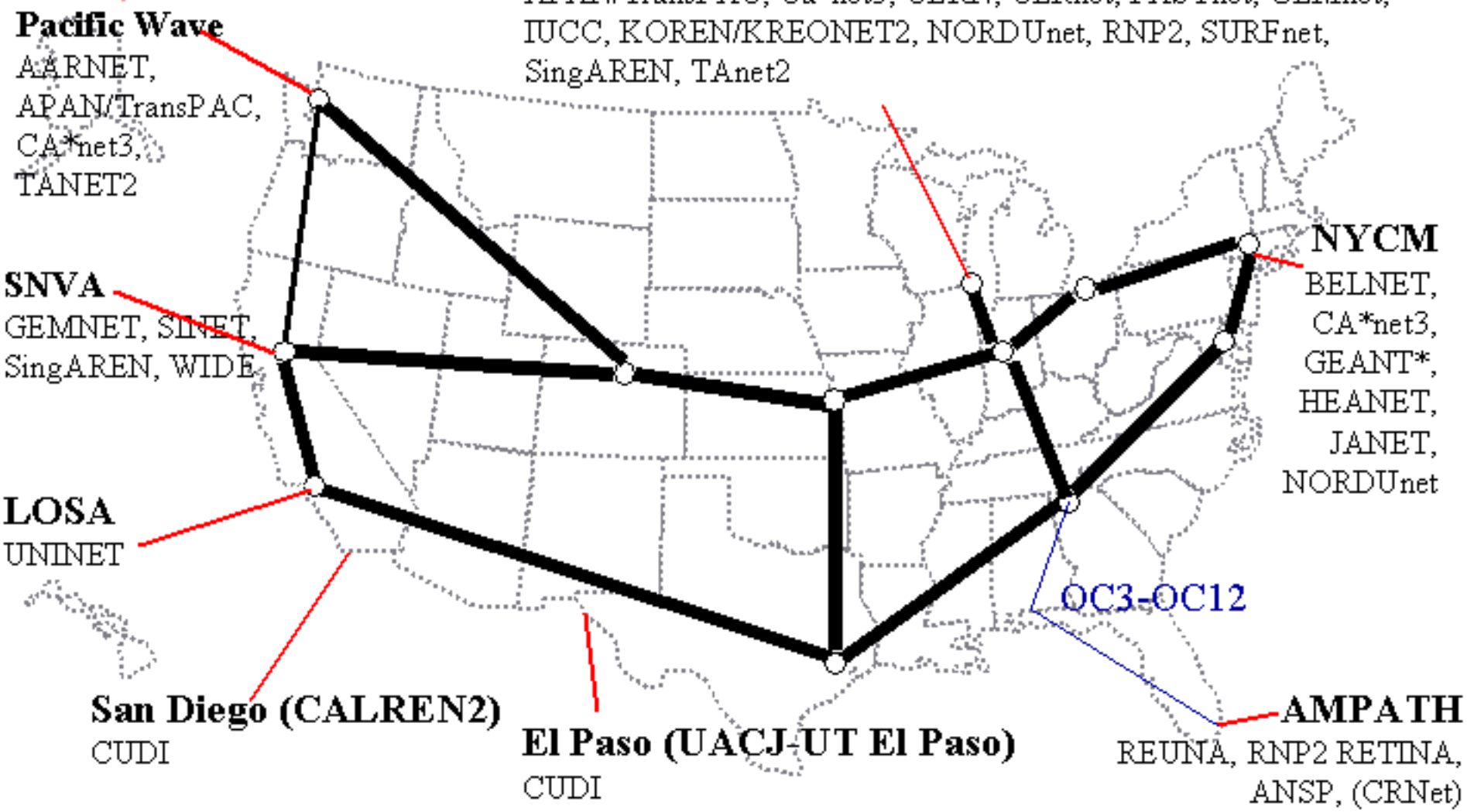
International transit service

- Collaboration with CA*NET3 and STARTAP

09 March 2002

INTERNET2

Abilene International Peering



* ARNES, CARNET, CESnet, DFN, GRNET, RENATER, RESTENA, SWITCH, HUNGARNET, GARR-B, POL-34, RCST, RedIRIS

Abilene cost recovery model

Connection (per connection)	**Annual fee**
OC-3 (155 Mbps)	$110,000
OC-12 (622 Mbps)	$270,000
Gigabit Ethernet (1 Gbps)	$325,000
OC-48 (2.5 Gbps)	$430,000
Participation (per university)	$20,000

Raw HDTV/IP testing

Packetized raw High Definition Television (HDTV) - 1.5 Gbps

- ISIe, Tektronix, & UW project/DARPA support

Connectivity and testing support

- P/NW & MAX Gigapops, Abilene and DARPA Supernet, Level(3)

SC2001 public demo

- November, 2001
- SEA -> DEN via Level(3) OC-48c SONET circuit

Implications for support of high performance flows over Abilene

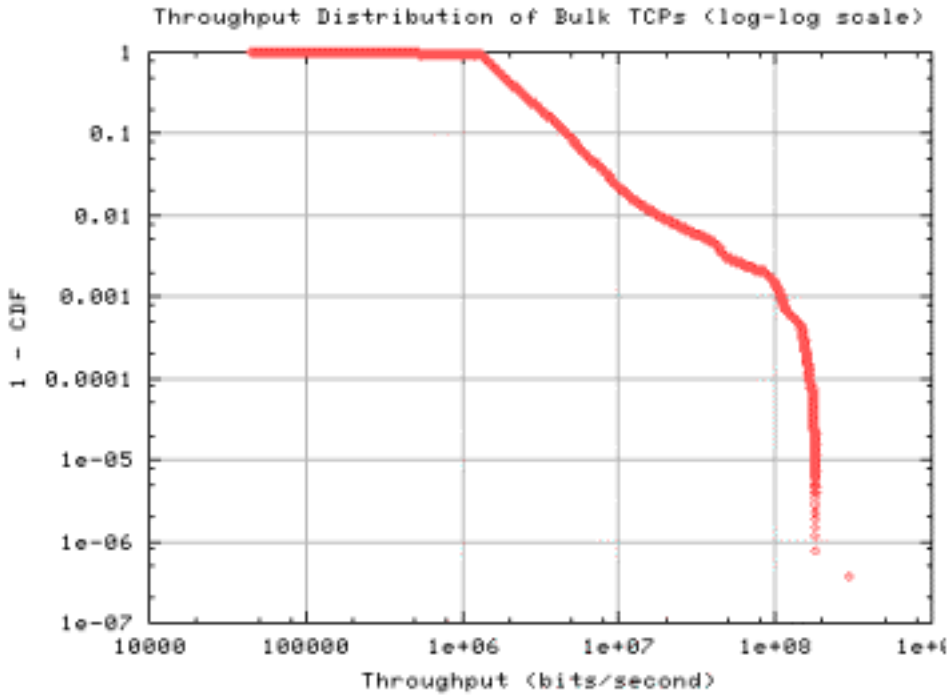
DARPA PIs Meeting: Seattle to Washington DC
1/6/02

- Abilene, P/NW & MAX GigaPoPs in Internet2 path
- 18 hrs of continuous, single-stream raw HD/IP
- UDP jumbo frames: 4444 B packet size
- Application level measurement
  - **3 billion packets transmitted**
  - **0 packets lost**, 15 resequencing episodes
- e2e network performance
  - **Loss: <8x10 $^{-10}$ (90% confidence level)**
  - **Reordering: 5x10 $^{-9}$**
- *Transcontinental* 1-Gbps TCP (std 1.5 kB MTU) requires loss at the level of **3x10 $^{-8}$ or lower**

End-to-End Performance: 'High bandwidth is not enough'

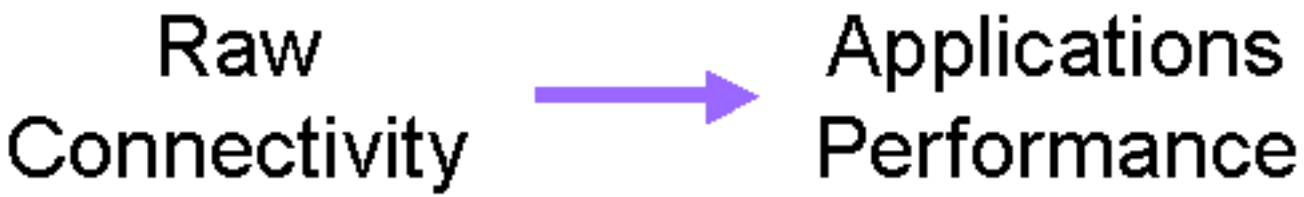
Bulk TCP flows (> 10 Mbytes transfer)

- Current median flow rate over Abilene: 1.9 Mbps



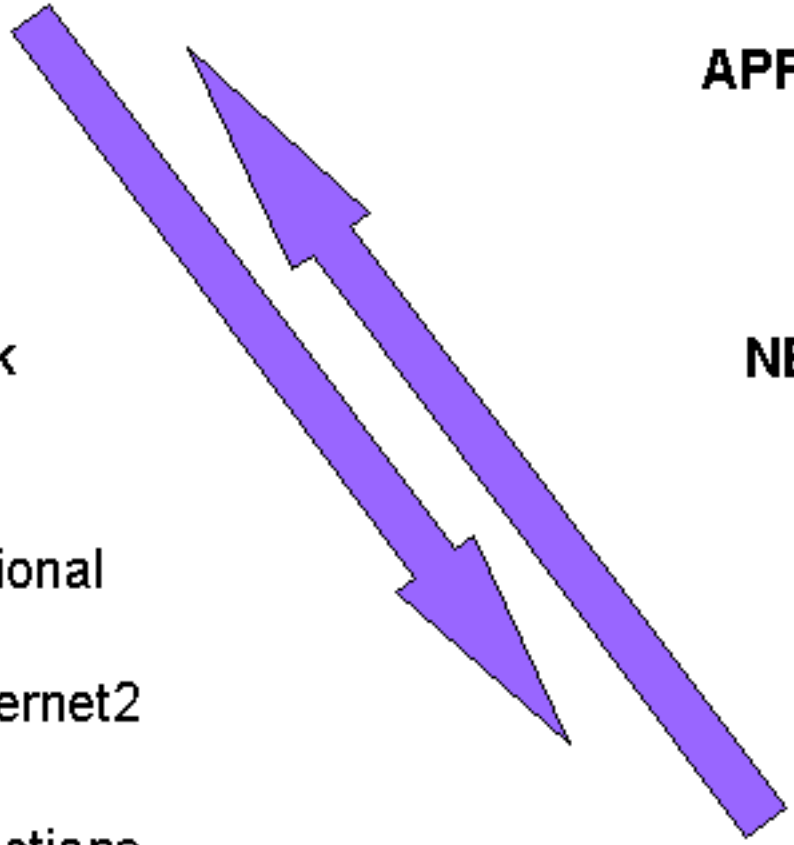
End-to-End Performance Initiative

To enable the researchers, faculty, students and staff who use high performance networks to obtain *optimal* performance from the *current* infrastructure on a *consistent* basis.



True End-to-End Performance requires a system approach

- User perception
- Application
- Operating system
- Host IP stack
- Host network card
- Local Area Network
- Campus backbone network
- Campus link to regional network/GigaPoP
- GigaPoP link to Internet2 national backbones
- International connections



EYEBALL

APPLICATION

STACK

JACK

NETWORK

. . .

. . .

. . .

. . .

Optical networking technology drivers

Aggressive period of fiber construction on the national & metro scales in U.S.

Many university campuses and regional GigaPoPs with dark fiber

Dense Wave Division Multiplexing (DWDM)

- Allows the provisioning of multiple channels (**λ's**) over distinct wavelengths on the same fiber pair
- Fiber pair can carry 160 channels (1.6 Tbps!)

Optical transport is the current focus

- Optical switching is still in the realm of experimental networks, but may be nearing practical application

DWDM technology primer

DWDM fundamentally is an *analog* optical technology

- Combines multiple channels (2-160+ in number) over the same fiber pair
- Uses slightly displaced wavelengths (λ's) of light
- Generally supports 2.5 or 10 Gbps channels

Physical obstacles to long-distance transmission of light

- Attenuation
  - Solved by amplification (OO)
- Wavelength dispersion
  - Requires periodic signal regeneration – an electronic process (OEO)

DWDM system components

Fiber pair

Multiplexing/demultiplexing terminals

- OEO equipment at each end of light path
- Output: SONET or Ethernet (10G/1G) framing

Amplifiers

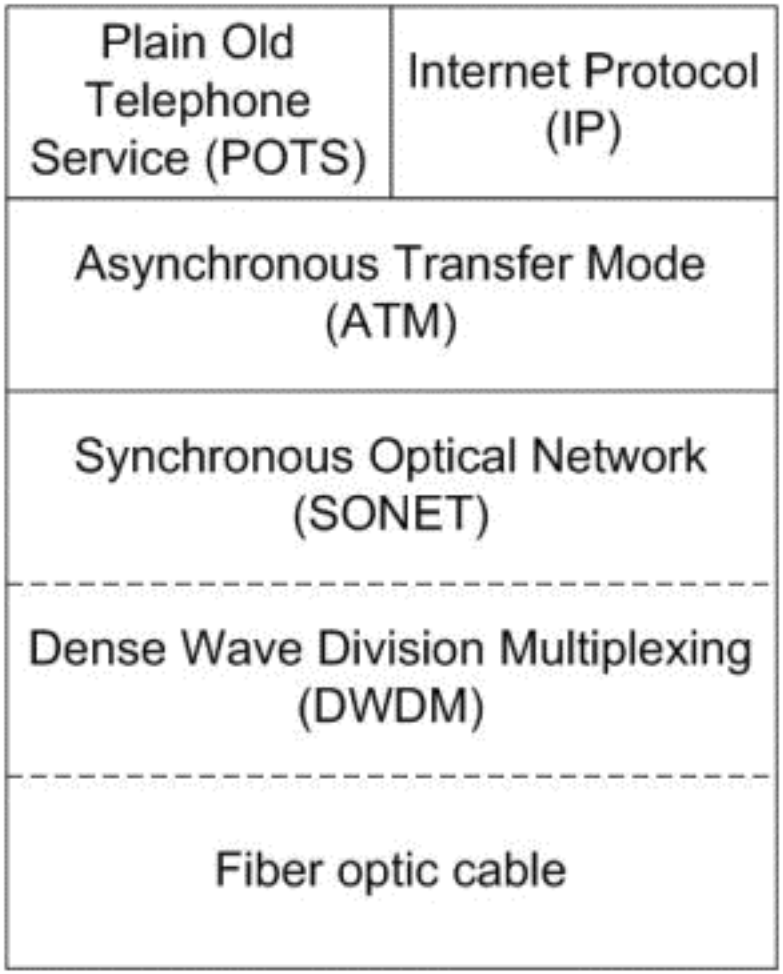
- All optical (OO)
- ~100 km spacing

Regeneration

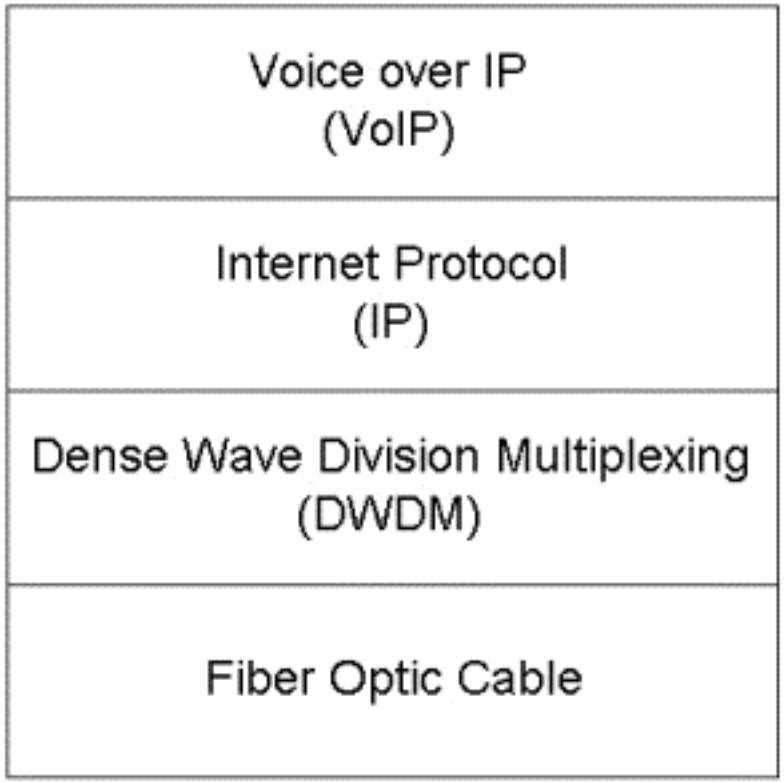
- Electrical (OEO) process – costly (~50% of capital)
- ~500 km spacing (with Long Haul - LH - DWDM)
- New technologies can lengthen this distance

Remote huts, operations & maintenance

Telephony's recent past (from an IP perspective in the U.S.)



IP Networking (and telephony) in the not so distant future



National optical networking options

1 – Provision incremental wavelengths
- Obtain 10-Gbps λ's as with SONET
- Exploit smaller incremental cost of additional λ's
  - 1st λ costs ~10x than subsequent λ's

2 – Build dim fiber facility
- Partner with a facilities-based provider
- Acquire 1-2 fiber pairs on a national scale
- Outsource operation of inter-city transmission equipment
- Needs lower-cost optical transmission equipment

The classic 'buy vs. build' decision in Information Technology

Future of Abilene

Original UCAID/Qwest agreement amended on October 1, 2001

Extension of for another 5 years – until October, 2006

- Originally expired March, 2003

Upgrade of Abilene backbone to optical transport capability - λ's (unprotected)

- x4 increase in the core backbone bandwidth
  - –OC-48c SONET (2.5 Gbps) to 10-Gbps DWDM

Two leading national initiatives in the U.S.

Next Generation Abilene

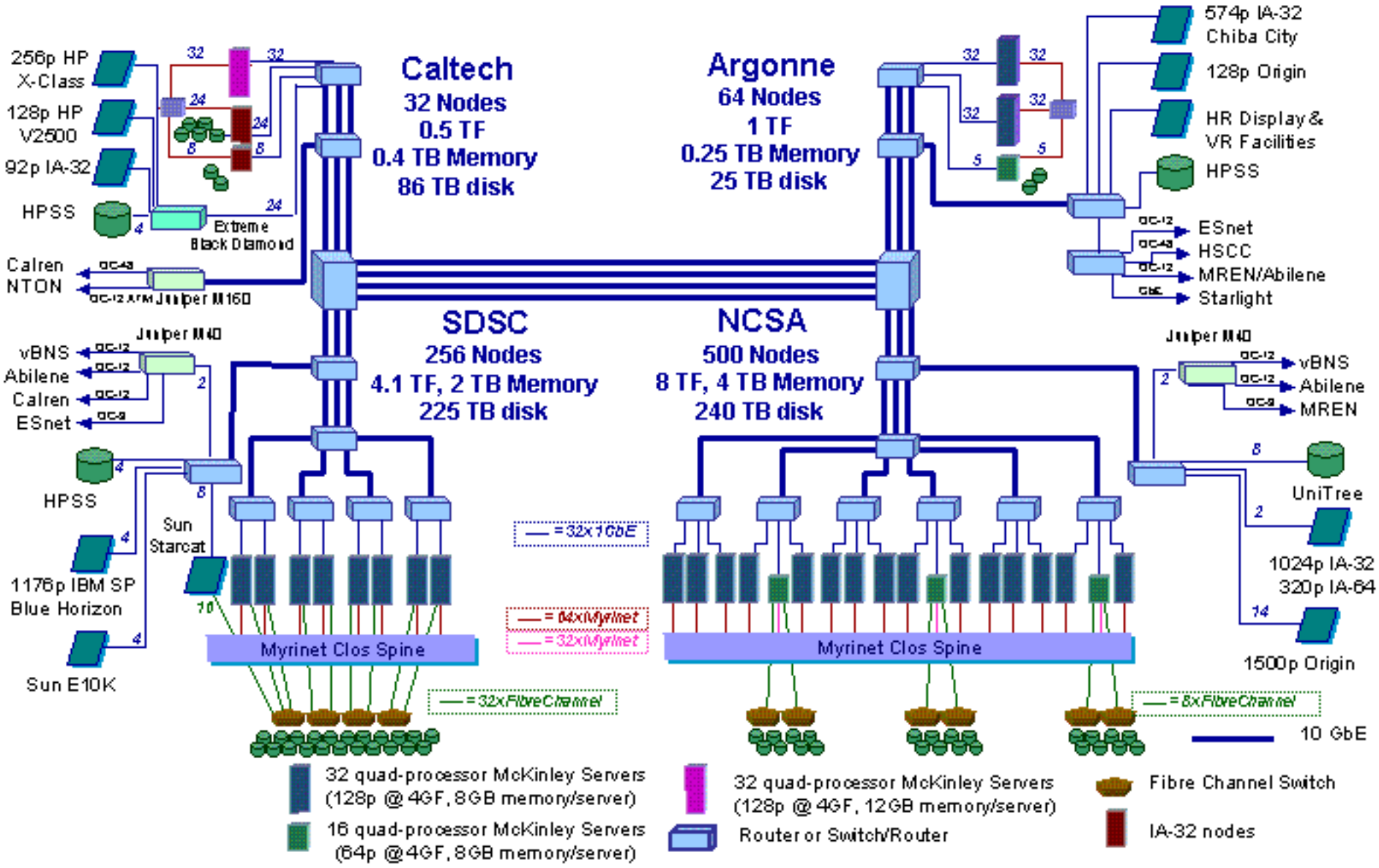
- Advanced Internet **backbone**
  - **connects entire campus networks of the research universities**
- 10 Gbps nationally

TeraGrid

- Distributed computing (Grid) **backplane**
  - **connects high performance computing (HPC) machine rooms**
- Illinois: NCSA, Argonne
- California: SDSC, Caltech
- 4x10 Gbps: Chicago ↔ Los Angeles

Ongoing collaboration between both projects

TeraGrid Architecture – 13.6 TF (Source: C. Catlett, ANL)



Key aspects of next generation Abilene backbone - I

Native IPv6

- Motivations
  - Resolving IPv4 address exhaustion issues
  - Preservation of the original End-to-End Architecture model
    - p2p collaboration tools, reverse trend to CO-centrism
  - International collaboration
  - Router and host OS capabilities
- Run natively - concurrent with IPv4
- Replicate multicast deployment strategy
- Close collaboration with Internet2 IPv6 Working Group on regional and campus v6 rollout
  - Addressing architecture

Key aspects of next generation Abilene backbone - II

Network resiliency

- Abilene λ's will not be *protected* like SONET
- Increasing use of videoconferencing/VoIP impose tighter restoration requirements (<100 ms)
- Options:
  - Currently: MPLS/TE fast reroute
  - IP-based IGP fast convergence (preferable)

Addition of new measurement capabilities

- Enhance active probing (Surveyor)
  - Latency & jitter, loss, TCP throughput
- Add passive measurement taps
- Support for computer science research – "Abilene Observatories"
- Support of Internet2 End-to-End Performance Initiative
  - Intermediate performance beacons

ABILENE NETWORK 10-Gbps OPTICAL UPGRADE - 2002-2003 (DRAFT)

Regional optical fanout

Next generation architecture: Regional & state based optical networking projects are critical

- Three-level hierarchy: backbone, GigaPoPs/ARNs, campuses
- Leading examples
  - CENIC ONI (California), I-WIRE (Illinois),
  - SURA Crossroads (Southeastern U.S), Indiana, Ohio

Collaboration with the Quilt

- Regional Optical Networking project

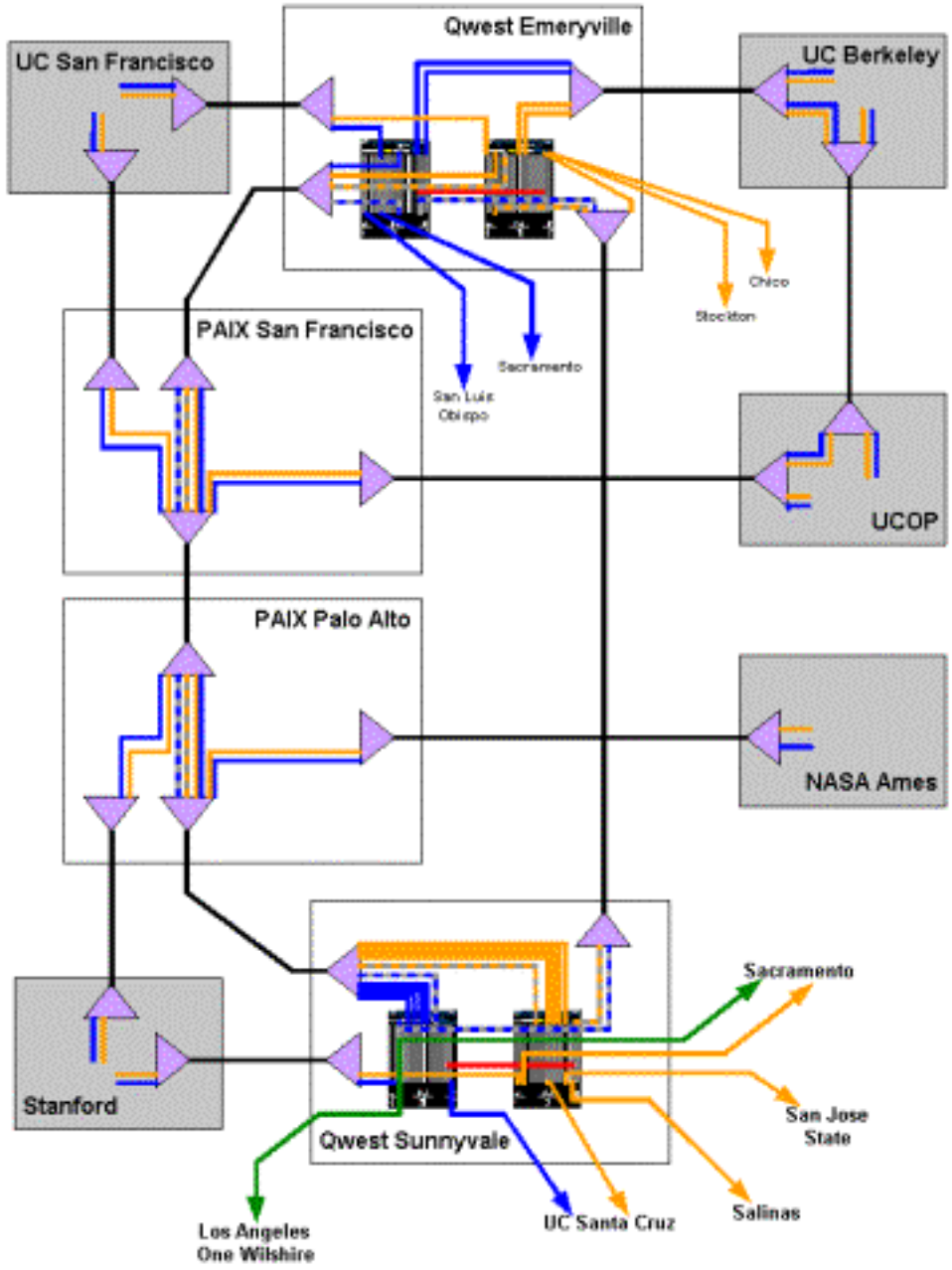
U.S. carrier DWDM access is now not nearly as widespread as with SONET circa 1998

- 30-60 cities for DWDM
- ~120 cities for SONET

Optical network project differentiation

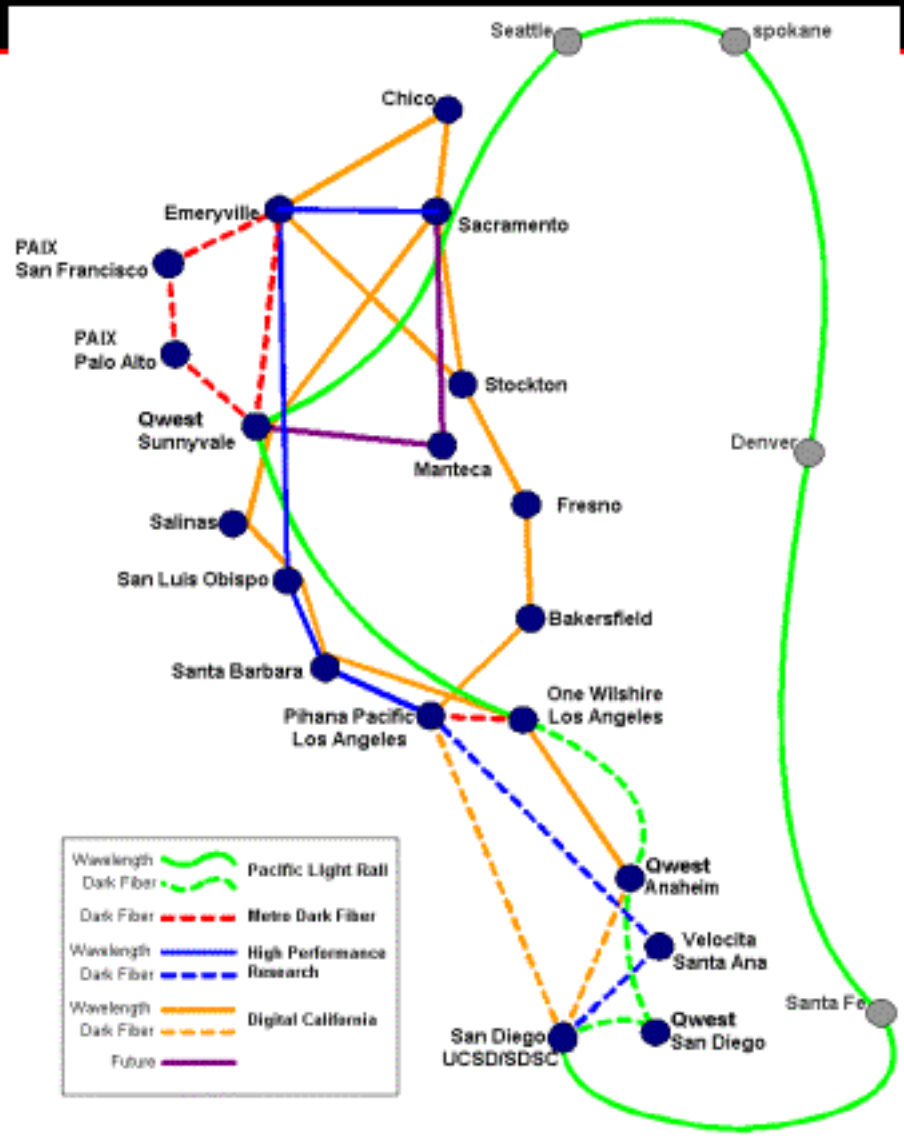
	Distance scale (km)	*Examples*	*Equipment*
Metro	< 60	UW(SEA), USC/ISI(LA)	Dark fiber & end terminals
State/ Regional	< 500	I-WIRE (IL), CENIC ONI, I-LIGHT (IN)	Add OO amplifiers
Extended Regional/ National	> 500	PLR, TeraGrid Abilene	Add OEO regenerators & O&M $'s

San Francisco Metro



California & Pacific Northwest

(Source: Greg Scott, CENIC/UCSC)



Conclusions

- Abilene future
  - UCAID's partnership with Qwest extended through 2006
  - Backbone to be upgraded to 10-Gbps in three phases
  - Native v6, enhanced measurement, and increased resiliency are new thrusts
  - Overall approach to the new technical design and business model is for an incremental, non-disruptive transition
  - Nicely positioned and collaborative with NSF's TeraGrid distributed computational backplane effort
- National Light Rail
  - Emerging & expanding collaboration to develop a persistent advanced optical network infrastructure capability to serve the diverse needs of the U.S. higher ed & research communities
  - Core partners: CENIC & P/NW, Argonne/TeraGrid, UCAID

For more information

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