Broadband Wireless Personal Area Networks- 60 GHz and Beyond

December 9, 2010 IEEE Globecom 2010

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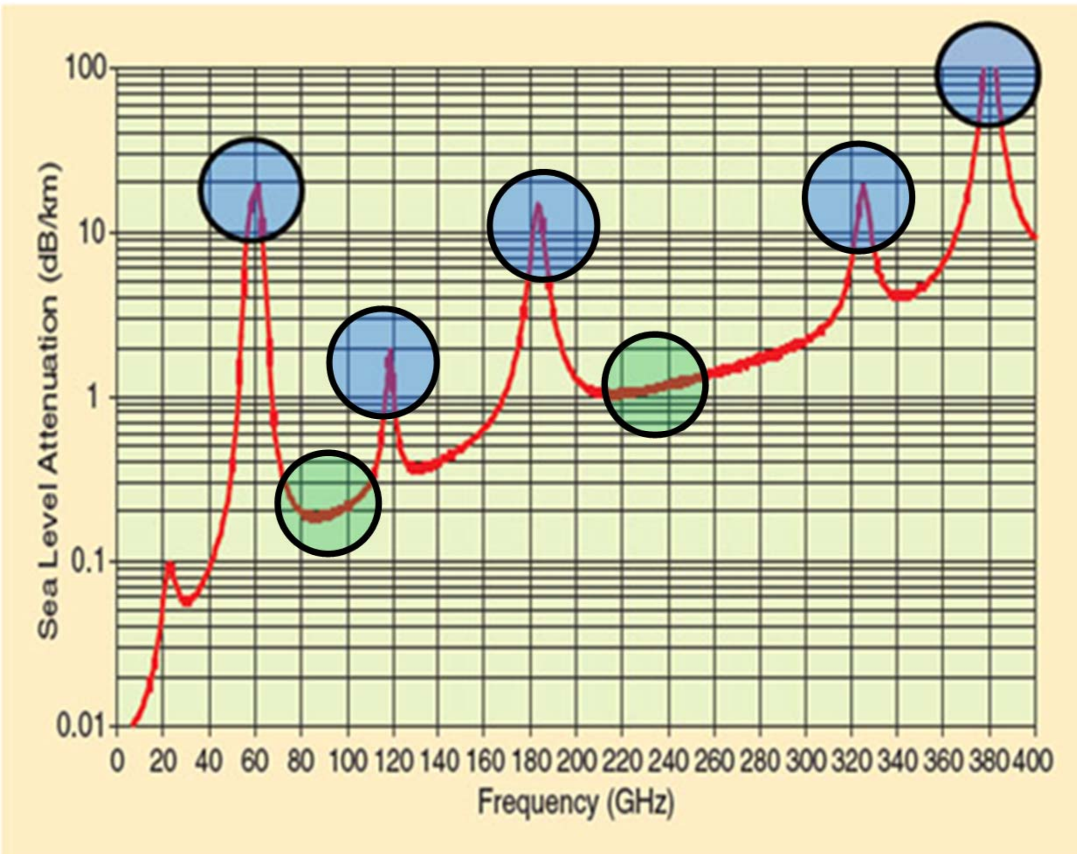
Dallas, TX

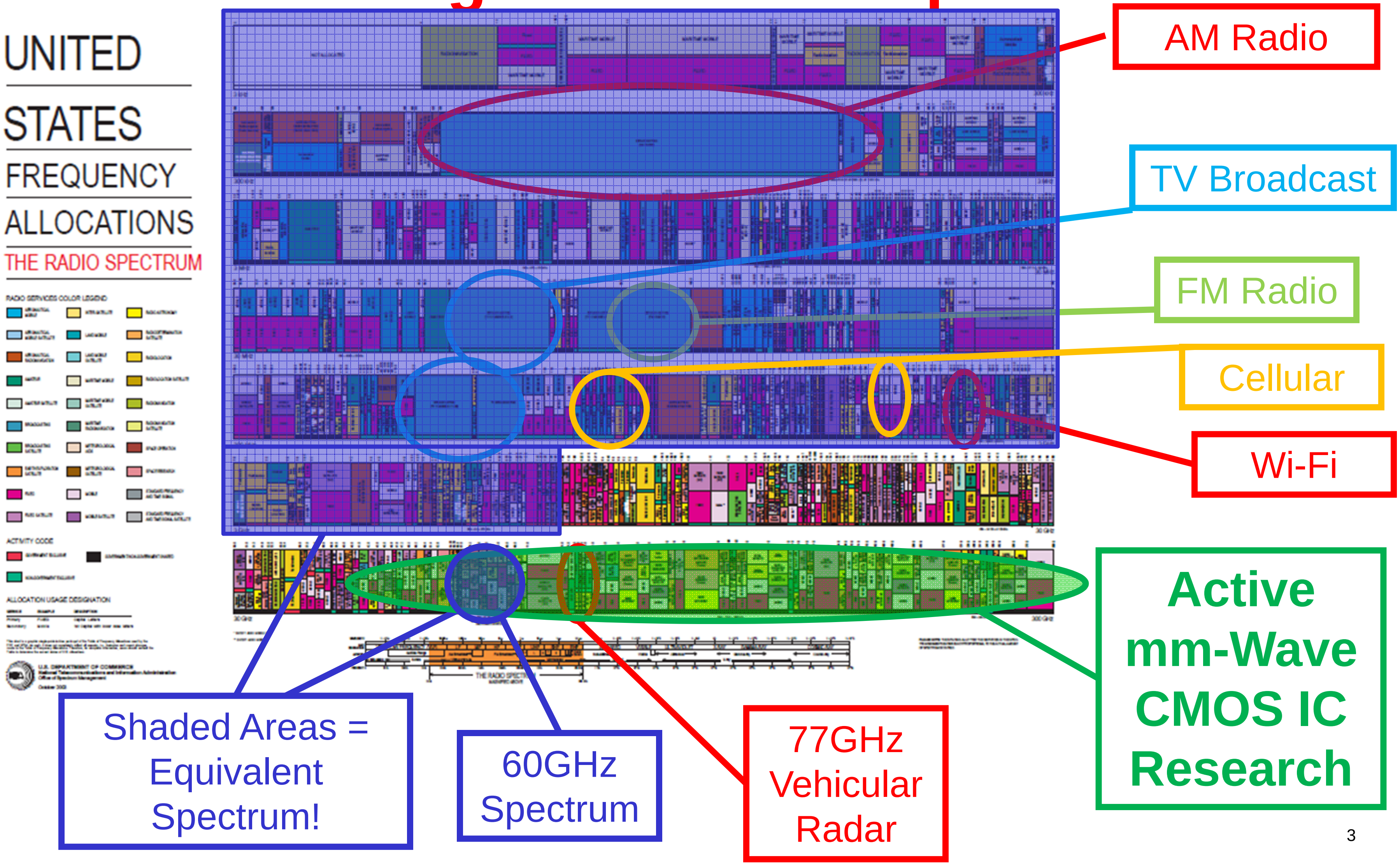
mm-Wave and sub-mm-Wave THz Propagation



- 60 GHz, 120 GHz, 183 GHz, 325 GHz, and 380 GHz for shorter-range applications
- World-wide governmental agreement on 60 GHz!
- 100 GHz and 240 GHz for longer-range applications

Wells, J., "Faster than fiber: The future of multi-G/s wireless,"*Microwave Magazine, IEEE*, vol.10, no.3, pp.104-112, May 2009.

mm-Wave and sub-mm-Wave
Orders of Magnitude More Spectrum

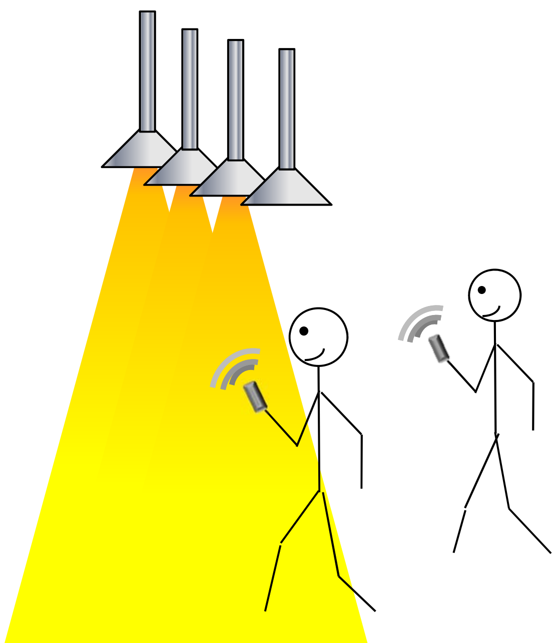


mm-Wave & sub-mm-Wave Short Range Applications

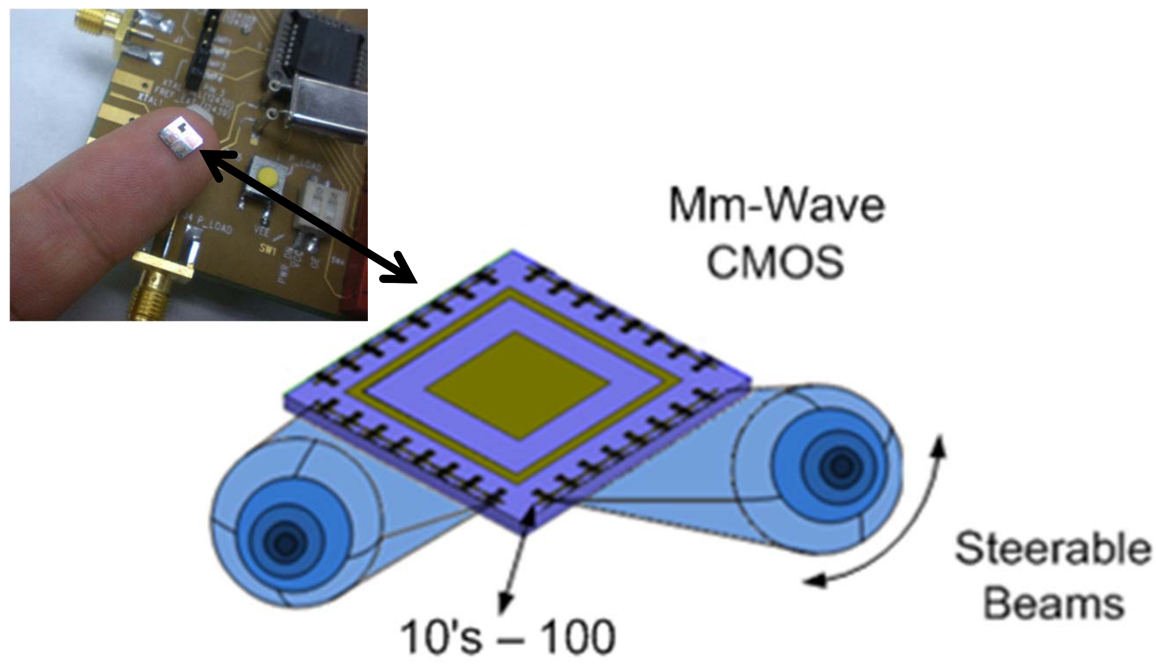
- 60 GHz band products ready for release: TV set top boxes available soon

- Applications: Information Showers, Wireless Interconnects, magnetic media & hard-drive replacement

Information Showers

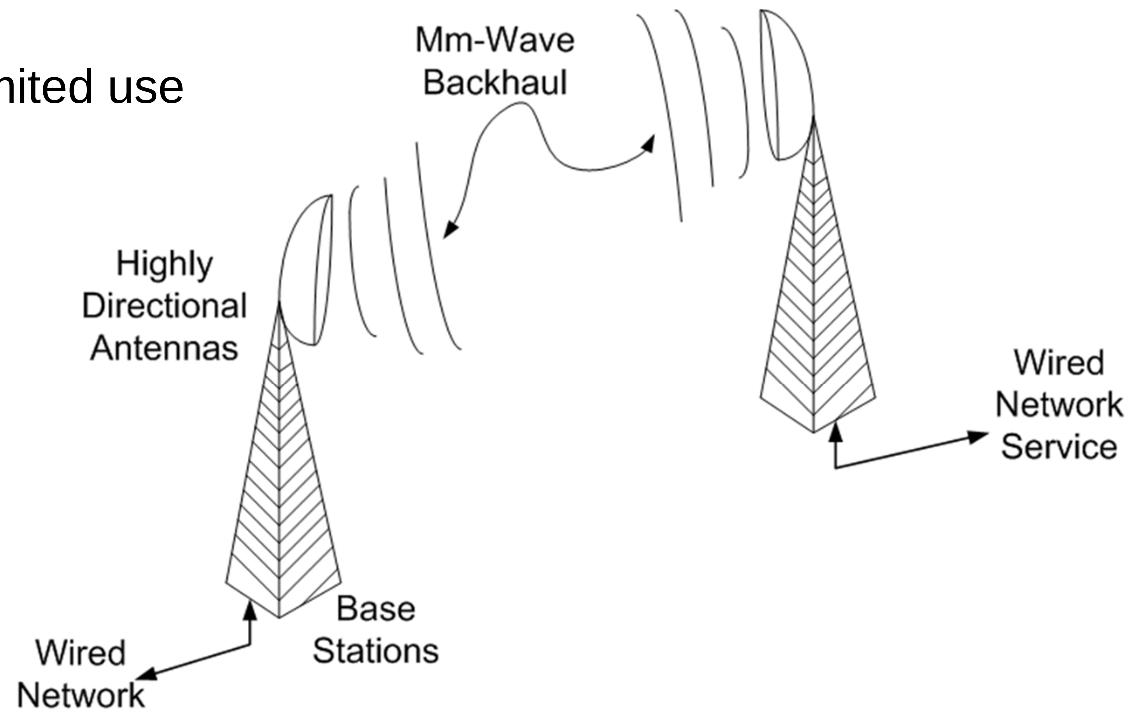


Inexpensive Ubiquitous Integrated Transceivers



mm-Wave Long Range Applications

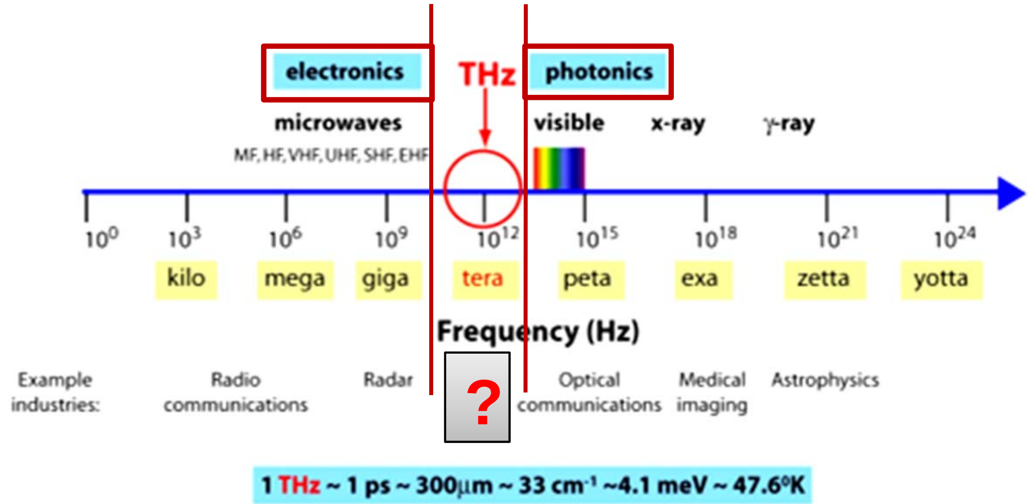
- Tremendous data rate growth for cellular systems
  - 10 % of 2.85 Billion users w/data in 2007 → Growing Exponentially
- Wireless mm-Wave and sub-mm-wave backhaul **Required!**
- 60 GHz backhaul already in limited use
- Highly directional antennas



Buddhikot, M.M.; , "Cognitive Radio, DSA and Self-X: Towards Next Transformation in Cellular Networks (Extended Abstract)," *New Frontiers in Dynamic Spectrum, 2010 IEEE Symposium*

Properties at THz

Frequency Range
Terahertz region – 0.3-10THz
But loosely – 100GHz and upwards
Wavelengths
3 mm to 30 μm



Properties

- Behaves partly as light - Can be focused with a lens
- Behaves partly as Radio Frequency waves for propagation – we can use antennas and metal structures for radiation and guidance at these frequencies
- Thought to be Non-ionizing (health wise safer)

Material Properties

- Good penetration cloth, wood, concrete, plastics, paper
- Absorbed heavily by water in various frequency bands within the THz range
- Reflected by metals
- A lot of naturally occurring compounds have resonances and interactions in this regime

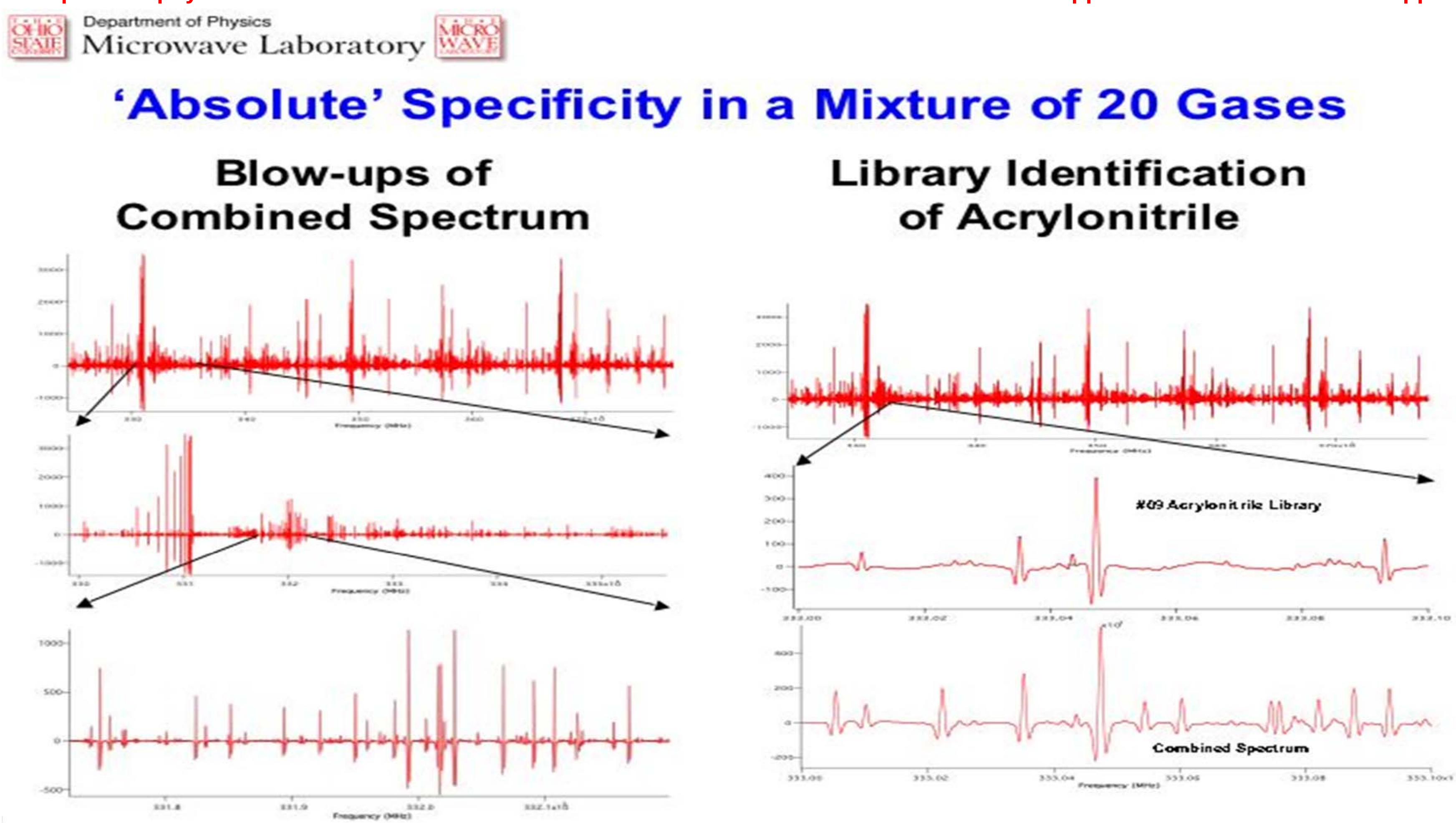
Application Space & Requirements

Application	Description	Signal Structure	Transceiver Requirement
Security	Sub-surface Imaging, Concealed explosives, weapons, drug inspection	Pulsed, FMCW, CW	Variable angle/Fixed angle
Medical	Imaging, monitoring, Early detection	Pulsed, FMCW, CW	Variable angle/Fixed angle
Non-destructive testing	Material Inspection, Structural integrity, Aviation and others	CW (Mostly)	Fixed angle/ Variable angle Amplitude detection
Spectroscopy	Chemical identification	CW, Stepped Frequency	Fixed angle, Amplitude Detection Wide tuning range
Communication	Mobile/Notebook docking (Terabit file transfers, HD stereo displays) Wireless Backhaul (20-40Gbpsec links)	CW – simple modulation	Very High Gain Rx and Tx antenna Electronic Beam Steering for simple link establishment

Spectroscopy Applications:

Accurate recognition to few part-per-trillion for many gases.
Abundant &unique “absorption” spectral lines in the 100-600GHz range.

Slide from: Prof. Frank C. De Lucia, Ohio State University, AMERDEC, 2006:
http://www.physics.ohio-state.edu/~uwave/2008site/Resources/talks%20without%20notes%20ppt%20files/HOE.HVL.1.19.06.ppt

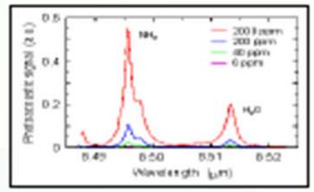
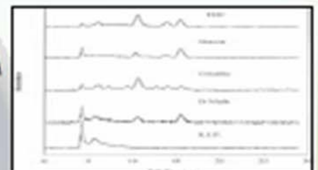
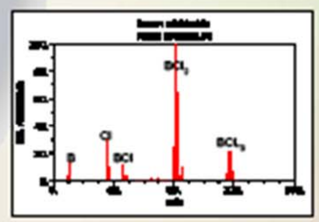
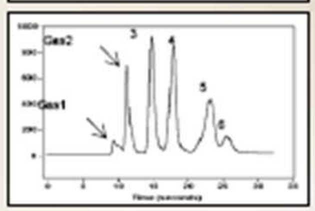


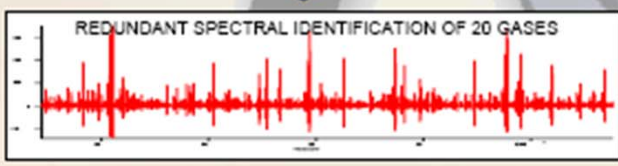
Spectroscopy Demonstration: Expensive setup

From Dr. Frank W. Patten DARPA-ATO-2005 Public released Proposer Day Conf. 2005 presentation.
Or http://www.schafertmd.com/conference/PACT/downloads/Reiss-Smart-Transitions-PACT-Proposers-Day.pdf

Identification Elements for Different Sensors

Chemical sensor Technologies	Identification Elements for Each Sensor (based on resolution)
Photo-Acoustic (IR)	~200
Gas Chromatography	~100
Mass Spectra	~500
Ion mobility	~50
MACS Rotational Spectra	~500,000



Advantages of Terahertz based rotational spectroscopy:
- Huge number of identifying lines
- Nearly 99% of the atmospheric clutter is ***transparent*** to THz rotational spectroscopy
- Quick identification of hundreds of chemical components.

Approved for Public Release

Mission Adaptable Chemical Sensor (MACS)
PROPOSERS DAY CONFERENCE
Dr. Frank W. Patten
4 November 2005

T=Chemical Actually Present ("truth")
O=Chemical Observed in Mixture
Present / Not Present

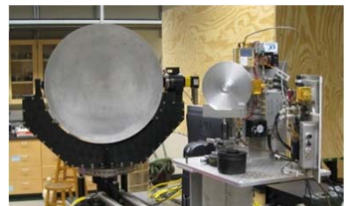
Species	T	O	Species	T	O
CH3Cl	Present	Present	Methanol	Not Present	Not Present
CH3Br	Not Present	Not Present	H2S	Present	Present
CH3I	Present	Present	C2H5OH	Present	Present
Acrolein	Not Present	Not Present	Methanethiol	Present	Present
Oxetain	Present	Present	Formic Acid	Present	Present
Thietain	Present	Present	CH2F2	Present	Present
Thiophene	Present	Present	Acrylonitrile	Present	Present
Vinyl Bromide	Not Present	Not Present	Vinyl Chloride	Not Present	Not Present
Ethylene Oxide	Not Present	Not Present	CH2CF2	Present	Present
CF3H	Not Present	Not Present	N2O	Not Present	Not Present
Triflouroethane	Present	Present	OCS	Present	Present
Thionyl Flouride	Present	Present	BrCN	Not Present	Not Present
Vinyl Flouride	Not Present	Not Present	CH3F	Present	Present
Carbonyl Flouride	Present	Present	Propyne	Not Present	Not Present
C2H5CN	Present	Present	CH3CN	Present	Present

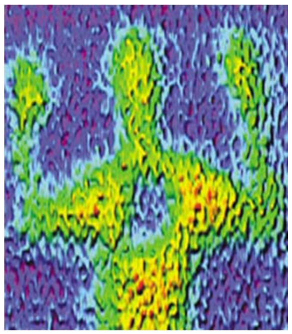
Imaging: Already Many applications Demonstrated.. Expensive Equipment.

Imaging uses the Reflection property of THz waves:
Applications in Medical and Security

Department of Physics
Microwave Laboratory

How do you look at THz images?

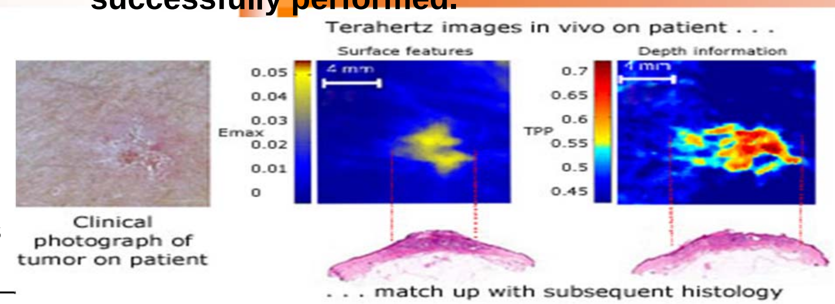




TeraView

http://teraview.com/terahertz/id/34

Terahertz in skin cancer
TeraView has worked with clinical collaborators to establish the ability of terahertz to distinguish between basal cell carcinoma and other forms of malignant, benign and healthy tissue associated with skin cancer and related diseases. Both extensive ex vivo measurements for tissue classification and histopathological use, and preliminary in vivo measurements directly on patients have been successfully performed.



Texas Instruments

Slide from**: Prof. Frank C. De Lucia, Ohio State University, AMERDEC, 2006**: http://www.physics.ohio-state.edu/~uwave/2008site/Resources/talks%20without%20notes%20ppt%20files/HOE.HVL.1.19.06.ppt

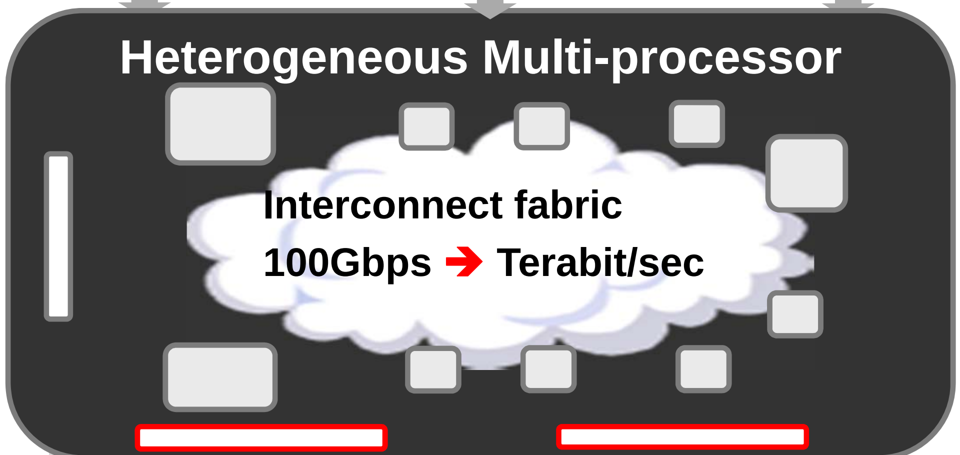
Mobile Application: 20+Gbpsec wireless "docking"!

Today:0.5Gbpsec ➔1-4years: 5Gbpsec➔ 5-10yrs: 20+Gbpsec
Stereo 4K Movie: 2(3D)*4096*2160* 60 Frames * 24bit =25.5Gbpsec!!

Broadcast
DTV/FM/HDR/DRB
1➔10Mbps
100Km

Cellular
Modems
3G ➔4G
10 ➔100Mb/sec
0.1 to 10Km

Connectivity
Networks
BT, WiFi, BAN
.1➔ 10Gbps
1m to 100m



Local content
DRAM/NV Memory
10's➔100's Gbps
1cm

Video capture
Image/Video/Gesture/HDI
.2➔2 Terabytes
2X 1080p60, 10 mins

External displays
Image sharing – 3D
.5 ➔3 Terabytes
2X QSXGA, 10 mins

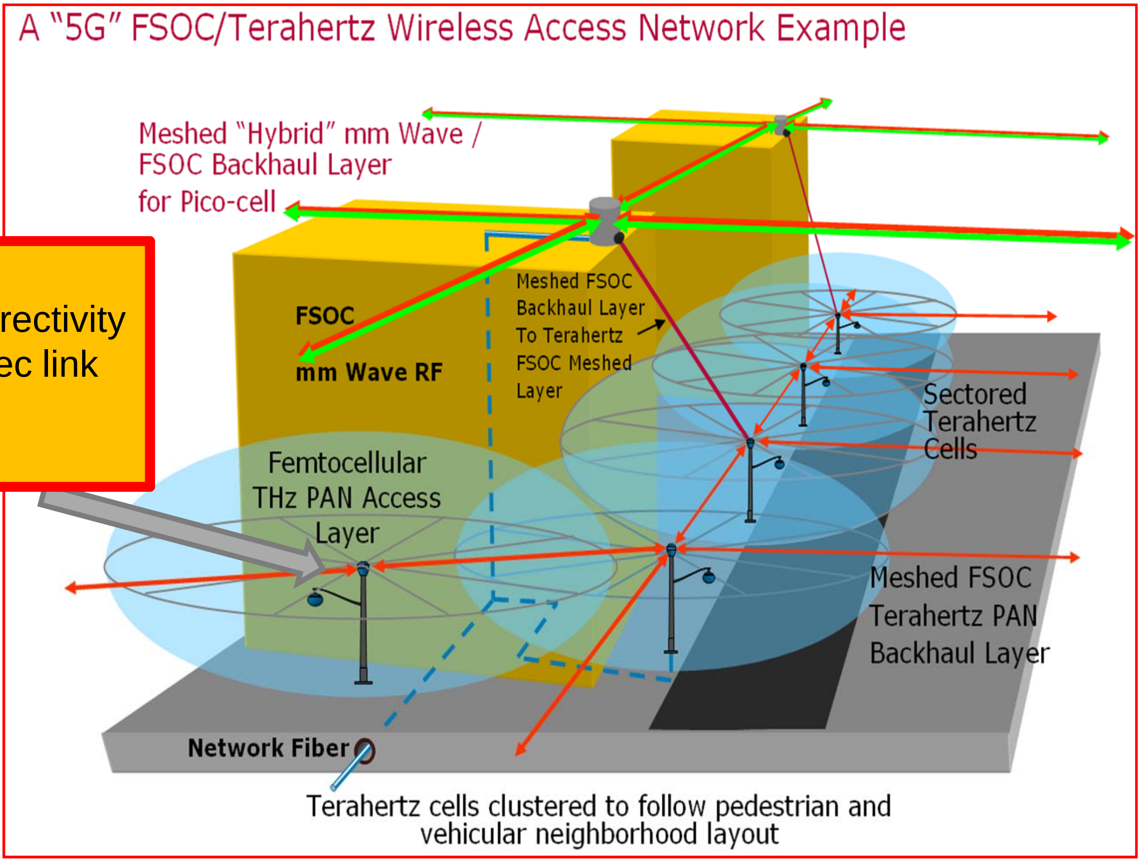
Bandwidth increases by 10~100X➔ Seamless adaptive connectivity?

From G. Delagi ISSCC-2010 Plenary Presentation

Texas Instruments

Telecommunication: Wireless THz links for Femtocell wireless back haul Network (Courtesy: David Britz AT&T , 2009)

Femtocell Needs:
1- High Antenna Gain/Directivity for Point to Point Gbpsec link
2- Low Cost
3- Power efficient



Courtesy: David Britz: dbritz@research.att.com
AT&T Labs Research – Shannon Laboratories

Broadband Wireless Personal Area Networks-
60 GHz and Beyond

Semiconductor viewpoint: Path to low cost manufacturability

Marco Corsi, Texas Instruments Fellow

Kilby Labs

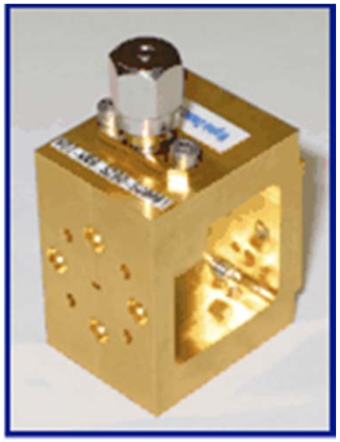
December 9, 2010

Sub-mmwave electronics today.

Active devices really do not have power gain. Circuitry built with multipliers and harmonic mixers that have inherent power loss.

Several suppliers of instrumentation and equipment exist namely Virginia Diodes and OML. Device and material characterization can be done with turnkey Instrumentation purchased from these suppliers and a few others.

VNAs now available to 1THz with 2THz on the horizon. A 140-220GHz VNA is now Less than $300k and this was > $700k less than a year ago. The instrumentation is Now more accessible than ever.



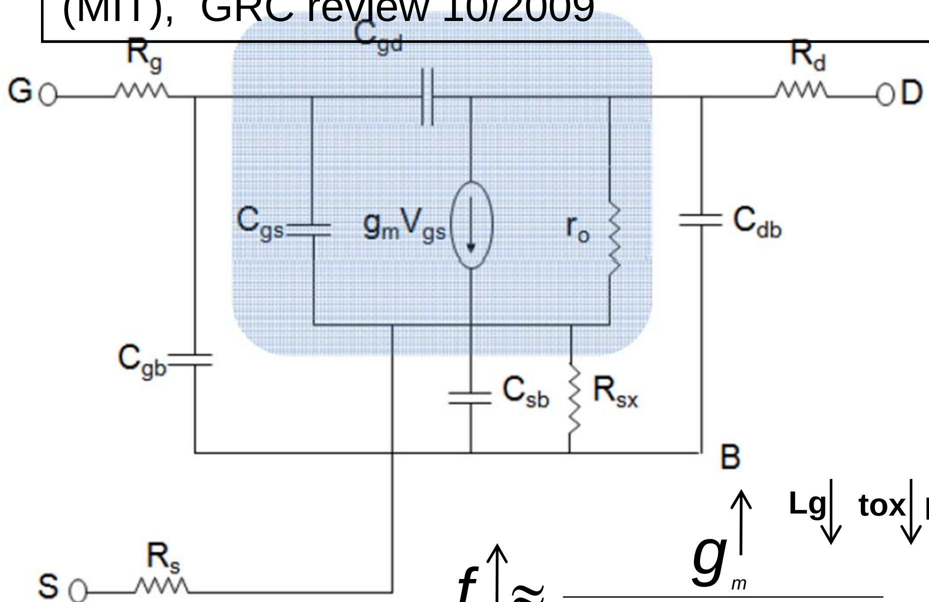
Current sub-mm electronics looks like traditional microwave design did 20 years ago. Just smaller.

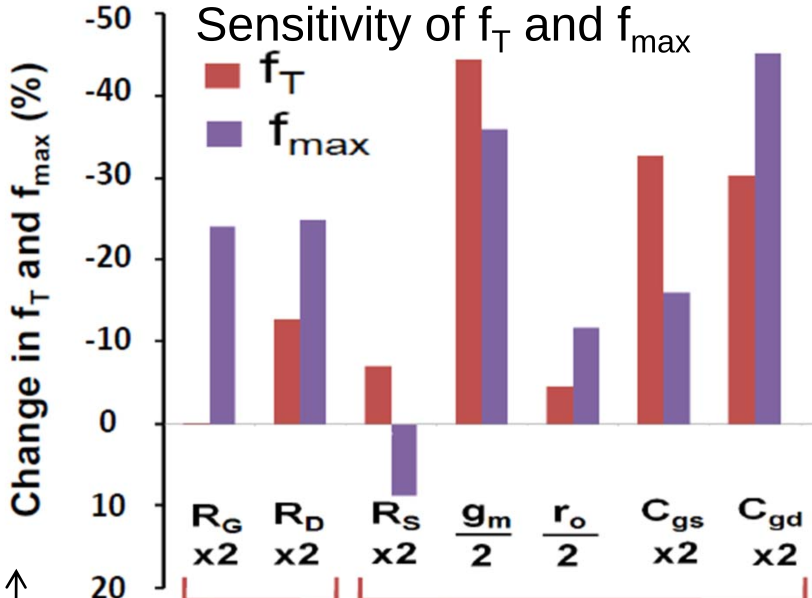
Can nm CMOS provide the power gain @ 300GHz?

Fmax is the frequency beyond which it is not possible to have power gain above unity using a single MOS device for a given process. It is also the maximum freq. of oscillation using a single device and is a figure of Merit that is most relevant to Tx and Rx chain design.
We need "Power Gain" > 1 to transmit, or to Receive in a lossy channel.

F_{max} is Sensitivity to process parameters: as gm, 1/Cgd, 1/Cgs, 1/Rg
➔ all improve with Process node shrink: effective Lg and Cgd, Cds reduce with lithography,
Idrive(channel mobility using stress techniques) go up hence gm goes up,
use of HiK dielectrics make effective Tox go down hence gm goes up and metal gate makes Rg go down

Adapted from U. Gogineni, J. del Alamo, et al., (MIT), GRC review 10/2009





Scale ideally

Highly layout dependent; do not scale well

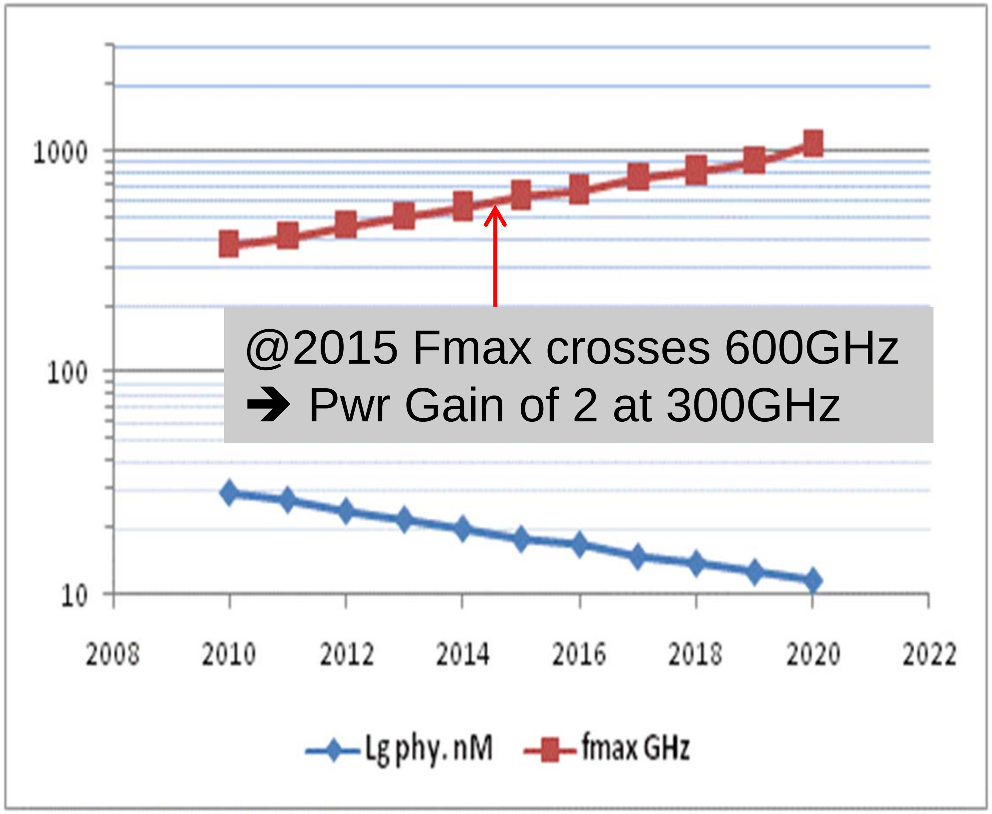
Lg↓ tox↓ Hi K↑

$$f_T \uparrow \approx \frac{g_m \uparrow}{2\pi(C_{gs}\downarrow + C_{gd})}$$

μ↑ Channel stress↑

$$f_{max} \approx \sqrt{\frac{f_T}{8\pi R_g C_{gd}}}$$

ITRS 2009 Roadmap for Fmax vs Process



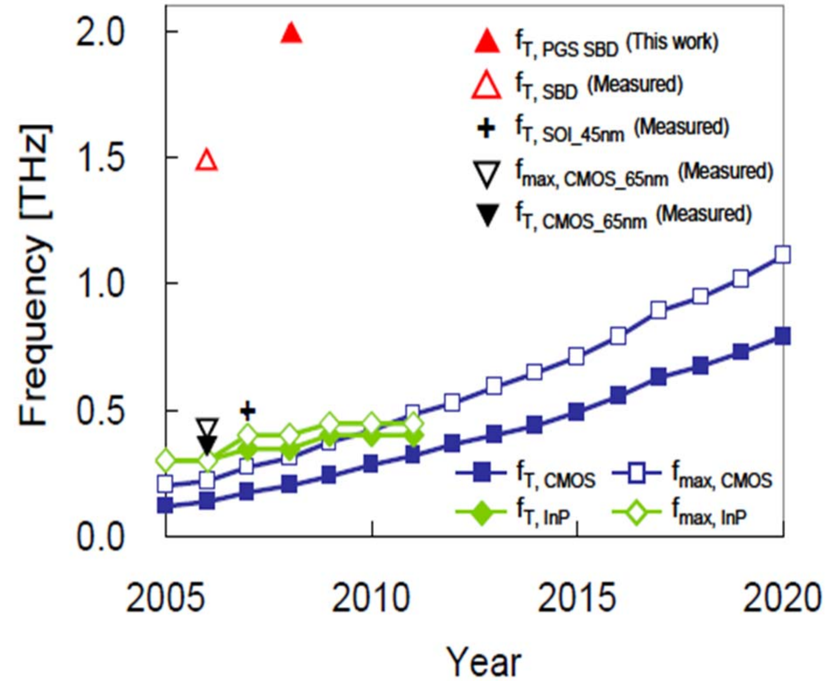


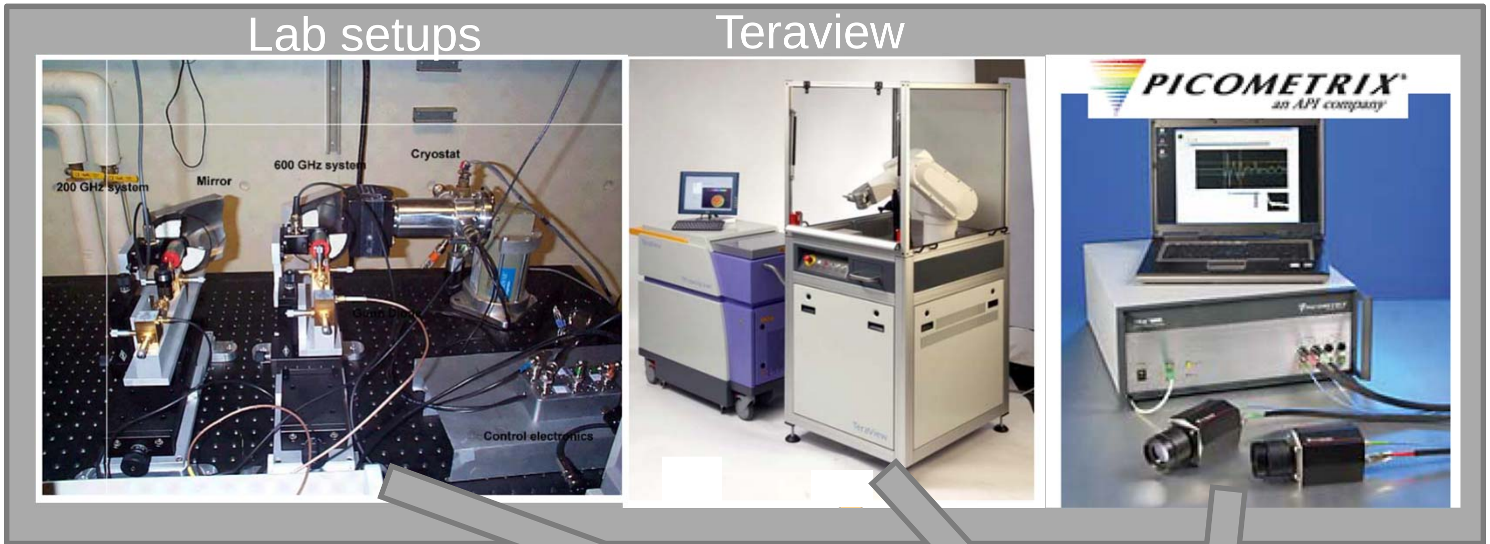
Figure 11.4.2: High frequency capabilities of NMOS transistors and PGS SBD's.

S. Sankaran et. al. ISSCC 2009, paper 11.4

Towards Terahertz Operation of CMOS

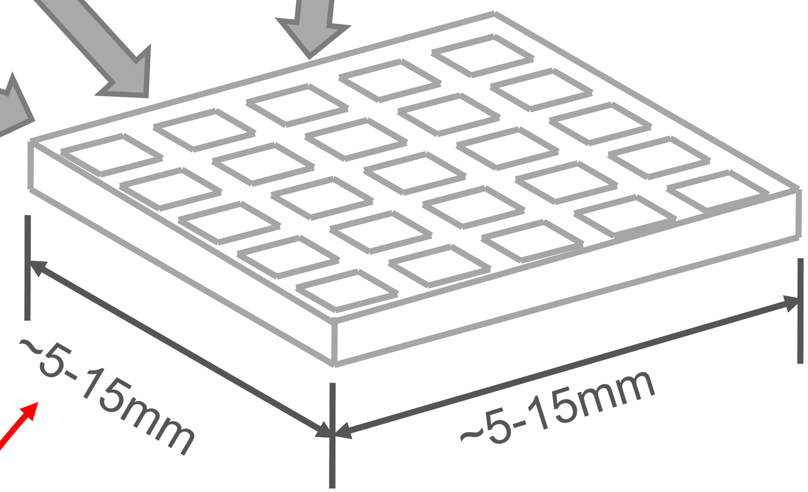
Copper Interconnect is norm

Big Picture – Goal for Semiconductor Manufacturer



Current methods

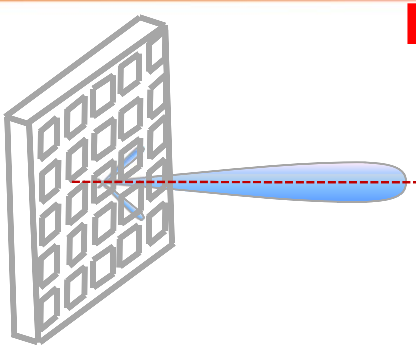
- – Expensive
- – Not end-user friendly
- – Requires
  - Large space (big lasers, spectrometers, etc)
  - Or exotic/special meta-materials
- – Need lots of power



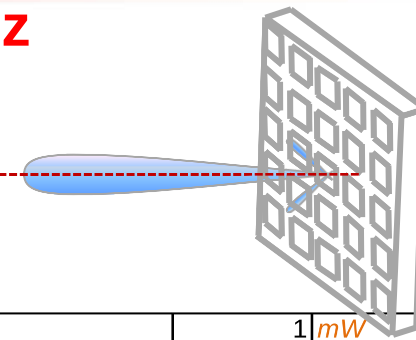
- **Goal**
  - – THz devices that are small and compact to fit in a typical 5x5mm2 → 15*15mm2 package for cost effective consumer apps
  - – → Few $ to 10's of $$ to enable high volume markets.
  - – Since gain is hard to achieve at THz, we rely on
    - Antenna arrays to produce gain
    - Accurate modeling of the devices at these frequencies to extract the maximum possible power out of the process

- Coherent CW THz source
- On-chip Phased Antenna Array
- On-chip sub-mm integrated TX/RX

Link Range Calculation at 300GHz Array Transceivers



>20Gbpsec link



$$R_{max} = \sqrt{\frac{P_t G_t G_r \lambda^2}{(4\pi)^3 kTB_n F L_d SNR}}$$

R_{max} = Maximum Reception Range (m)

P_t = Tot .Power Radiated from Antenna (W)

G_t = Transmit antenna gain (dBi)

G_r = Receive antenna gain (dBi)

λ = Carrier wavelength (m)

k = Boltzmann's constant ($J/{}^oK$)

T = Mean temperature (${}^oK$)

B_n = Signal Bandwidth (Hz)

F = Receiver Noise Figure

L_d = Atmospheric Attenuation ($Loss/km$)

SNR = SNR expected at the receive detector

Transmitted Power per antenna	1	mW
Transmit Antenna Element Gain (Patch antenna)	9	dBi
Transmit Antenna Array Power Gain **(Array=4 x 4 elements)**	12.0	dB
Receive Antenna Element Gain (Patch antenna)	9	dBi
Recieve Antenna Array Power Gain **(Array=4 x 4 elements)**	12.0	dB
Carrier Wavelength in Air (Carrier Frequency = 300GHz)	0.001	m
Incoming Noise Energy (kT @ 290K)	4.00E-21	J
Receiver Bandwidth	5	GHz
Receiver Noise Figure	10	dB
Atmospheric Attenuation (10dB/km @25mm/hr rain)	0.22	dB
SNR at receiver detector	9	dB
Maximum Range **"Mobile docking soln."**	**2.21**	m

~1W Rx or Tx, **$**
Chip Size: <10mm2

Transmitted Power per antenna	1	mW
Transmit Antenna Element Gain (Patch antenna)	9	dBi
Transmit Antenna Array Power Gain **(Array=32 x 32 elements)**	30.1	dB
Receive Antenna Element Gain (Patch antenna)	9	dBi
Recieve Antenna Array Power Gain (Array=32 x 32) elements)	30.1	dB
Carrier Wavelength in Air (Carrier Frequency = 300GHz)	0.001	m
Incoming Noise Energy (kT @ 290K)	4.00E-21	J
Receiver Bandwidth	5	GHz
Receiver Noise Figure	10	dB
Atmospheric Attenuation (10dB/km @25mm/hr rain)	1.25	dB
SNR at receiver detector	9	dB
Maximum Range **"Femto-cell wireless backhaul"**	**125.37**	m

~50W Rx or Tx, **$$$**
Chip Size: <280mm2

Why is directivity needed (Beyond Range)?

From: Siliconization of 60 GHz, Ali. M. Niknejad

IEEE microwave magazine   February 2010

High Directive Tx and Rx antennas result in:

➔Much Lower Delay spread for multi-path

➔Sub nsec (horn; G=25db) vs >10nsec

➔Much lower Freq. fading dips in freq over the wide band channel

➔No need for equalization (e.g DFE)

➔Hundreds of FIR taps needed

➔No need for OFDM modulation expensive for 5GHz+ BW

➔Lower Blocker level at Rx

➔Easier FE design/Linearity req.

➔ Arrays are a key for Sub-THz communication

➔Electronically Steerable beams allow Locking Rx to Tx antenna beams simplifying deployment.

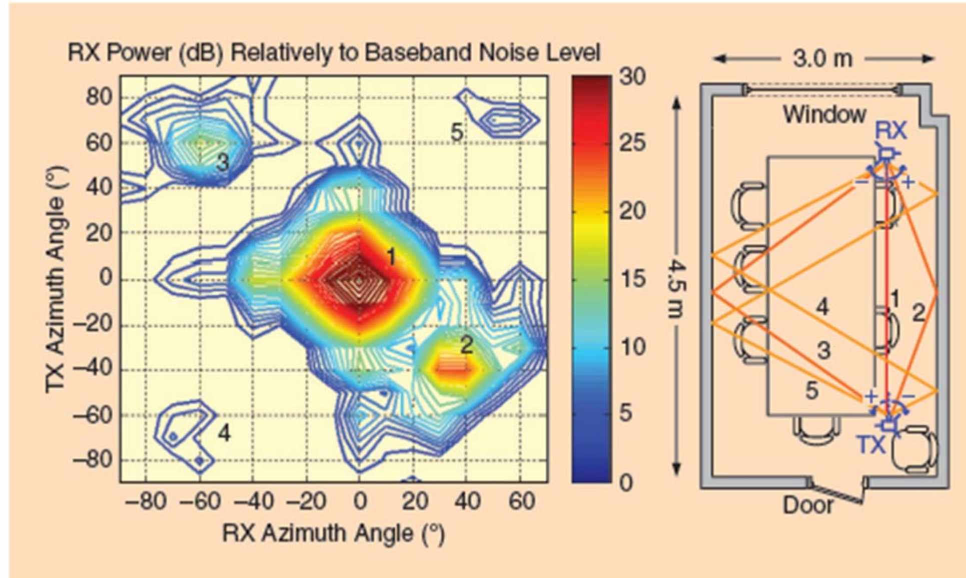
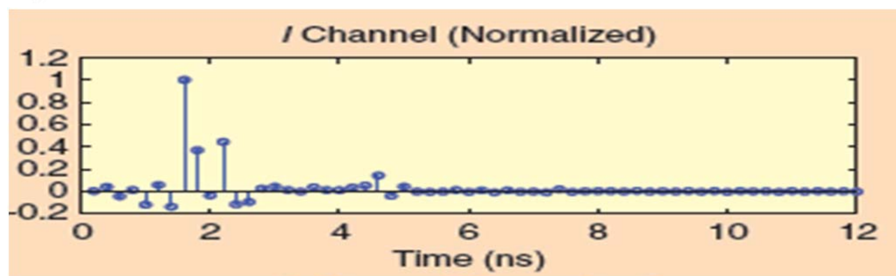
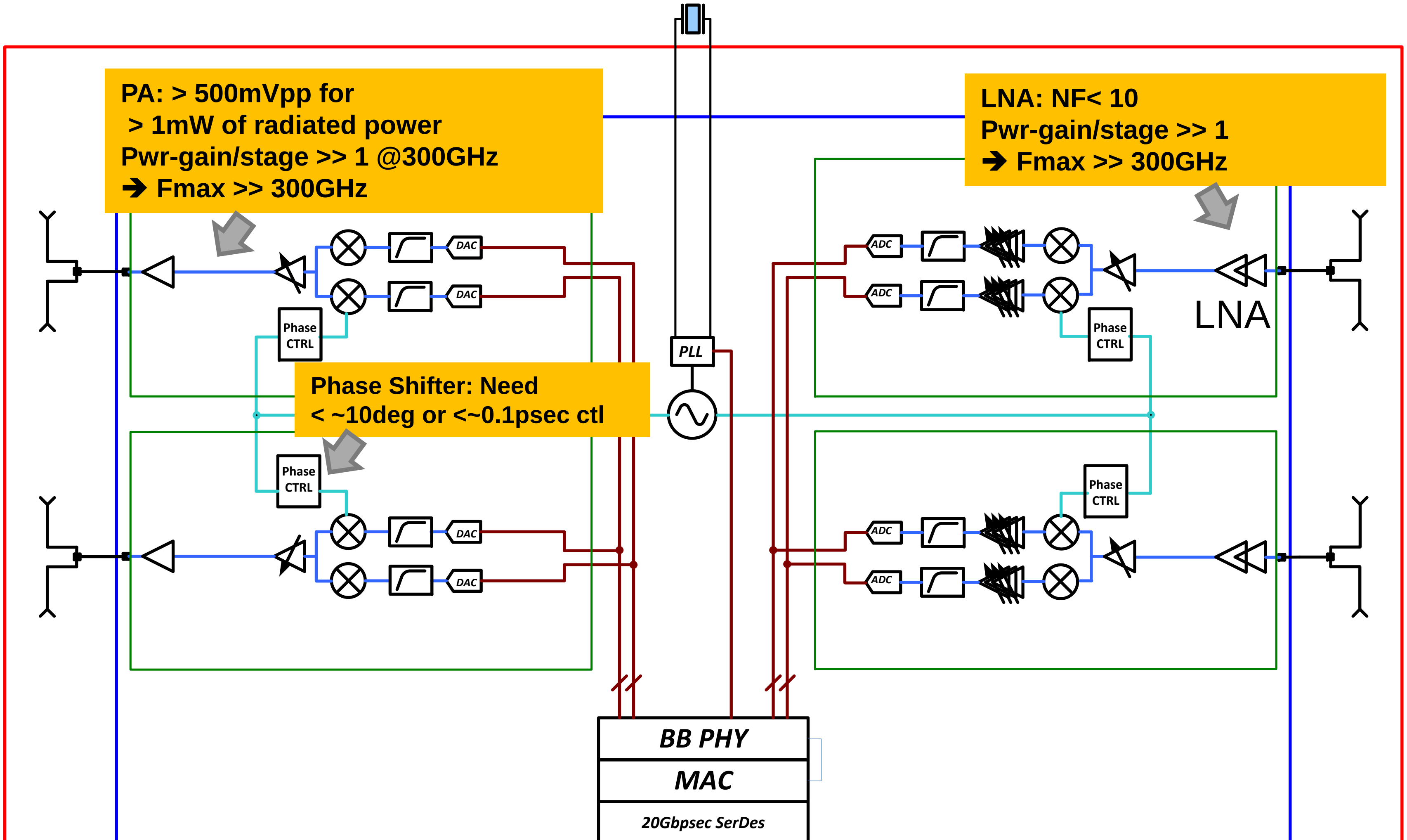


Figure 3. *The measured 60 GHz channel in a conference room setting. The measurements clearly show evidence of quasi-optical propagation, e.g., simple to resolve multipath reflections. From [1].*



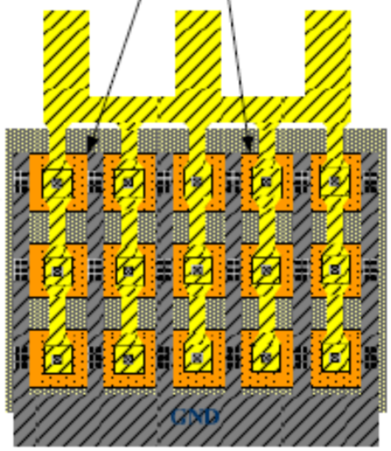
Typical Array Transceiver

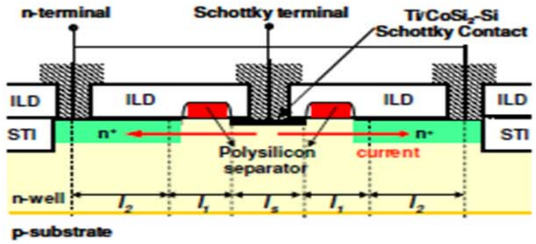


For Power Efficiency of the Transceiver, you want the Mixer (freq. translation) right after least # gain stages from 1st LNA

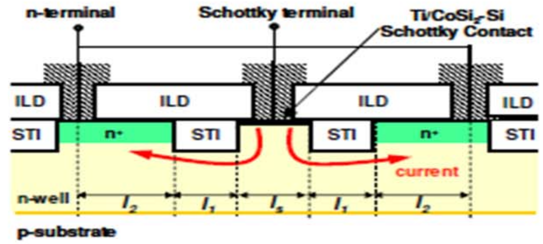
➔ MOS passive Mixer Noise Figure is also very critical and also improves with higher Fmax, and lower Cgs

Schottky diodes on CMOS-New component – No mask adder





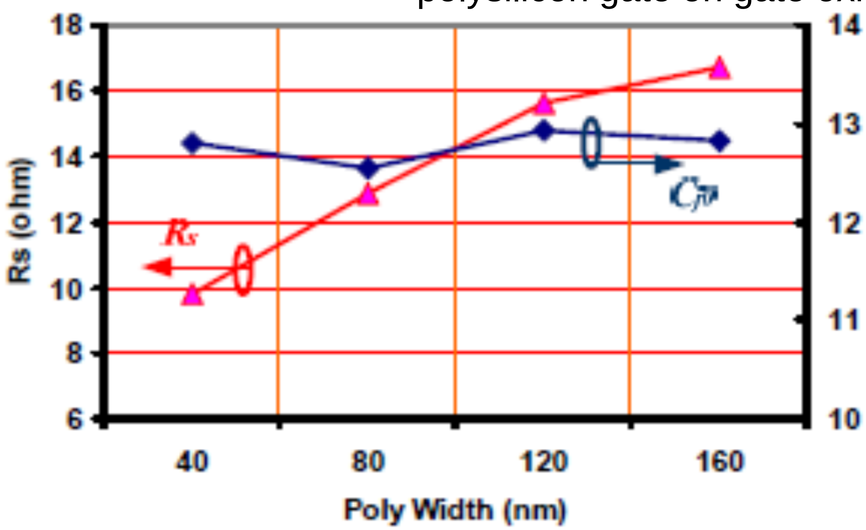
Polysilicon gate separated Schottky barrier diode.

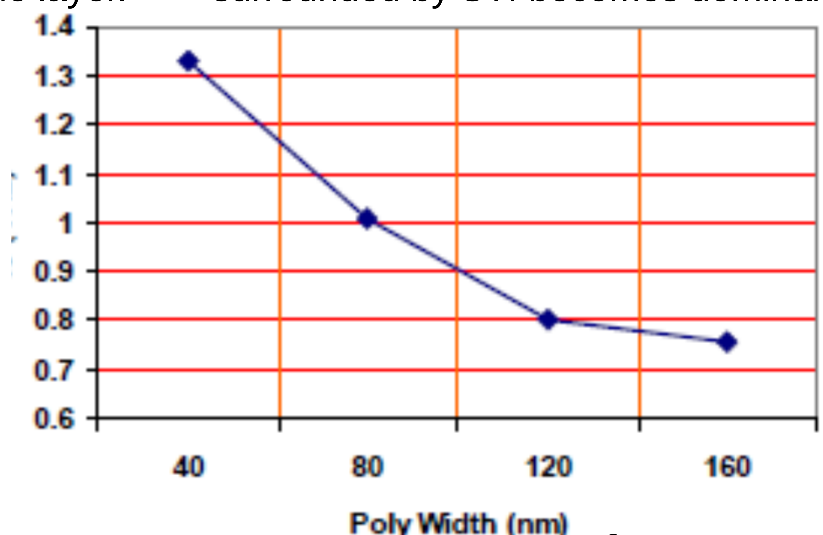


Shallow trench separated Schottky barrier diode.

Schottky diode area is separated by polysilicon gate on gate oxide layer.

The resistance of silicon region surrounded by STI becomes dominant.





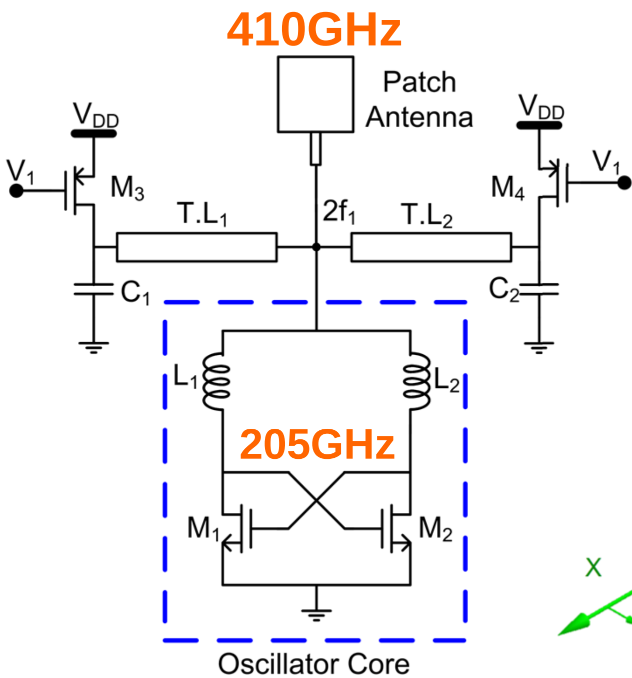
- S. Sankaran et. al. ISSCC 2009 & Kenneth. K. O, UTD , private communication

$$f_{cutoff} = \frac{1}{2\pi R C_0}$$

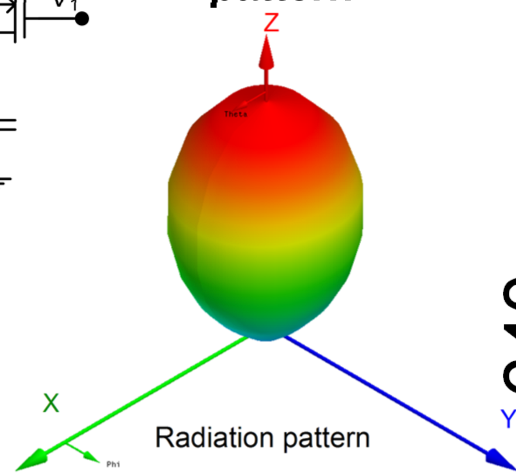
Cutoff frequency : 1~ 2THz

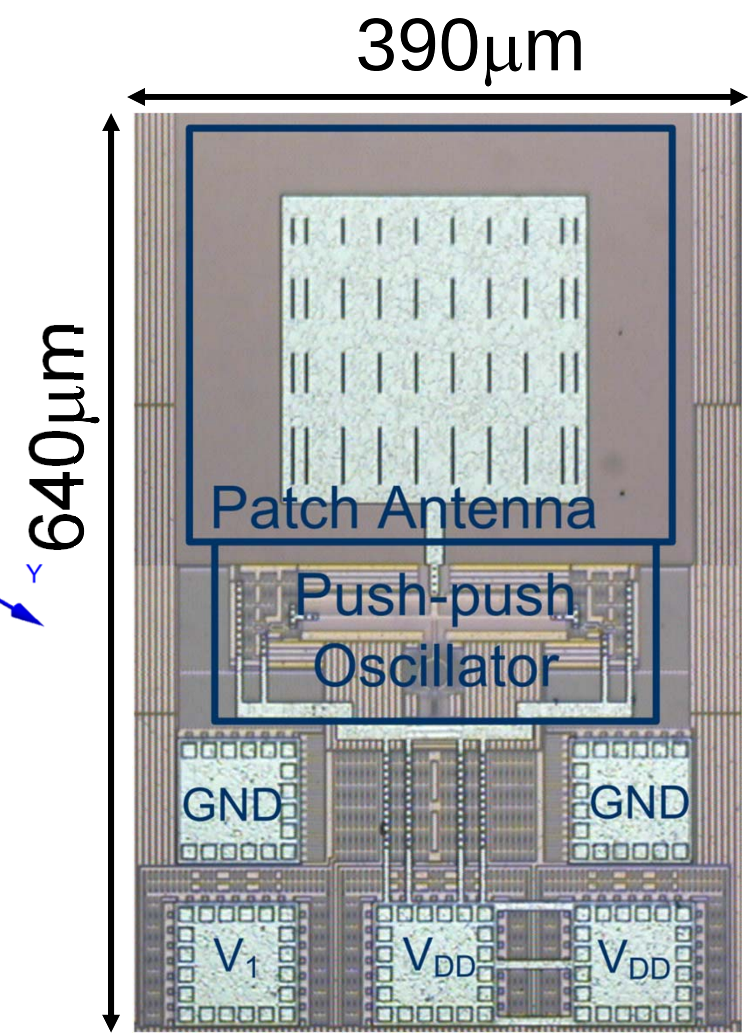
Texas Instruments

45nm TI CMOS process THz Signal Source



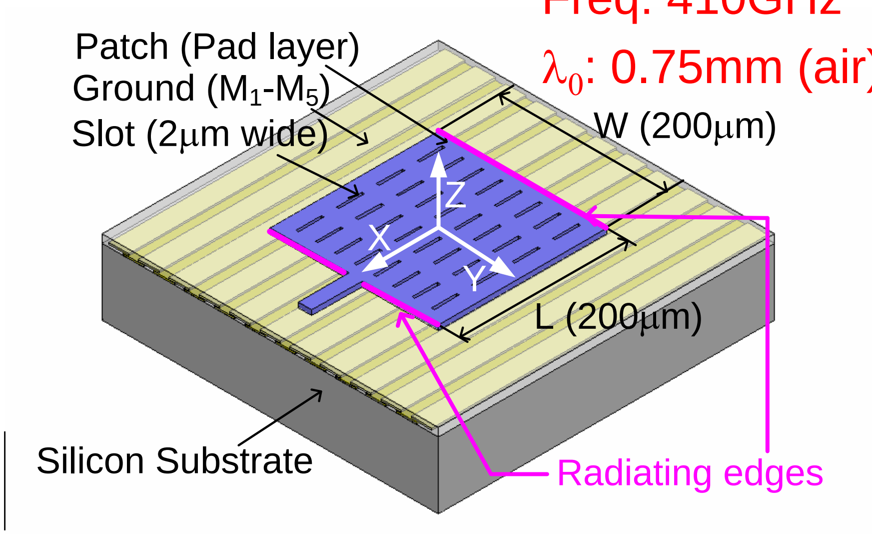
Ant radiation pattern





Freq: 410GHz

λ_0: 0.75mm (air)



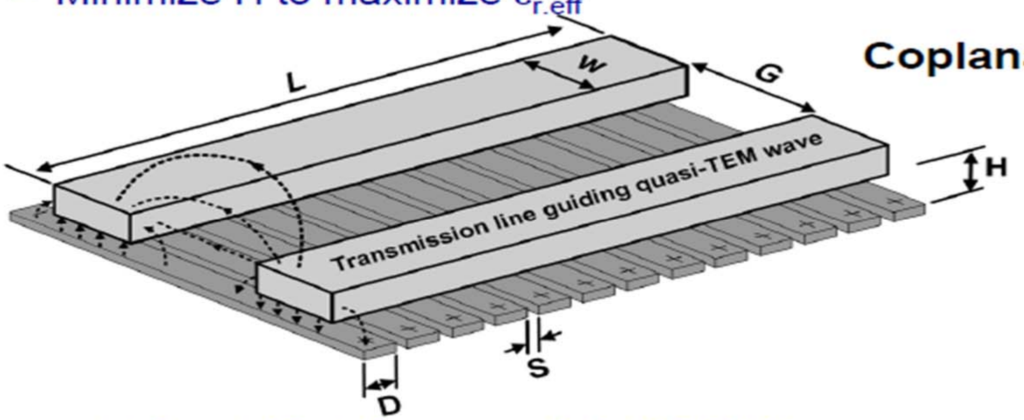
E. Y. Seok et al., "410-GHz CMOS Push-push Oscillator with a Patch Antenna," 2008 International Solid-State Circuits Conference, pp. 472-473, Feb. 2008, San Francisco, CA.

Texas Instruments

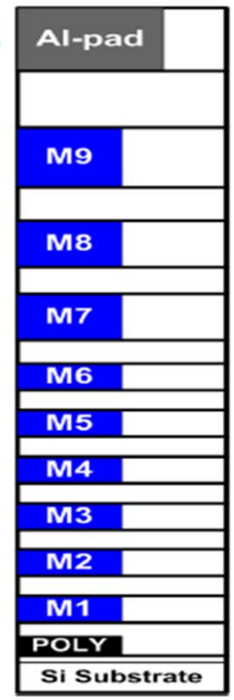
Can we tightly control phase on CMOS?
➔ Digital Controlled Artificial Dielectrics

Differential AD Transmission Line in CMOS

- ***Floating metal strips*** inserted underneath RF t-lines
  - Originally for shielding of conductive substrate
  - Recently utilized for increasing effective diel. constant
- CMOS is a multiple (n>7) metal interconnect process
  - Take advantage of process
  - Minimize H to maximize $\varepsilon_{r,eff}$



Coplanar Strip



Cross Section

– D. Huang, et al, Digest of Tech. Papers, pp. 1218-1227, ISSCC 2006
– D. Huang, et al, Tunable Artificial Dielectrics, US Patent App. 20080204170

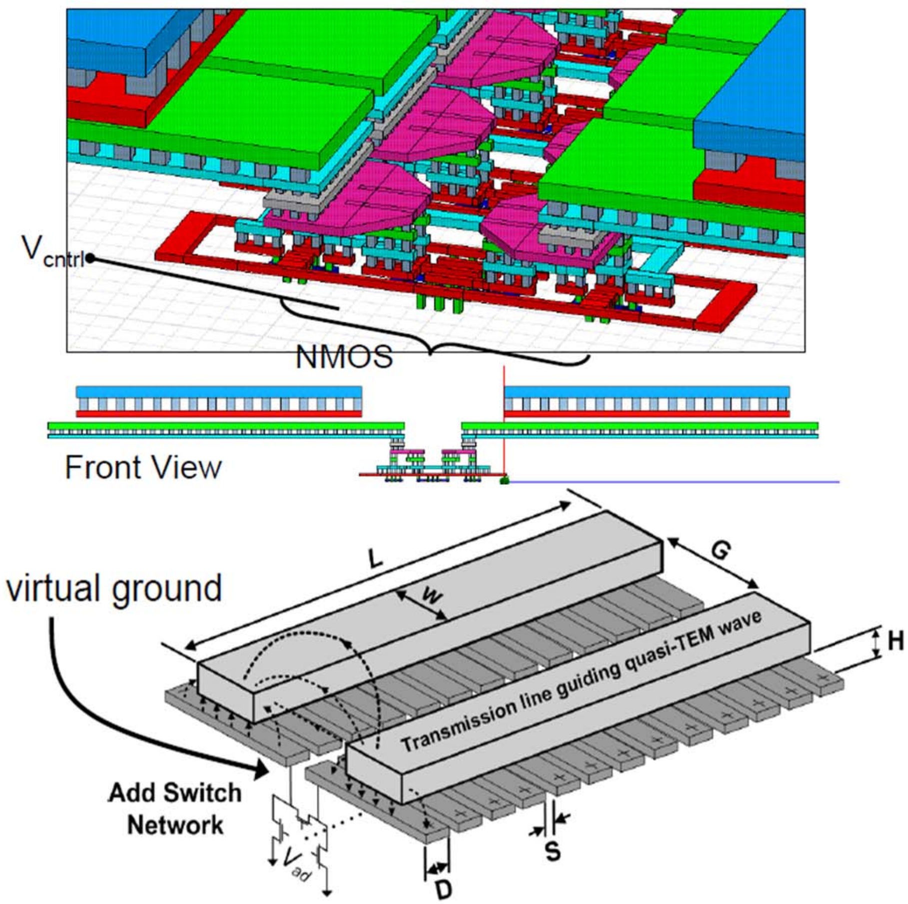
Work Done at UCLA D. Huang (now at TI)

Texas Instruments

Steps of 5 deg at 60GHz = 0.23psec
→ Fine control of array delay possible

Physical CMOS Layout

- ❑DiCAD transmission line
  - (NMOS via connected to floating strips)



❑Effective dielectric constant increases from 7 to 28

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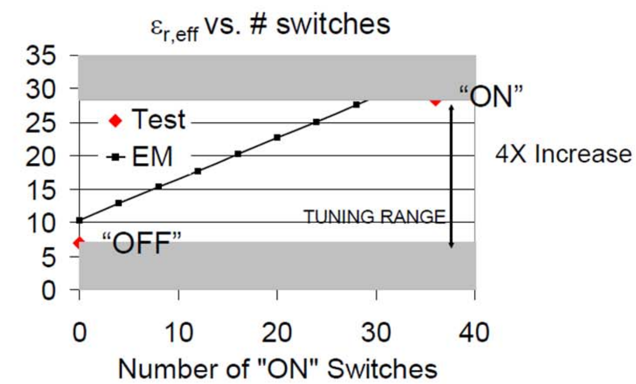

Phase Shift (DiCAD)

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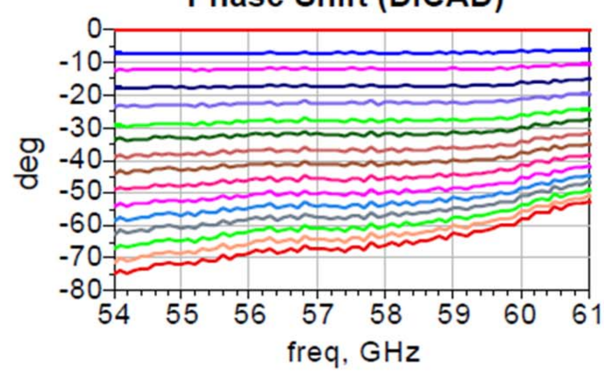


TEXAS INSTRUMENTS

How do we get radiation efficiency from Silicon?

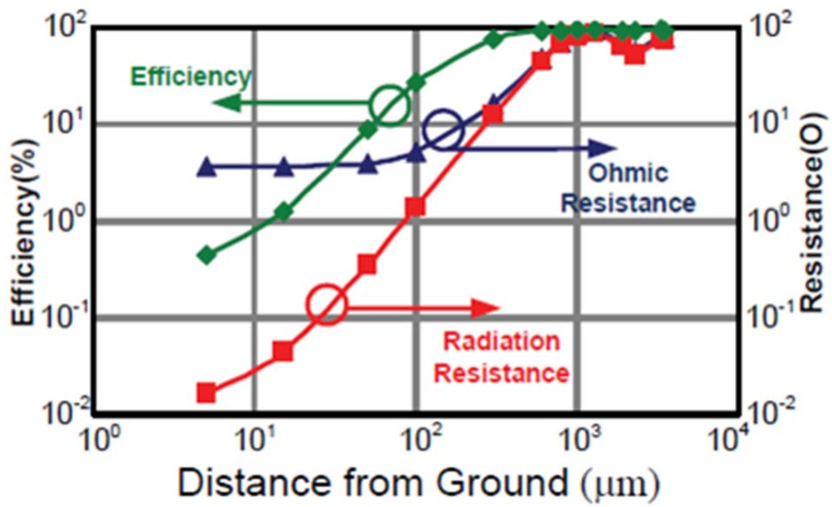
Combine Silicon with Package technology for a complete solution.

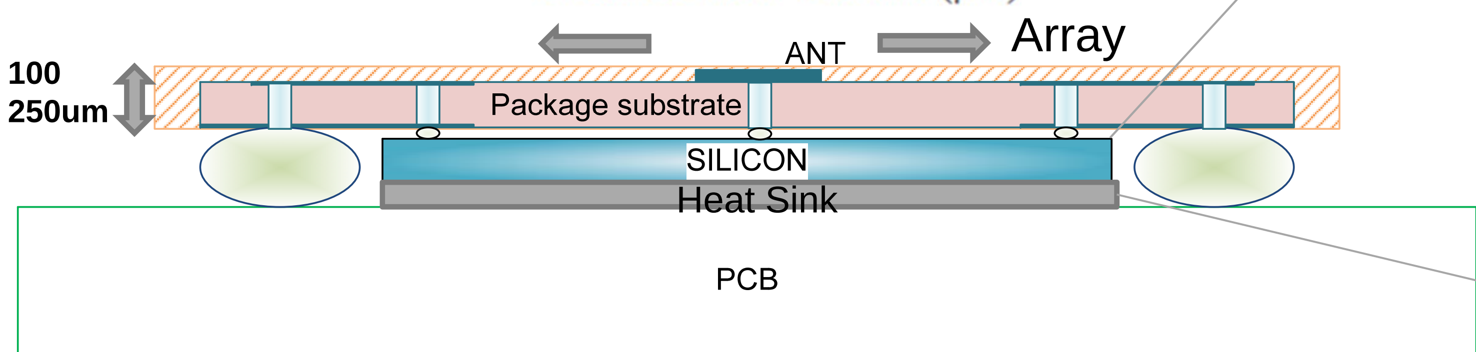
Advanced Package technology allows < 100um pitches for routing

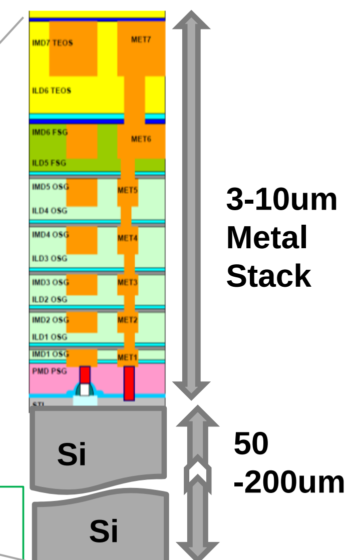
Enabling working on 1mm Wavelength traces.

Moves Radiating element farther out from ground plane improving Radiation efficiency ➔ > 80% of power radiated possible.

Ali Hajimiri,
mm-Wave Silicon ICs:
Challenges and
Opportunities,
CICC 2007







Broadband Wireless Personal Area Networks-
60 GHz and Beyond

PHY and MAC Challenges

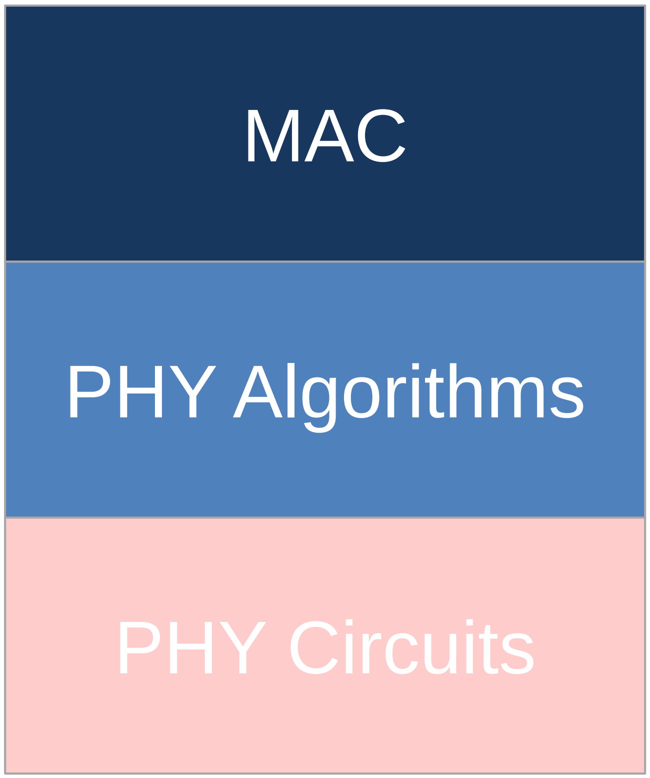
Prof. Robert W. Heath Jr.

The University of Texas at Austin

Wireless Networking and Communications Group

December 2010

PHY, MAC, and Circuits



- 60GHz makes different tradeoffs between circuits, algorithms, and protocols compared with microwave systems
  - Circuits play a more substantial role
  - Digital signal processing is more challenging due to ADC and processing requirements

60 GHz Indoor Channel Properties 1

TABLE 1 Office material attenuation at 60 GHz and 2.5 GHz

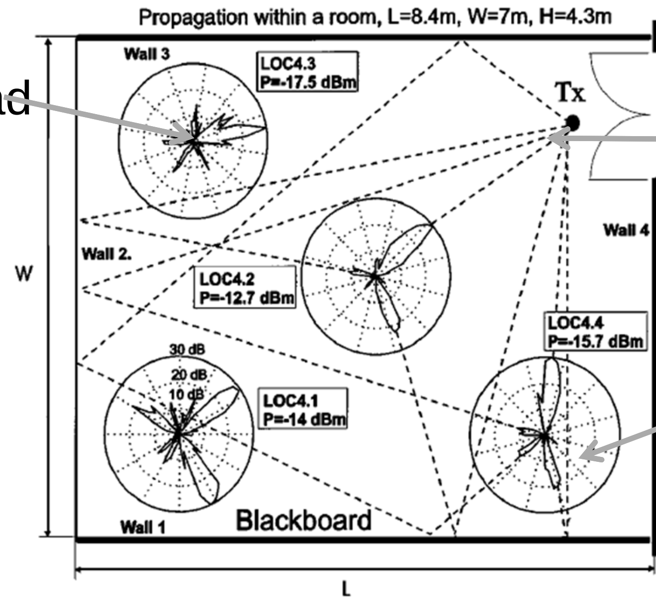
Material	Loss at 60 GHz	Loss at 2.5 GHz
Drywall	2.4 (dB/cm)	2.1 (dB/cm)
Whiteboard	5.0 (dB/cm)	0.3 (dB/cm)
Glass	11.3 (dB/cm)	20.0 (dB/cm)
Mesh Glass	31.9 (dB/cm)	24.1 (dB/cm)

- Path loss exponent between 1.5 and 2.5
- Attenuation higher in most materials
  - Signal more isolated in rooms (better reuse)
  - Multi-room coverage may require repeaters or multi-hop (complex MAC)

C. R. Anderson and T. S. Rappaport, “RF Propagation Characteristics at 2.5 GHz and 60 GHz.“ 2002-2004.

60 GHz Indoor Channel Properties 2

30 degree angle spread



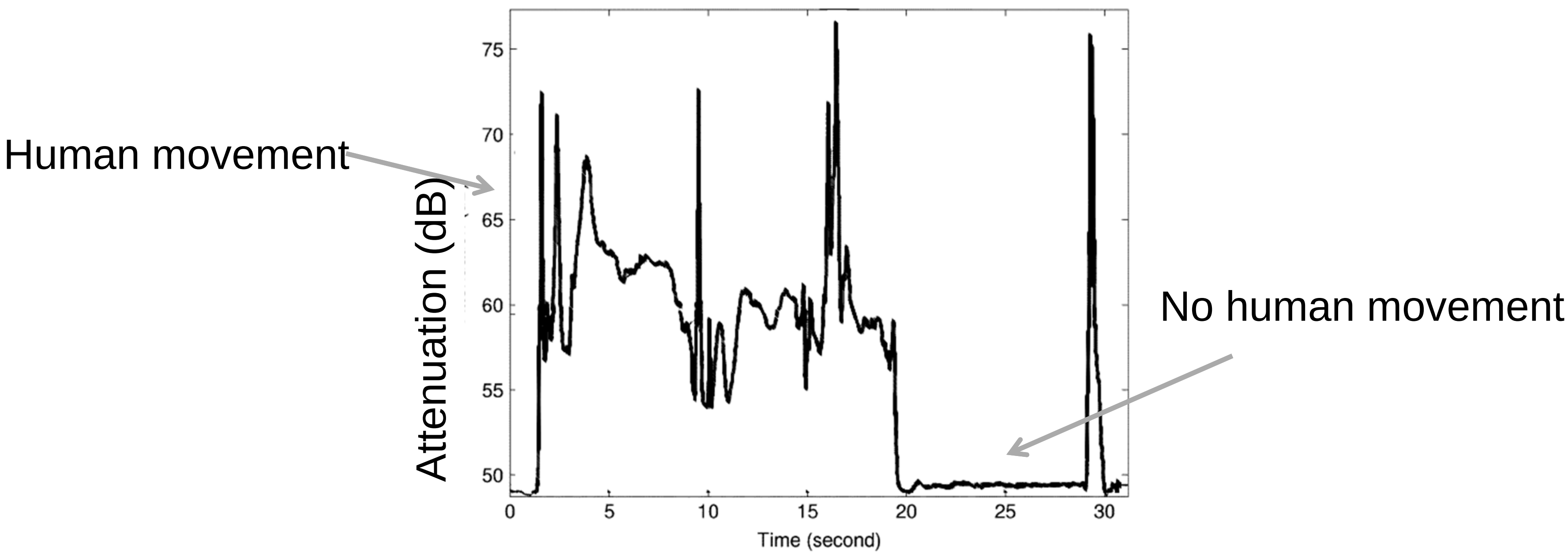
Different path lengths create multi-path interference

4 clusters

- Delay spread: 3ns (LOS) to 15 ns (NLOS)
  - Need to equalize 5 to 60 taps of multi-path!
- Multipath scattering clusters: 2 to 11
  - Beam diversity may be possible
- Angle spread anywhere from 8 to 120 degrees
  - Spatial diversity is available, MIMO may be possible

H. Xu, V. Kukshya, and T. S. Rappaport, "Spatial and temporal characteristics of 60-GHz indoor channels," IEEE Trans. on Sel. Areas in Commun. Vol. 20, no. 3, pp. 620-630, 2002.

60 GHz Indoor Channel Properties 3



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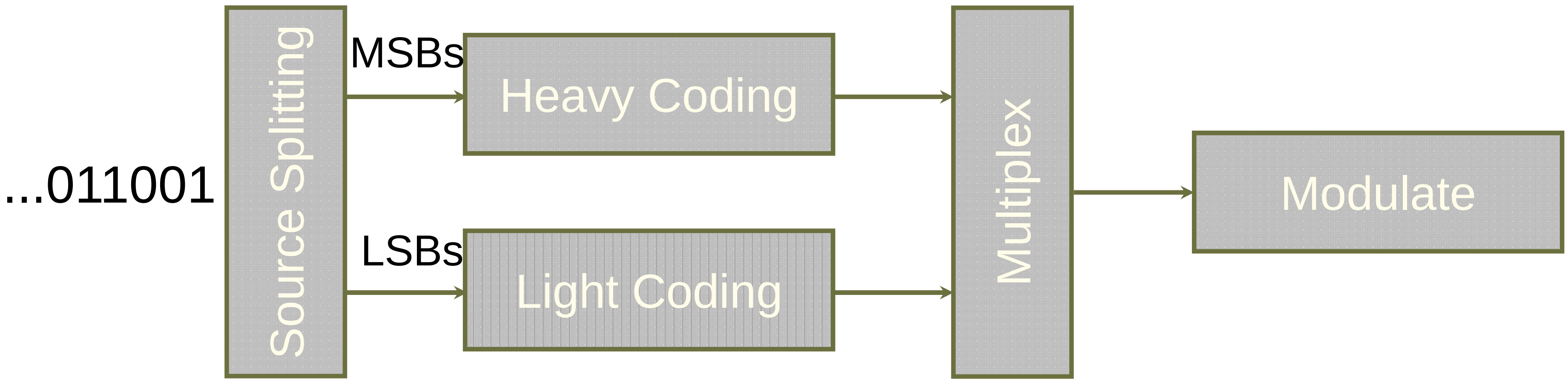
S. Collonge, G. Zaharia, and G.E. Zein, "Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel," *IEEE Transactions on Wireless Communications*, Nov. 2004.

PHY Modulations

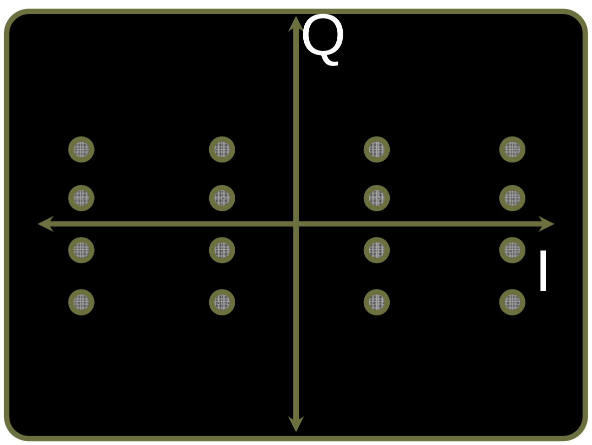
Modulation	Advantages	Disadvantages
Constant Envelope	Low PAPR; operates with simpler RF components	Low spectral efficiency; hard to equalize
SC-FDE	Requires lower precision ADCs; lower PAPR; can operate with little or no coding	IFFT/FFT both at receiver (asymmetry); cannot capture frequency diversity as well
OFDM	Best spectral efficiency; offers best potential for interference handling	Requires linear PA, backoff; requires robust FEC; sensitive to phase noise

Accommodating Video via PHY

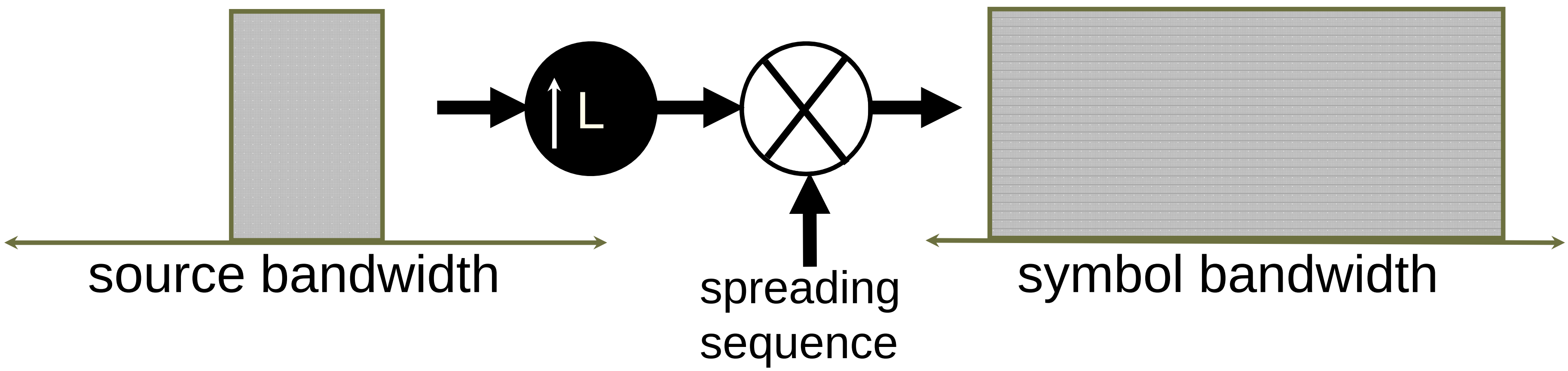
Unequal error protection



Skewed constellations

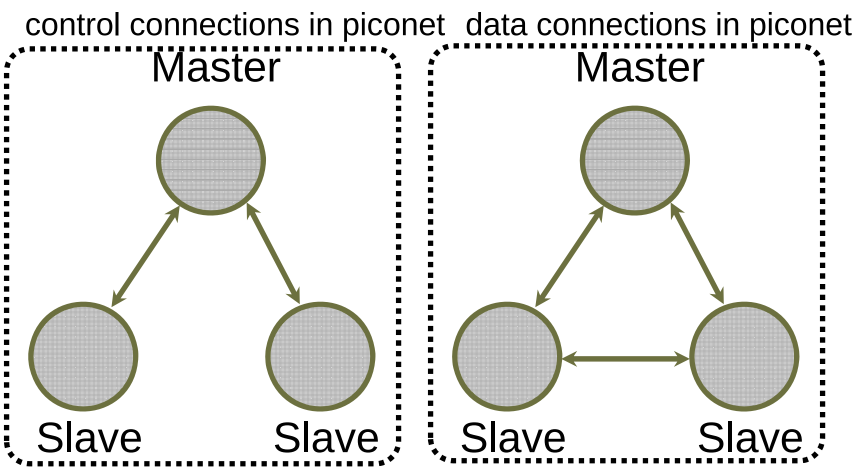


Spreading at the PHY



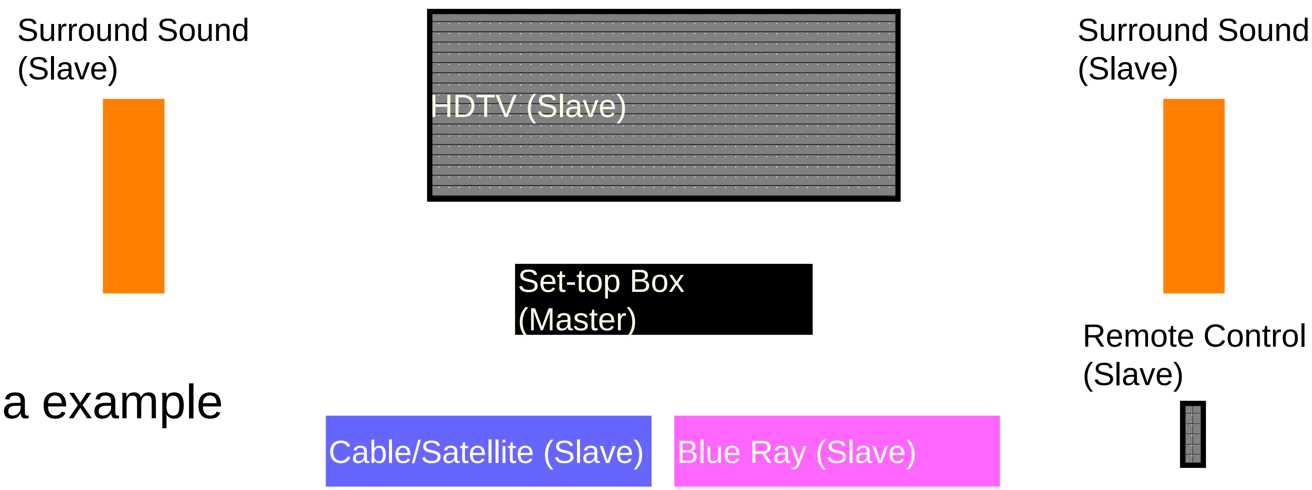
- Beamforming often not available
- Control channels, omni antennas, etc.
- Sacrifice spectral efficiency to maintain link
- May have L <= 64

MAC WPAN Concept



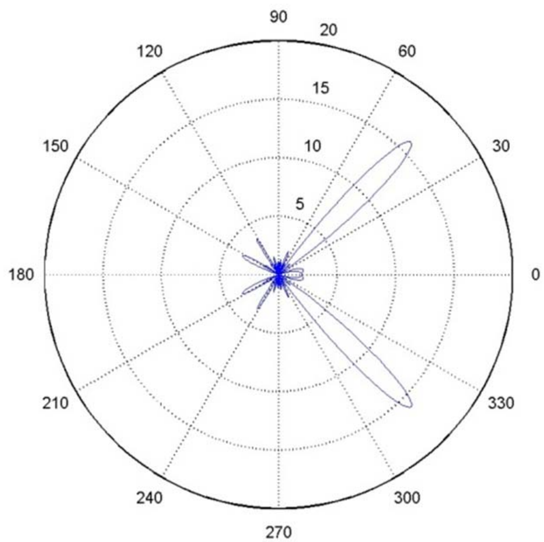
Ad hoc access through piconets

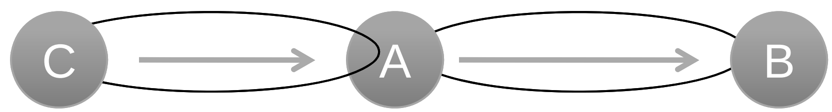
Protocol for neighbor discovery, master election, resource allocation, and network maintenance must be provided by WPAN standard.



Multi-media example

Directional Antennas

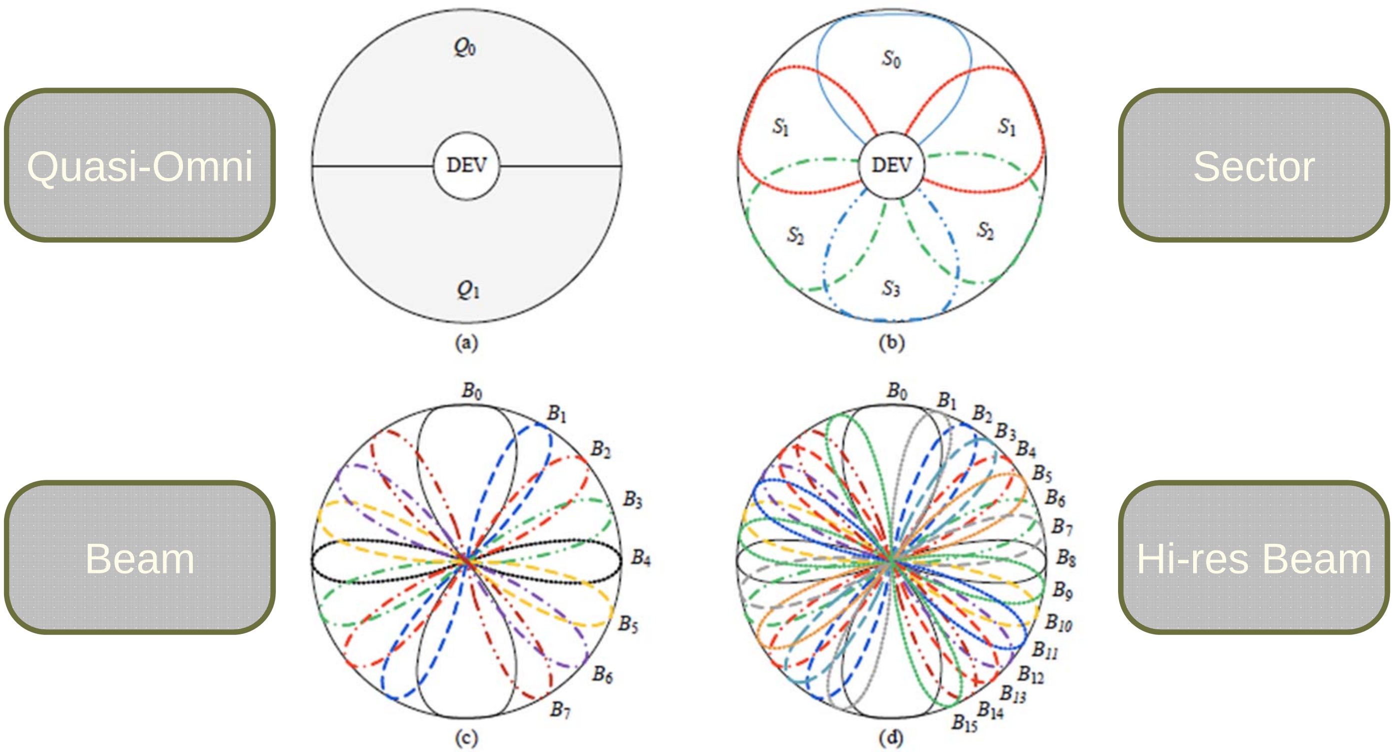




A talking to B
C does not hear A
Called deafness

- Directional antennas are important for 60GHz
  - Provides array gain to reduce link margin
  - Multi-beam diversity for LOS outages
  - Reduces extent of multi-path (less equalization)
  - Large arrays possible c/o small wavelength
- Directional antennas complicate MAC protocol

Directional Antennas MAC



- Link setup may be performed via omni pattern
- Training and feedback for beam selection, feedback, and tracking

60 GHz Current mm-Wave Standards

Name	Forum Type	Status	Maximum Data Rate (Gbps)		Applications
			OFDM	SC (Single Carrier)	
WirelessHD	Industry Consortium	Spec. 1.0, Jan 2008	4	_	Uncompressed HD video
ECMA-387	International Standard	Draft 1.0, Dec 2008	4.032	6.35	Bulk data transfer and HD streaming
802.15.3c (TG3c)	International Standard	Released October 2009*	5.7	5.2	Portable point-to-point file transfer and streaming
802.11ad (TGad)	International Standard	Target completion Dec 2012	>1		Rapid upload/download, wireless display, distribution of HDTV
WiGig	Industry Consortium	Released May 2010*	7 Gpbs*		File transfers, wireless display and docking, and streaming high definition

Singh, H.; Su-Khiong Yong; Jisung Oh; Chiu Ngo; , "Principles of IEEE 802.15.3c: Multi-Gigabit Millimeter-Wave Wireless PAN," *Computer Communications and Networks, 2009. ICCCN 2009. Proceedings of 18th Internatonal Conference on* , vol., no., pp.1-6, 3-6 Aug. 2009
"WiGig Alliance Publishes Multi-Gigabit Wireless Specification and Launches Adopter Program," WiGig press release, Retrieved July 4, 2010, from