Upper Millimeter —Wave History, Technology and Applications for Gigabit Class Communications Services

IEEE 802 LMSC Plenary Session

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Sunnyvale California

Gigabit Class Millimeter Wave Radio Systems

The Millimeter Wave community is presenting at IEEE because:

- Computers demand higher data rates in metro and wide area networks —**There is a local loop bottleneck**
- Fiber optics will likely never be available to 3.5 Million business locations that represent some 60% of the US GNP
- Millimeter radio technology can deliver 1 to 10 Gigabit data rates at up to 4 or 5 nines for 1 to 3.5 km over some 75% of the US **This breaks the local loop bottleneck!**
- With this business opportunity, we need to begin the standardization process

This is a different class of Radio

- Gigabit class low cost radios

Not your father’s Oldsmobile

(Nor his "Atwater-Kent" either

Some facts before we get started

- If you have fiber in the sidewalk in front of your building, it costs on the order of $75K to $200K to light up the facility (carrier grade rules)
- Trenching costs are $200K to $1.5 Million per km in an urban area
- These are the likely reasons most business buildings will not receive fiber in our professional lifetimes

Some more facts

- The FCC has authorized 7 GHz of spectrum in the 60 GHz band (57 to 64) for unlicensed use
- This frequency can be used for point to point links at Gigabit speeds for up to 1 km at 4 nines in about 50 % of the US

And just a few more

- Recent filings with the FCC are aimed at opening an additional 15-20 GHz of spectrum above 60 GHz
- The windows in these higher frequencies can enable Millimeter wave links operating at up to 10 Gigabits at 4 nines at up to 3 km to 4 km in about 50 % of the US

And finally,

- 64 bit computers operating at 32 Gbytes throughput are upon us
- They are a single chip microprocessor

- Now an **opinion**:

  Computers are happy when they communicate with other computers at some major fraction of their operating speed!

Terahertz Technology
Applications for Radio and Fiber Optics

- Market Update
- Technology Update
- System Descriptions
- Applications

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Whoops!! One more thing before we get started:

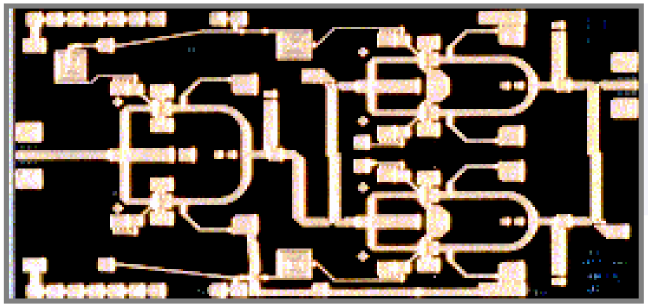
- Above 20 GHz a wire bond really starts to be a very good antenna.
- The effects of the wire bond can be “tuned out” the circuit performance,
- However: The tuning circuits are inherently narrow band.

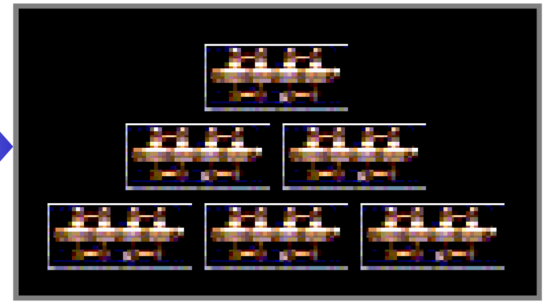
- You probably want flip chip at high millimeter wave frequencies

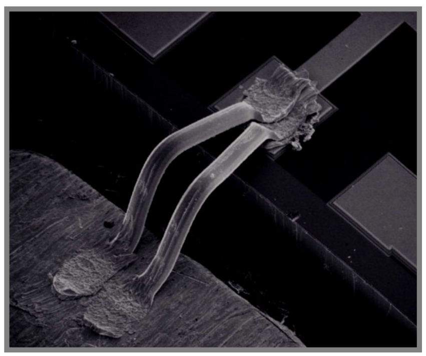
Cost Advantage -*Breakthrough Flip-Chip Design*

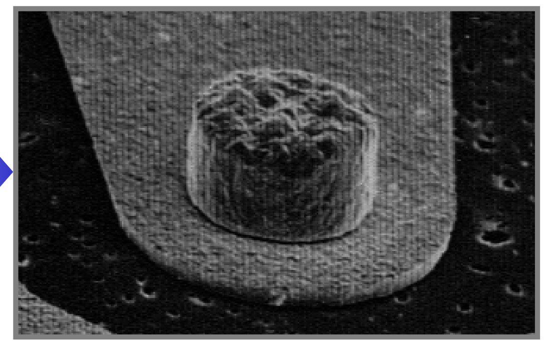
Traditional Monolithic MmW IC & Wire Bond

Endwave Flip-Chip





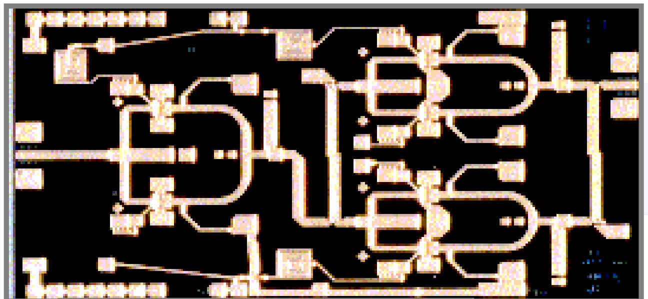


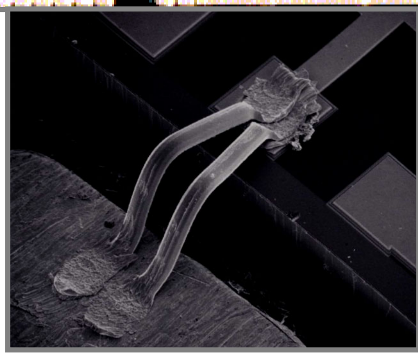


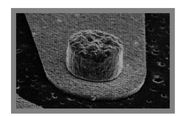
Cost Advantage*Breakthrough Flip-Chip Design*

Traditional Monolithic MmW IC & Wire Bond

Endwave Flip-Chip

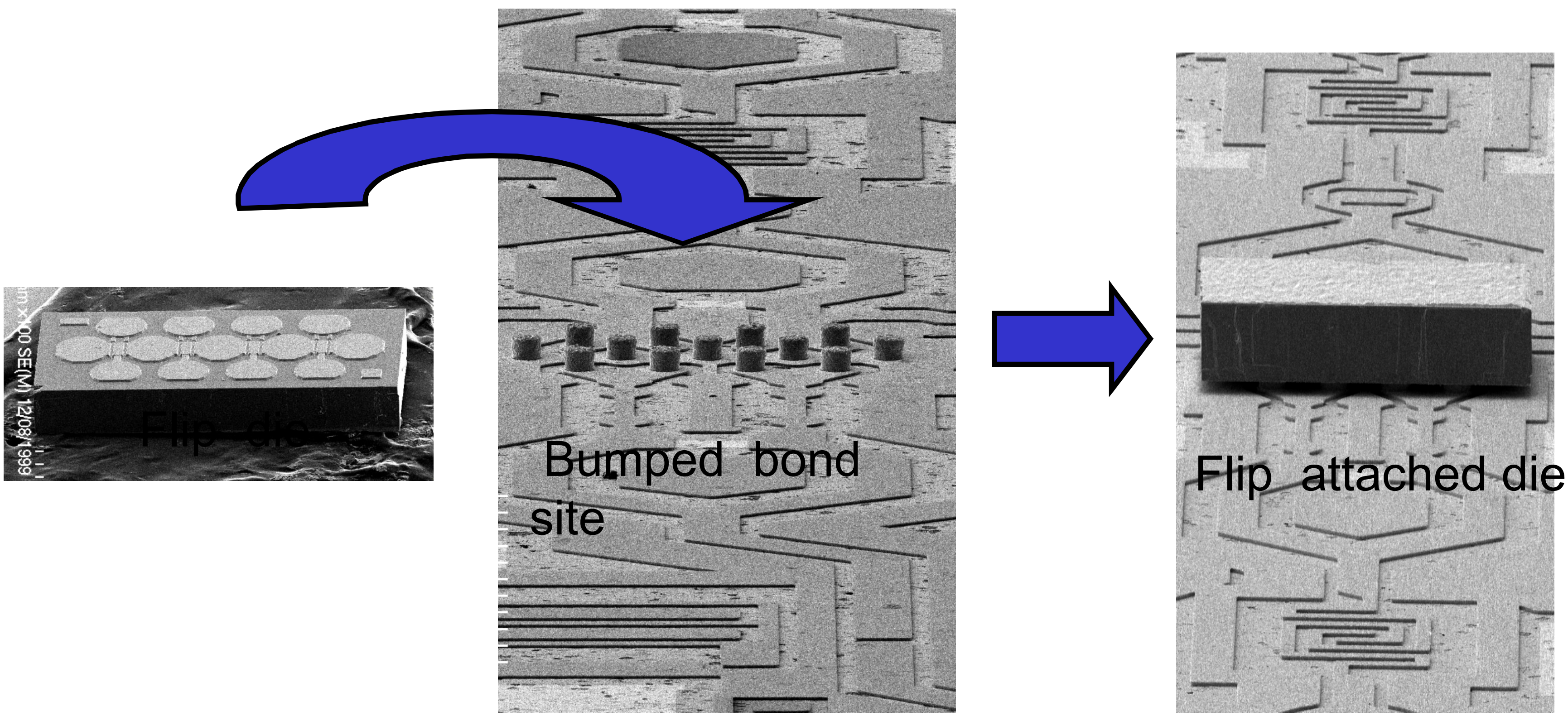




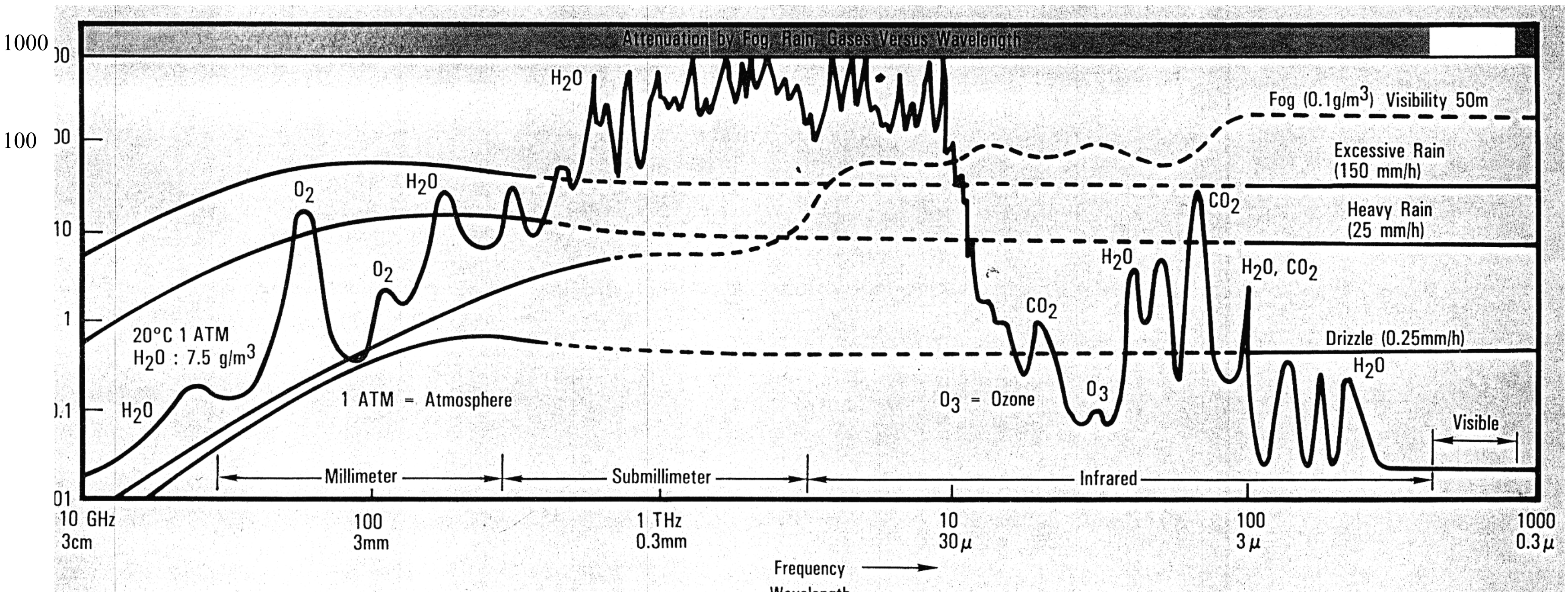


10:1 — 20:1 Size Reduction
10:1 Reduction in Antenna Effect (Inductance)
90% GaAs and Indium Phosphide Saving

MCIC Flip Attach

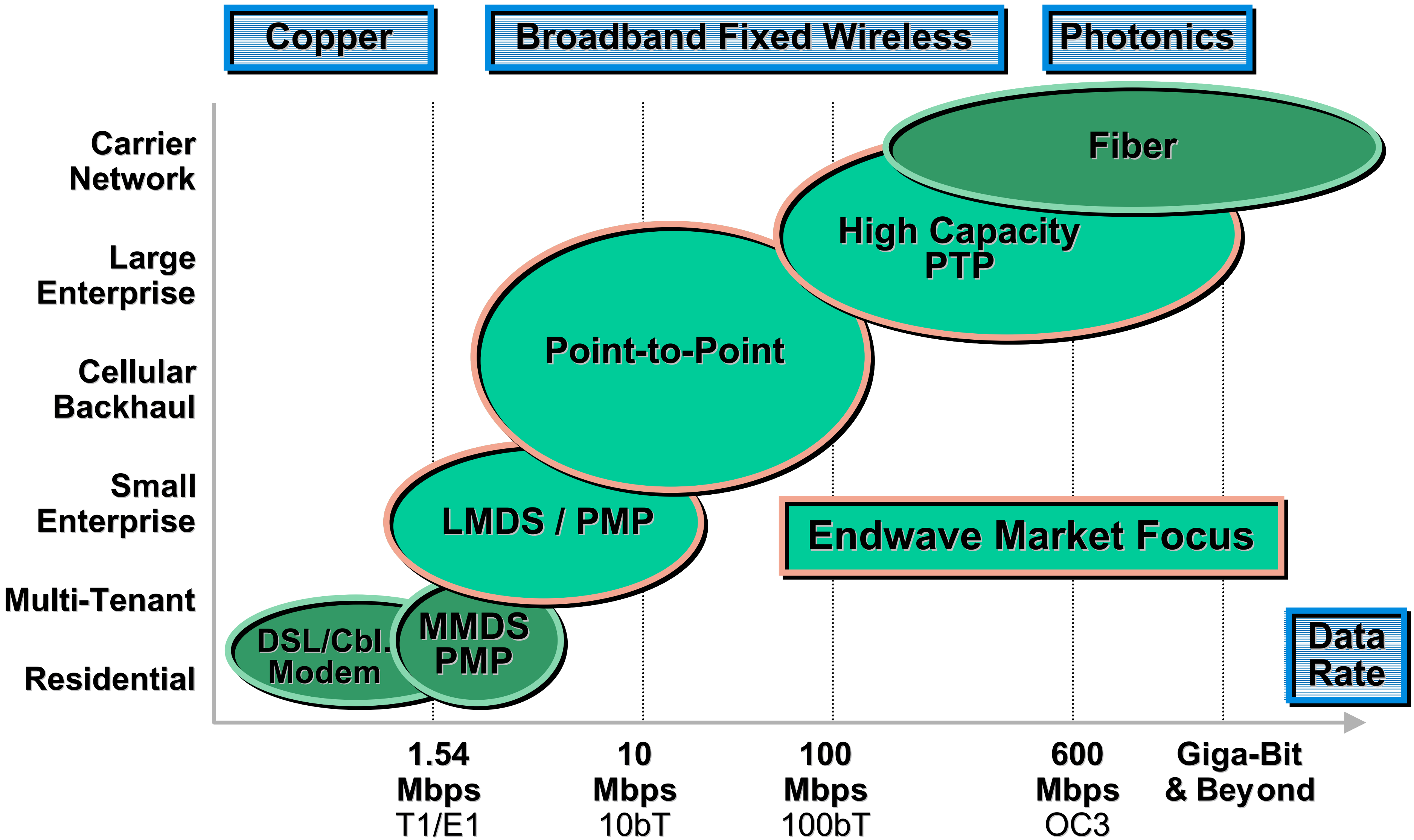


Attenuation by Rain, Fog, Gases VS. Wavelength

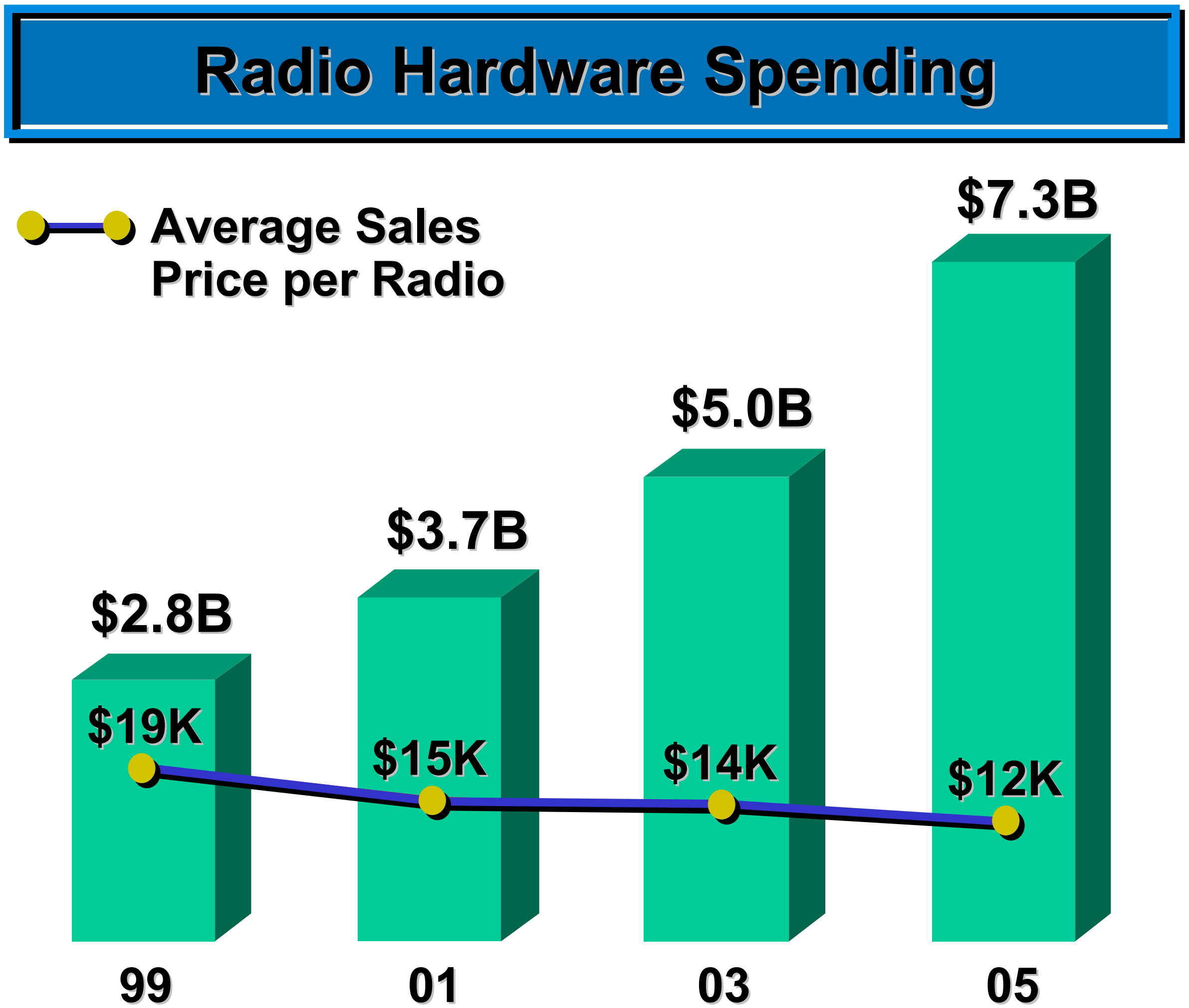


Source: TRW, Electromagnetic Spectrum Chart

Access Technology Development



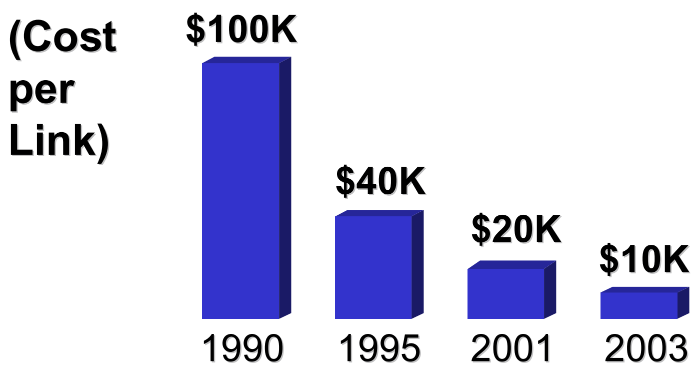
Microwave-Millimeter Wave Radio Market



Sources: CIBC World Markets, Strategies Unlimited, Company Analysis

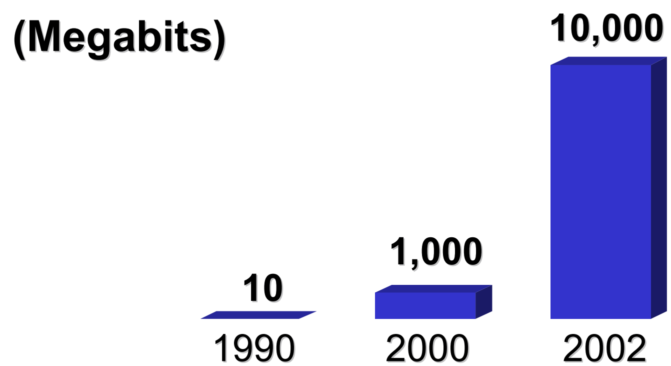
Radio Technology is Better than You May Think

Lower Radio Cost



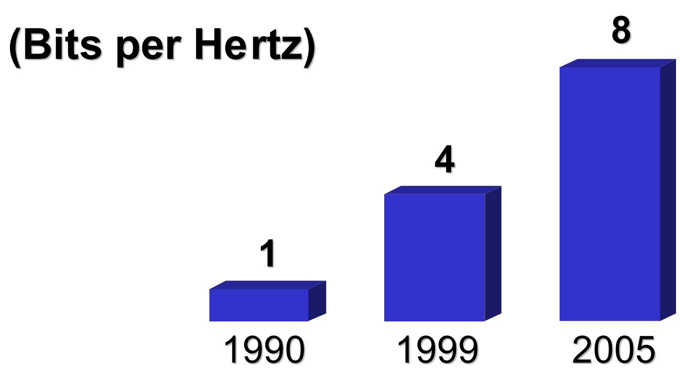
Source: Company Analysis

Growing Radio Data Rates



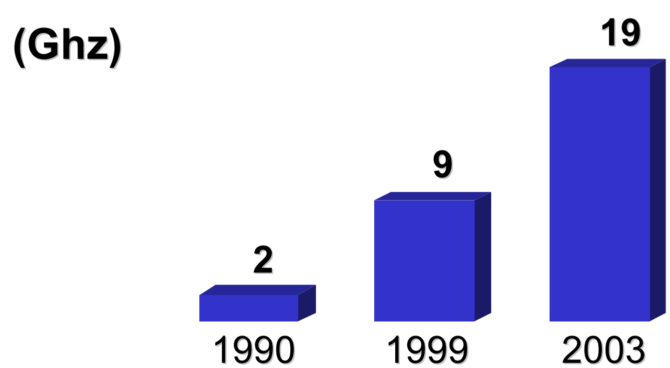
Source: DMC Stratex, Harmonix, Nokia, Harris

Greater Radio Spectrum Efficiencies



Source: DMC Stratex, Harmonix, Nokia, Harris

More Spectrum is Available

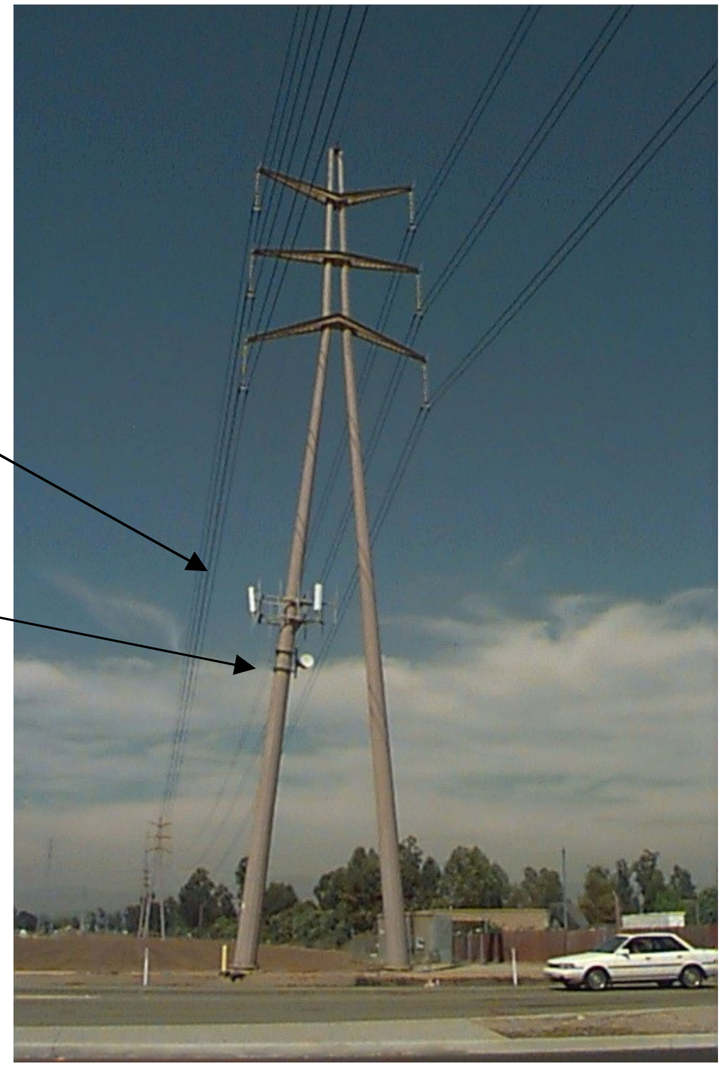


Source: FCC

Cellular Base Station on Powerline

Cellular Antennas

Millimeter Wave
Radio Backhaul



Cell Site Backhaul — 90 % of Millimeter Wave Radio Market

- Cell site backhaul- millmeter wave radio — 85% international, 15% U.S.
- 2 or more carriers justifies a radio backhaul in U.S.

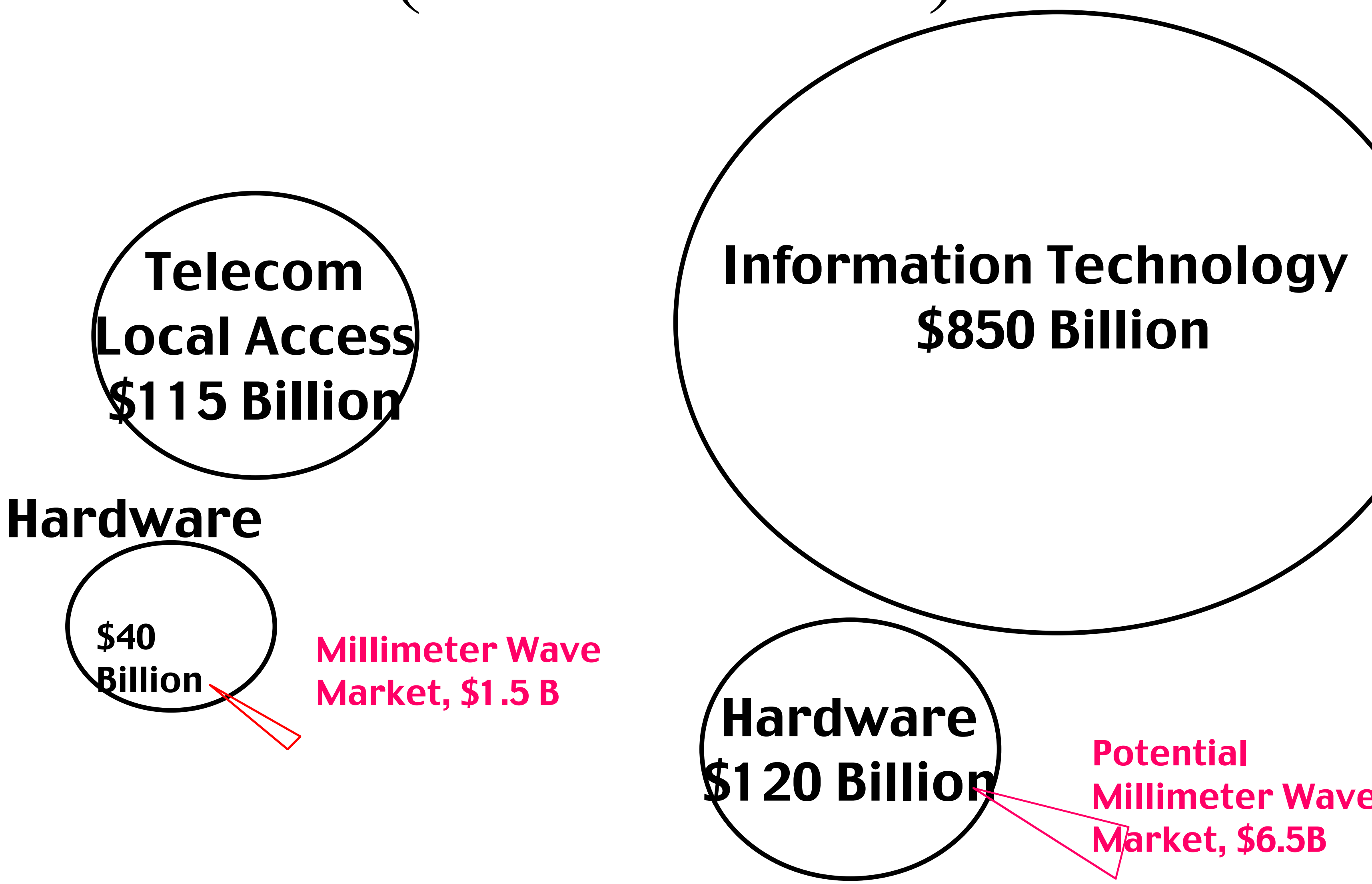
The View From Silicon Valley

- Next generation computing requirements are huge
- The distinction between computing and communications becomes less distinguishable
- Computers want to communicate at somewhere near microprocessor operating speed
- Legacy communication architectures and hardware are no solution in the last mile

Primary Market Driver Computer Performance

- Computer Performance sets the bar for communications needs
- Computer Performance defines communications systems performance
- Computer performance is pervasive — impacts every aspect of business and life in general

Computer Vs.Telecom Markets (Local Access)



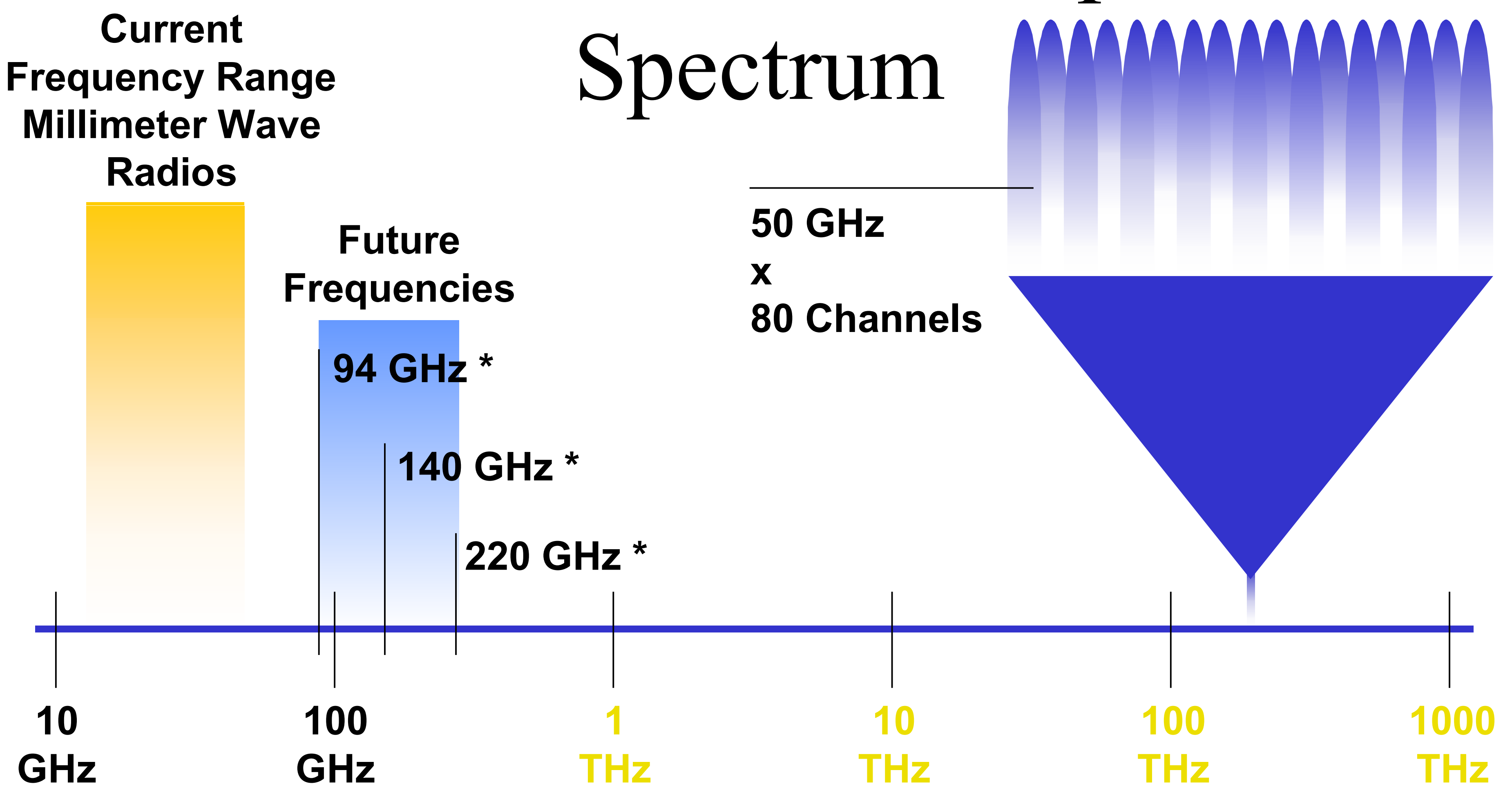
Ethernet Growth

- Year 2000, 7 Million Gigabit Ethernet LAN s sold.
- Growth is 270% per year
- 10 Gigabit supplier base has exceeded 40 companies
- Ethernet formats compatible with SONET

Fiber Optic Market

- This market will likely pave the way for Millimeter wave radios above 80 GHz

Millimeter Wave & Optical Spectrum



* In Development

Teraherz Radios —New Technology for Local Access

OUTLINE

- Overview of Access Technologies
- Terahertz and Sub Teraherz Technologies
- Overview of Radio Technologies
- New Spectrum Possibilities
- The Interface and Convergence With Optical Technologies
- Applications of 1 and 10 Gigabit Ethernet Access Networks
- Players
- Investment Strategies

Boundary Conditions for the Teraherz Radio Tutorial

- Primary market driver for interconnect data rate increase is computer performance.
- Fiber Optic systems are growing to near infinite data rates.
- LANs use Fiber Optics for 1 Gigabit and above to provide connectivity to the desktop.
- MANs and WANs use fiber very effectively for backbone and backbone rings.
- First mile and last mile local access connectivity is limited by infrastructure cost and difficulty (trench cost, not fiber cost.)

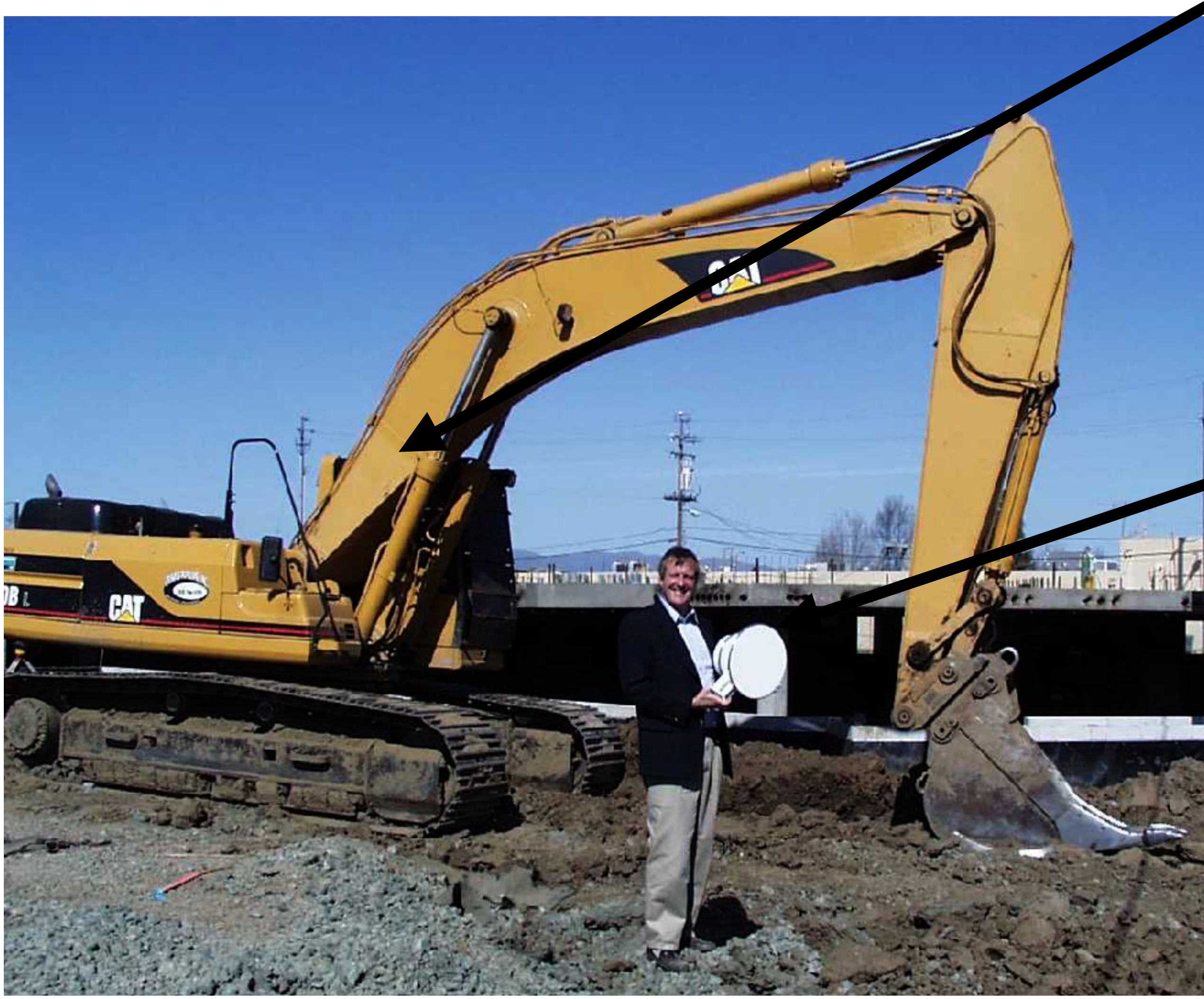
Boundary Conditions (continued)

- Radios and Free Space Lasers will provide high speed local access for 80% to 90% of business locations for the next 10 to 15 years.
- Legacy networks will only continue to be successful on voice centric applications.
- Ethernet architectures in the MAN and WAN are poised for success, in addition to the Ethernet in the traditional LAN.

The Most Significant (Market) Boundary Condition

- Todays Millimeter wave radio market is dominated by Legacy Architectures
  - Cellular (Mobile Cell Sites) Backhaul is 80 % of Mmwave radio market.
  - The transition to 3G and 2.5 G and GPRS is driving data rates from a few Mbits/sec (4 T1 or 8 T1) to OC-3 (155 Mbits/sec)
- This course is based on a totally different market — computer to computer networks- a community that needs Gigabits and 10 Gigabits

Ultra - Broadband Installation Tools

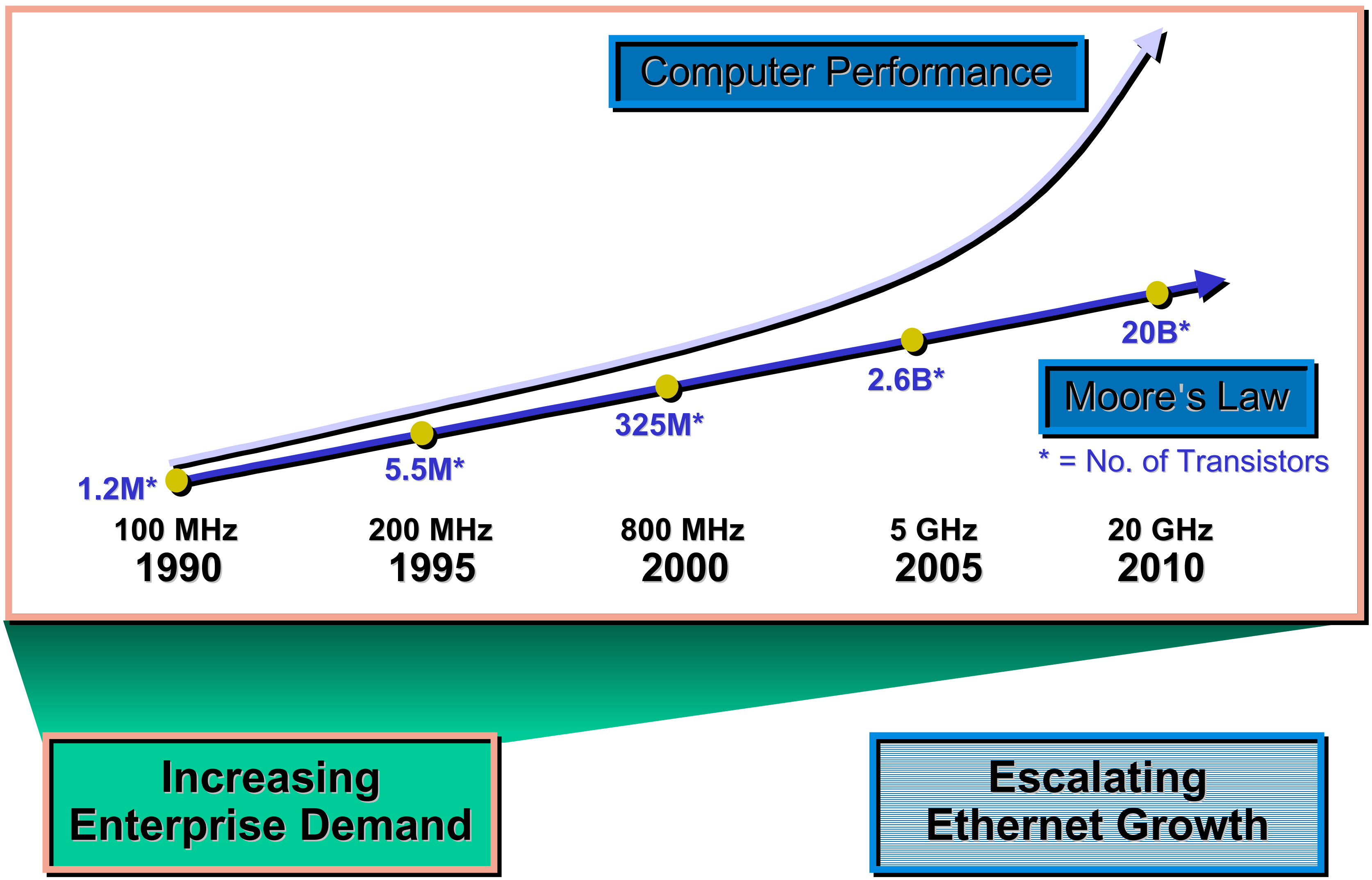


- **Fiber Optic**
  - Avg. $1 Million per Metro mile
  - Months to deploy
- **Fixed Wireless**
  - Avg. $30 - $80k per Metro mile
  - Hours to deploy

Market Drivers

- Computer performance
- Storage Area Networks
- Video Conferencing
- Meta- Computing
- Internet Backbones
- 3G and 2.5 G Mobile Network Backhaul
- Cost of trenching

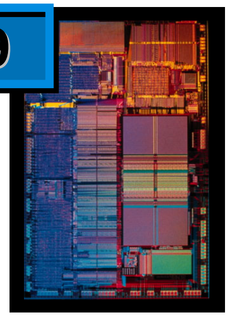
Increasing Demand forComputer to Computer Bandwidth



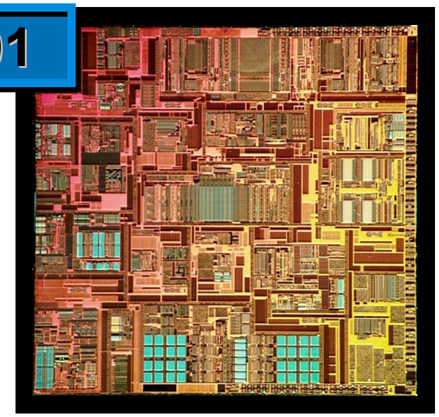
Source:

Increasing Demand for Computer to Computer Bandwidth

1989



2001



Intel 486	Intel Itanium™ *
1.2 Million Transistors 100 Mhz	325 Million Transistors 800 Mhz

Increasing Enterprise Demand

Escalating Ethernet Growth

Sources: In-Stat / MDR, Intel, Forbes

** With Permission from Intel. Photos are Estimated Scale.*

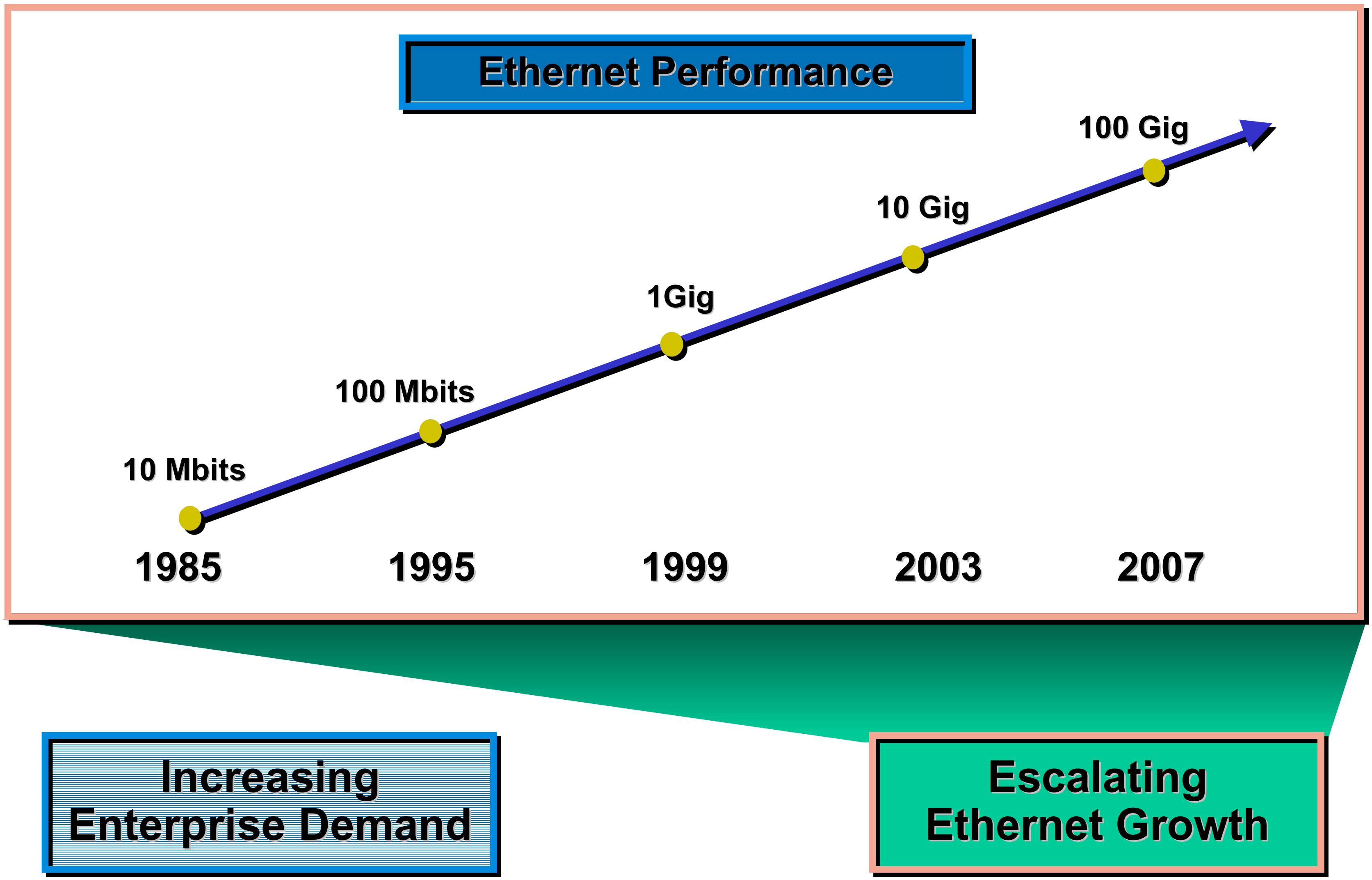
Increasing Demand for Computer to Computer Bandwidth

Ethernet		ATM
1,500 Bytes	**Payload Size**	48 Bytes
$25K	**Switch Cost**	$250K
Data	**Focus**	Voice

Increasing Enterprise Demand

Escalating Ethernet Growth

Increasing Demand for Computer to Computer Bandwidth



Increasing Demand for Computer to Computer Bandwidth

Increasing Adoption

- 80% of the World's Data Begins and Ends on the Ethernet
- Expansion Beyond the LAN to the MAN and WAN
- 3.6 Million Gigabit Ethernet Switch Ports Sold in 2000
- 40% Annual Growth in Units Sold

Increasing Enterprise Demand

Escalating Ethernet Growth

Source: Dell Oro Group, Fiber Street

Storage Area Networks

- Presently use Fibre Channel at 1 or 2 Gigabits
- Present use is for storage campus
- Desire Metropolitan and Wide Area solutions

Video Conferencing

- Standard TV (NTSC) is 6 MHz RF Bandwidth with 60 dB dynamic range
- Digitized, this is 120 Mbits/sec
- MPEG 3 Compression reduces data rate to approximately 3 Mbits/sec average
- Decompression is easy
- Real time compression is very difficult
- Extra bandwidth (40 Mbits) make real time compression compatible with microprocessor

Meta-Computing

- Primary driver is Biotech designers
- Next major user is EDA
- Other users, weather, aerodynamics
- Desire Terabit and Petabit files
- Use multi Exabit storage

Internet Backbones

- Internet continues to grow at 2X per 3 months
- Next generation IP is based on Gigabit channels

Access Technology Overview

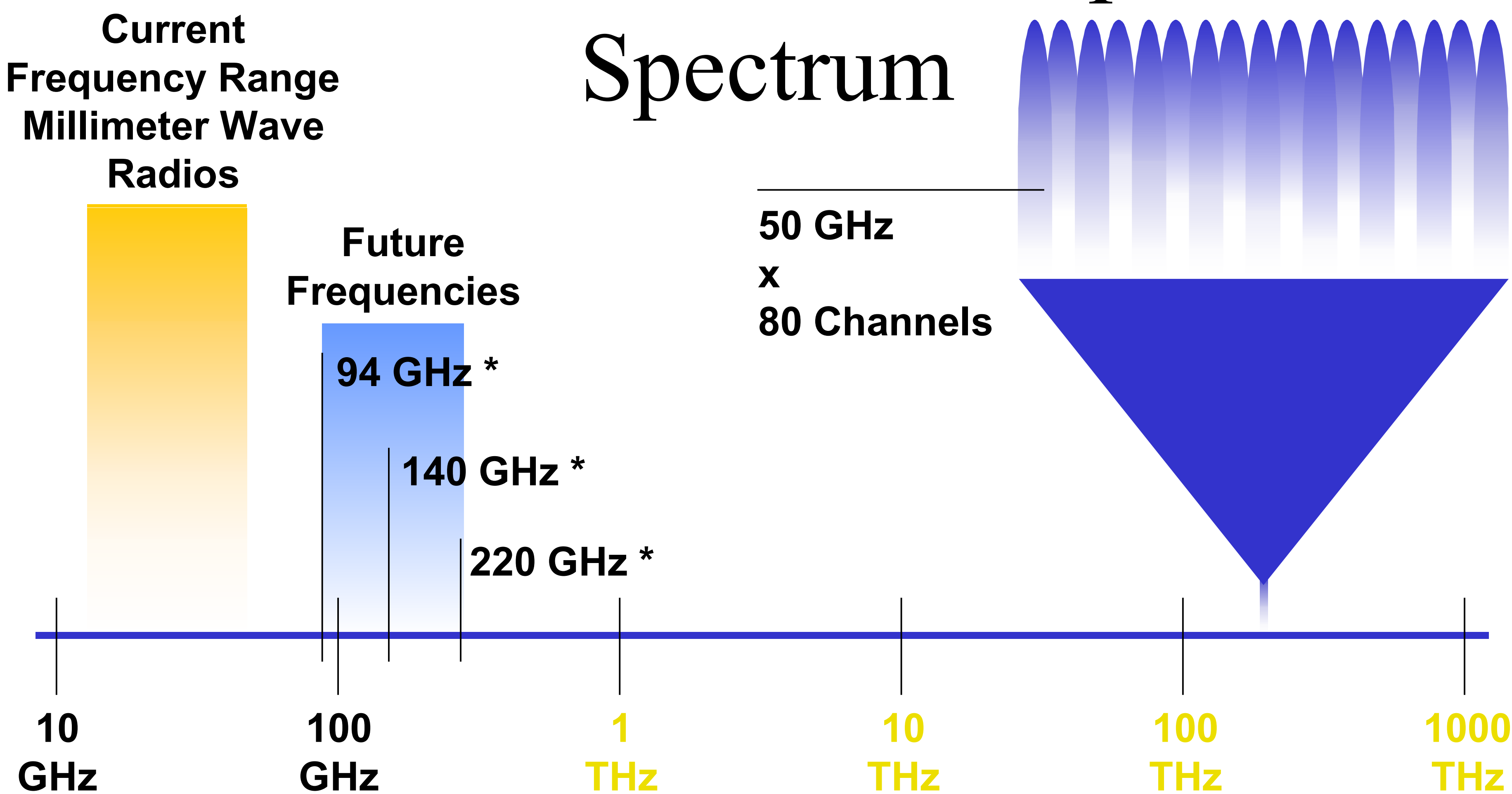
- Legacy Copper
- DSL
- Cable Modems
- Coax
- Lower Frequency Wireless (PCS,Cellular,MMDS, UNII, ISM)
- Millimeter Wave
- Free Space Lasers
- Satellite

Terahertz and Sub Terahertz Technologies

- GaAs
- InP
- GaN
- Diamond
- Ferielectric Materials
- Lasers
- Vacuum Devices
- Propagation

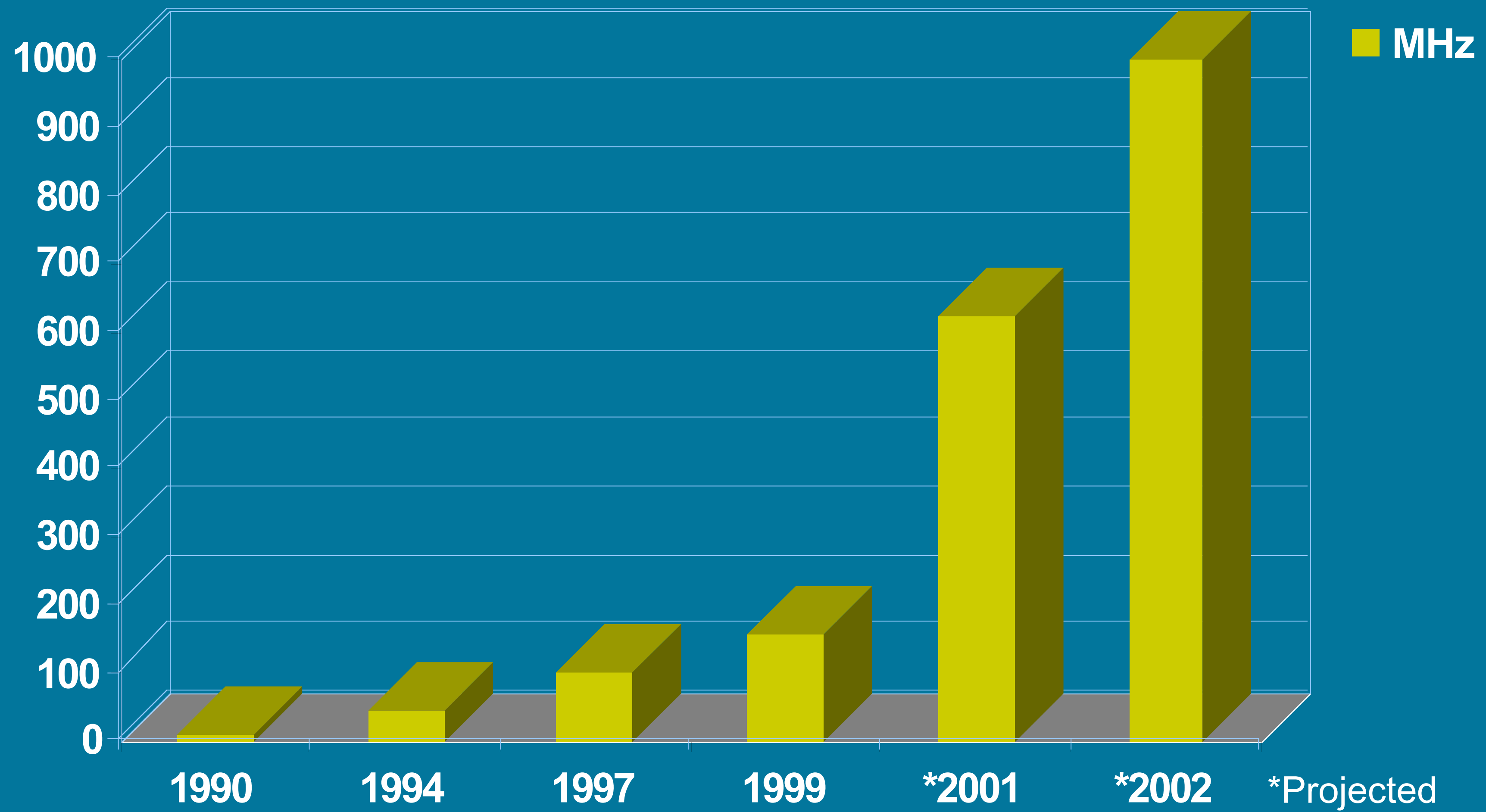
Millimeter Wave Radios Above 40 GHz

Millimeter Wave & Optical Spectrum

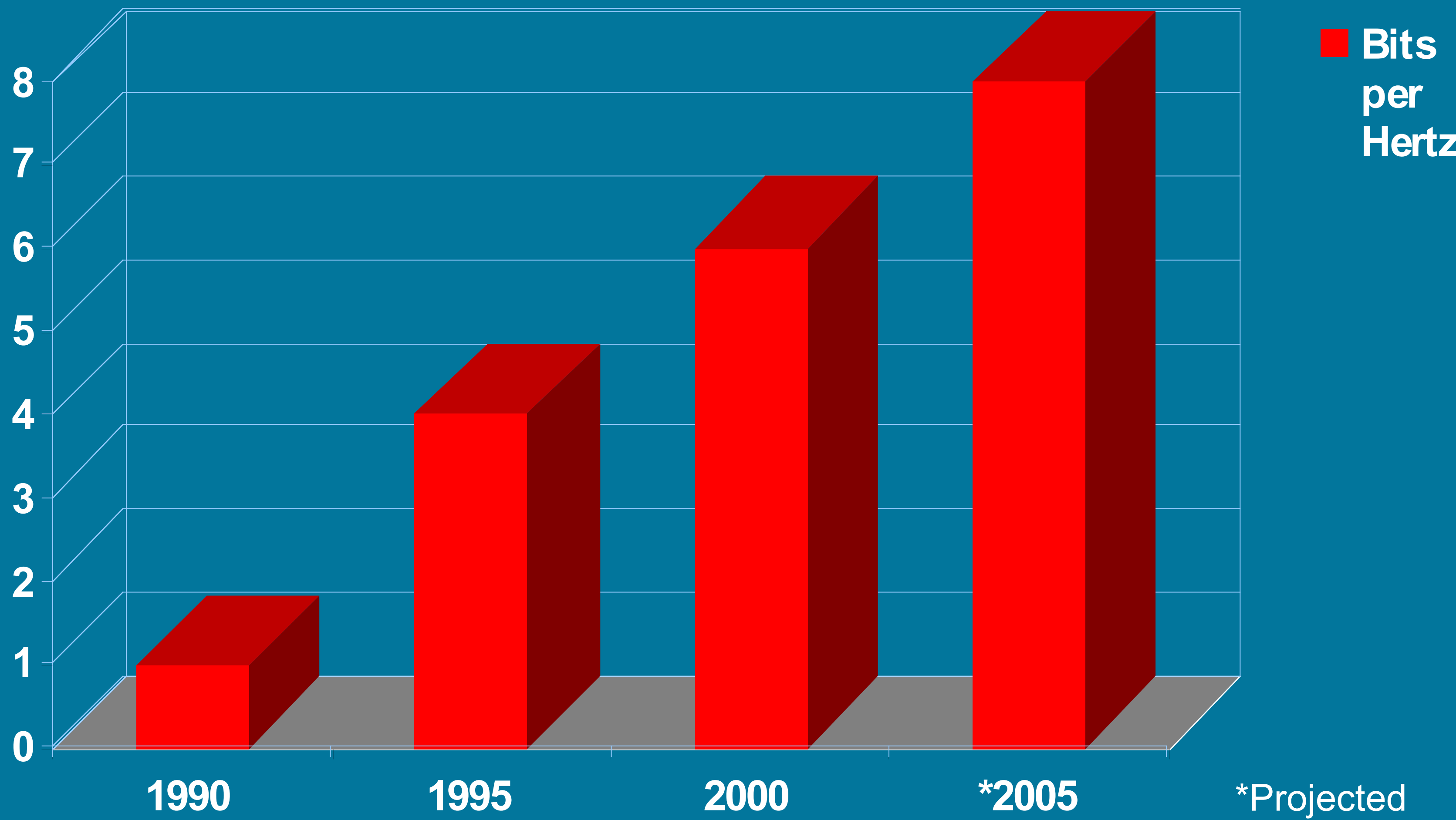


* In Development

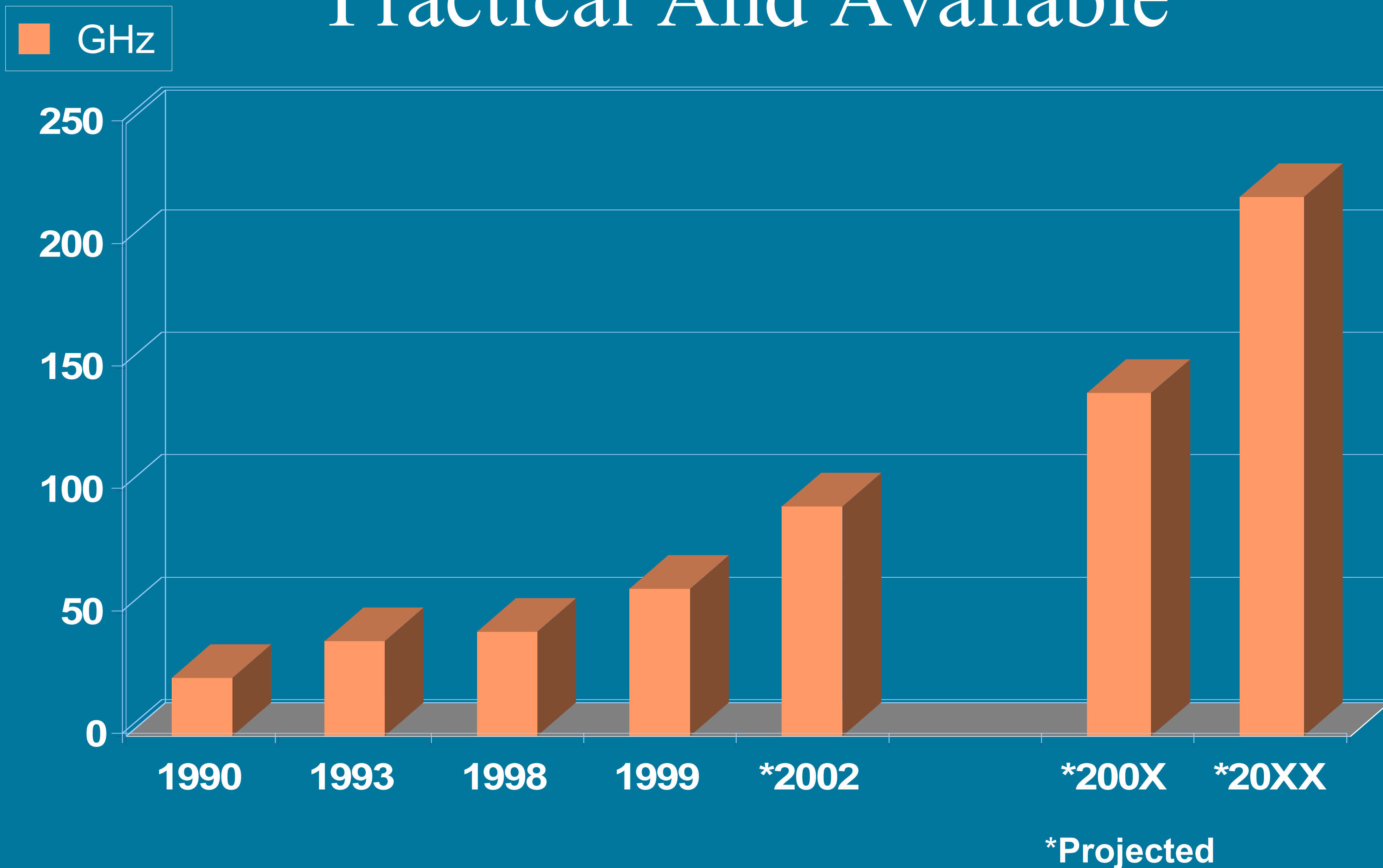
BWA Data Rates Continue To Grow (Millimeter Wave Radio Performance)



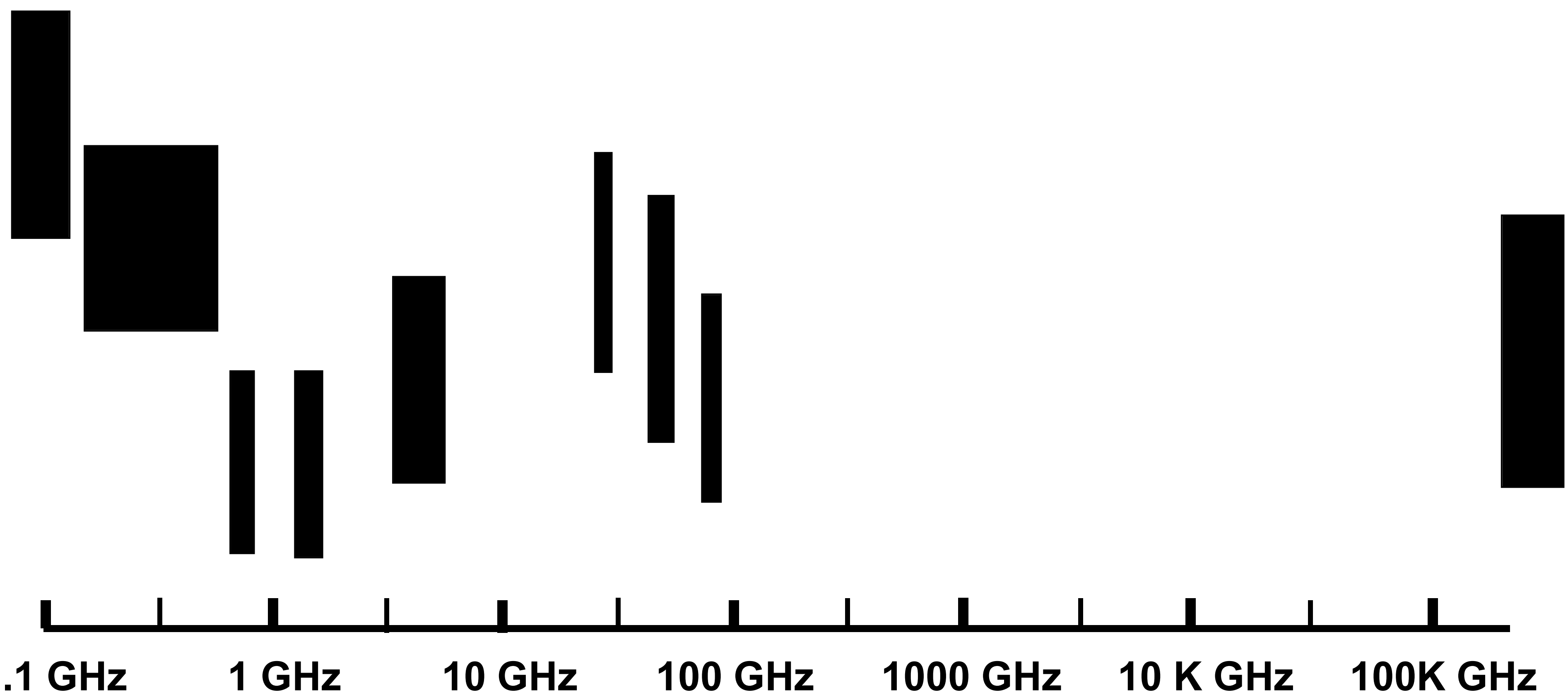
Radio Spectrum Efficiencies Have Increased Substantially



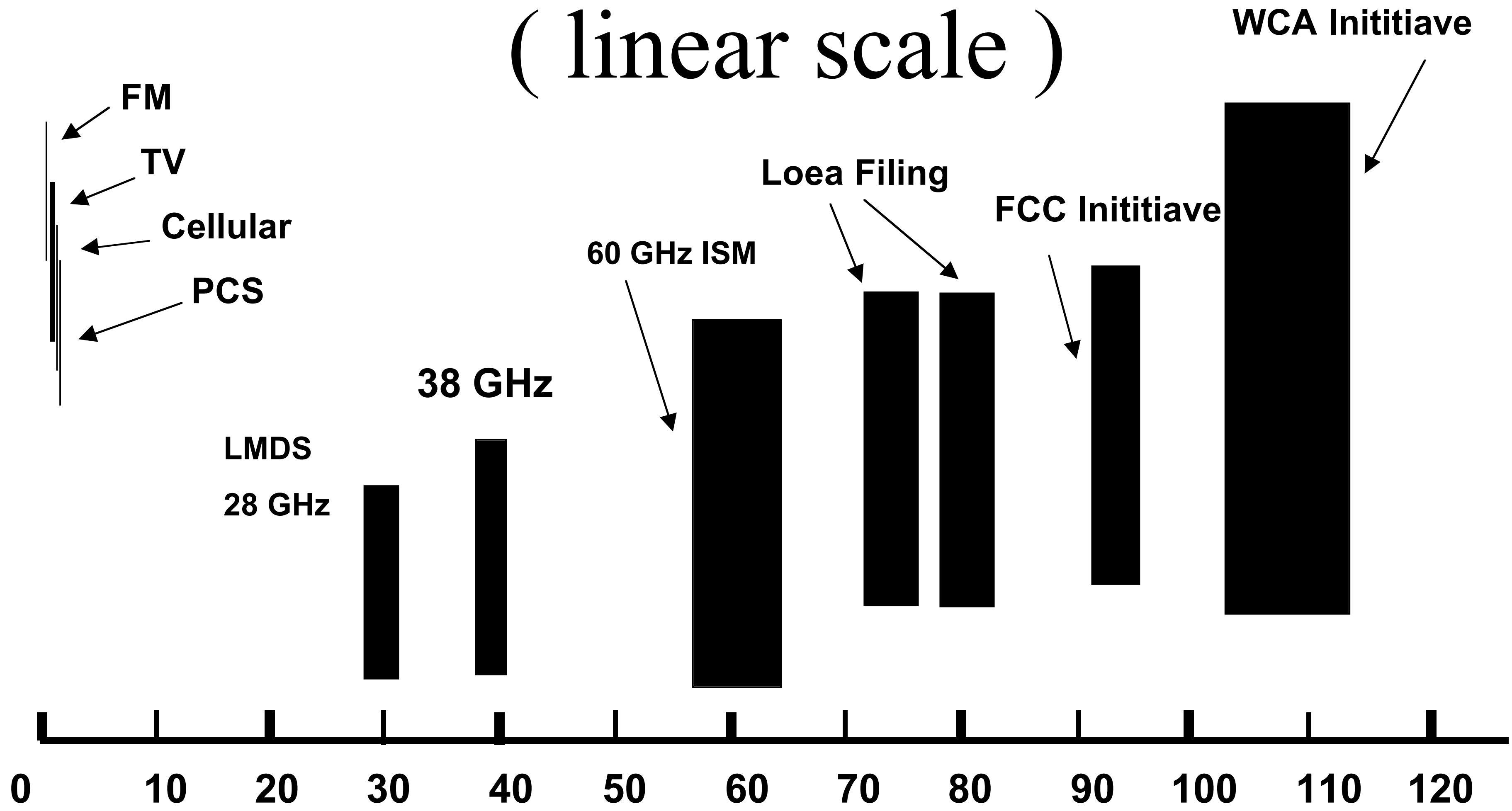
Higher Frequencies Become Practical And Available



Radio Spectrum Allocations



Radio Spectrum Allocations
(linear scale)



Next Generation Radio Architectures

- 10 plus GHz RF bandwidth each direction needed for low cost architectures
  - 1 bit per hertz modems are achievable
  - Oscillator performance is achievable
  - Power amplifier performance is difficult today
- Spectrum opportunities above 40 GHz extend into 300 GHz range
- Radios should stay in step with LAN, MAN and WAN performance
  - 10 Gbits in pilot production
  - 100 Gbits on drawing board

Overview of Radio Technology

- Link Margin
- Transmitters and Receivers
- Antennas
- Modulation and Bits per Hertz
- Atmospheric Considerations (Propagation)
- Frequency Reuse
- Platform Considerations (Towers, Buildings, Aircraft, Blimps, Satellite)

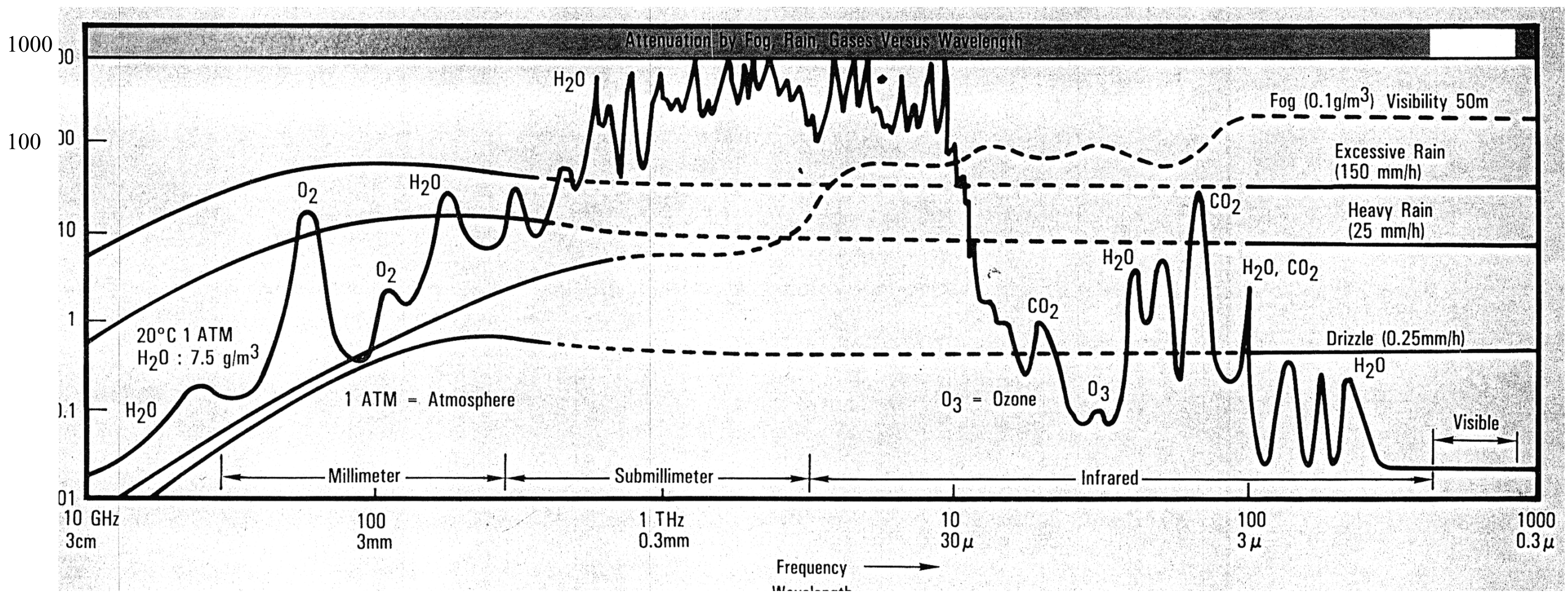
Radio Technology

- To begin:
  - Noise floor at — 114 dBm/ MHz
  - This is one Millionth of one Millionth of one Two Hundredth of a watt for 1 MHz of bandwidth
  - Or, $1/200^{th}$ of a Trillionth of a watt for 1 MHz of bandwidth
  - For 1 GHz of bandwidth the noise floor is 1000 times higher than for 1 MHz
- A radio link has to deliver a signal to the receiver that is 20 to 100 times larger than the noise floor, for typical applications.

Radio Technology —Atmospheric Effects

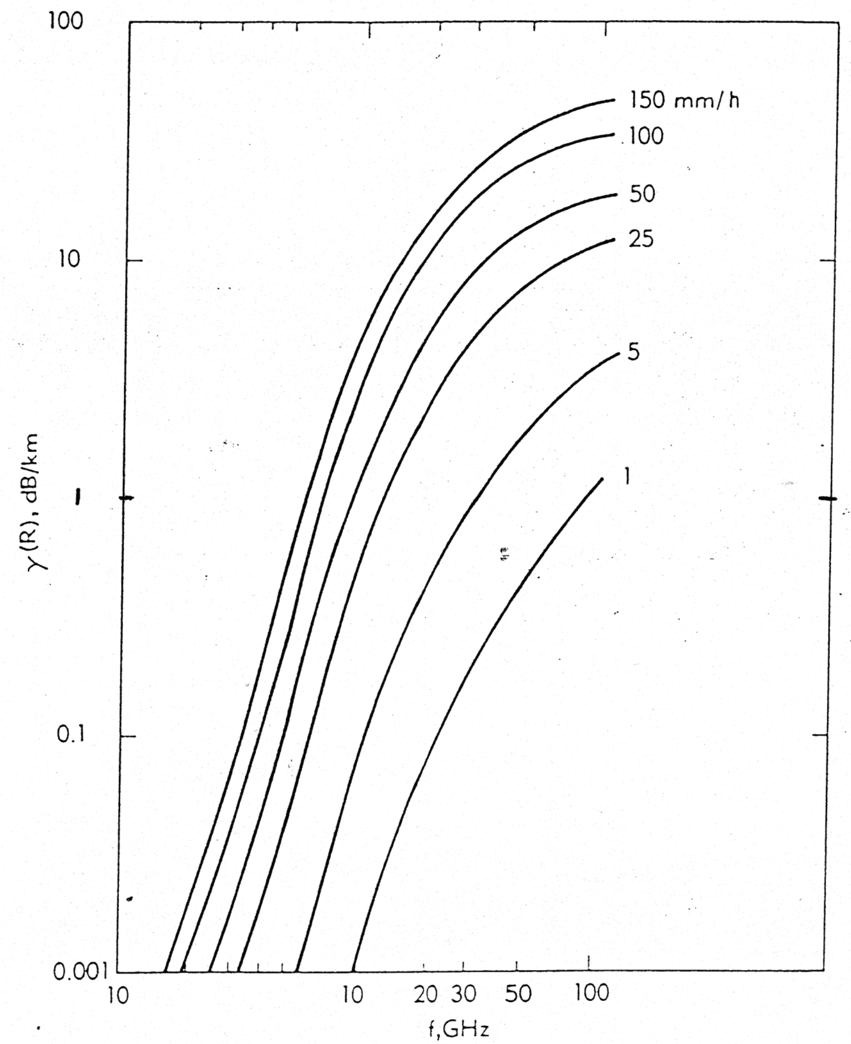
- Free Space Attenuation is just one factor-
  - Rain Effects
  - Atmoshperic atomic and molecular attenuation
  - Snow Effects
  - Fog Effects
  - Ice build up on antennas
  - Radome losses
  - Atmospheric anomalies (lens effects)
- Link engineering needs to address these factors — they are geographically unique

Attenuation by Rain, Fog, Gases VS. Wavelength



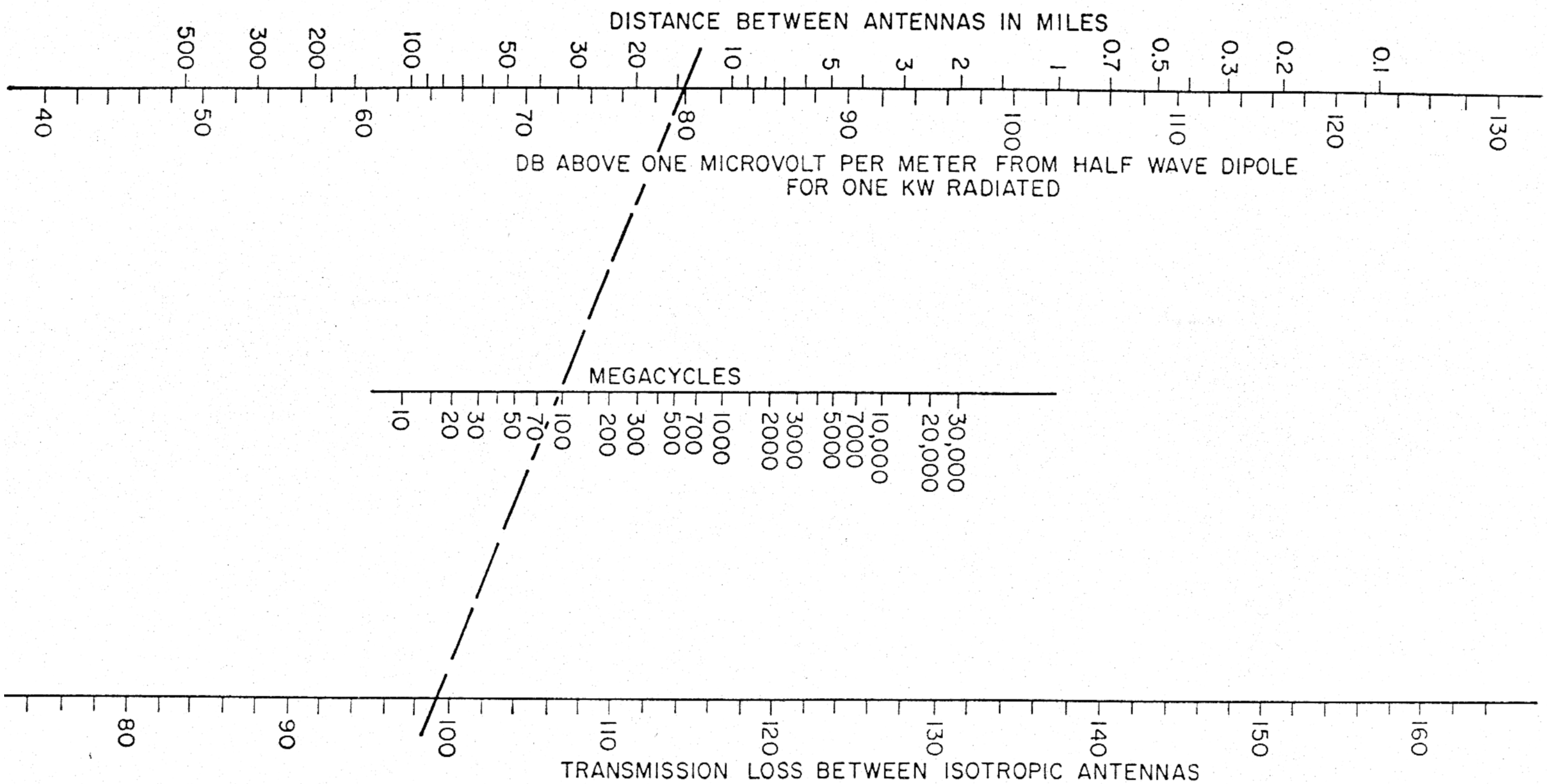
Source: TRW, Electromagnetic Spectrum Chart

Rain-Induced Specific Attenuation



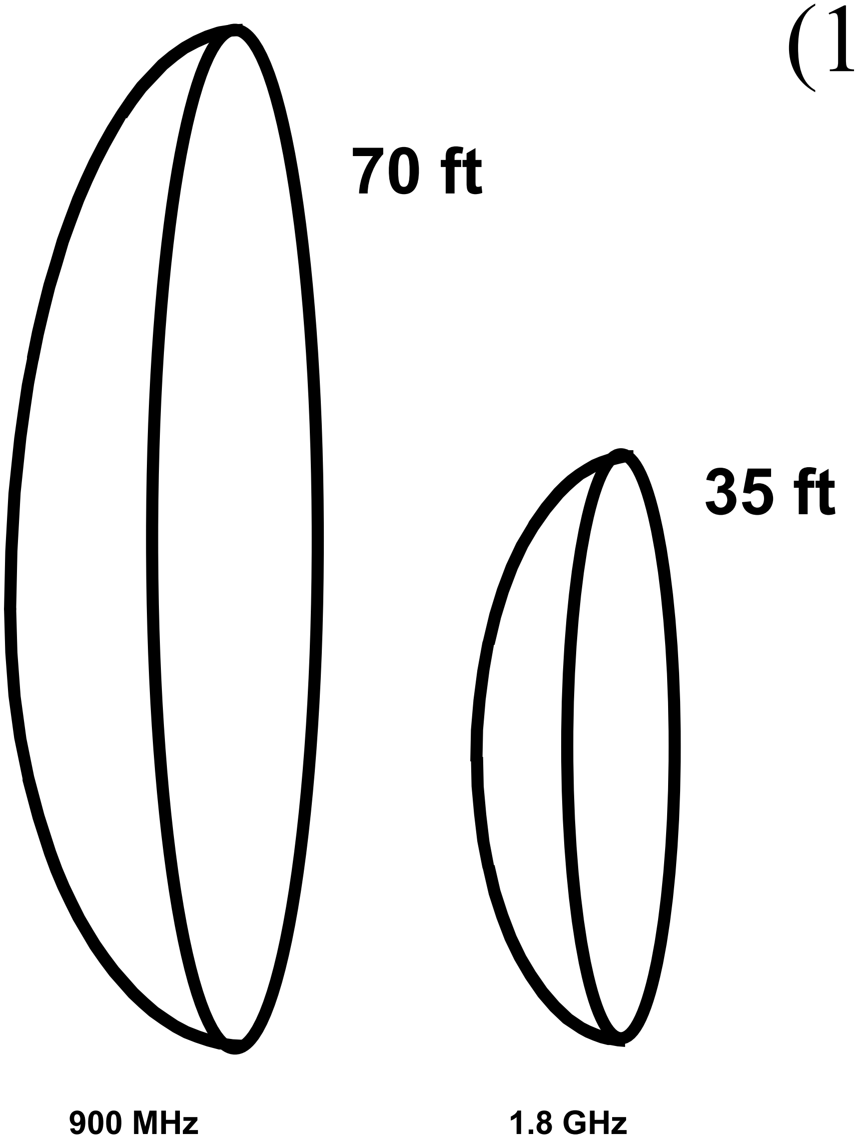
Source: Johnson and Jasik, Antenna Handbook, Mcgraw Hill

Free-Space Transmission



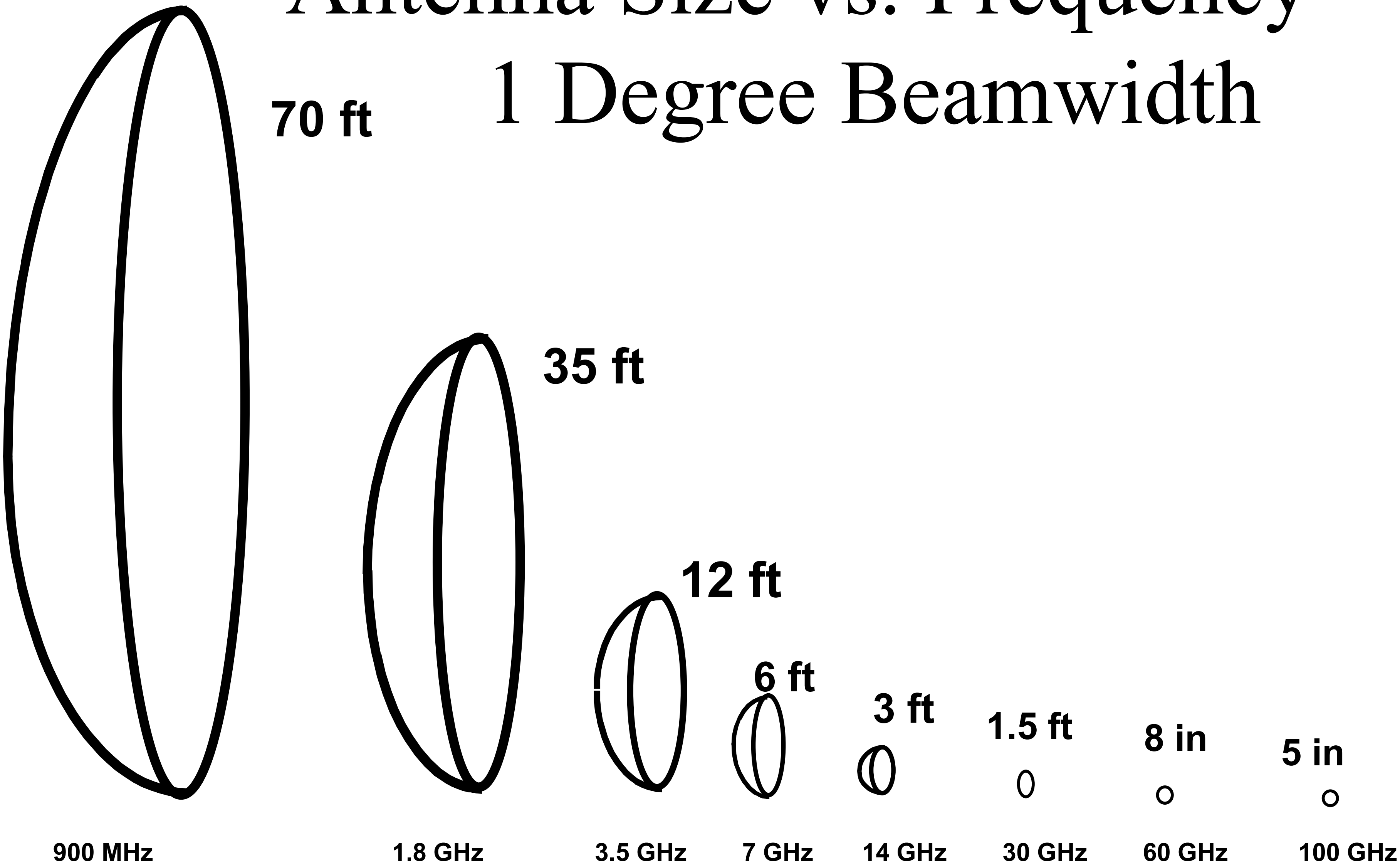
Source: Jasik, Antenna Handbook

Antenna Size vs. Frequency (1 Degree Beamwidth)

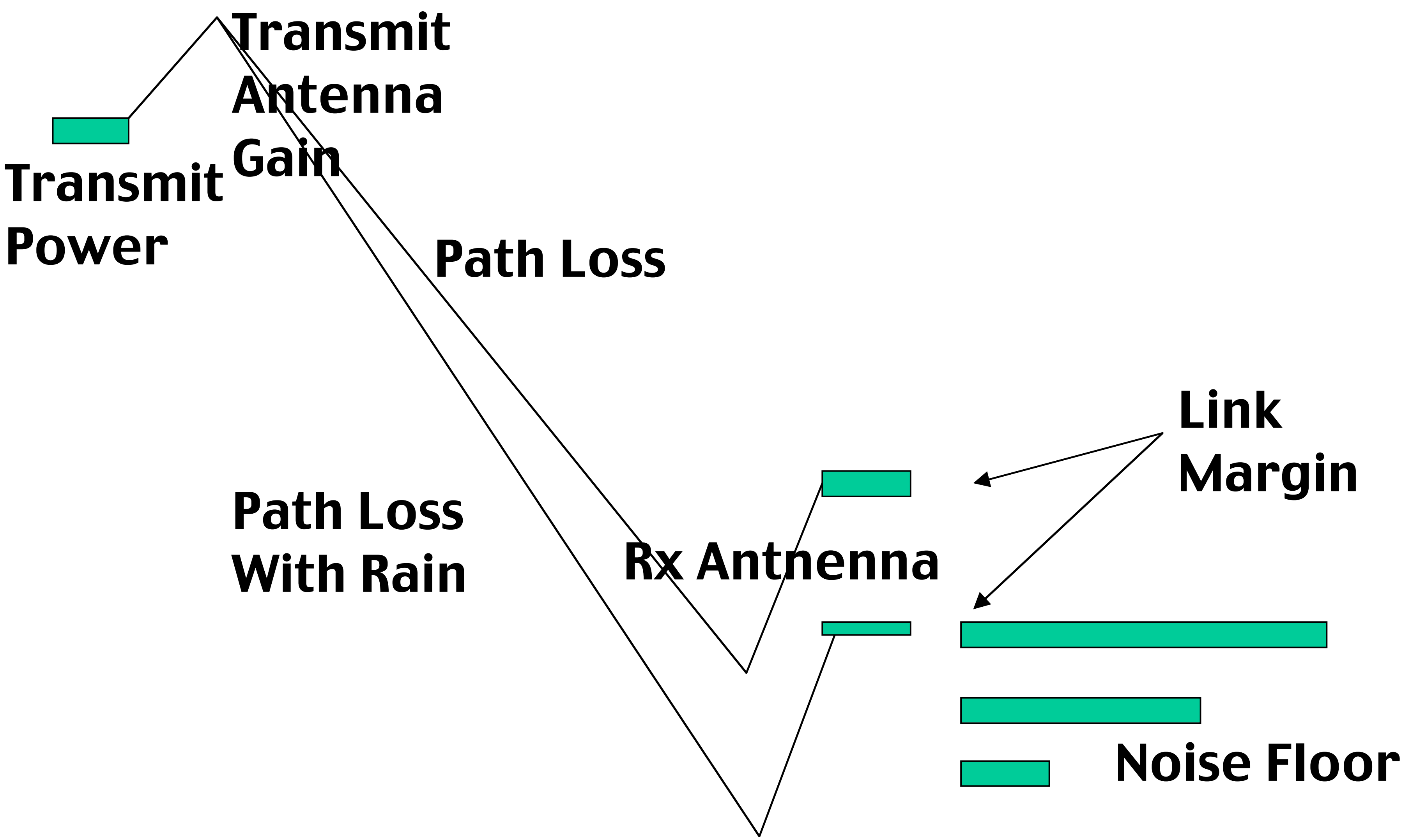


If we could use antennas like these, 10 megabits on a cell phone would be easy

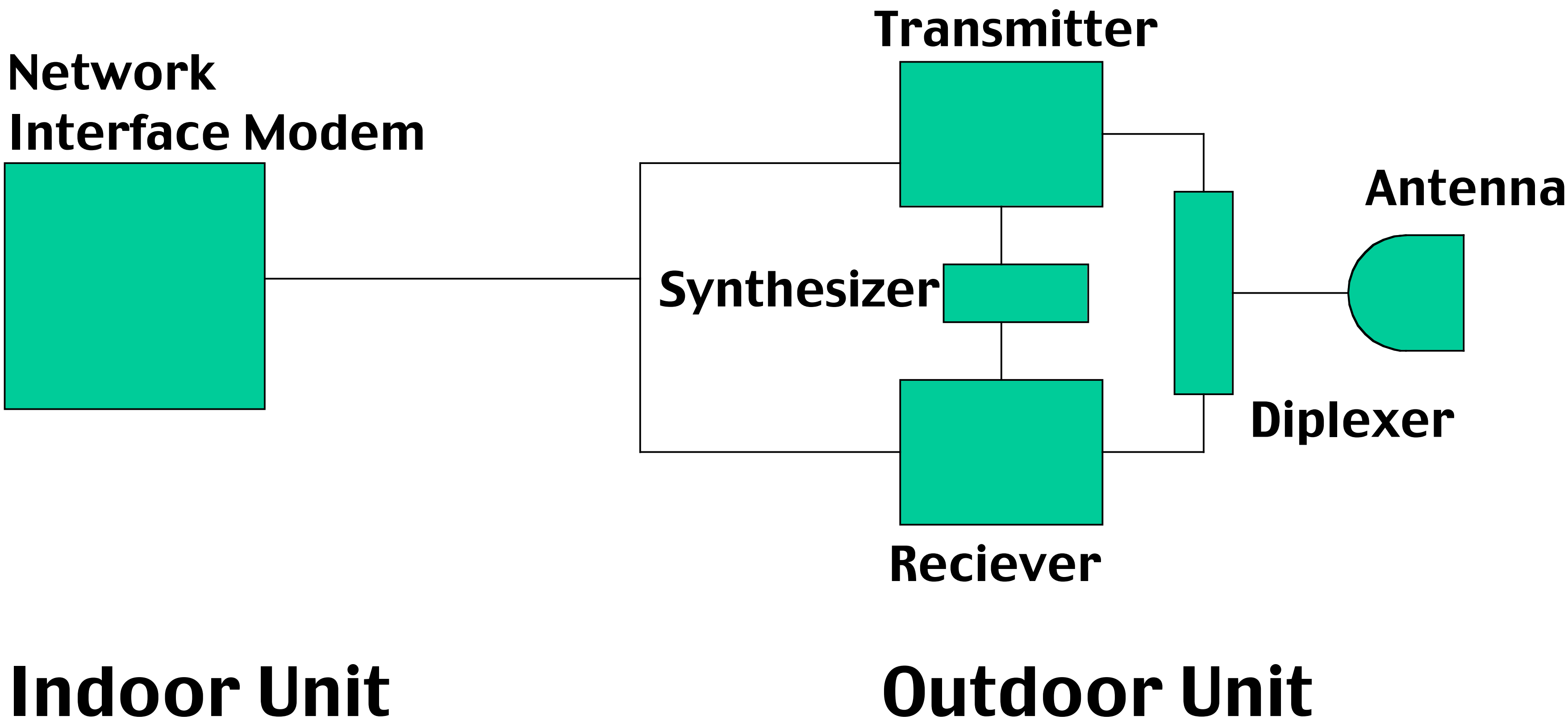
Antenna Size vs. Frequency
1 Degree Beamwidth



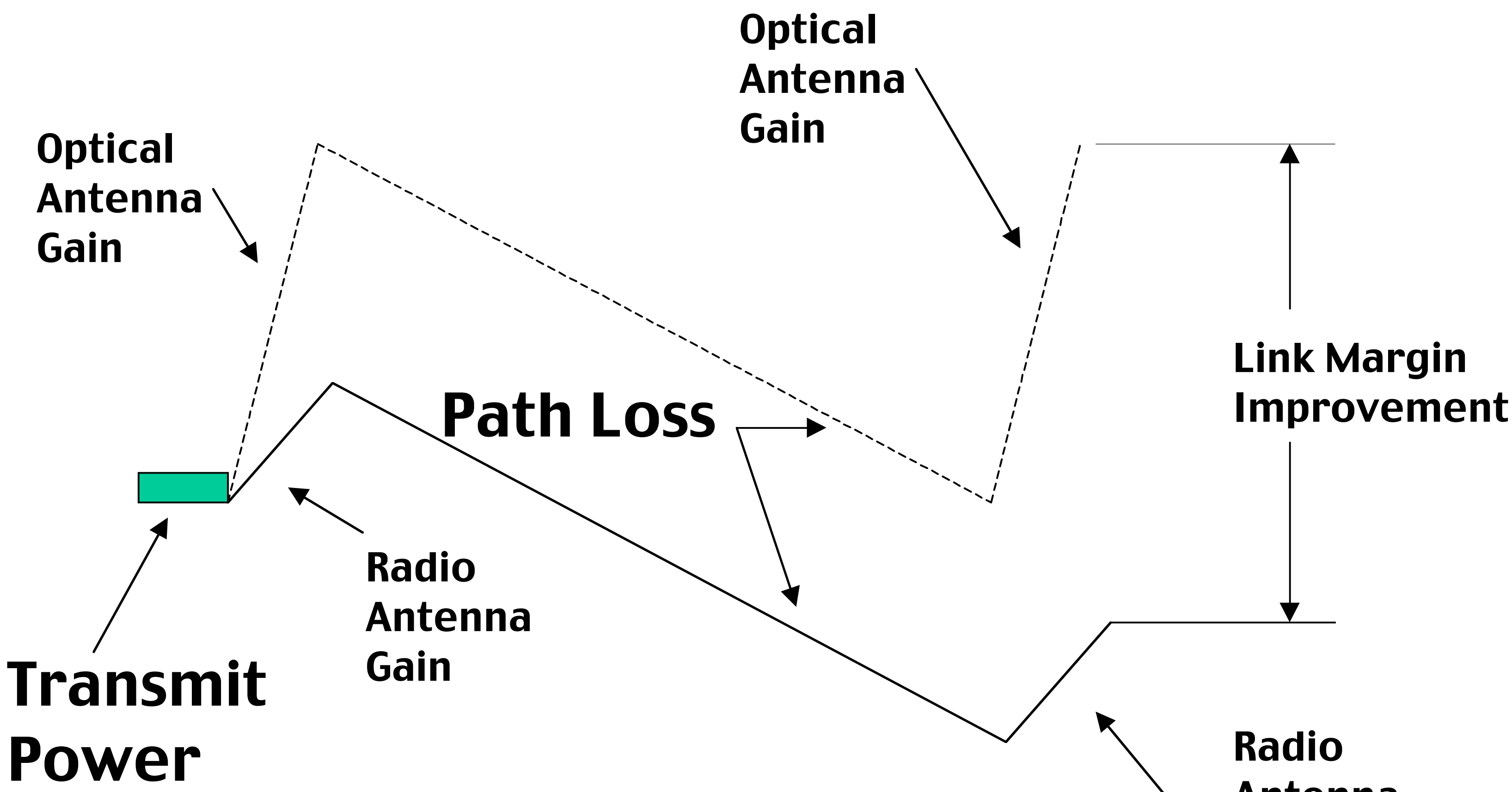
Link Margin Chart



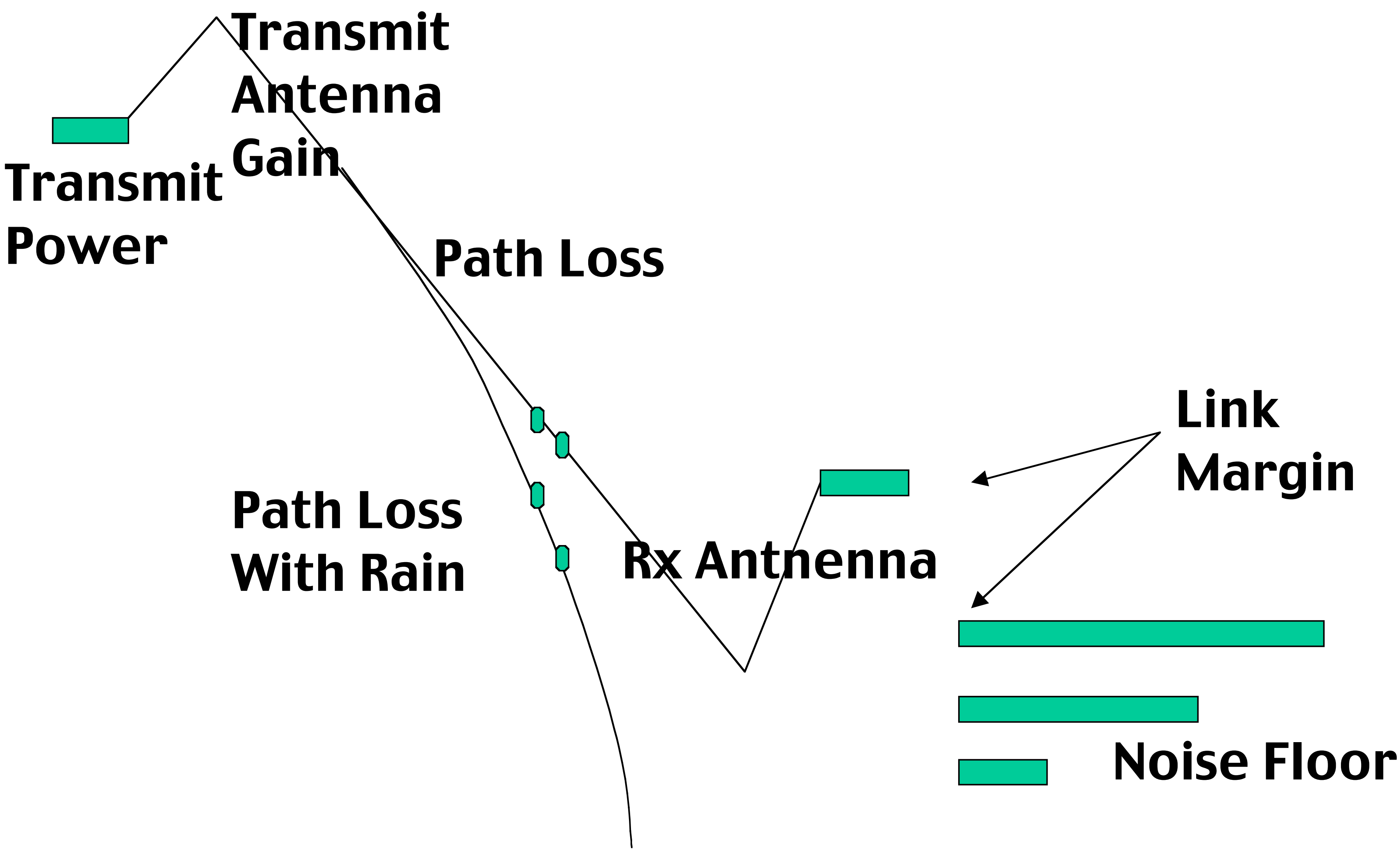
Radio Block Diagram — FDD System



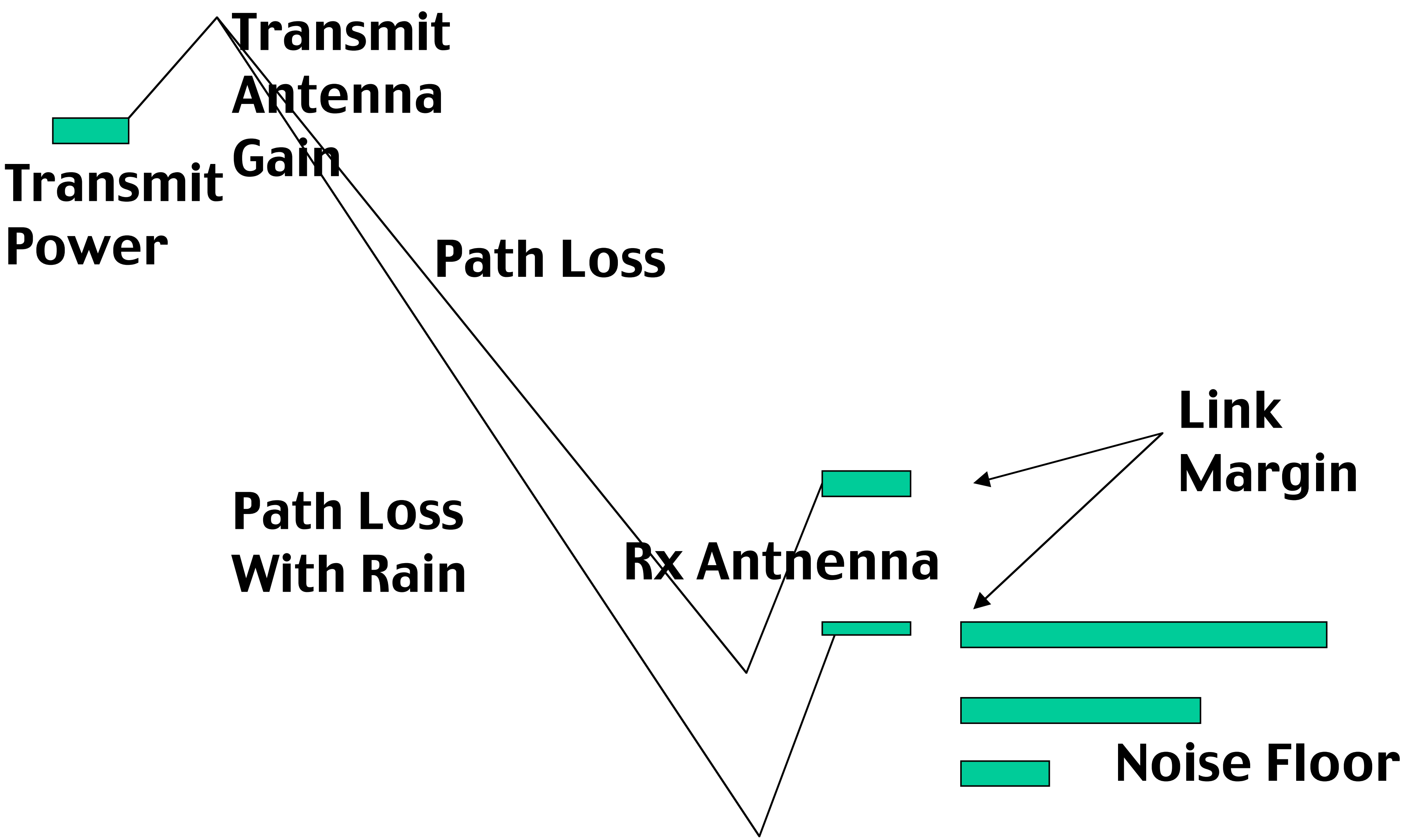
Link Margin Chart - The Optical Advantage (Antenna Gain)



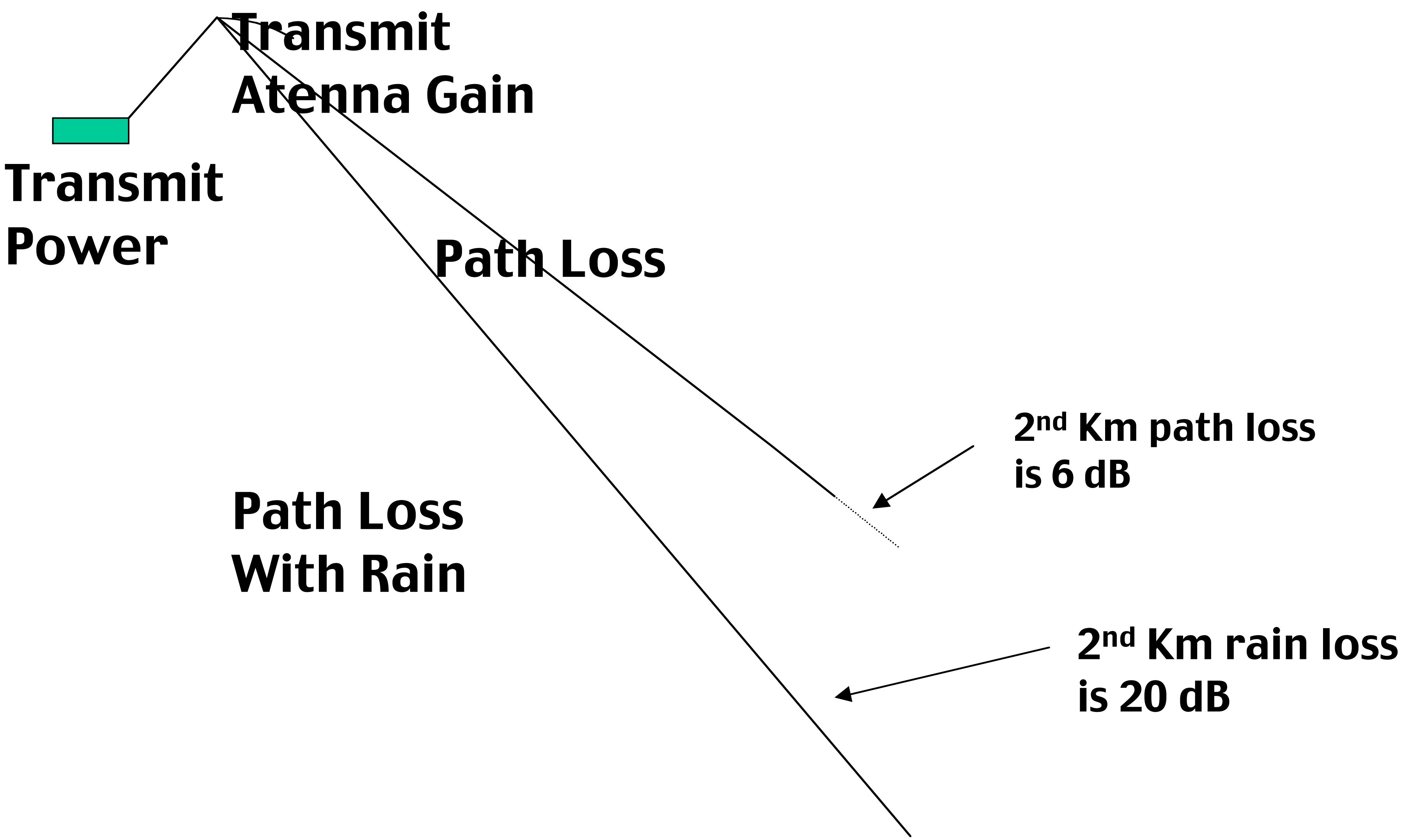
Link Margin Chart
Rain Fade Effects



Link Margin Chart



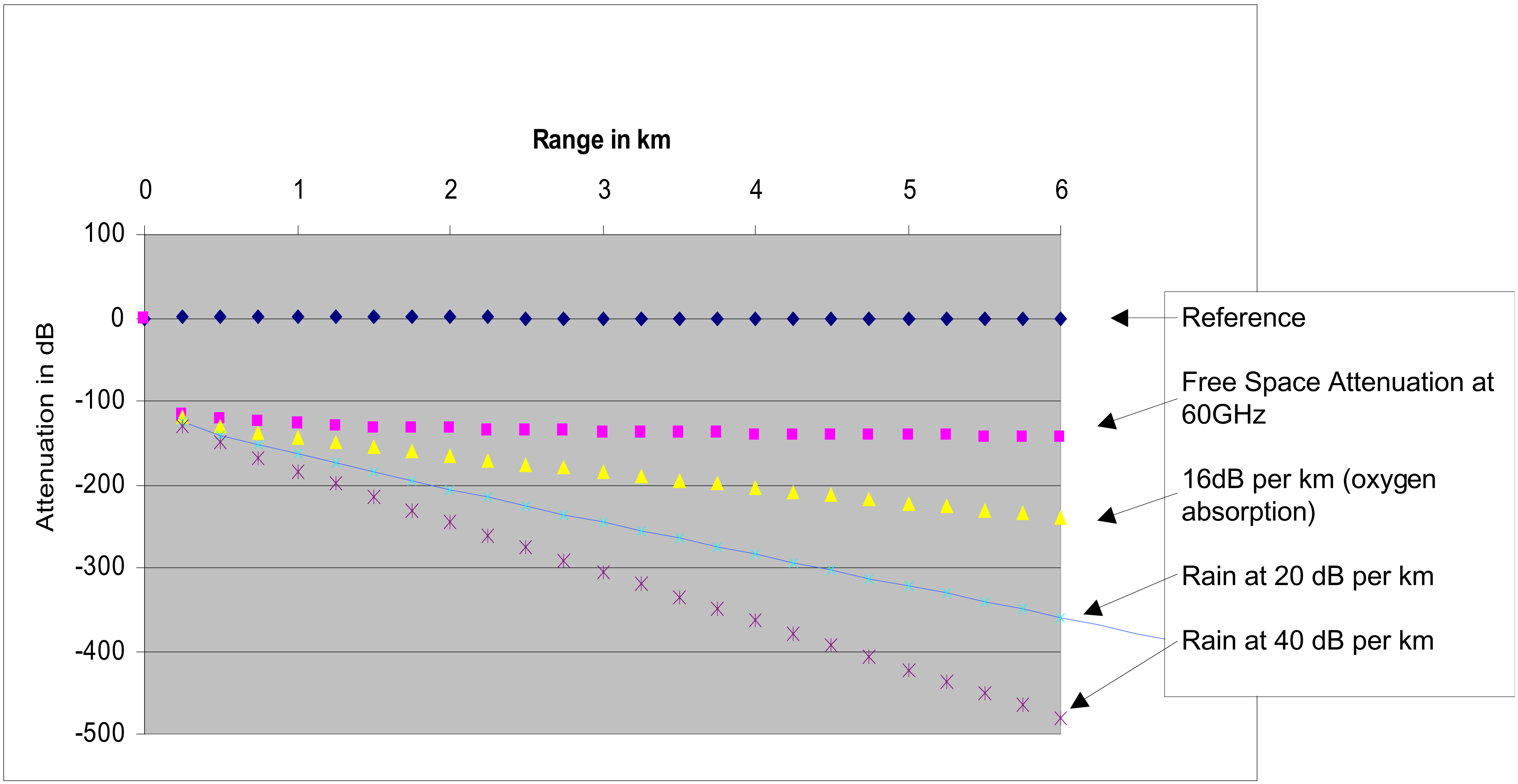
Link Margin Chart With 2nd Kilometer Rain Effects



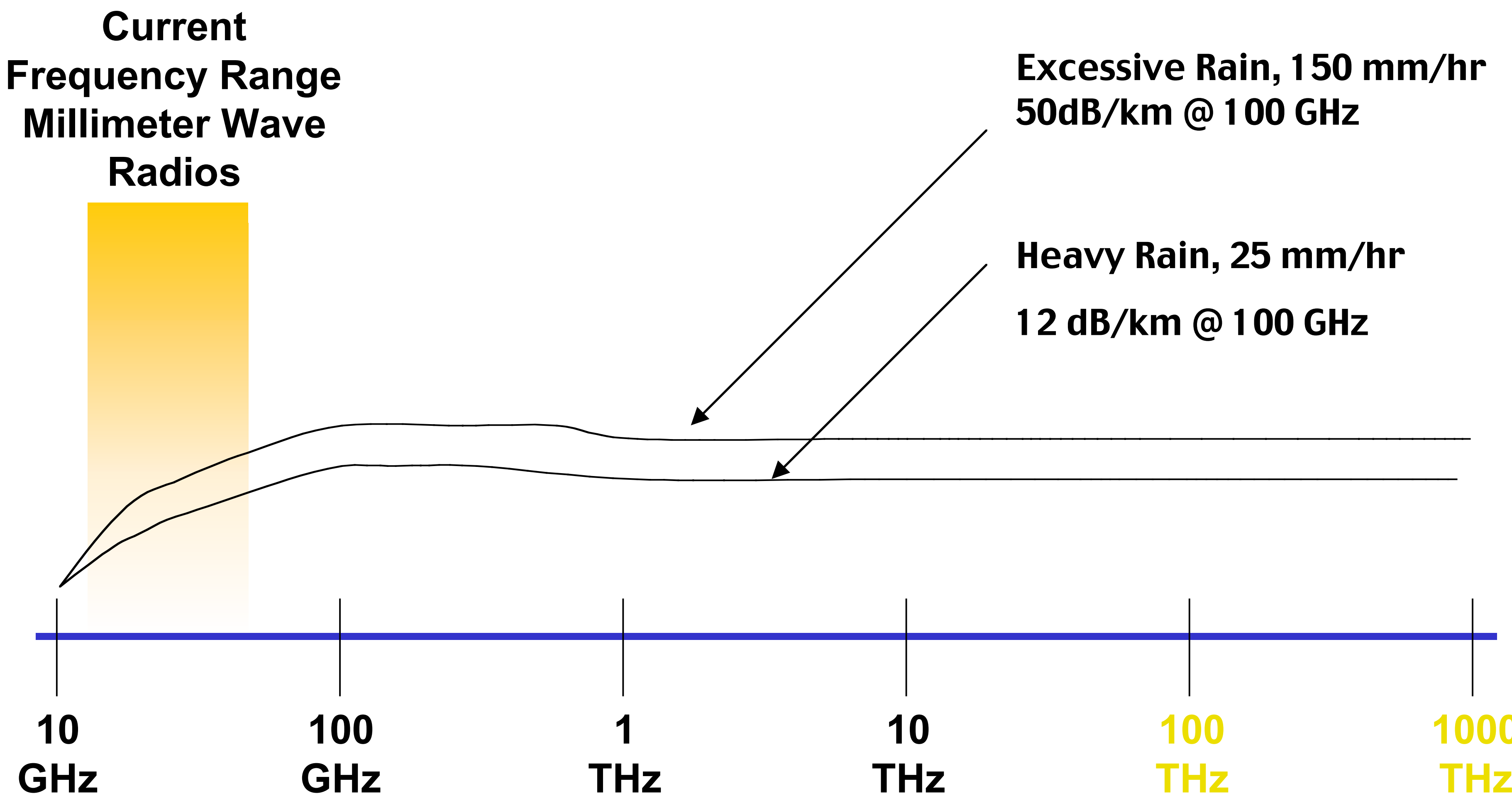
Link Margin Drivers

- Transmit Power 1/10th watt to 10 watts
    - 10 dBm to 40 dBm (or —20 dBw to 10 dBw)
- Noise Figure 2 dB to 10 dB
- Diplexer 2 dB
- Space Loss 140 dB to 150 dB @ 100 GHz
- Rain Loss 20 dB to 40 dB per kilometer
- Antenna Gain 30 dB to 60 dB
- Carrier to Noise Ratios 13 dB to 40 dB

Attenuation VS. Range at Various Rain Rates at 60 GHz

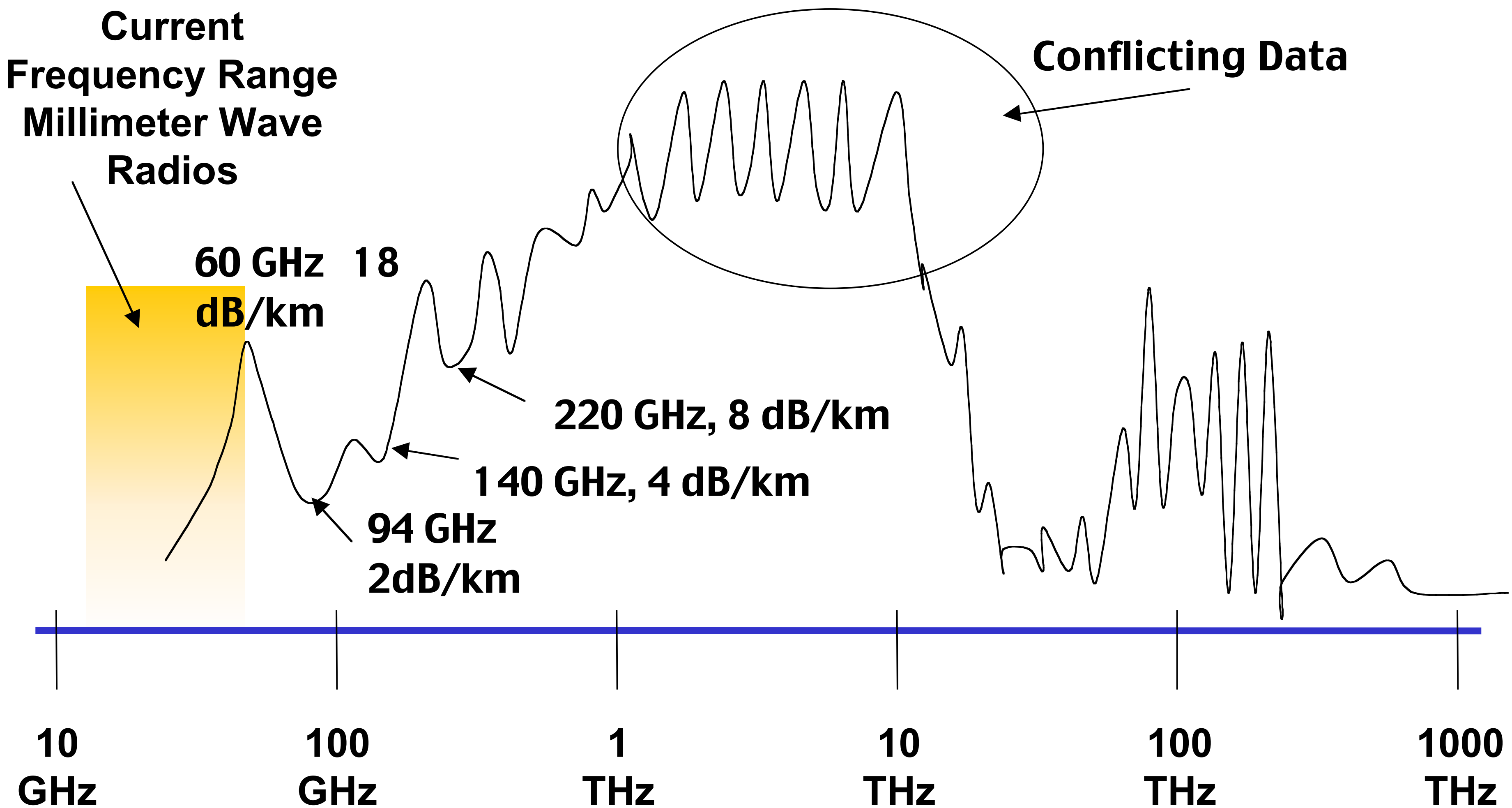


Millimeter Wave & Optical Spectrum
Rain Attenuation

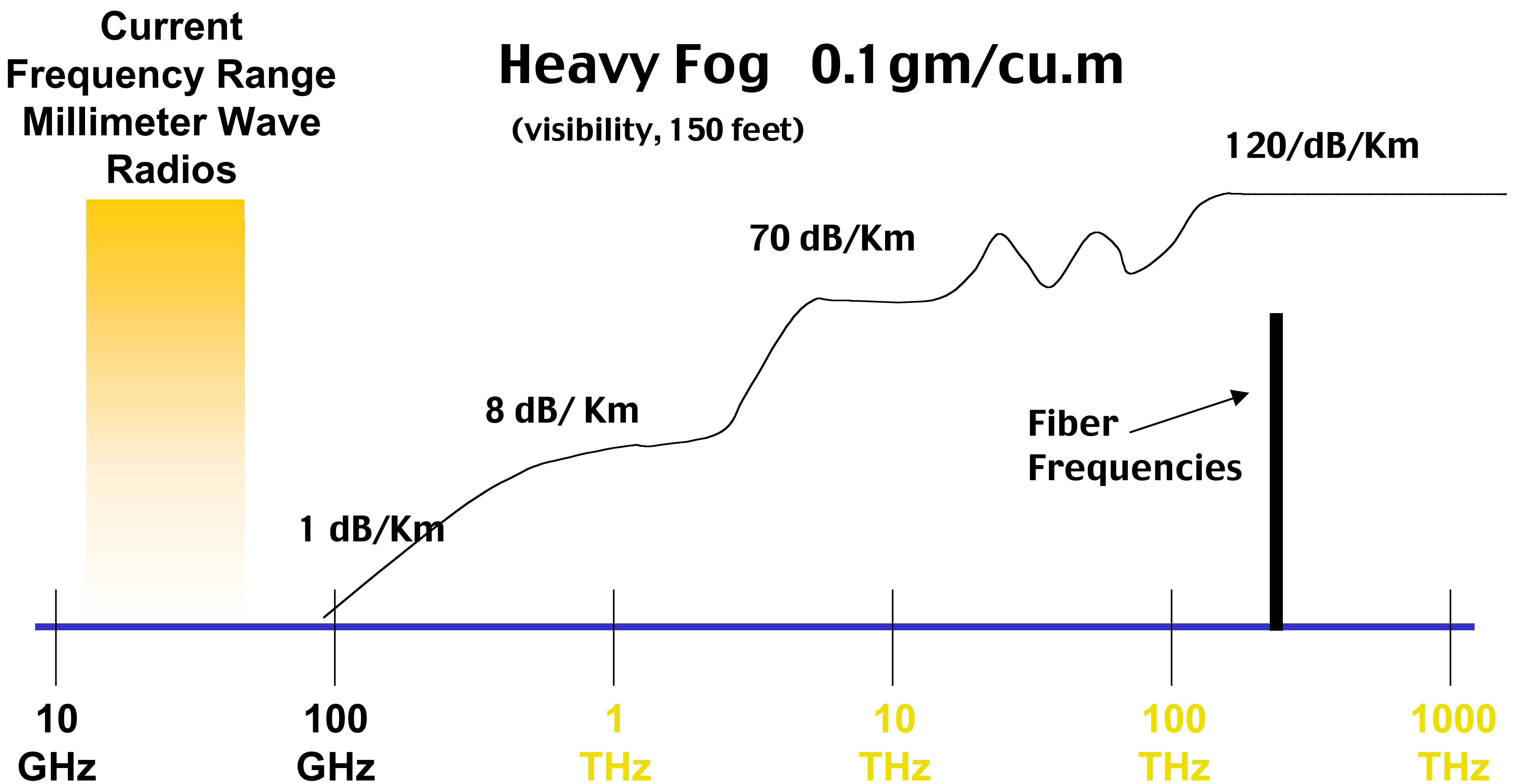


* In Development

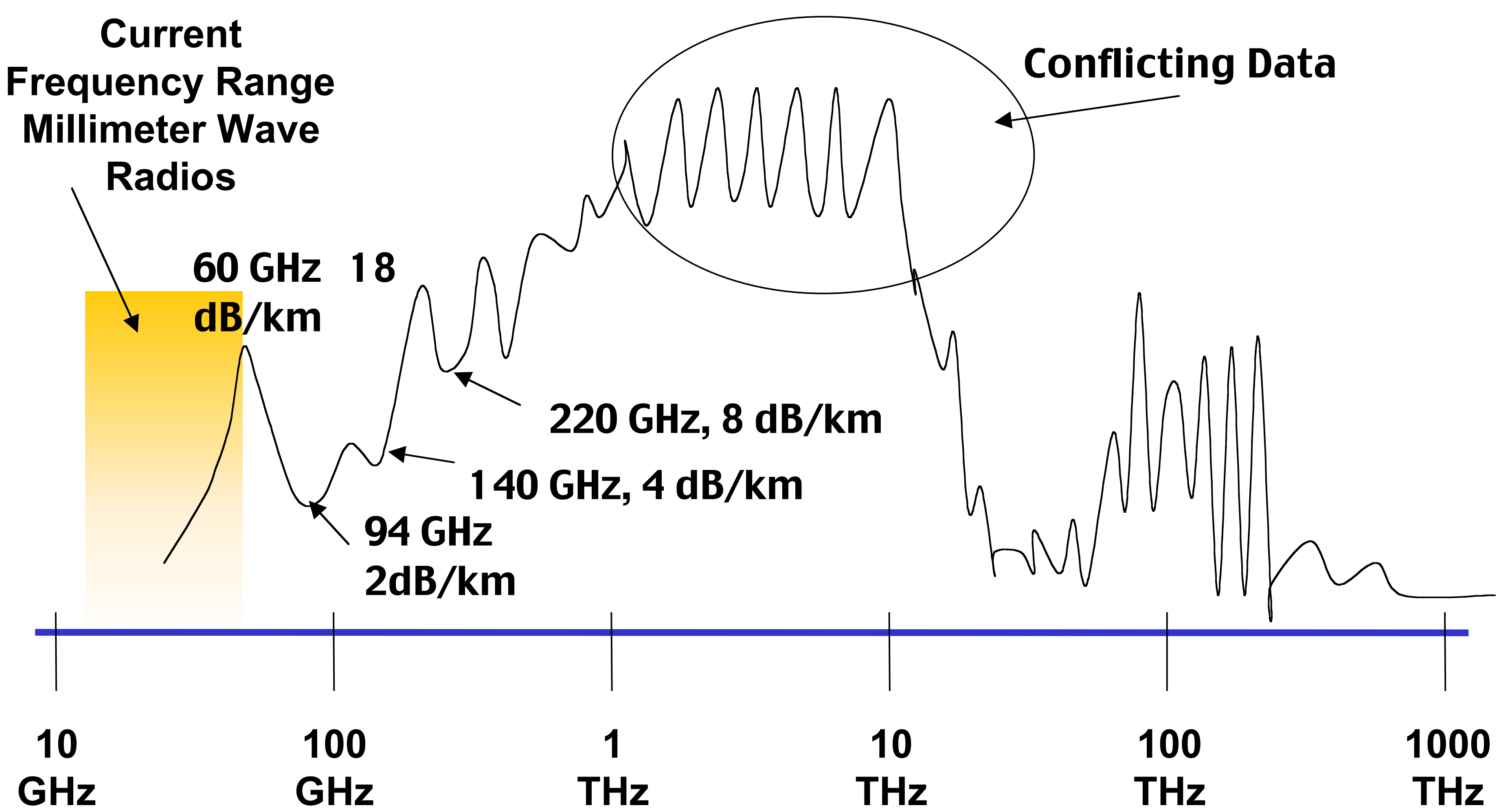
Millimeter Wave & Optical Spectrum
Oxygen and H_20 Attenuation



Millimeter Wave & Optical Spectrum
Fog Attenuation



Millimeter Wave & Optical Spectrum
Oxygen and $H_2 0$ Attenuation



Antenna Gain — the Most Cost Effective Link Margin Increase on the Planet

- Conference Room Engineering
  - Antenna size in the conference room
  - Antenna size on the roof
- Double diameter, multiply the link margin by almost 20X (12dB)
- This is the same as a 1 watt amplifier doing the work of a 20 watt amplifier

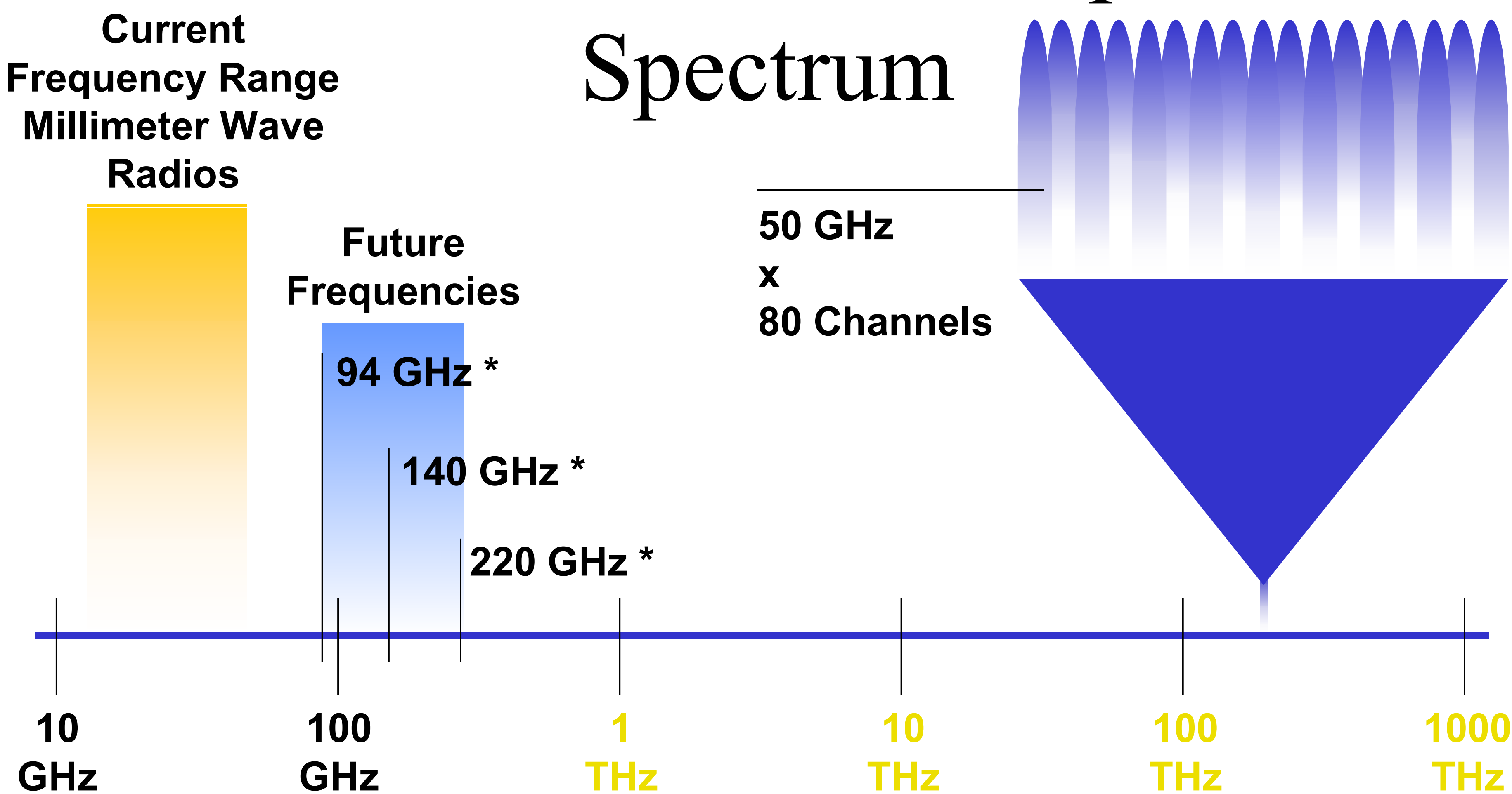
Diplexing Formats

- FDD   Frequency Domain Diplex
- TDD   Time Domain Diplex
- PDD   Polarization Domain Diplex
- CDD   Code Domain Diplex
  - Solves Adjacent Cell Problems

Frequency Selection Factors

- Lower frequency — Larger antenna
- Higher frequency — Smaller antenna
- Lower Frequency — Less Weather Effect
- Higher Frequency — More weather effect
- Lower Frequency — Lower data rate
- Higher Frequency — Higher data rate
- Lower Frequency — Lower Frequency Reuse
- Higher Frequency- Higher Frequency Reuse

Millimeter Wave & Optical Spectrum



* In Development

Millimeter Wave Physics of Distance

- For Space Loss:
- Double the distance, Power reduces by 4X

- For Rain Loss:
- Double the distance, Power reduces by 10,000X

- (Rain loss increases from 40 dB to 80 dB)

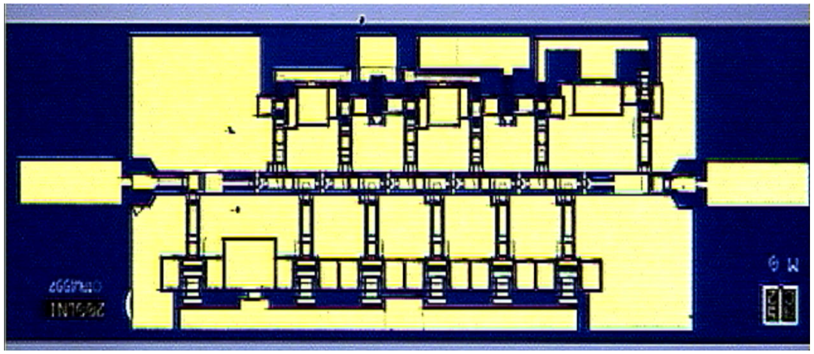
Frequency Selection Factors (Continued)

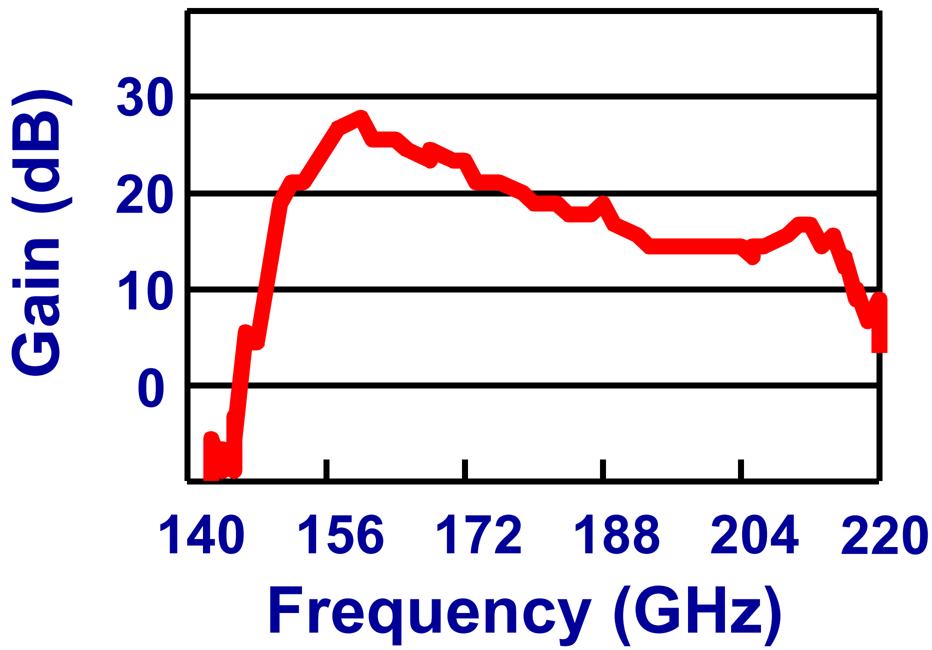
- Larger antenna — smaller beamwidth
  - Enables more frequency reuse
  - Example
    - Cellular frequency, frequency reuse of several thousand times in a metropolitan area
    - Millimeter wave frequency, frequency reuse of _ to 2 Million times within a metropolitan area

- 650 X more reuse   900 MHz vs 60 GHz

150 - 215 GHz InP HEMT MMIC LNA

- 16 dB gain at 215 GHz
- 27 dB gain at 160 GHz
- 6-stage CPW design
- 65 GHz bandwidth



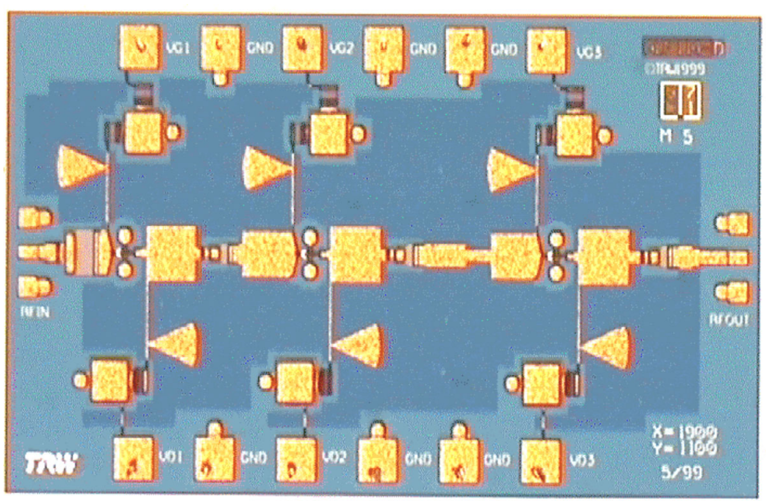


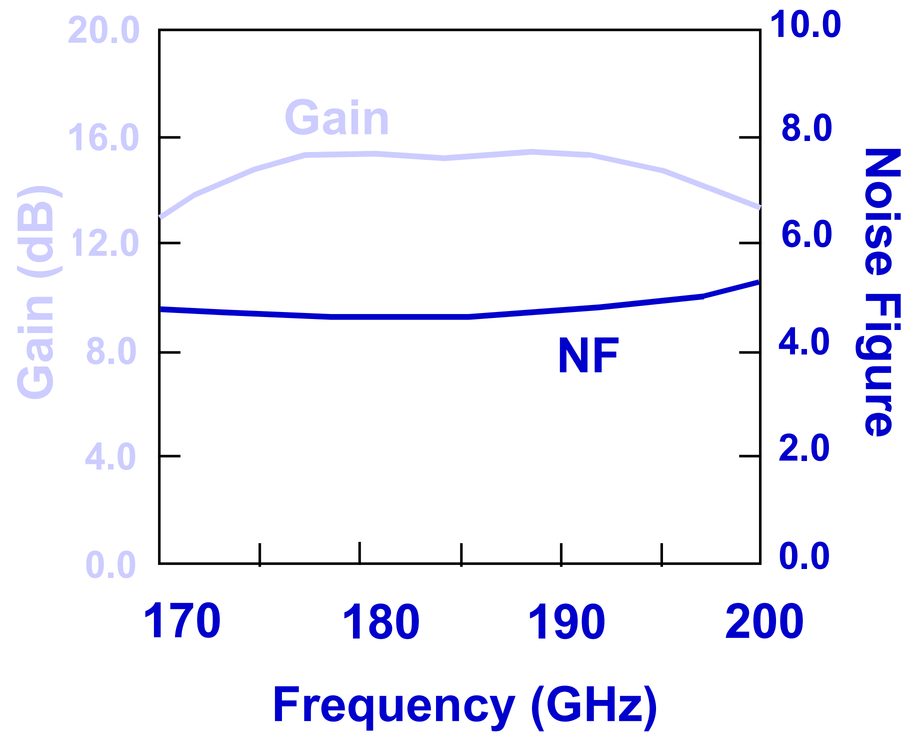
Ref: S. Weinreb et al IEEE-MGWL July 1999

200 GHz InP HEMT Low Noise Amplifier

170 - 200 GHz performance

- **3 stage single-ended LNA**
- **15 dB gain at 190 GHz**
- **4.8 dB NF at 190 GHz**
- **Port-to-port module results**





Source: Al Lawrence, Velocium

LANs, MANs, and WANs

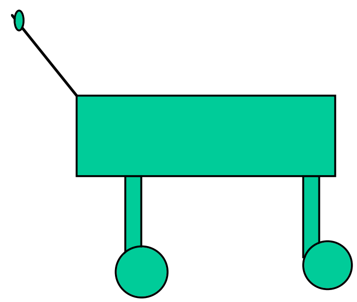
- LAN — Local Area Network
  - Typically within a building or campus
  - Typically Ethernet
- MAN — Metropolitan Area Network
  - Typically within a single large city
- WAN — Wide Area Network
  - Up to a national or worldwide footprint

Network Architecture Details

- ATM — Asynchronous Transfer Mode
  - 53 Byte Packet (5 Byte header, 48 Byte Info Field)
- IP — Internet Protocol
  - Variable Information Field, Header says how large
- SONET/SDH — Synchronous Optical Network, Synchronous Digital Hierarchy
  - 810 Byte Frames, 51.84 Mbits/sec data increments
- Ethernet
  - 8000 Byte Frame size , optimized for high speed data transmission
- Fibre Channel
  - 2 additional bits per 8 bit byte
  - 12.5 — 400 Mbytes per second rates

Ethernet vs. ATM

Ethernet



ATM

Cost to Fiber America's Businesses

- 750,000 large business buildings
  - $540 Billion
- 3,000,000 small business buildings
  - $300 Billion

- Total - $840 Billion

Cost to Radio America's Businesses (For 1 Gigabit)

- 750,000 large business buildings
  - $60 Billion
- 3,000,000 small business buildings
  - $60 Billion

- Total - $120 Billion

- 7:1 advantage, radio vs. fiber

Radio vs. Fiber Connectivity

- Radio installation permits multiple suppliers to easily serve the same building
- In theory — eliminates BLEC and CLEC chokehold (monopoly) at the building level

Fiber Trenching Costs

- $25 - $50 K per mile in open farm land
- $250 K to $ 3 Million per mile in urban areas
    - Boring
    - Trenching
    - Encasement
    - Splice Points
    - Map inaccuracies
    - Hand digging zones
    - Permits and easements
- Fiber Cuts
    - 0.018 per mile per year probability - 15 mile link, 2.4 Hours downtime per year on average

Roadmaps

- Computer Road map
- LAN road map
- Metro road map
- WAN road map

Communications Laws

- Shannon’s Law
- Moore’s Law
- Metcalfe’s Law
- Gilder’s Law
- Doug’s (or Ed’s) Law
    - Backhoes don t follow Moore s Law

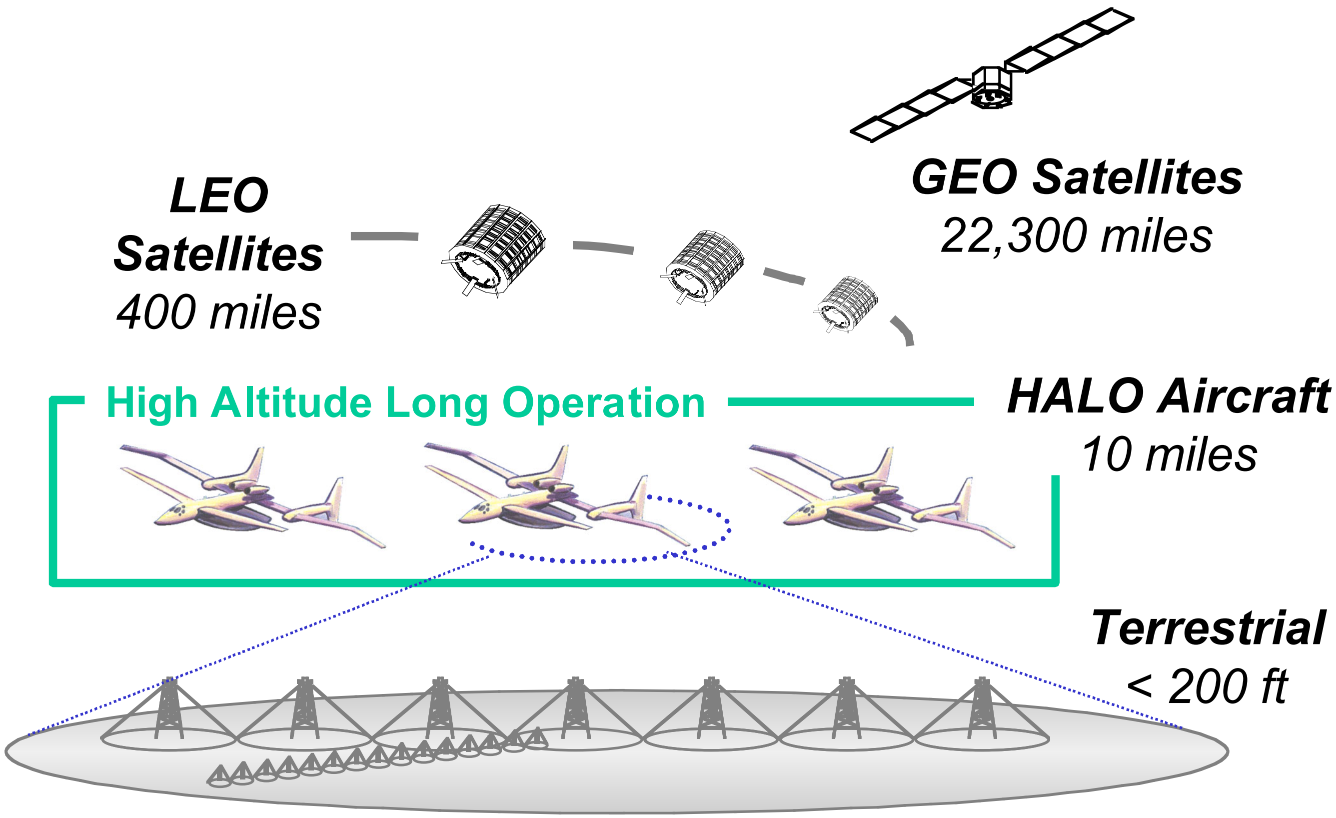
Early Adopter Likelyhood

- Biotech
- Enterprise Inter/Intra Net
- Then video conferencing
- Games?

New Spectrum Possibilities

- Unlicensed Bands
- Licensed Bands
- Worldwide Coordination
- Terrestrial vs. Satellite vs. Navigation Applications

Stratospheric, Satellite and Terrestrial Platforms



Metropolitan Last Mile Solution

HALOStar

Terahertz Radio Convergence with Optical

- 10 Gigabit data rates transition to 40 Gbits
- _ bit per hertz transistion to 4 bits per hertz
- Lambda channel width versus data rates vs. cost vs. mmwave circuits
- Life beyond C band and L band in metro nerworks

The Players (60 GHz and Above)

- Radio Companies
  - Harmonix
  - Sierra Com
  - Nokia
  - Telaxis
  - Loea
  - Boeing
  - TRW
- Free Space Laser Companies
  - Terabeam
  - fSona
  - Lightpointe
  - Airfiber

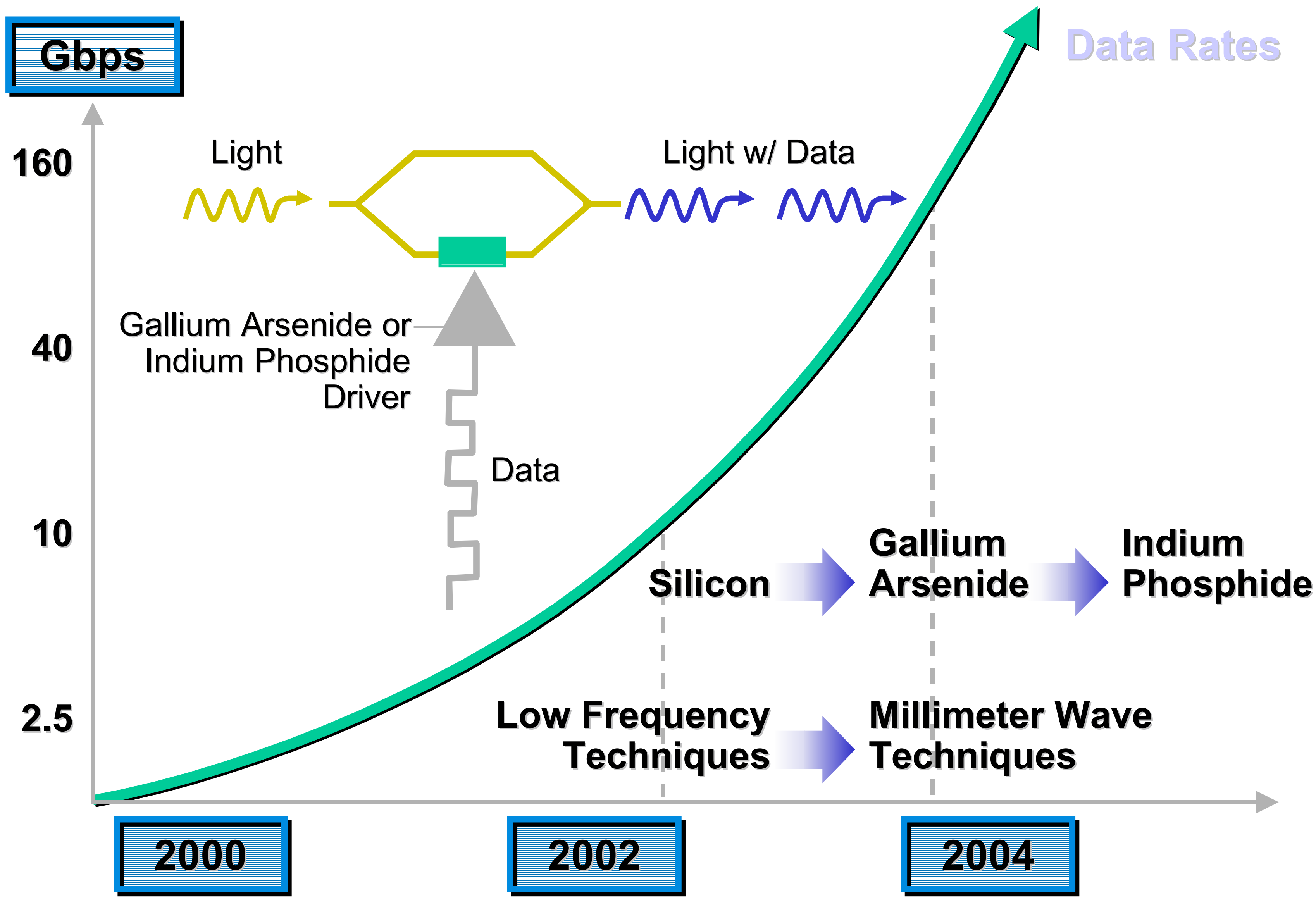
Investment Strategies

- Legacy Architectures
  - LAN
  - MAN
  - WAN
- Ethernet Architectures
  - LAN
  - MAN
  - WAN
- Licensed Spectrum Vs. ISM and Unlicensced
  - Low Frequency
  - Millimeter Wave Spectrum
  - Submillimeter Wave Spectrum
- Computer Speeds and Applications
- Killer Applications of Massive Bandwidth

Related Technologies

- Fiber Optic Transceivers
    - 10 Gbit entering production
    - 40 Gbit in alpha sites
    - 100 Gbit in Prototype
    - 160 Gbit in laboratory
- Millimeter Wave Cameras
    - 60 GHz to 400 GHz experimental data
    - Security Screening applications
    - Powerline radar and synthetic vision aerospace apps

MmW Technology is Key for Next-Gen Fiber Optic Circuits



Summary

- Worlds Largest Bandwidth Market
- It hasn’t happened yet
- Fiber optic transceiver development will drive sub terahertz radio technology
- Stage is set to break local loop fiber optic bottleneck with Millimeter Wave Radios
- We need Gigabit Radio standards

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