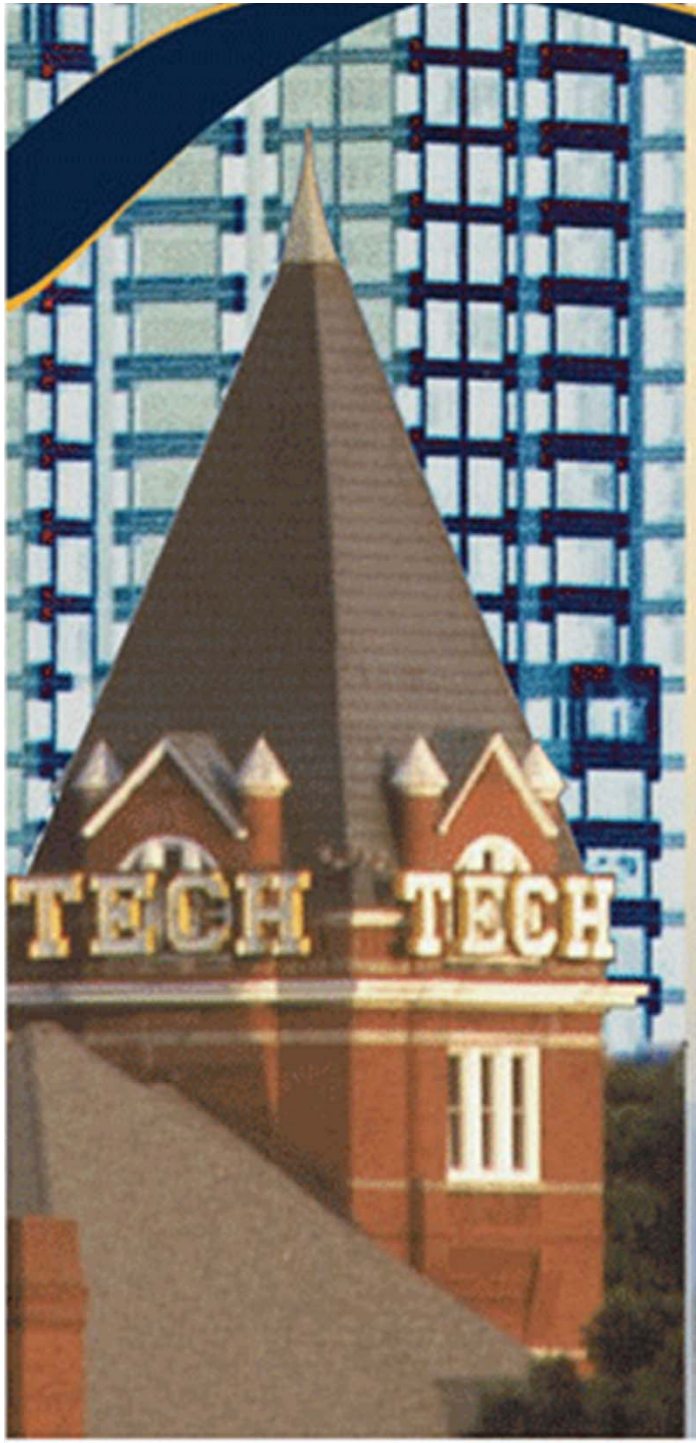


Symposium for Celebration of 50th Anniversary
Dept. of Physics and Astronomy

UNIVERSITY OF CALIFORNIA
UCRIVERSIDE

Frontiers of Fiber-Optics Communications:

Emerging Technologies and Applications

Gee-Kung Chang

Byers Eminent Scholar Chair Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250

May 28, 2011

The Beginning: High Energy Physics, UCR

Joined Dept. of Physics and Astronomy of UCR in 1970

My Ph.D. Thesis Committee Members at UCR:

- ***Robert T. Poe***, Experimental and Theoretical Atomic & Hardon Physics
- ***Anne Kernan,*** Strong Interactions
- ***Sun-Yiu Fung***, E-M Interactions
- ***Bipin Desai***, Quantum Field Theory
- ***Benjamin Shen***, Thesis Advisor

I Completed my thesis in 1976, "Strange particle productions at CERN ISR"

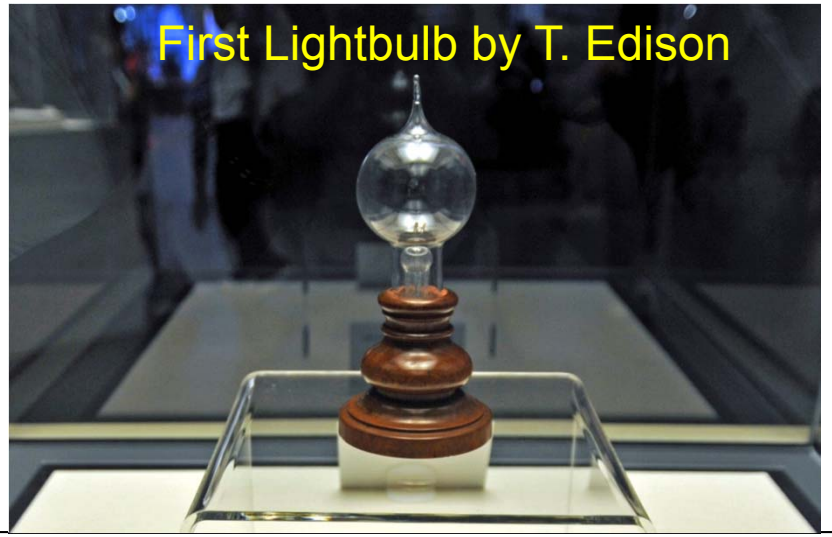
Research Faculty Members in High Energy Physics, 1970-1976

- John Layter
- Dave Sager
- Bill Gorn
- S. Y. Chu

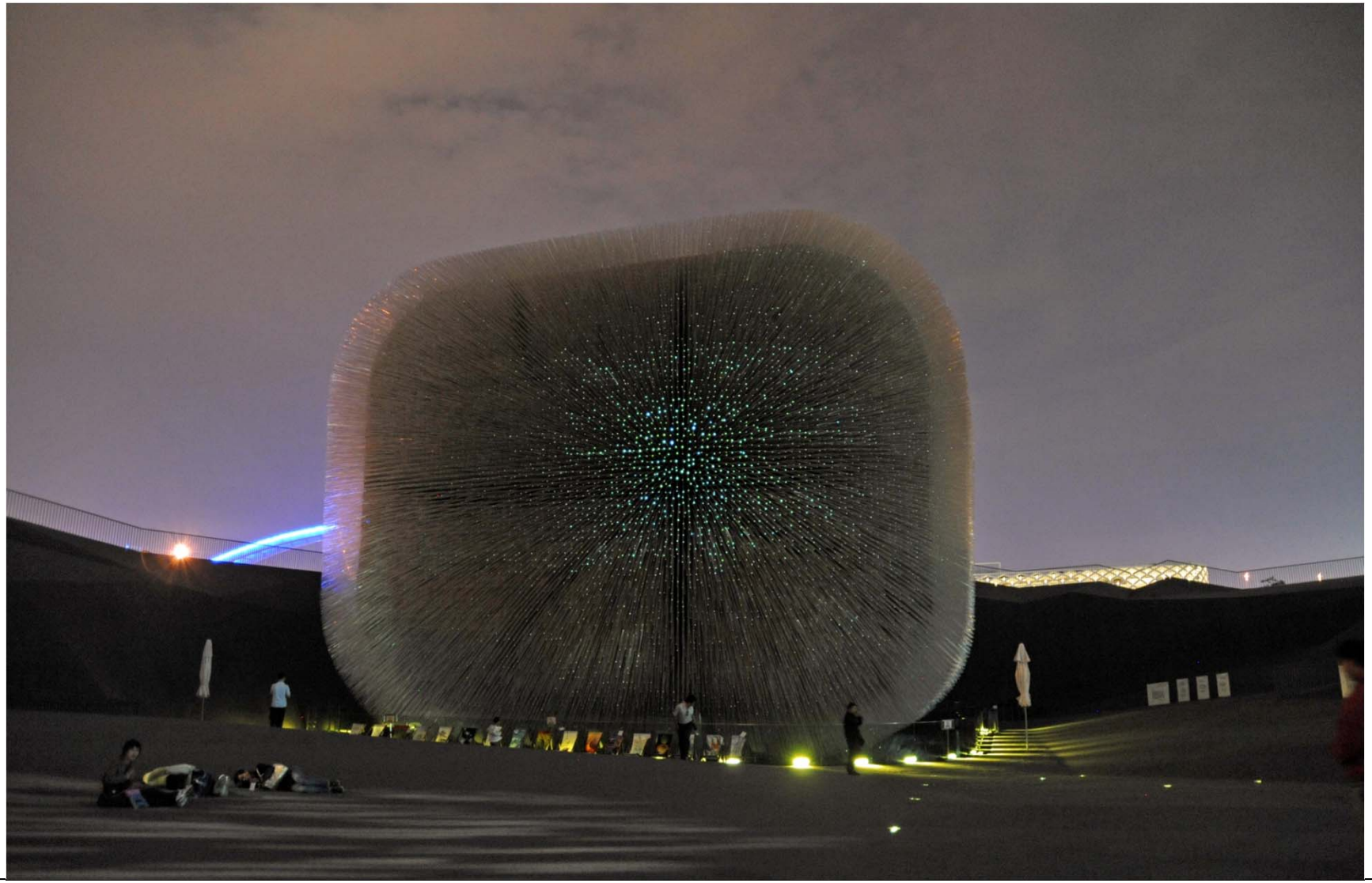
Journey from Physics to Electrical & Computer Eng

- **Lawrence Berkeley Lab, 1973-74**
  - Heavy ion collisions in streamer chamber, Exp. 152, Shen-UCR
- **CERN ISR, 1975-76**
  - Strange particle production in pp ISR experiment
- **Brookhaven National Lab, 1976-77**
  - pp collisions
- **Cornell Electron Synchrotron, 1977-78**
  - Built CLEO for > 1 GeV photon detection for e+ e- annihilations
- **Bell Labs, Bellcore & Telcordia Technologies, 1979-2001**
  - Avalanche photodiode for 1 eV photon detection
  - HEX switch: realized high energy cross-connects in silicon ICs
  - Elected to a Fellow for pioneering contributions to Optical Networks
- **OpNext, Inc, 2001-2002**
  - VP & Chief Technology Strategist for R&D in optoelectronic systems
- **Georgia Institute of Technology, 2002-present**
  - Endowed Chair Professor in Electrical and Computer Engineering
  - Pioneer in VHT Wireless over Fiber Technologies and Applications
  - Fellow of IEEE and Optical Society of America

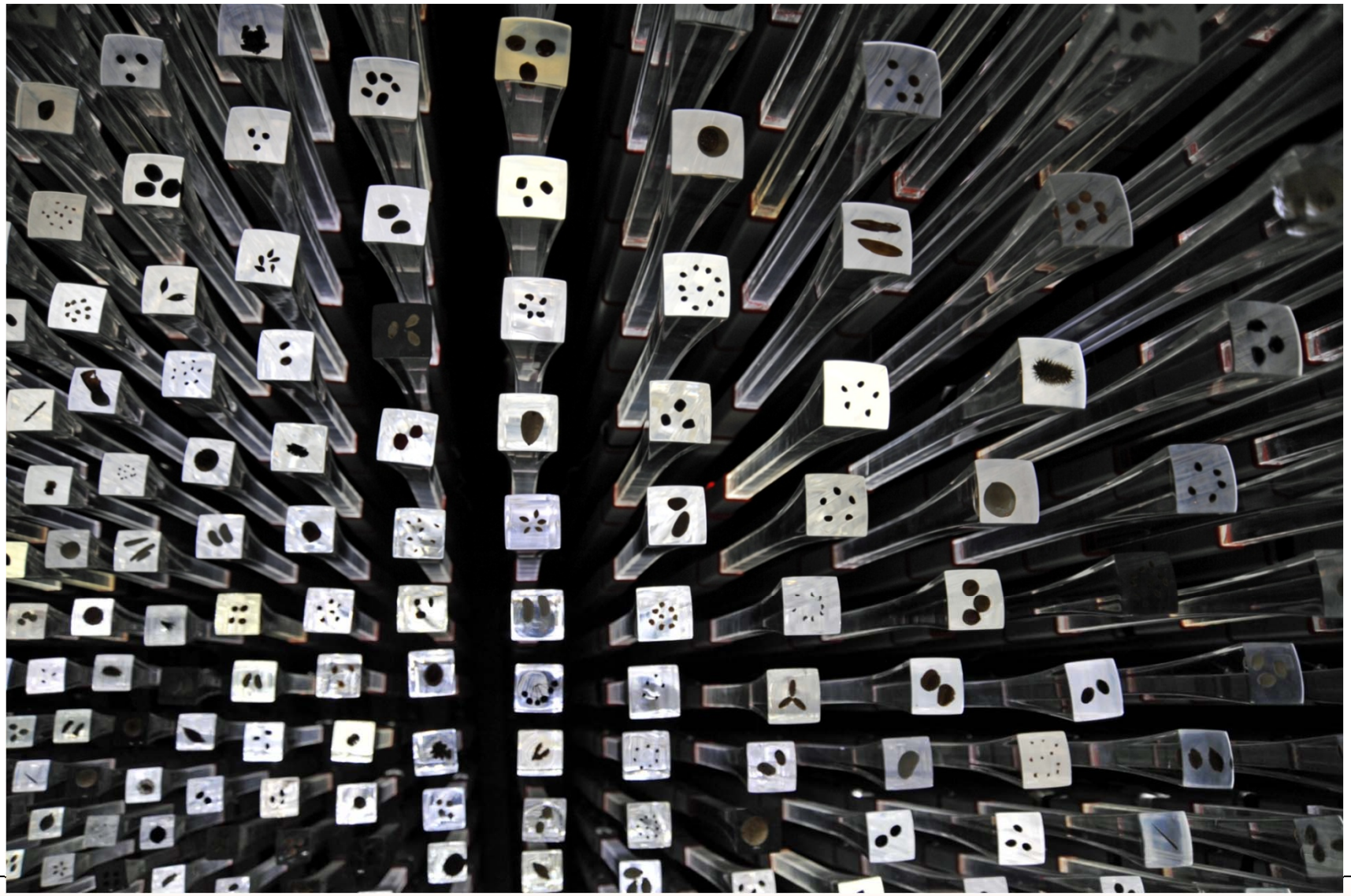
Highlights of Past World Expos
Innovations in Communications:1877-1900



First Light at Dusk: UK Pavillion



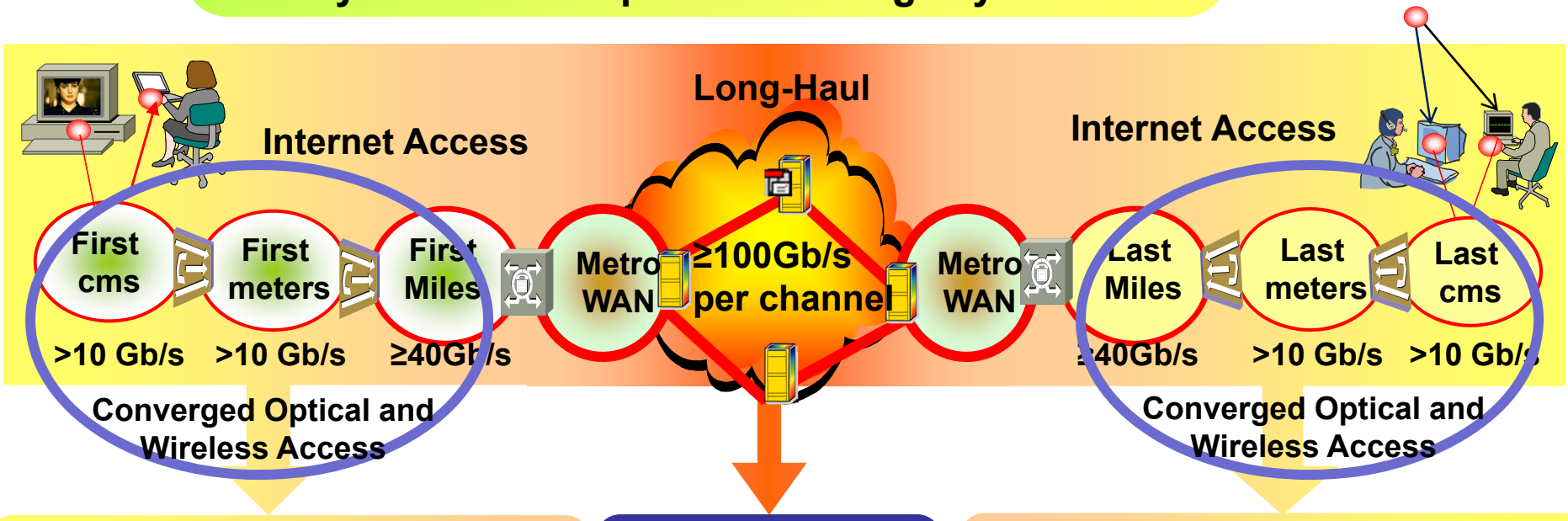
Optical Waveguides:
Sowing Information Seeds of the Future



End-to-End Broadband Internet Connectivity

- Multi-view 3-D HD Video Distribution
- Interactive Multimedia and Game Contents
- Very High Throughput Telepresence and Telehealth
- High Performance Computers and Data Centers
- Exa-bytes data transport and storage systems

Inside the box
Last centimeters
Interconnect



FSO/MM-W opt interconnect | RF over Optical | TDM-PON WDM-PON OFDMA-PON

100G - 400G-1000G DWDM Core

TDM-PON WDM-PON OFDMA-PON | RF over Optical | FSO / MM-Wave Optical interconnect

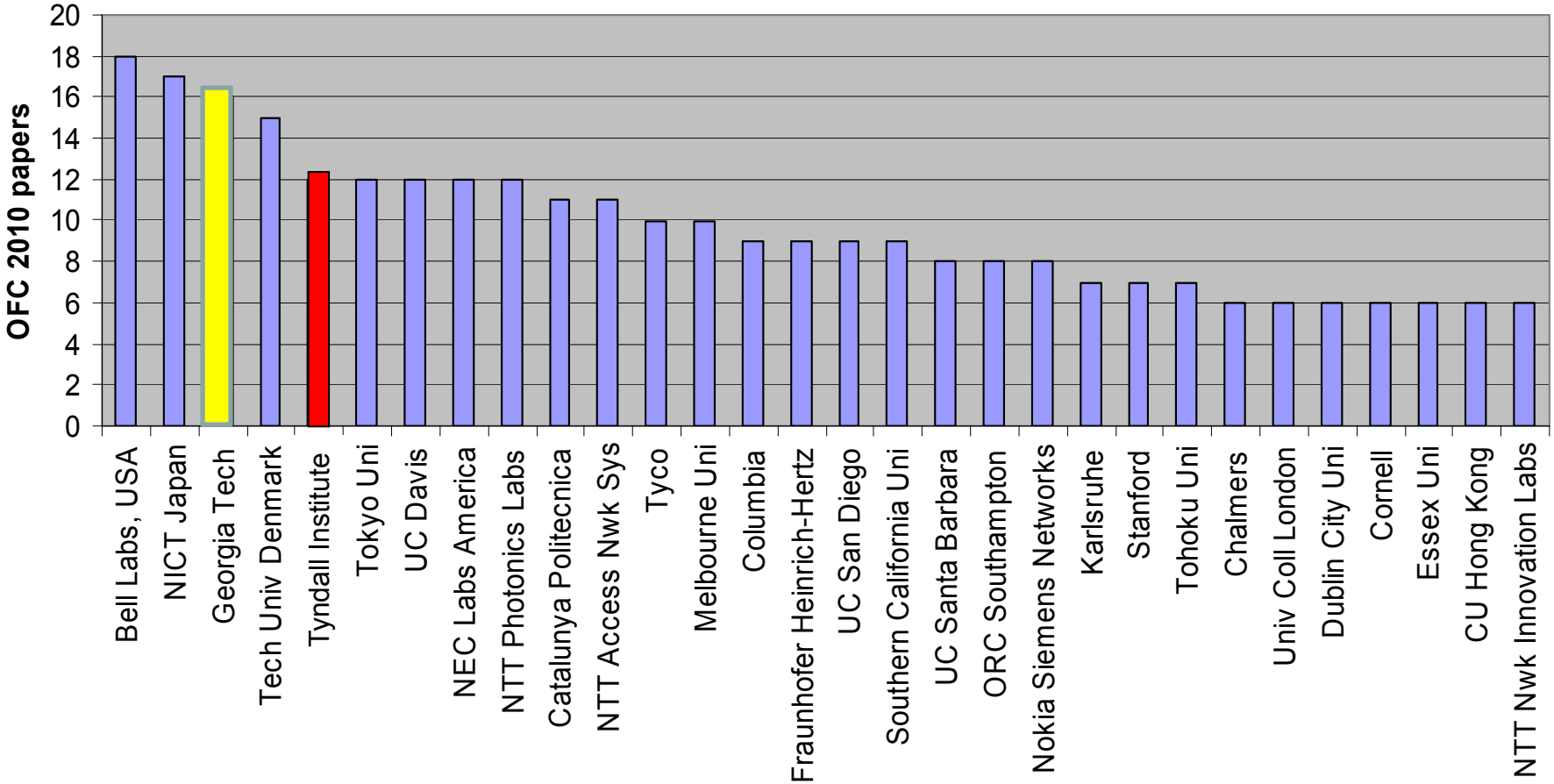
Access for Internet of Things
Converged Optical and Wireless Access Networks

1. Layered architecture
2. Consistent user experience
3. Seamless transition between networks and devices
4. A single, common service platform, with uniform treatment of network access
5. Communications and entertainment that adapt to customer's lifestyle

IMS: Internet multimedia subsystem

Optical Networking Research Groups in the World
by Total Numbers of Papers Accepted by OFC 2010

Total number of papers accepted by Optical Fiber Communications Conference 2010, the premier optical communications conference in the world



Compiled by **Tyndall** National Institute, Ireland

Georgia Institute of Technology

Georgia Tech 100G Research Center

Founding Members

- ADVA Optical Networking
- OFS
- Verizon
- Ciena

Member Companies

- Optametra
- Oclaro
- Nistica
- Picometrix
- Rsoft
- Hitachi
- IBM

Supported by Georgia Research Alliance

Terabit Optical Networking Research: Future Challenges

There are 40 Tera Hz bandwidth available in singlemode fiber.

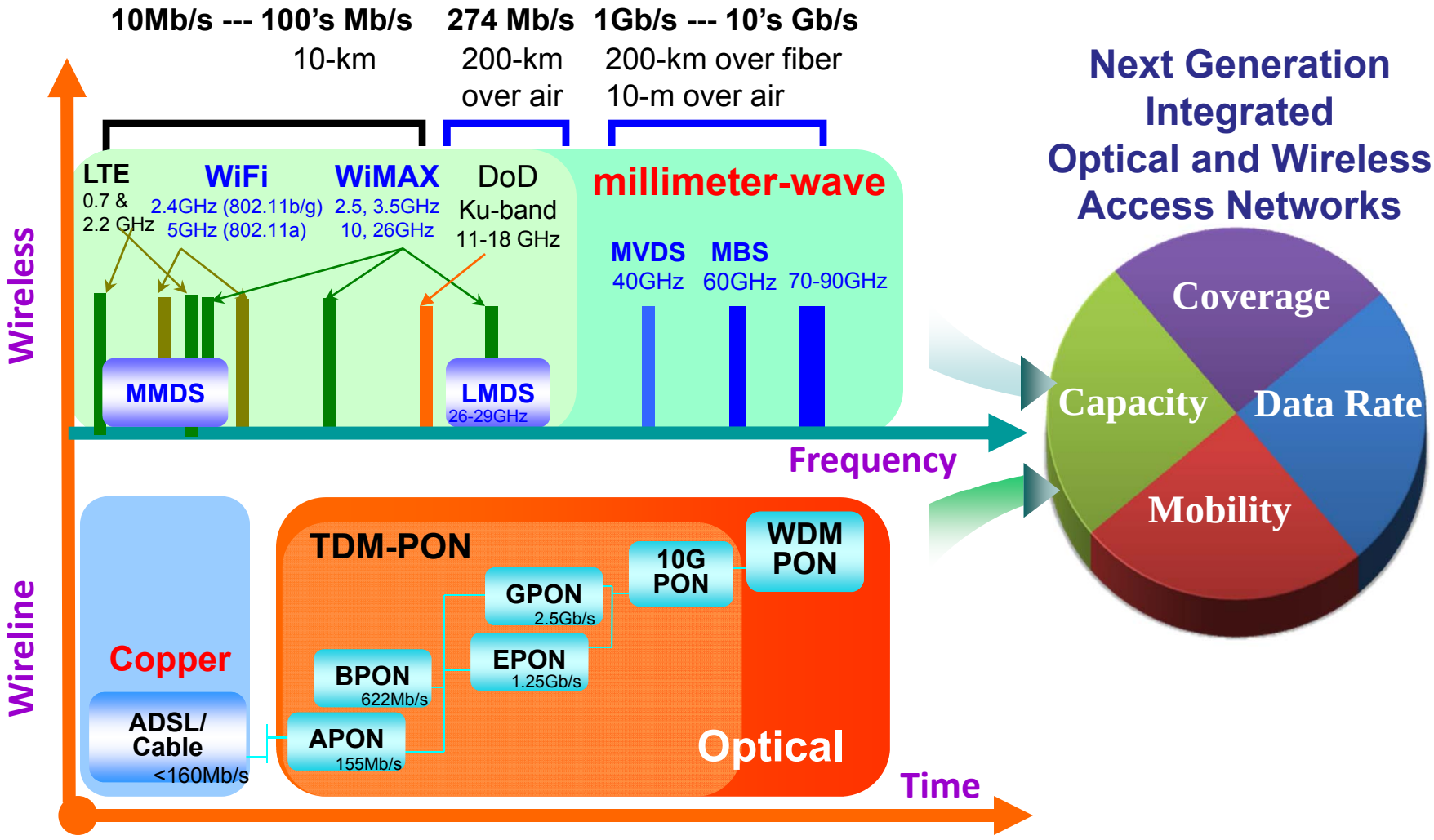
Towards pitabit (10^{15}) per fiber Optical Transport System:

with 10^3 wavelengths per fiber and 10^{12} bits per wavelength

100G, 400G, and 1000G per wavelength Systems

- **QPSK, 16QAM, 32QAM, and 64 QAM multi-level modulation**
- **Hybrid Schemes: Polarization Multiplexing, Coherent WDM, OTDM**
- **Future of wavelength grid, do we need 25 GHz/50 GHz ITU-T grid?**
- **Coherent Demodulation Algorithms**
- **OFDM and OFDMA**
- **Superchannel, multi-carrier systems**

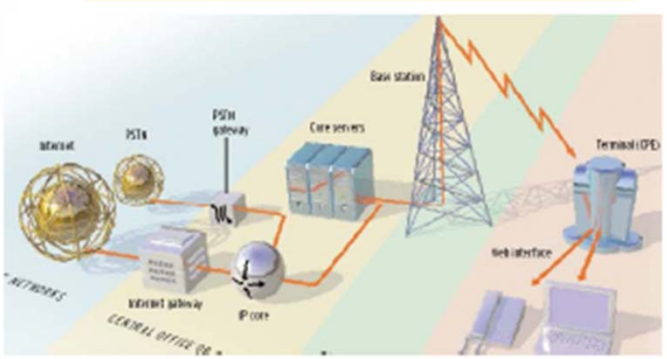
Optical and Wireless Access Convergence



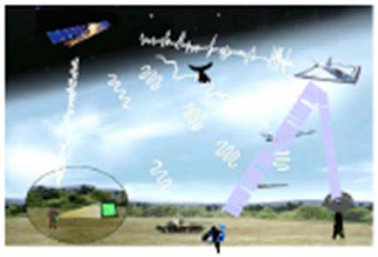
MMDS: multichannel multipoint distribution service, LDMS: local multi-point distribution service
MVDS: microwave video distribution system, MBS: mobile broadband system

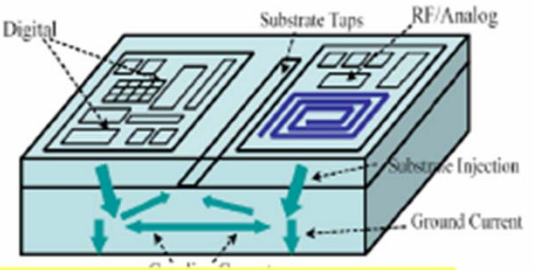
Emerging Fiber-Optic Applications

Compact communication systems with higher data rates backhauls



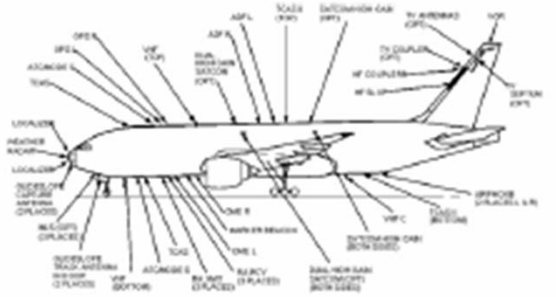
Miniaturization need for sensors and mobile systems





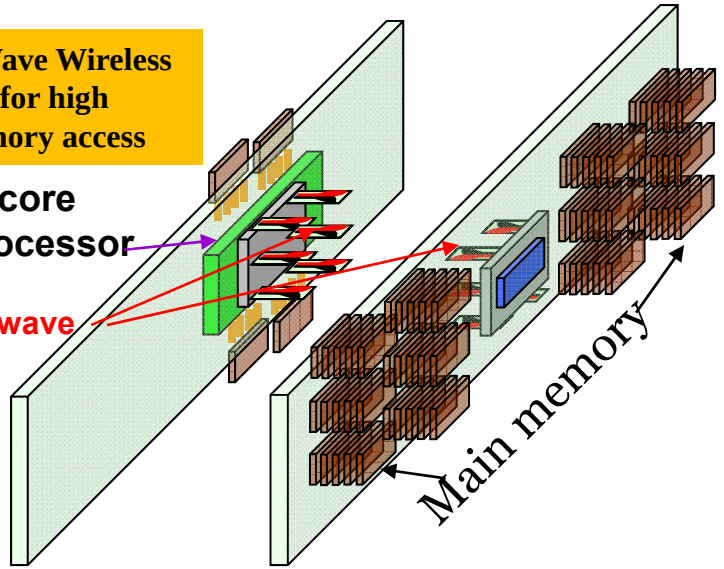
More than 50% of a system-on-a-chip consists of passive RF devices — *RF & Microwave Magazine 2006*

Multifunctionality to sensors decrease complexity & cost



54 antennas on Jetliner

Millimeter Wave Wireless Interconnect for high capacity memory access



Interconnects for HPC and Data Center

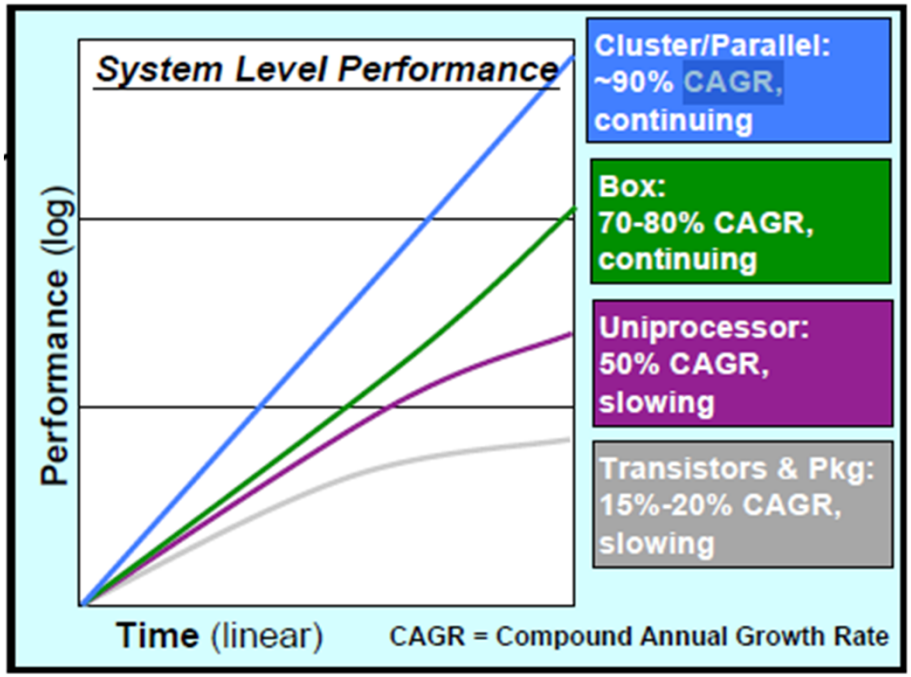
- As the speed or silicon transistors begins saturating, the development of high-performance computing or data centers continue growing exponentially.
- Recently, the highest computational speed is about 1 petaflops per second (10^15). HPC of 1 exaflop per second (10^18) is expected in 10 years.

Top high performance computers

Tienhe-1A, NUDT, China
2.57 petaflops

Cray Jaguar, Cray, USA
1.75 petaflops

Roadrunner, IBM, USA
>1 petaflops



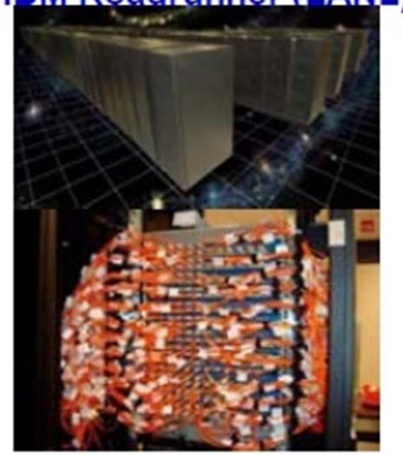
OFC'11, OThH3 (IBM)

Interconnects Bottleneck

- **Even the CPUs of Top 10 HPC still runs around 1.8 GHz to 3.0 GHz. Therefore, the bottleneck of HPC parallel computing lies majorly in the "interconnects"**

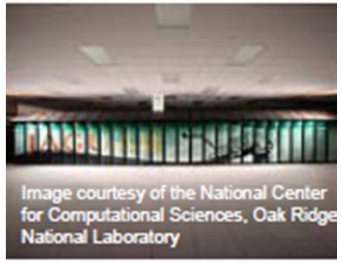
Petaflop Supercomputer

IBM Roadrunner (LANL)



- 5Gb/s/ch transceivers
- 55 miles of Active Optical Cables

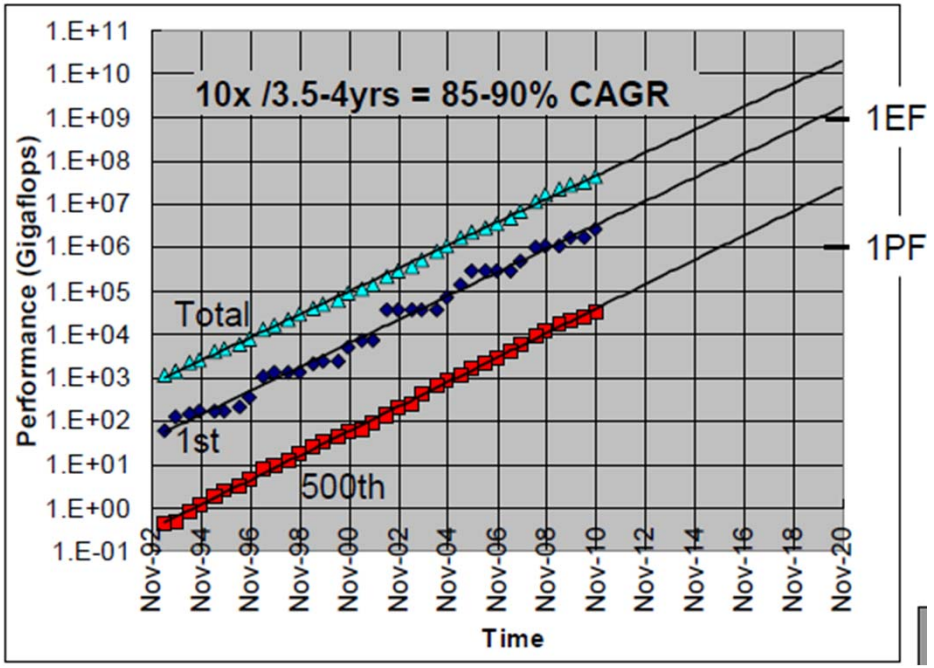
Cray Jaguar(ORNL)



- Was #2 in June, 2009
- Infiniband
- 3 miles of Optical Cables, longest = 60m

Active optical cable

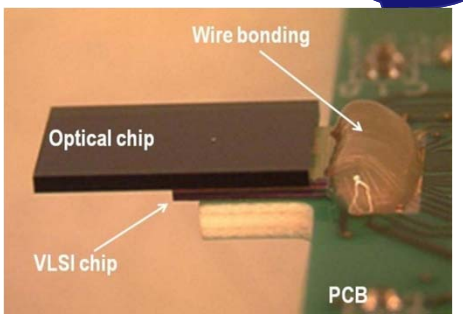
Supercomputer roadmap



Optical Interconnects for Exaflop Computers

- **Board-Level Packaging**
  - **O-E-O Electrical Packet switching**
  - **Cable/fiber**
    - **Total throughput/Card Edge**
    - **$/Gbps (components+packaging+test)**
    - **pJ/Gbps**
  - **New Topology**
    - **Fat-Tree**
    - **Flattened Butterfly, dragonfly…**
  - **Requirement:**
    - **100k Computational nodes**
    - **16 x 50Gb/s per node**

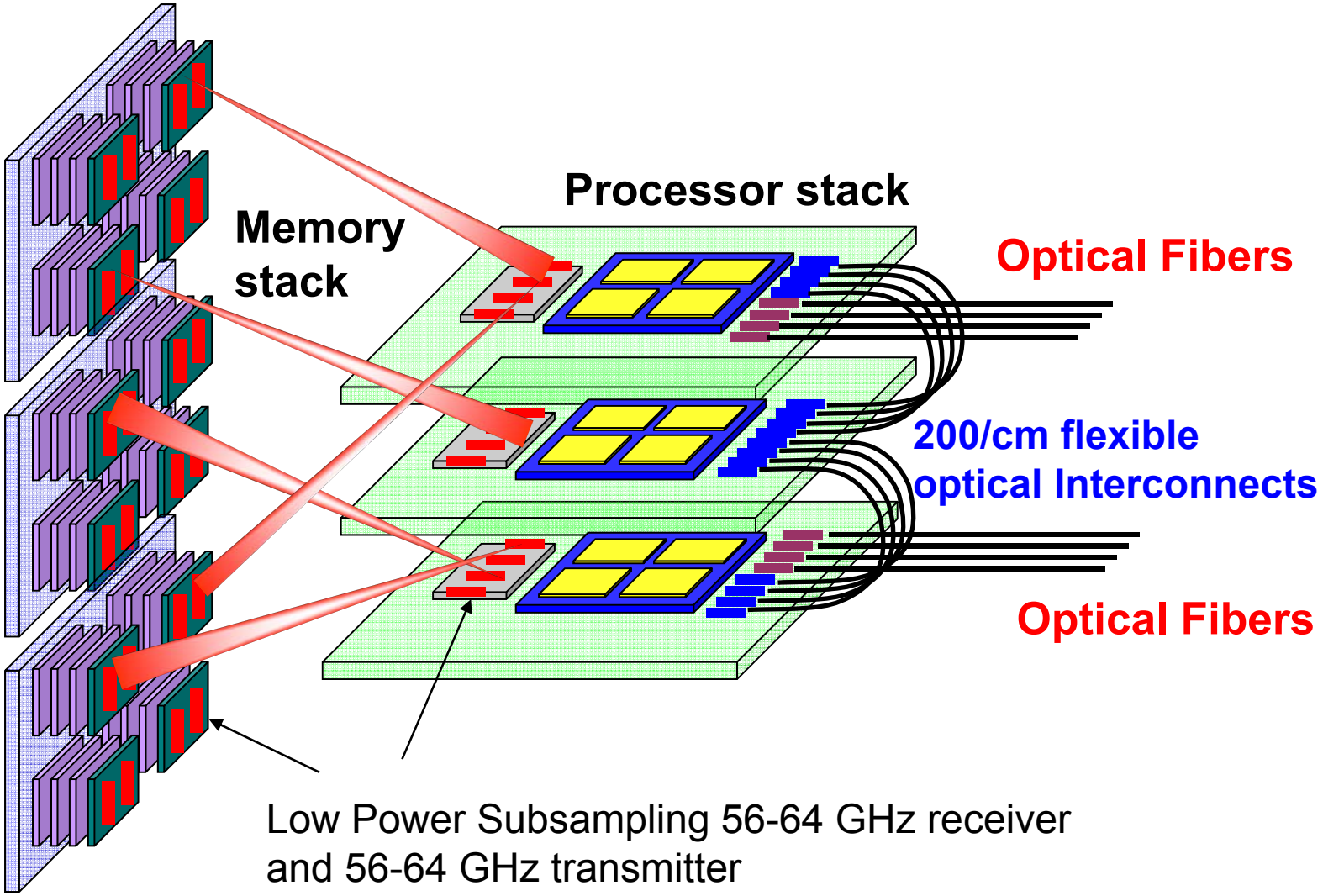
Google IBM Fujitsu Intel



- Interconnects > 10m
  - Optical Fiber-Array Connector
  - Active Optical Cable
  - VCSEL/PD
  - VCSEL/CMOS Integration

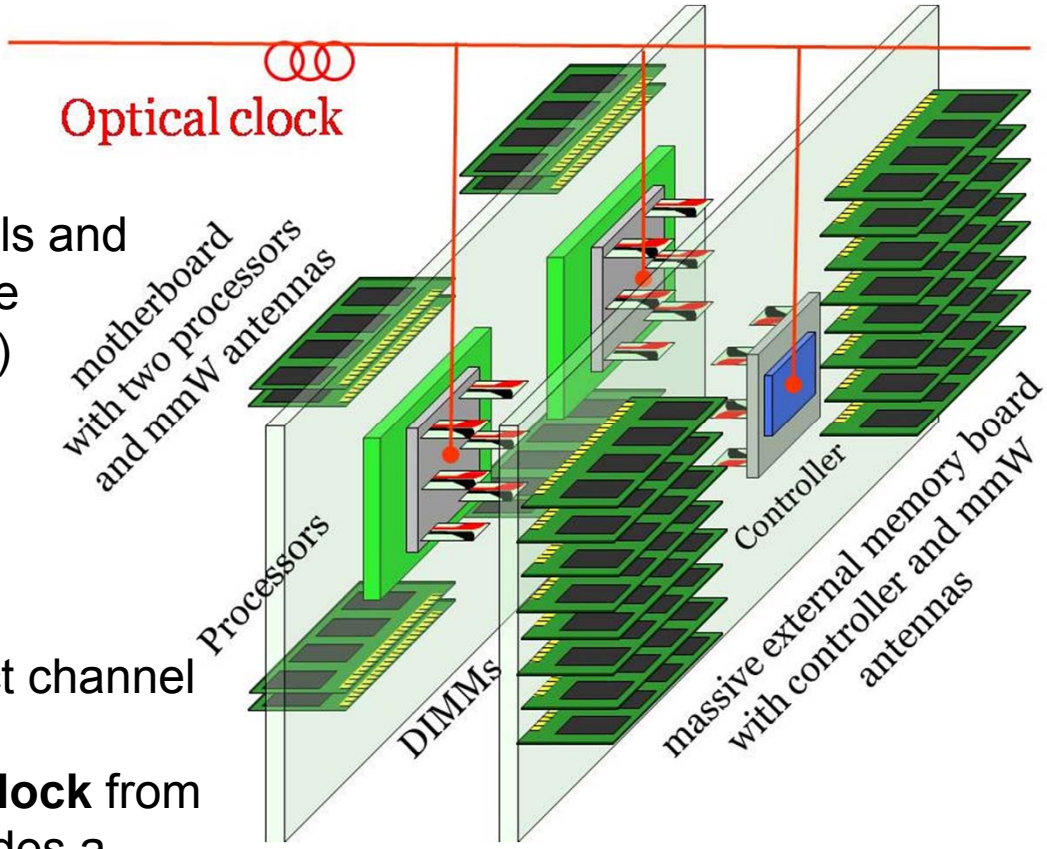
- Integrated Interconnects > 10m
  - Optical circuit switch
  - Polymer waveguides
  - Silicon Photonics
  - Photonic Lightwave Circuit
  - Free Space Optics
  - Modulation formats (QAM, DSP)
  - Gbps/fiber (WDM, PolMux…)

Optical Wireless over Optical Fiber
Interconnects for High Speed Memory Access



Optically Assisted MM-Wave Memory Access
Terabit interconnects without backplane

More memory interconnect channels and faster memory DIMMs can enhance system performance. (Intel Core i7)



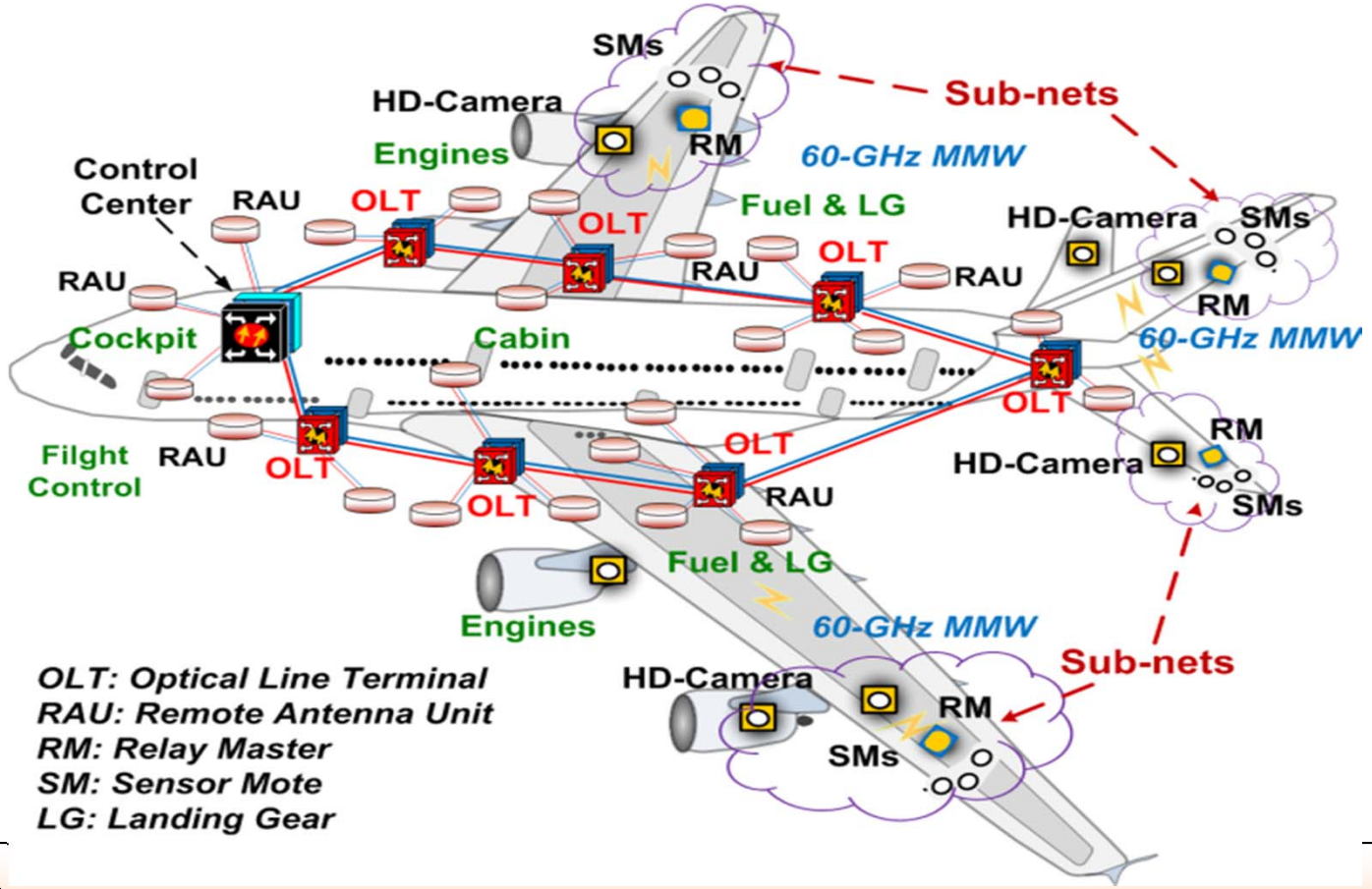
Design Features:

- 40-100Gbps wireless interconnect channel
- 90~65nm CMOS
- A **centrally distributed optical clock** from an off-board modulated laser provides a correlated, self tracking local oscillator (LO). VCOs PLLs are not required.

DIMM: dual in-line memory module

Avionic Millimeter-Wave over Fiber Sensor Communications Networks

- Minimize interference with RF control and command systems
- Secure and less vulnerable to E-M wave attacks
- Super high bandwidth: ≥ 10 Gb/s wireless channels
- Frequency reuse and directional link for deterministic sensor communications



60GHz Wireless Communications Systems

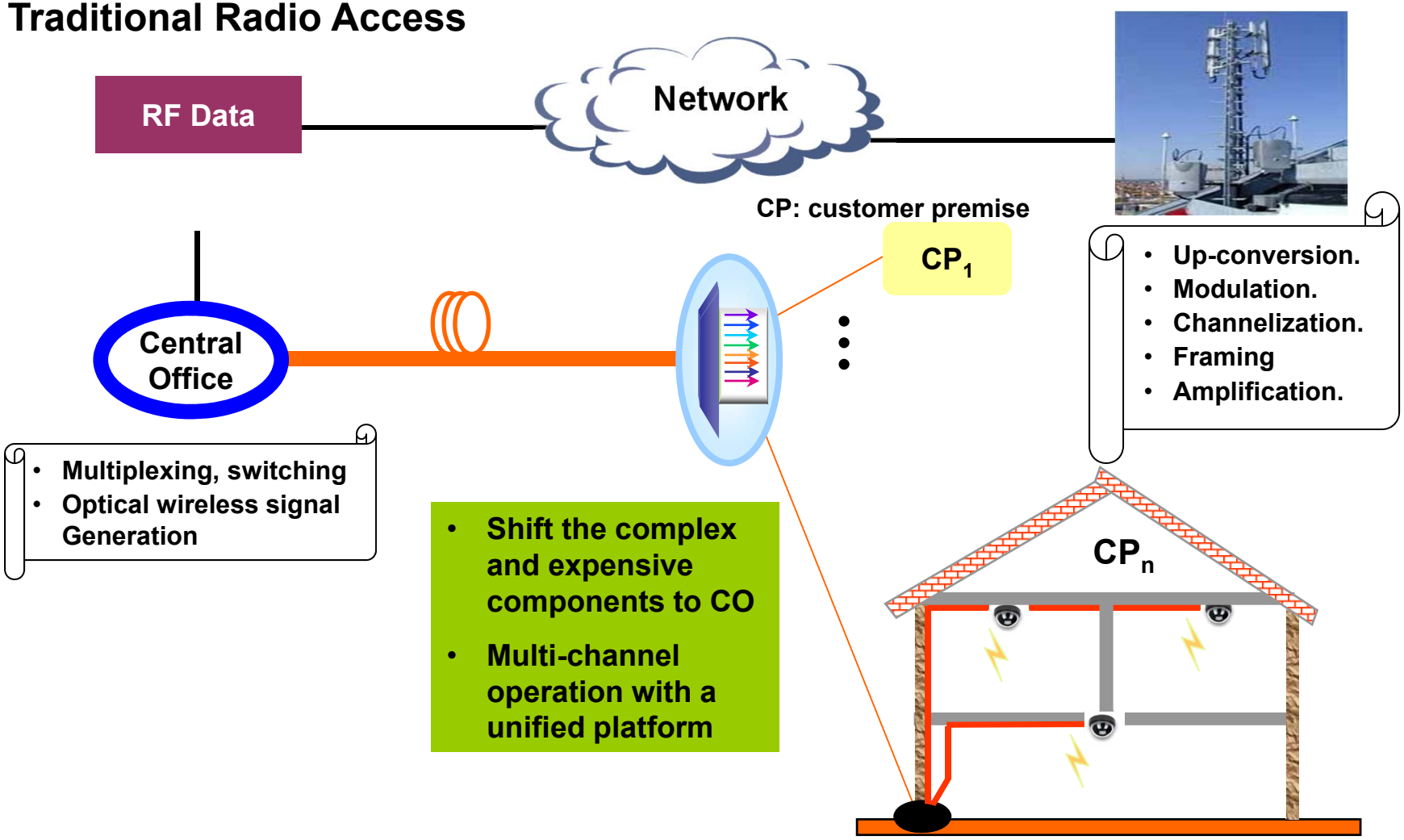
Commercial Applications and Standardization Efforts

Commercial Applications:

- ✓ **Peer to peer connectivity (3Gbps)**
  - **side-loading data transfer**
  - **video streaming**
- ✓ **Wireless Display (1.5-10Gbps)**

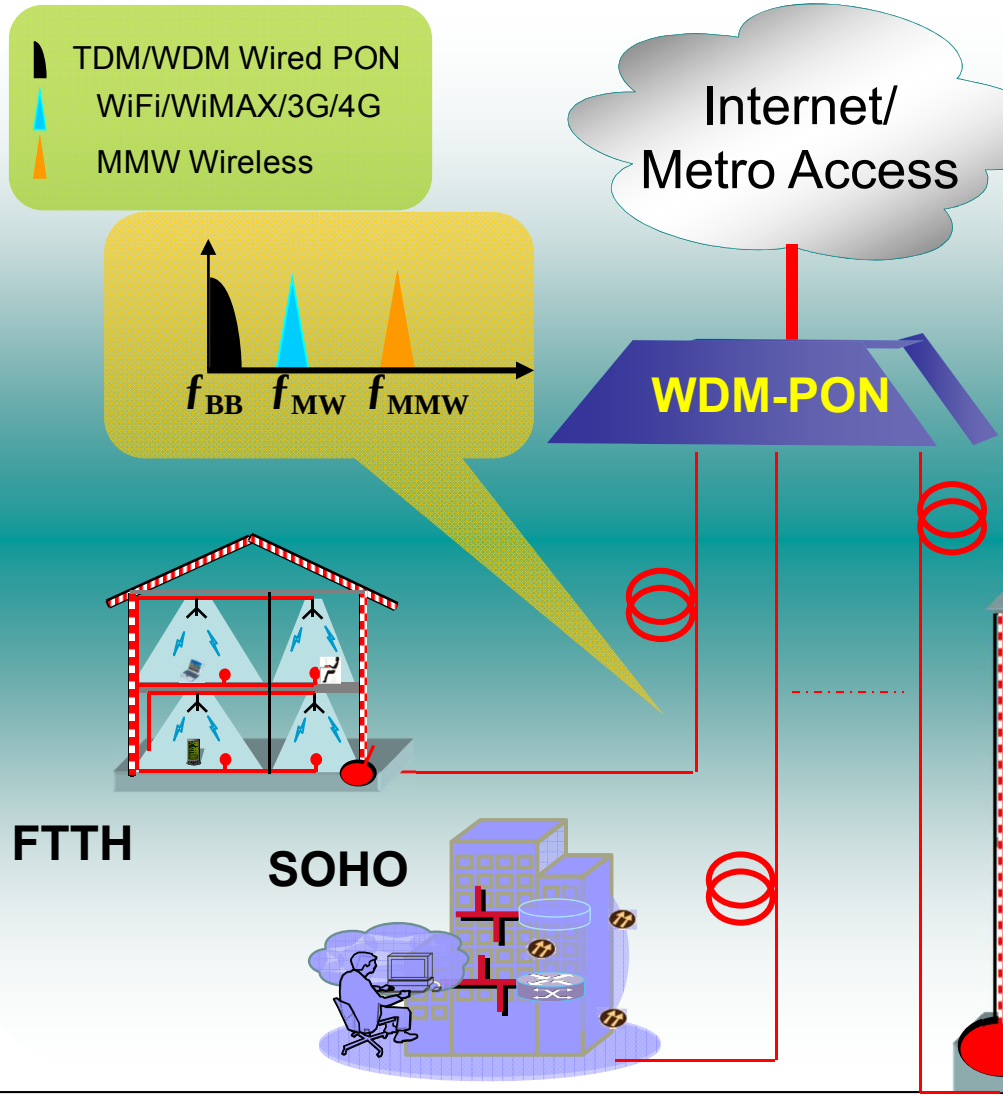
Impact of Radio over Fiber on Wireless Networking Architectures

Traditional Radio Access



Radio-over-Fiber Wireless Access Network

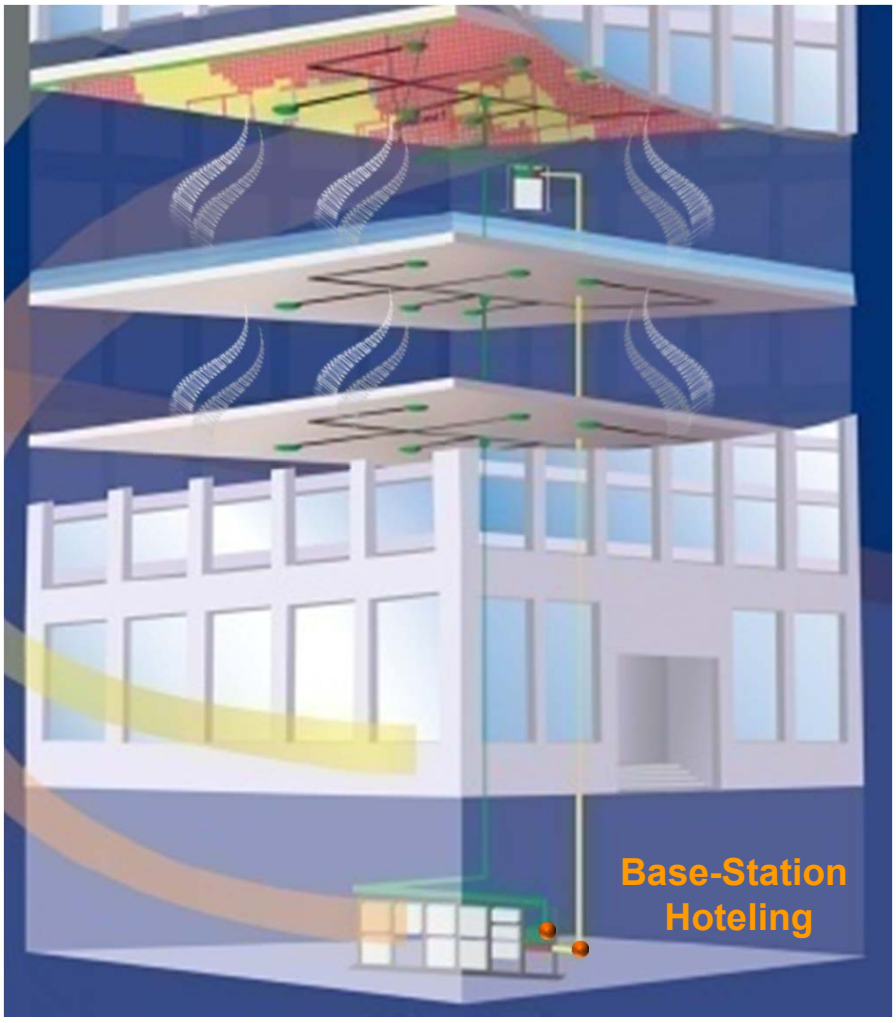
Combining the Best of Both Worlds: Fiber and Wireless



Radio-over-Fiber System

- ✓ Huge bandwidth (multi-band operation)
- ✓ Low attenuation (enhanced reach)
- ✓ No multipath issues
- ✓ Immunity to RF interference
- ✓ Highly scalable through WDM-PON
- ✓ Unprecedented high capacity, high mobility at any time, any where

Wideband Optically Distributed Antenna System for In-building Multi-gigabit Wireless Networks

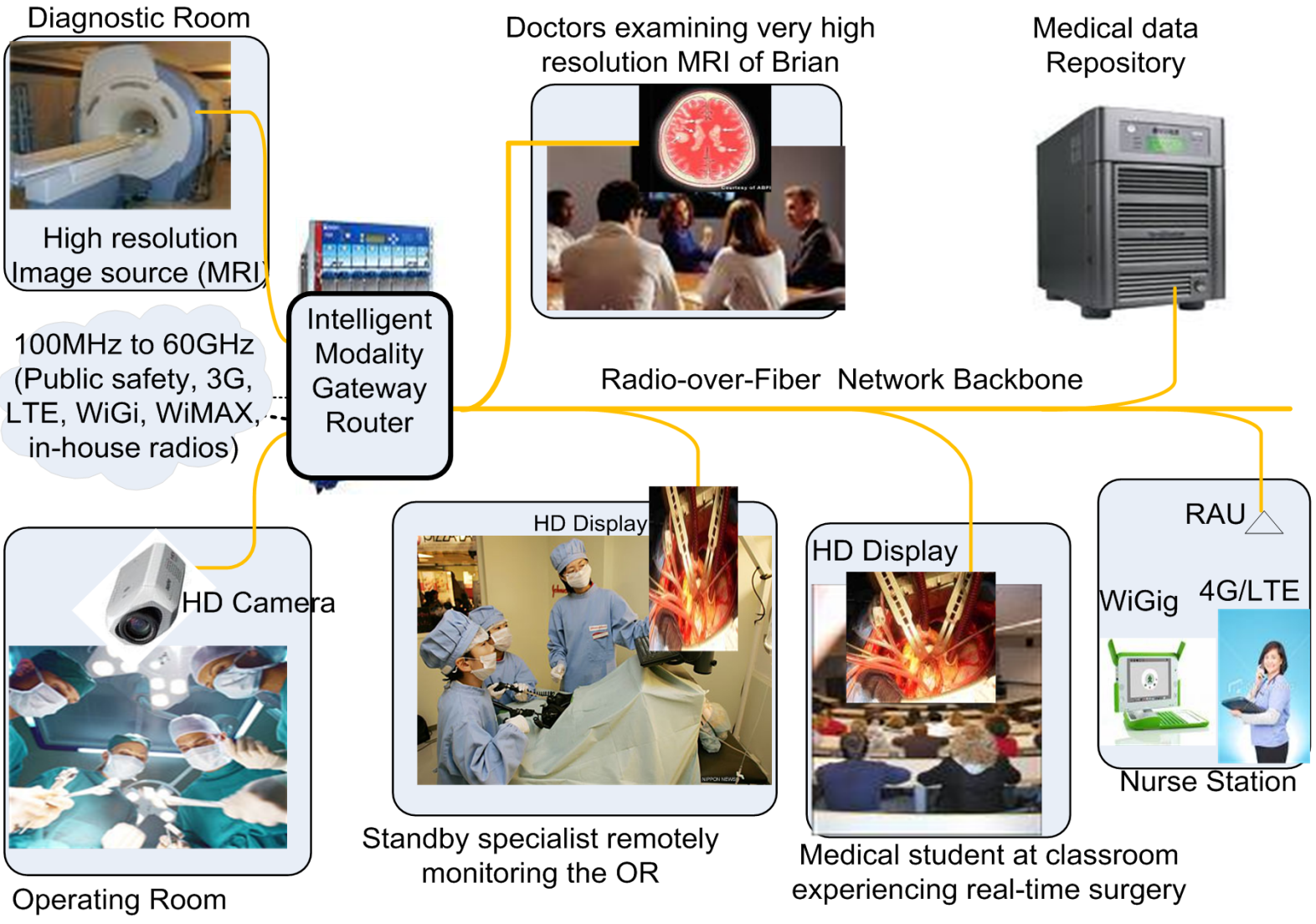


70~80 % of mobile phone calls originate inside of buildings, and full coverage is critical to data services revenue growth

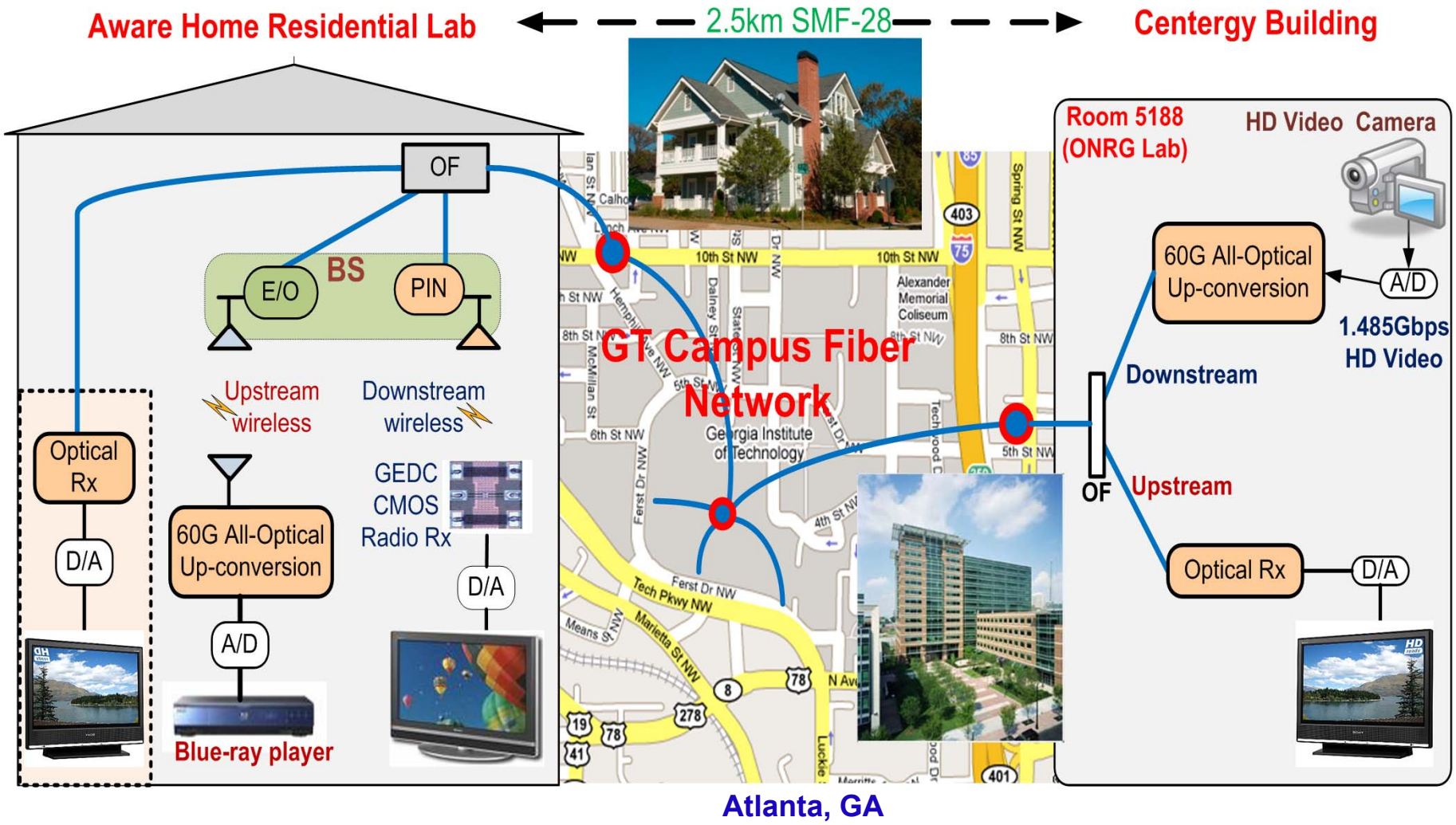
$2B market in 2008, exceeding $15B by 2013 (***source: ABI Research***)

- **Multiple base stations located in the basement are connected to antennas via optical fibers**
- **Antennas are distributed throughout the building to provide full coverage without dead spots**
- **All connections are transparent to the service provider. The standard wireless protocols handle all call management.**

Broadband e-Health Services:
Converged Optical and Wireless Access Network



Emerging Internet Access Demonstration:
Georgia Tech VHT Wireless over Fiber Access Network

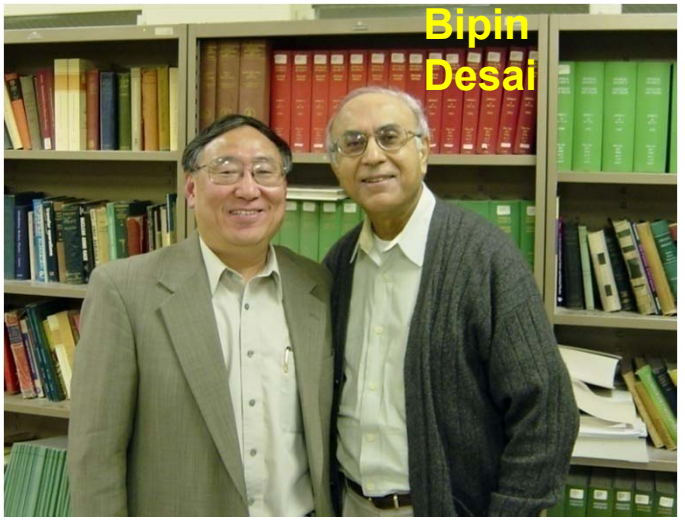


Atlanta, GA

Converged Broadband Access Networks
--- a New Frontier of Optical Communications

- Convergence of broadband wireless over fiber network architecture creates new wave of communications
- Very high throughput, low latency, HD-video and data applications are emerging for next generation converged optical and wireless access networks.
- Design and manufacturability of low-cost, optical, RF, and electronic components and systems for the converged access networks are needed urgently.
- The time is right for RF and photonics industry to harness revenues from emerging RF, millimeter-wave photonics technologies.

Celebration of 50th Anniversary Dept. of Physics and Astronomy, UCR



Celebration of 50th Anniversary , UCR Physics

Ph.D. degrees awarded in my group (now 14) at Georgia Tech

New Frontiers for Physics

The Nobel Prize in Physics 2000

- **Zhores I. Alferov, Herbert Kroemer, Jack S. Kilby**
- **For advancements in high-speed semiconductor devices and integrated circuit (IC) technologies**

The Nobel Prize in Physics 2007

- **Albert Fert, Peter Grünberg**
- **For their discovery of Giant Magnetroresistance phenomenon and revolutionized techniques for retrieving data from hard disks.**

The Nobel Prize in Physics 2009

- **Charles K. Kao, Willard S. Boyle, George E. Smith**
- **For their contributions in optical fiber communications and charge coupled devices (CCDs) in display technologies**