THE UNIVERSITY OF TEXAS AT AUSTIN
WHAT STARTS HERE CHANGES THE WORLD

WNCG

MIMO at Millimeter Wave

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Heath Group in the WNCG @ UT Austin

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10 Current Students

Heath Group in the WNCG @ UT Austin

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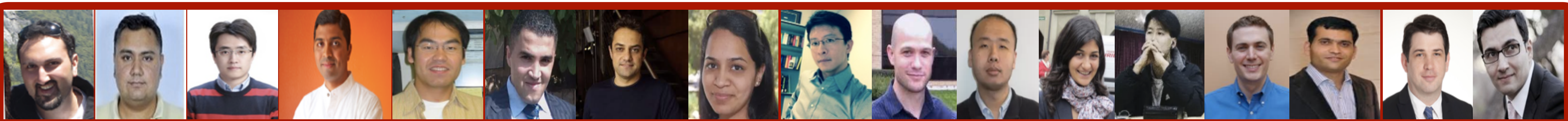
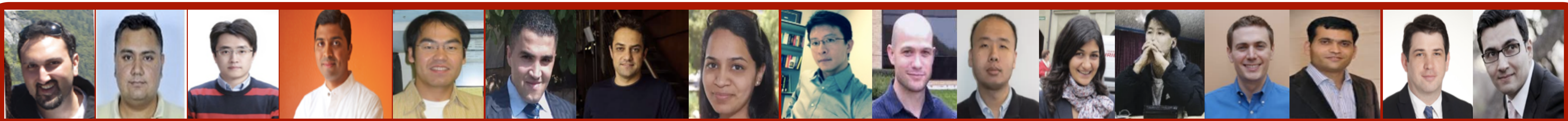


23 Graduated Students

Heath Group in the WNCG @ UT Austin

10 Current Students

Paulraj grand-students



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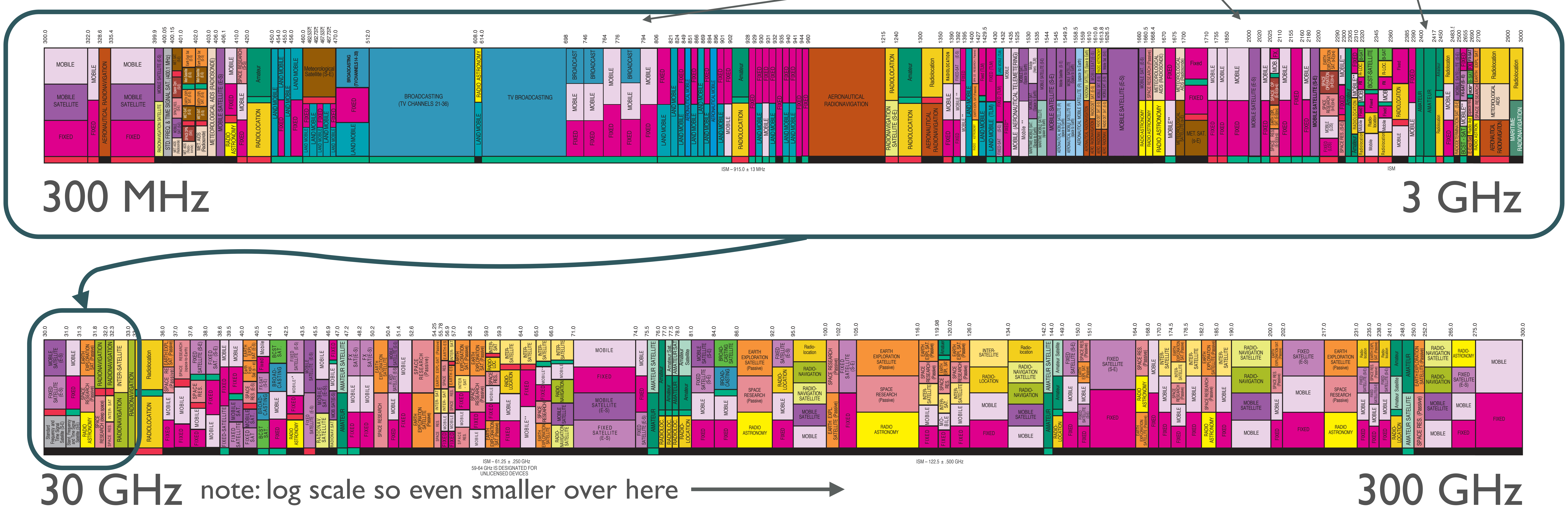
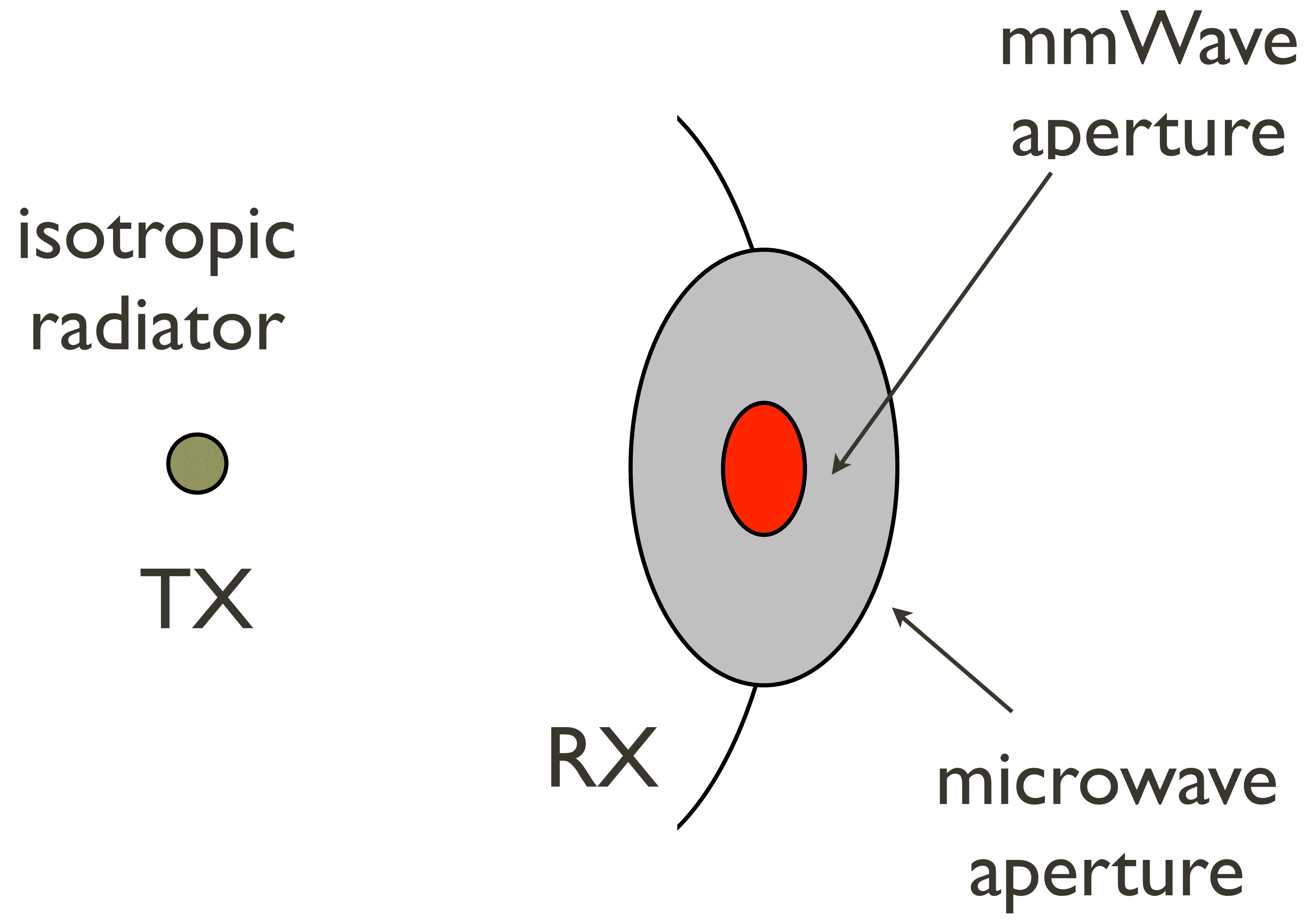
Motivation

Why Millimeter Wave?



- Huge amount of spectrum available in mmWave bands
- Technology advances make mmWave possible for low cost consumer devices
- mmWave research is as old as wireless itself, e.g. Bose 1895 and Lebedew 1895

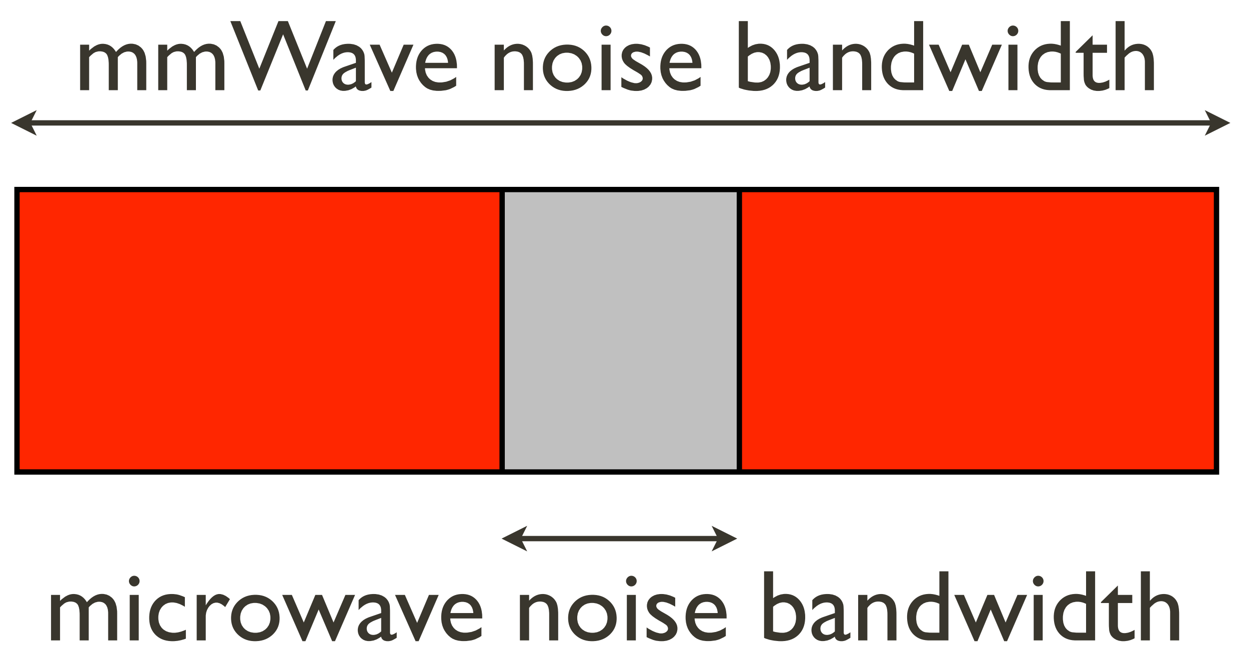
Gain and Aperture in mmWave



$$P_{\rm rx} = \boxed{\frac{P_{\rm tx}}{4\pi R^2}} \boxed{\frac{\lambda^2}{4\pi}}$$

receive spectral density

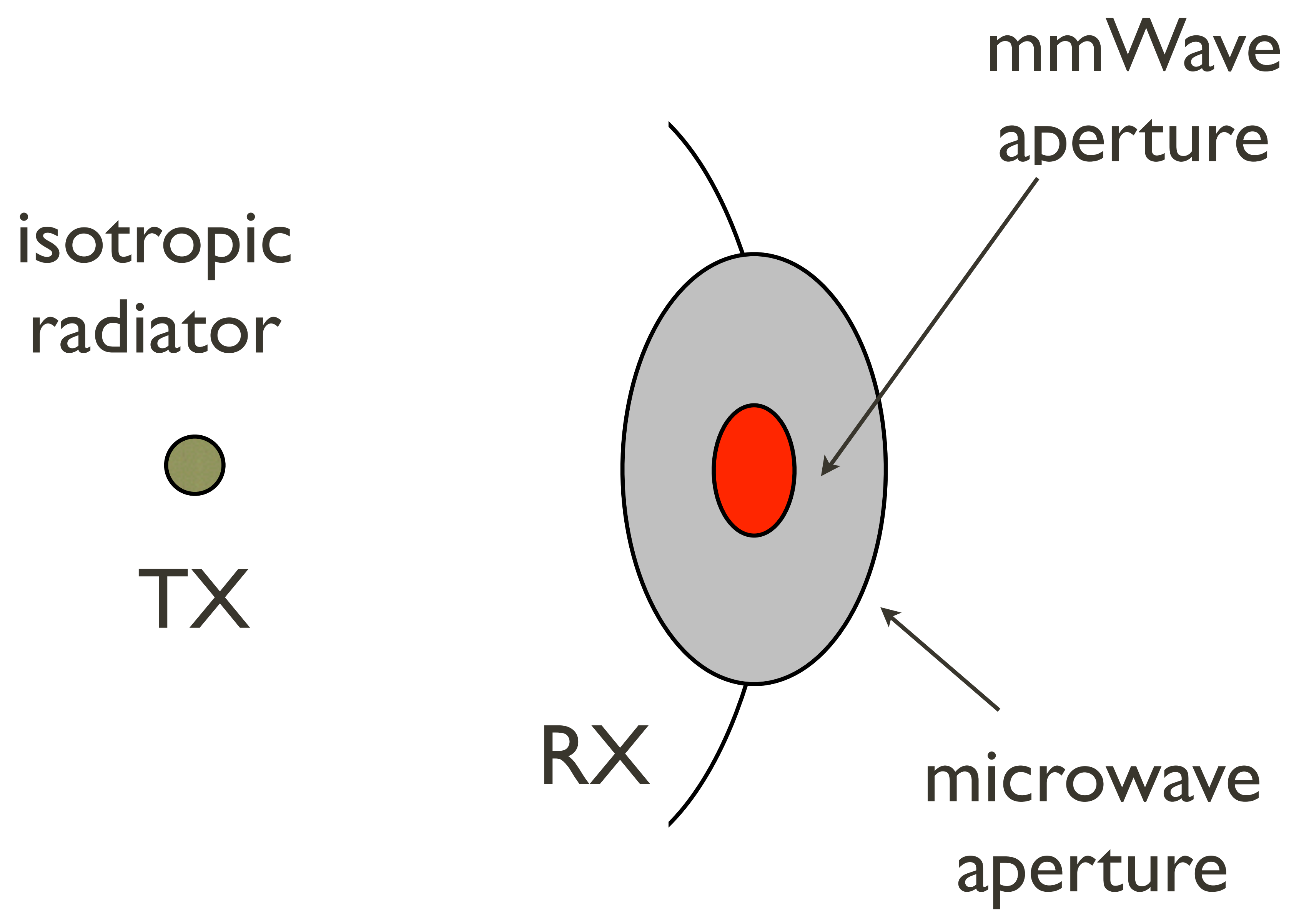
receive aperture



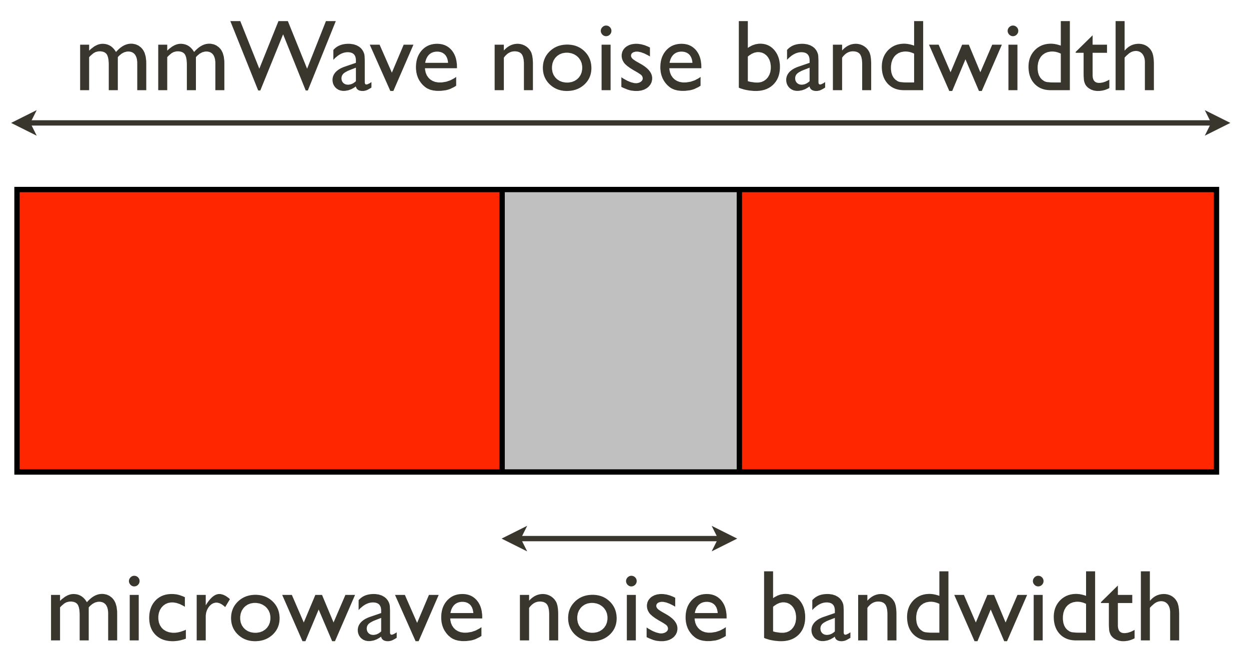
$$N_o = kT_{\rm e}B$$

- Smaller wavelength means smaller captured energy at antenna
  - 3GHz->30GHz gives 20dB extra path loss due to aperture
- Larger bandwidth means higher noise power and lower SNR
  - 50MHz -> 500MHz bandwidth gives 10dB extra noise power

Gain and Aperture in mmWave



$$P_{\mathrm{rx}} = \underbrace{\frac{P_{\mathrm{tx}}}{4\pi R^2}}_{\text{receive spectral density}} \underbrace{\frac{\lambda^2}{4\pi} {\color{red}G_{\mathrm{rx}}}}_{\text{effective receive aperture}} \underbrace{{\color{red}G_{\mathrm{tx}}}}_{\text{transmit antenna gain}}$$



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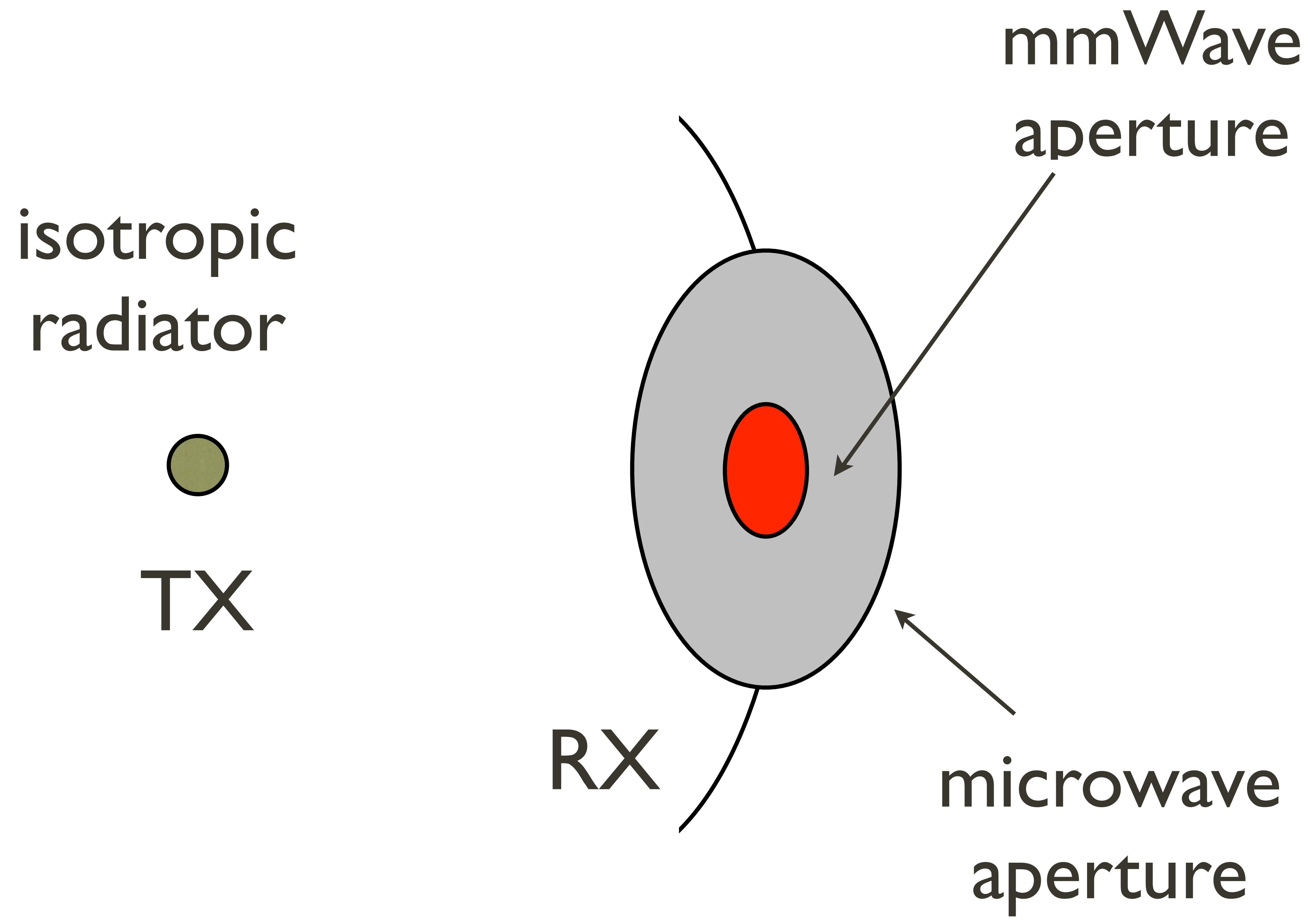

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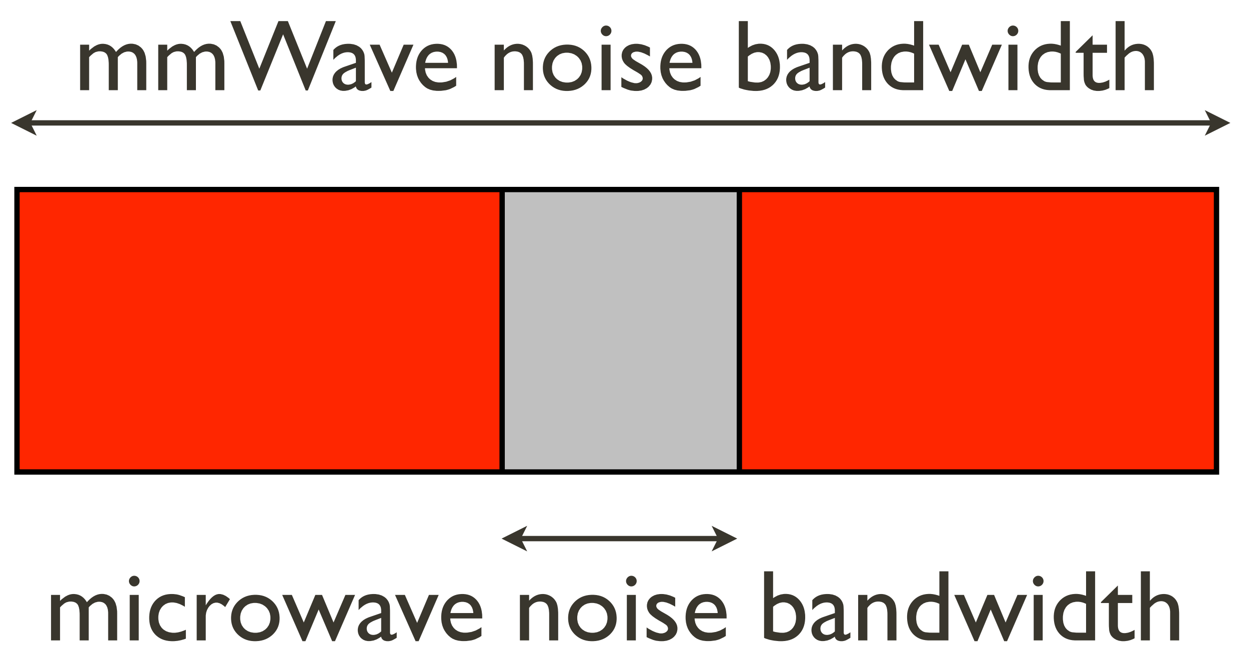

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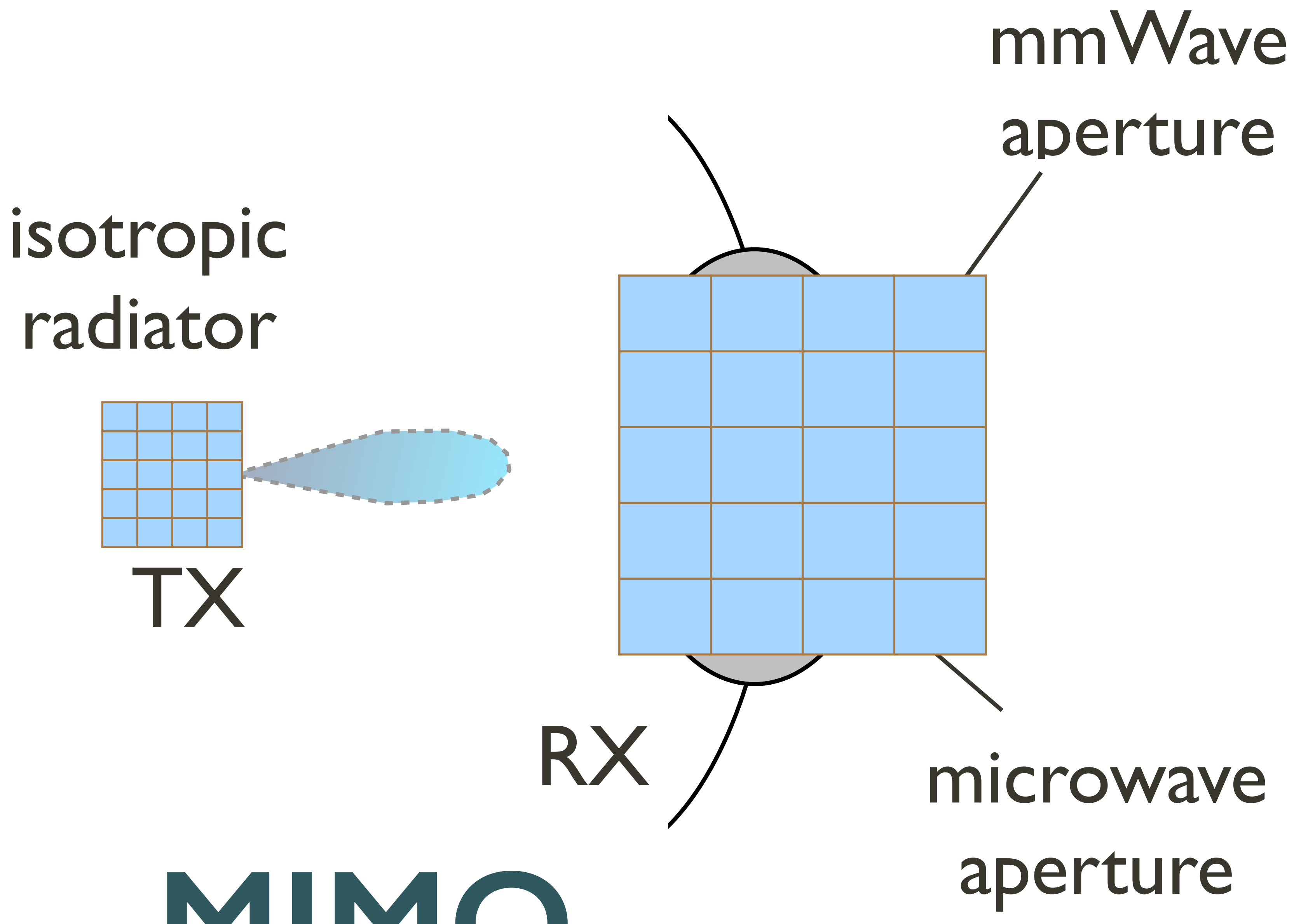

MIMO

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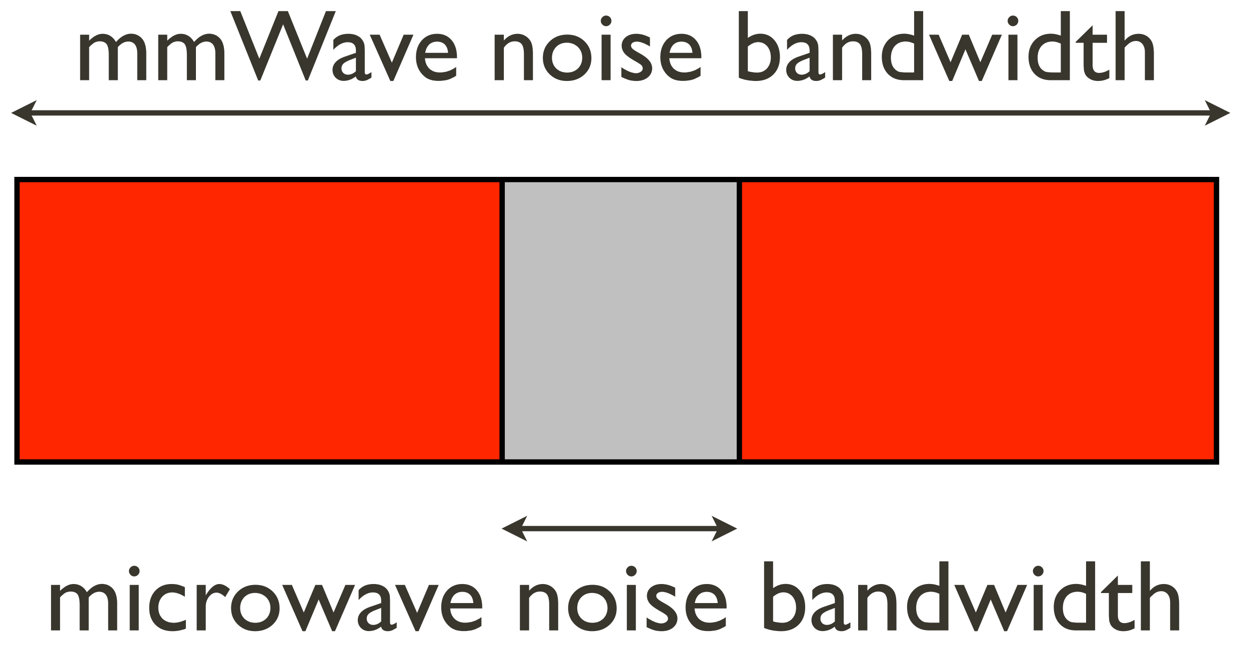

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Exploit gain from large antenna arrays

Constraints in mmWave Inform Theory & Design

quantized phase shifters

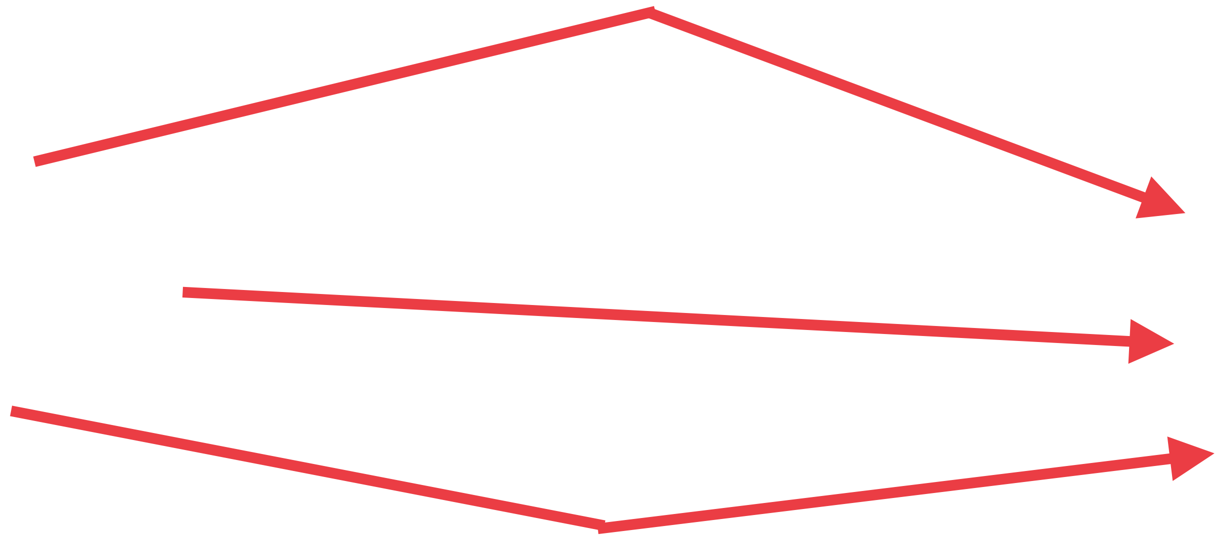
insertion loss

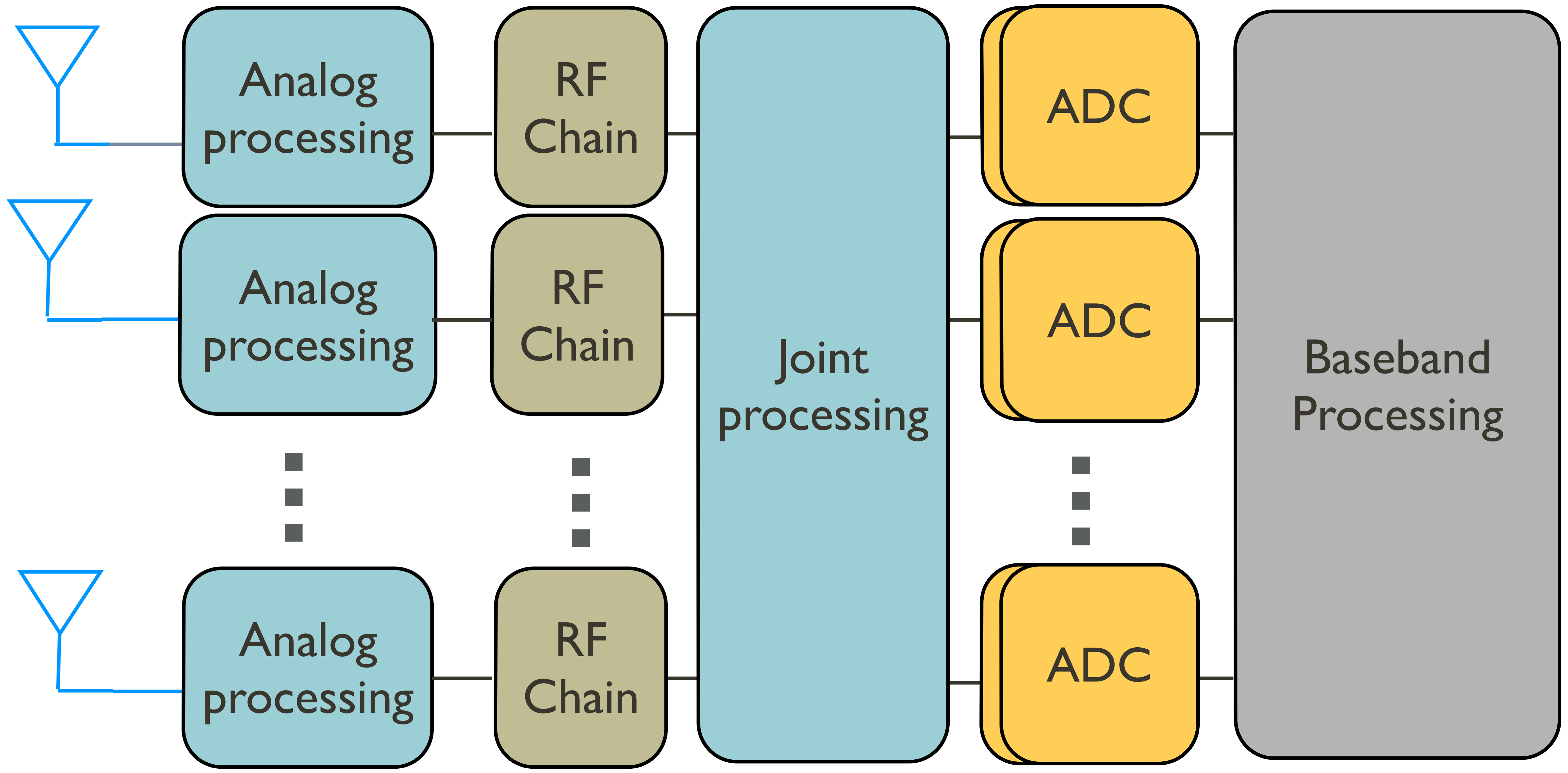
mixed signal power consumption

penetration loss

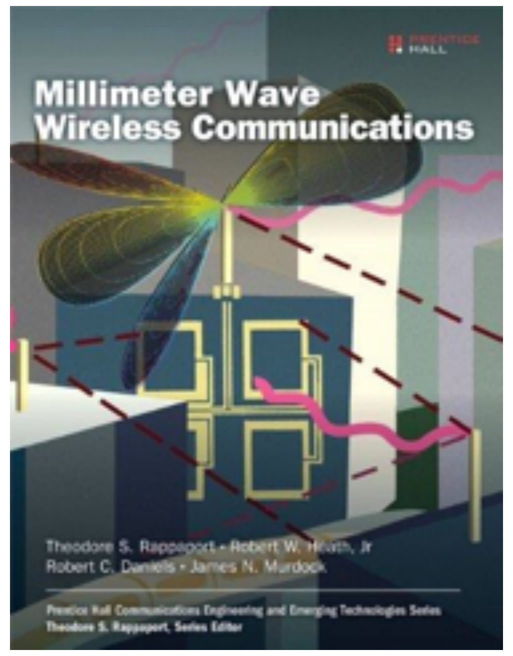
orientation

mobility





no rich scattering



efficient antennas

feed antennas

array geometry

phase noise

low gain

linearity

beam tracking

equalization

synchronization

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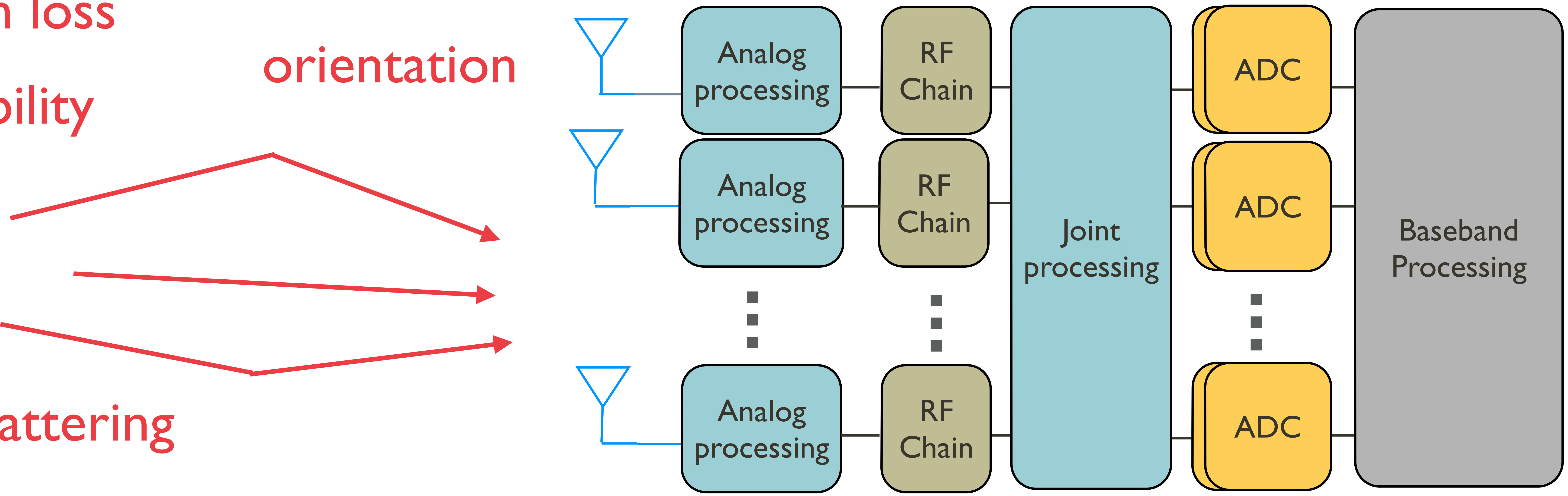

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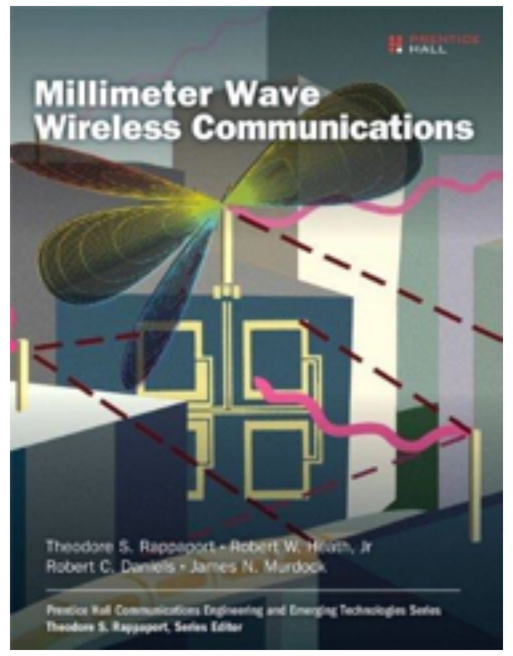

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Compounded by use of MIMO with 8 to 256 antennas or more

The Channel at Microwave vs. mmWave

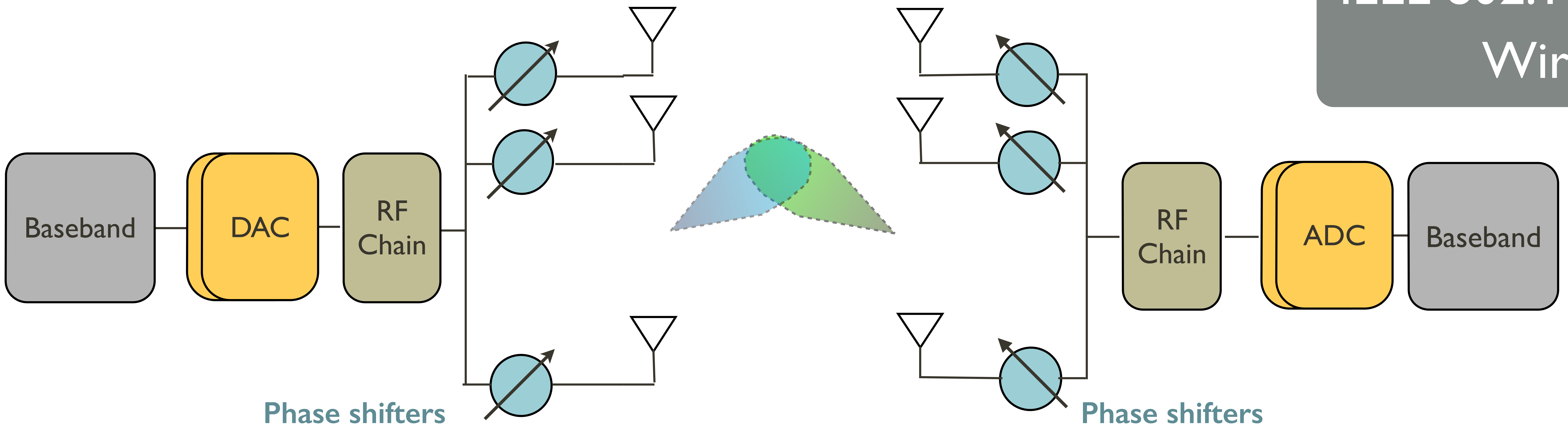
	microwave WiFi or Cellular	mmWave WiFi	mmWave 5G (???)
bandwidth	1.4 MHz to 160 MHz	2.16 GHz	100 MHz to 2 GHz
# antennas @ BS or AP	1 to 8	16 to 32	64 to 256
# antennas @ MS	1 or 2	16 to 32	4 to 16
delay spread	100 ns to 2 us	5 to 47 ns	12 to 40 ns
angle spread	1° to 60°	60° to 100°	up to 50°
# clusters	4 to 9	< 4	< 4
orientation sensitivity	low	medium	high
small-scale fading	Rayleigh	Nakagami	non-fading or Nakagami
large-scale fading	distant dependent + shadowing	distant dependent + shadowing	distant dependent + blockage
path loss exponent	2-4	2 LOS, 2.5 to 5 NLOS	2 LOS, 3.5 to 4.5 NLOS
penetration loss	some	varies	possibly high
channel sparsity	less	more	more
spatial correlation	less	more	more

LOS: line-of-sight NLOS: non-line-of-sight Data synthesized from various sources

MIMO at mmWave

Analog Beamforming

De-facto approach in IEEE 802.11ad / WiGig and Wireless HD

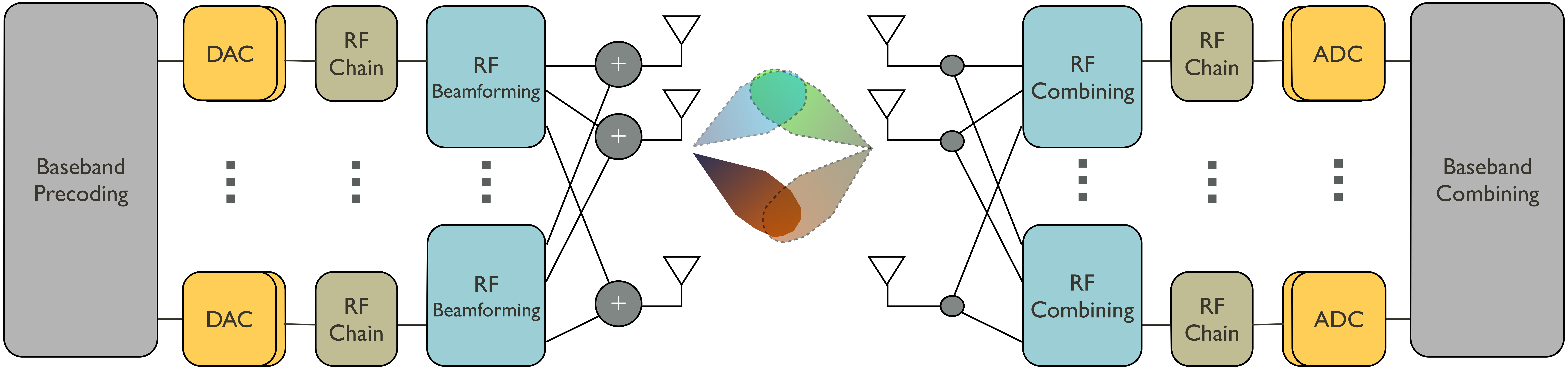


- Motivated by power consumption of ADCs and hardware complexity
- Suitable for single-stream transmission, multi-stream and multi-user complicated
- Joint search for optimal beamforming and combining vectors w/ codebooks

* J.Wang, Z. Lan, C. Pyo, T. Baykas, C. Sum, M. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada *et al.*, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1390–1399, 2009.
* S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," IEEE Transactions on Communications, vol. 61, no. 10, pp. 4391–4403, 2013.

Hybrid Beamforming

Current research direction in industry and academia

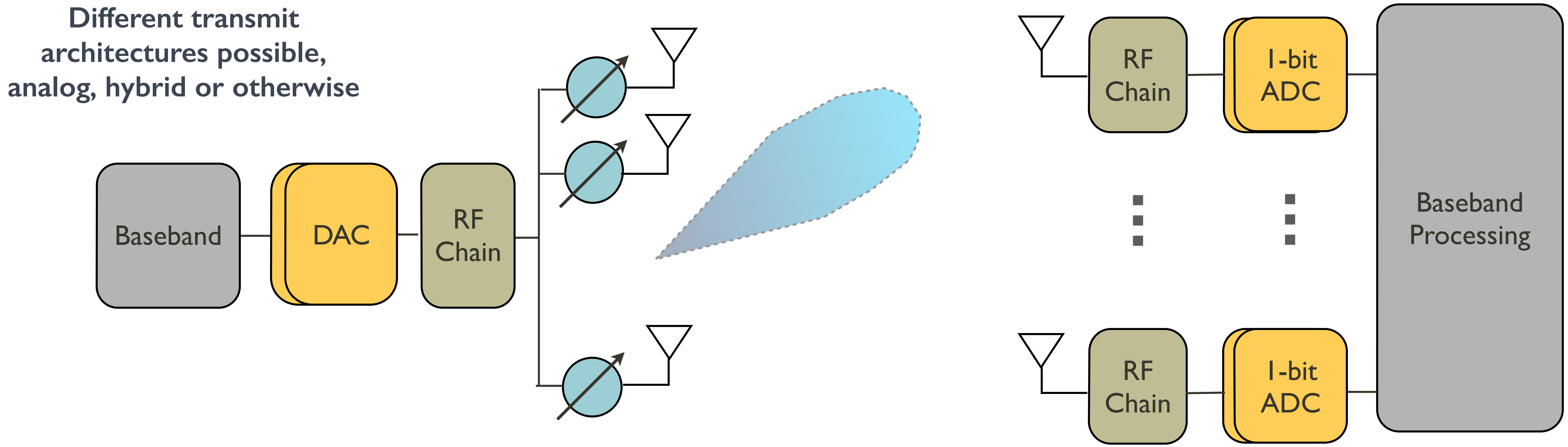


- Makes compromise on power consumption and hardware complexity
- Hybrid analog/digital precoding enables spatial multiplexing and multi-user MIMO
- Digital can correct for analog limitations
- Approaches baseband digital performance *, can exploit sparsity **

* O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath Jr, "Spatially sparse precoding in millimeter wave MIMO systems," IEEE Trans. on Wireless Commun., vol.13, no.3, pp.1499-1513, March 2014.
** A. Alkhateeb, O. E. Ayach, G. Leus, and R. W. Heath Jr, "Channel estimation and hybrid precoding for millimeter wave cellular systems," to appear in IEEE Journal of Selected Topics in Signal Processing, arXiv preprint arXiv:1401.7426, 2013.

Ultra Low Resolution Receiver

Current academic research direction

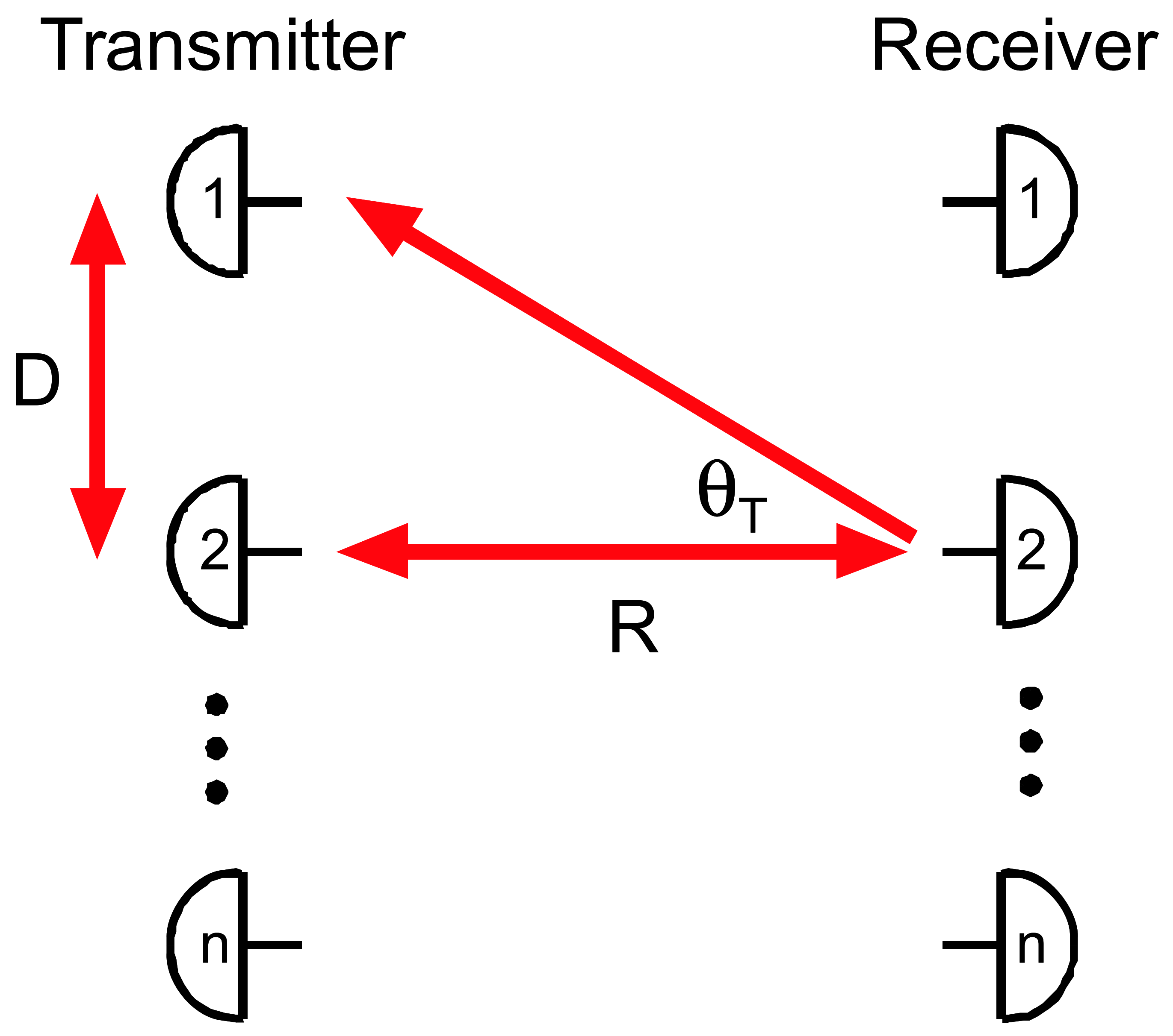


- Use1-bit ADCs (pair) for each RF chain, ultra low power solution
- Perform digital combining for all the highly quantized received signals
- Promising high SNR capacity results at high SNR*
- Many open topics: channel estimation, equalization, constellation optimization

* J. Mo and R. W. Heath Jr., "High SNR capacity of millimeter wave MIMO systems with one-bit quantization," in Proc. of ITA Feb. 2014.
See also extensive work by research groups led by U. Madhow, J. Nossek, G. Fettweis, G. Kramer, and O. Dabeer and others

Line-of-Sight MIMO

Current academic research direction



Angular separation of the Tx elements

$$\theta_T \cong \frac{D}{R}$$

Antenna spacing
Link range

Angular resolution of the Rx array

$$\theta_{res} \cong \frac{\lambda}{n \cdot D}$$

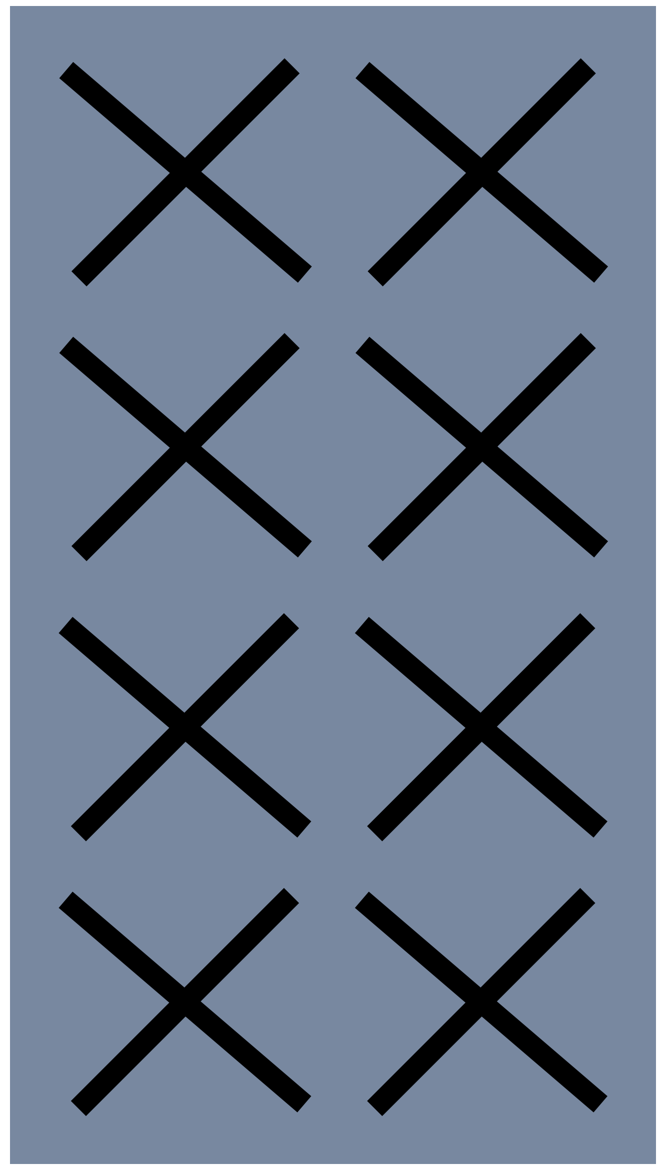
$$\theta_T \geq \theta_{res} \Rightarrow D = \sqrt{\frac{R \cdot \lambda}{n}}$$

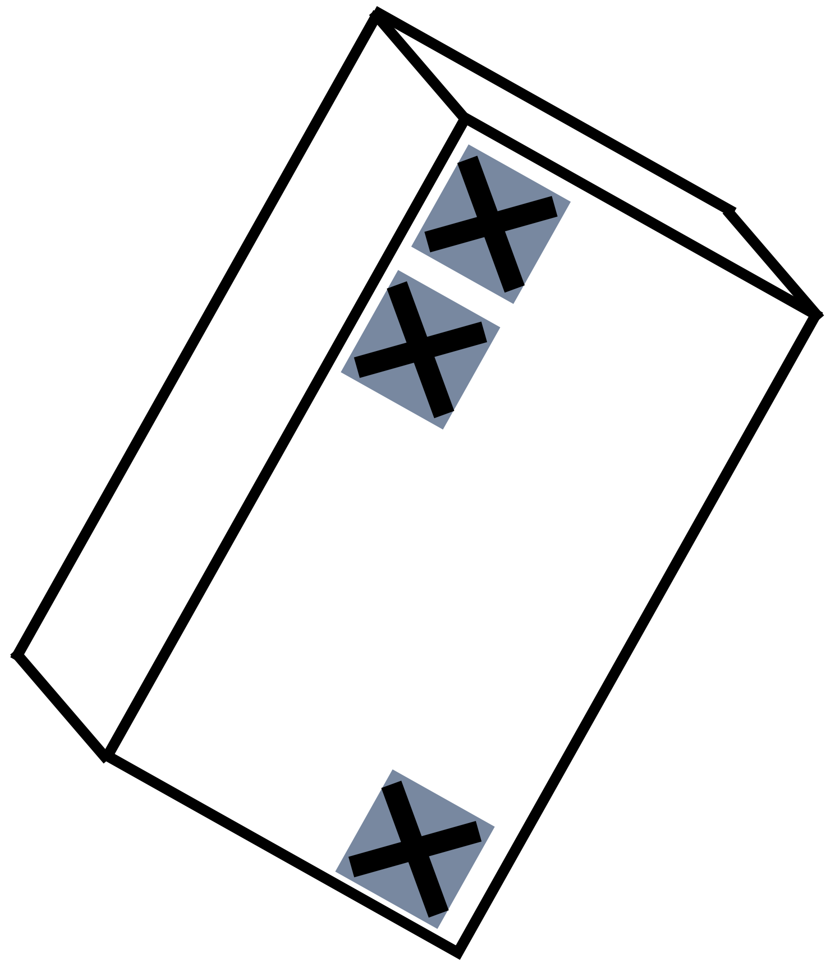
mmWave LOS MIMO system*

- Multiple parallel mmWave LOS MIMO links can be established
- System relies on antenna element spacing from diffraction-limited optics
- Links are robust to deviations in antenna alignment and array positioning
- 300Gbps data rates*
- Applications
  - Data centers
  - Chip-to-chip

* C. Sheldon, E. Torkildson, M. Seo, C. P. Yue, M. Rodwell, and U. Madhow, "Spatial multiplexing over a line-of-sight millimeter-wave MIMO link: A two-channel hardware demonstration at 1.2Gbps over 41m range," in 38th European Microwave Conference, October 2008.

MIMO with Polarization





- Polarization works at mmWave
- Helps orthogonalize channels
- System design needs to deal with challenges, e.g., mobile misorientation
- Mobile orientation can be estimated without explicit channel knowledge*
- Diversity and multiple users**

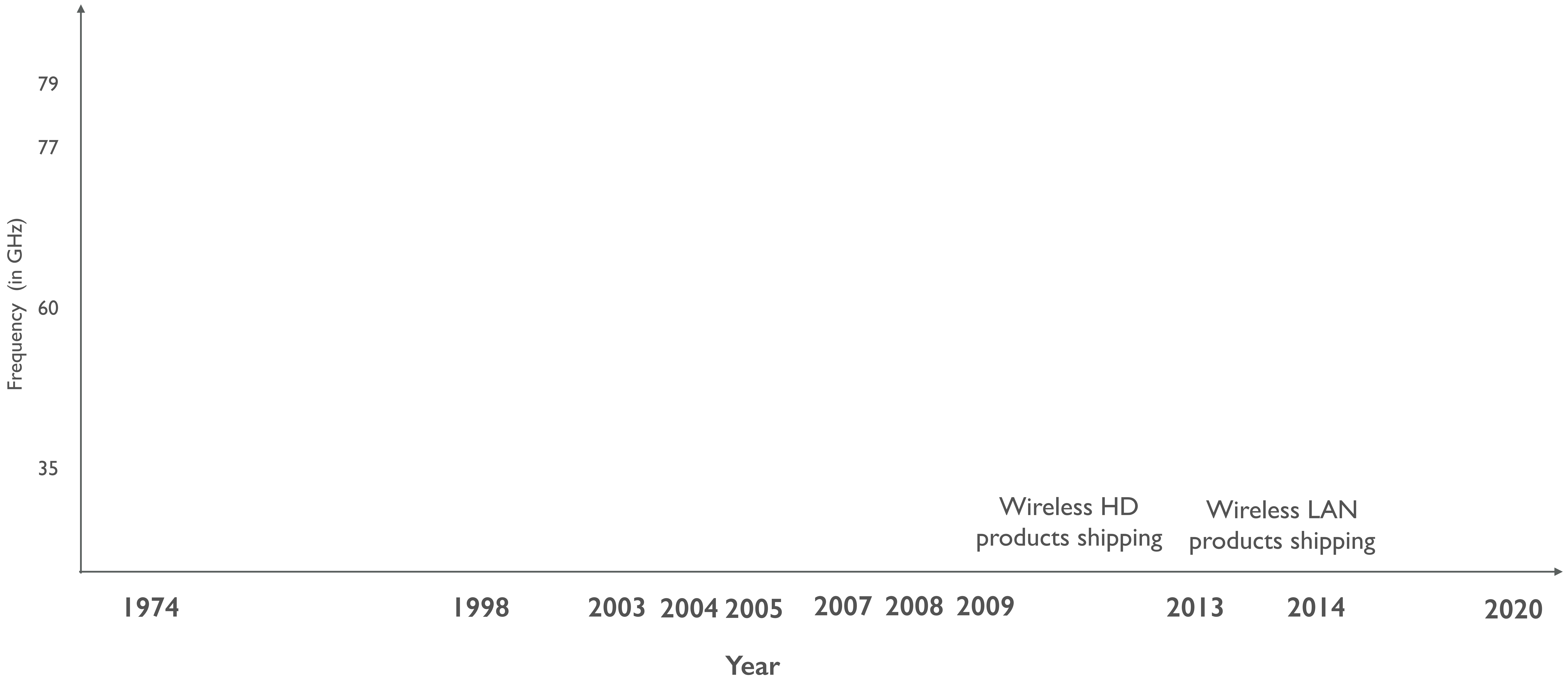
Current academic & industry research direction

* A. A. Khaled, R. W. Heath. Jr., S. Rajagopal, S. Abu-Surra, and J. Zhang, "Cross-polarization RF precoding to mitigate mobile misorientation and polarization leakage," *IEEE Consumer Communications and Networking Conference (CCNC),* Las Vegas, CA, Jan. 10-13, 2014.

** J. Song, S. G. Larew, D. J. Love, T. A. Thomas, A. Ghosh, "Millimeter wave beamforming for multiuser dual-polarized MIMO systems," *Global Conference on Signal and Information Processing (GlobalSIP), 2013 IEEE* , vol., no., pp.719,722, 3-5 Dec. 2013

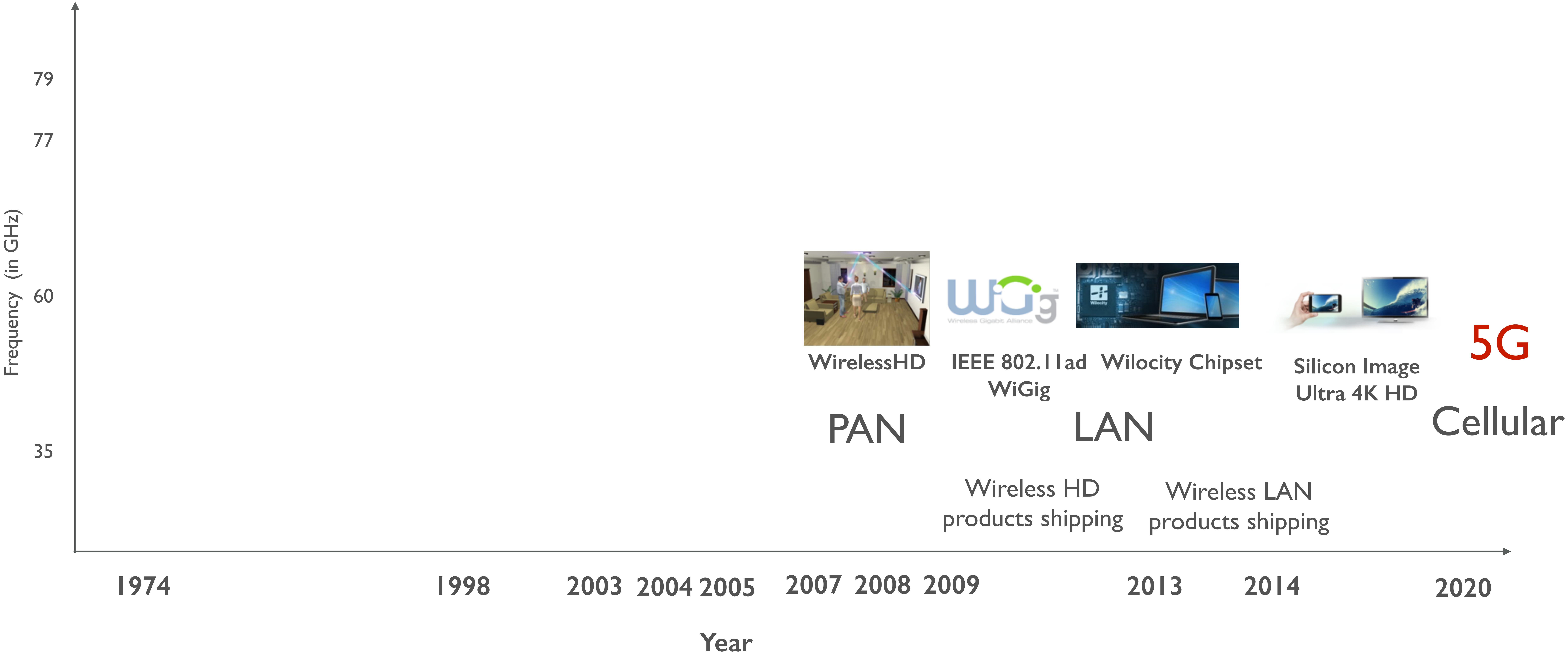
Consumer Applications of mmWave MIMO

mmWave in Consumer Applications



Source: Holger H Meinel and Juergen Dickmann. Automotive radar: From its origins to future directions. Microwave Journal, 56(9),2013.

mmWave in Consumer Applications



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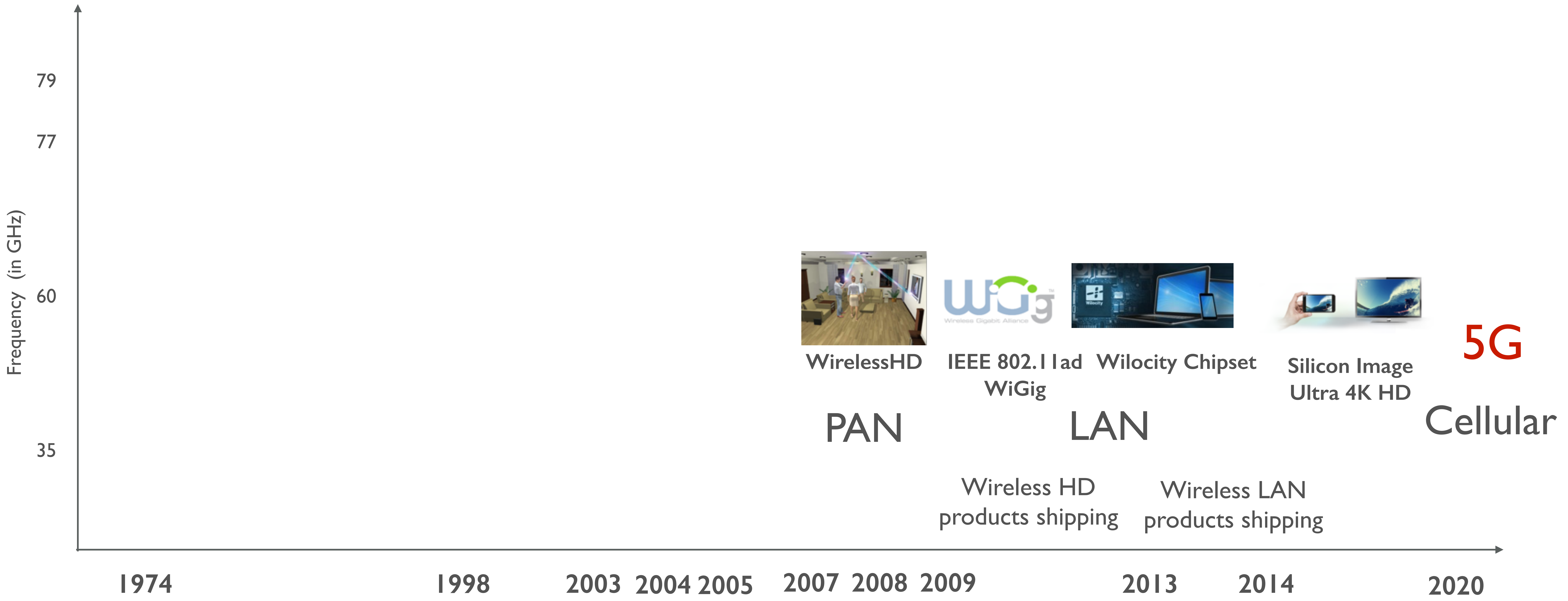
mmWave in Consumer Applications



Major interest in wireless applications yet radar far predates wireless

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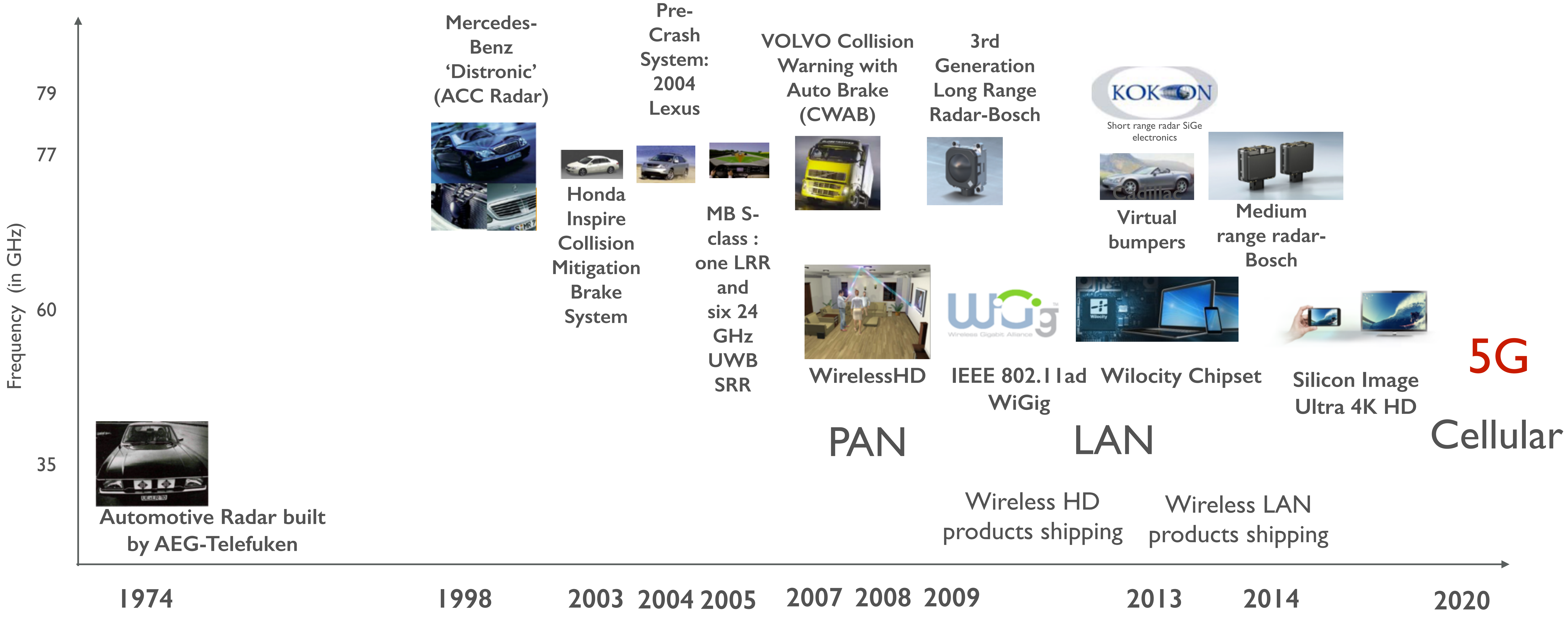
mmWave in Consumer Applications



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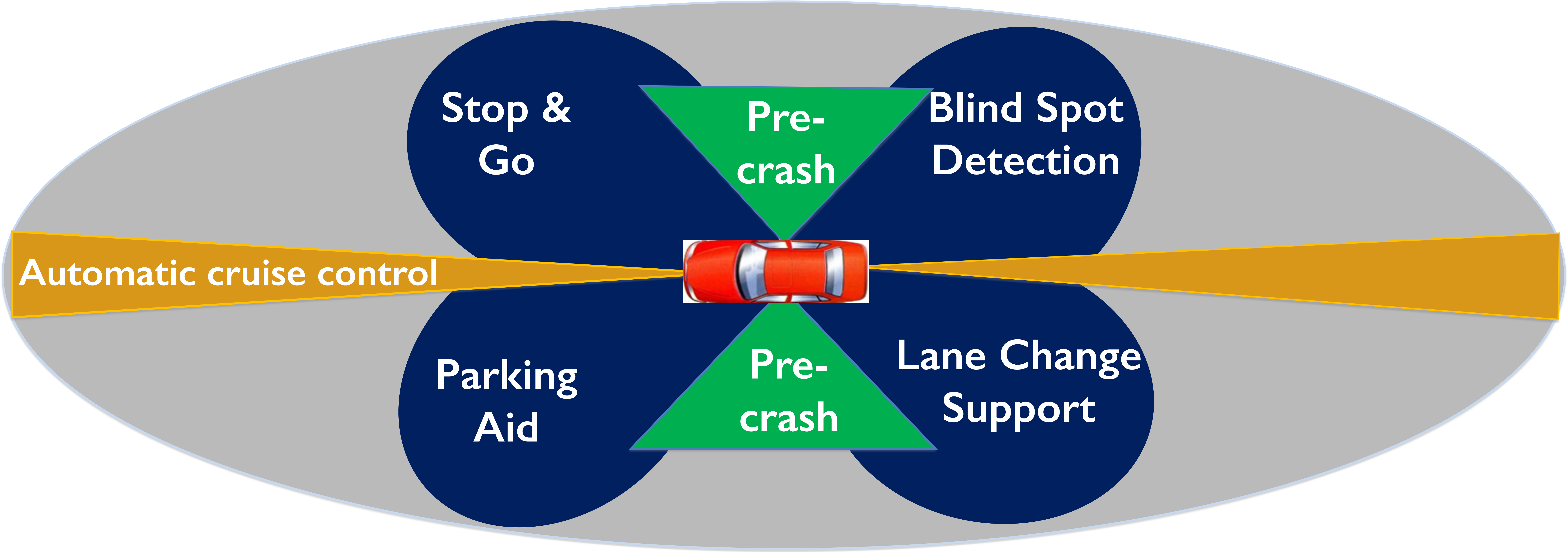
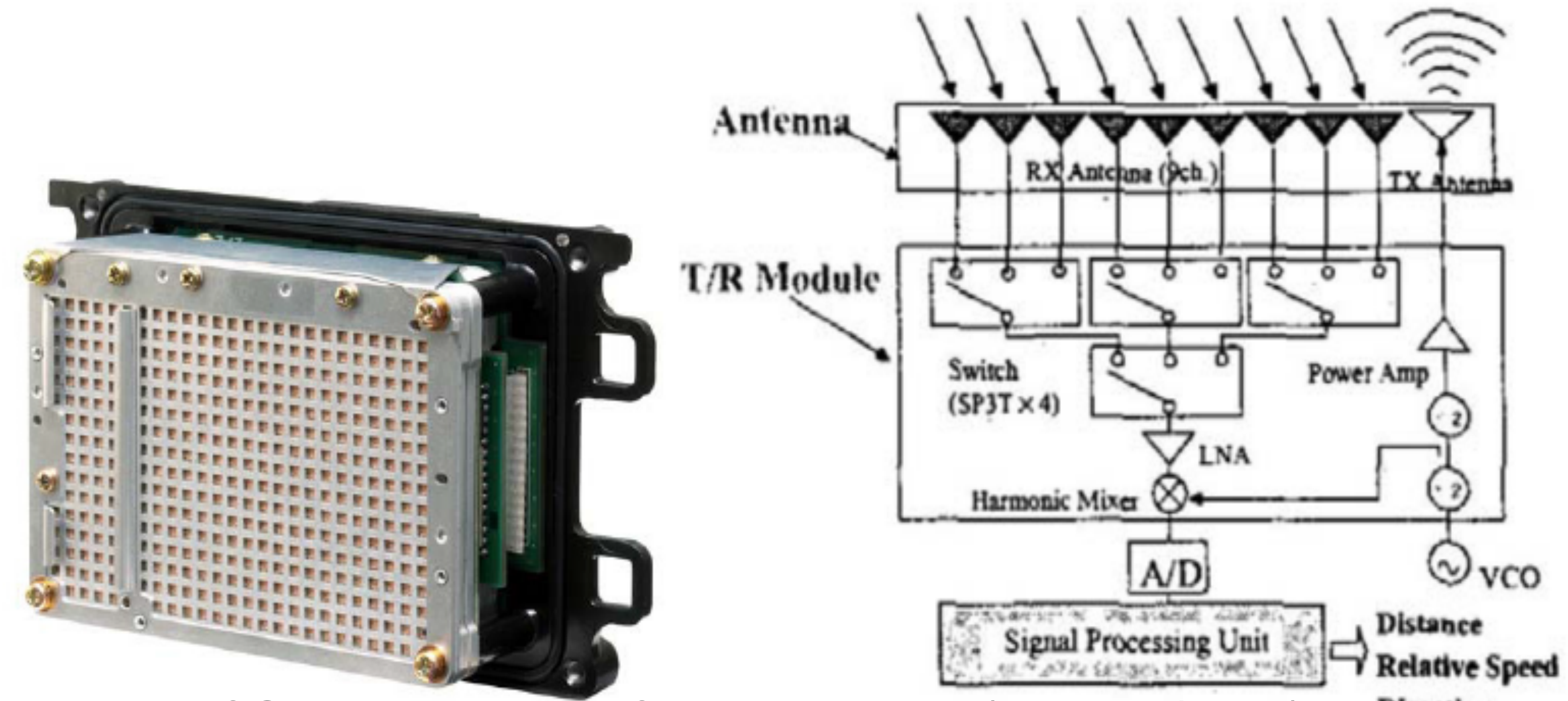
Concept of Automotive Radar



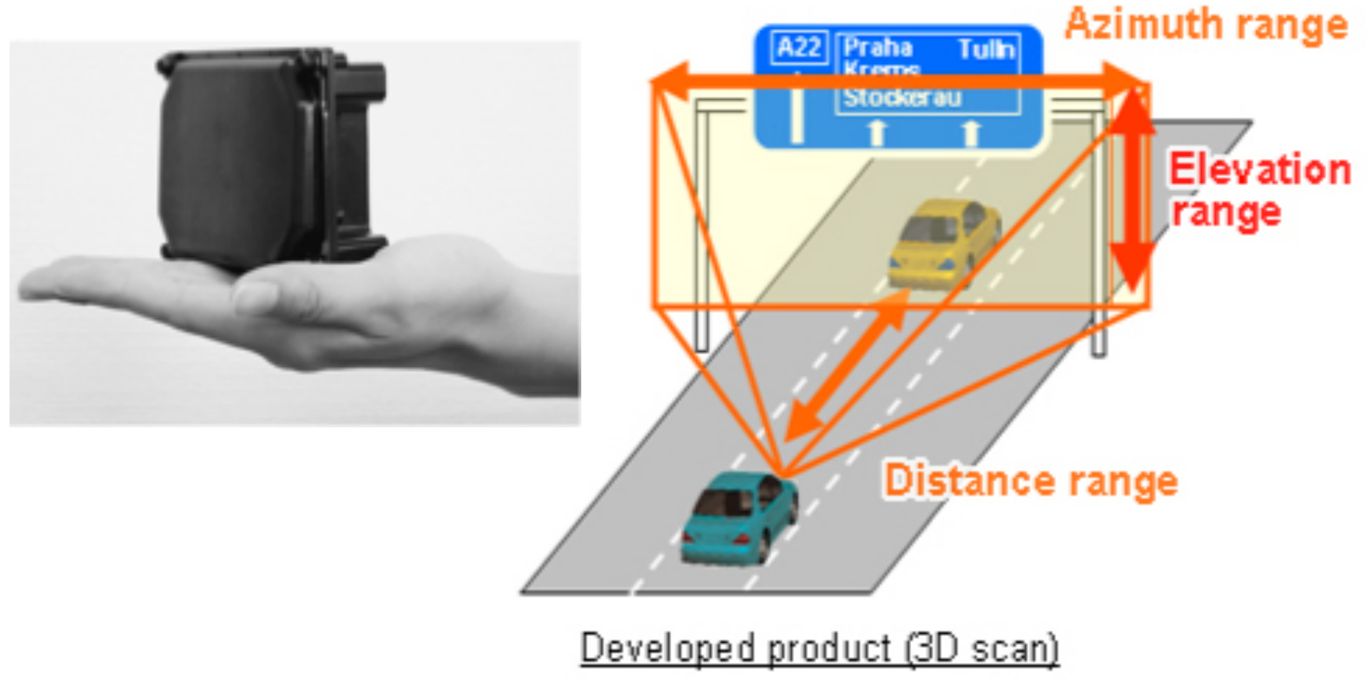
- Long range radar (LRR) operates in 76-77 GHz with a bandwidth of 600 MHz
- Short range radar (SRR) operating in 24GHz band is getting replaced by 79-81 GHz band
- Medium range radar (MRR) operates in 77-81 GHz with a bandwidth of 600 MHz

How Multiple Antennas are Incorporated



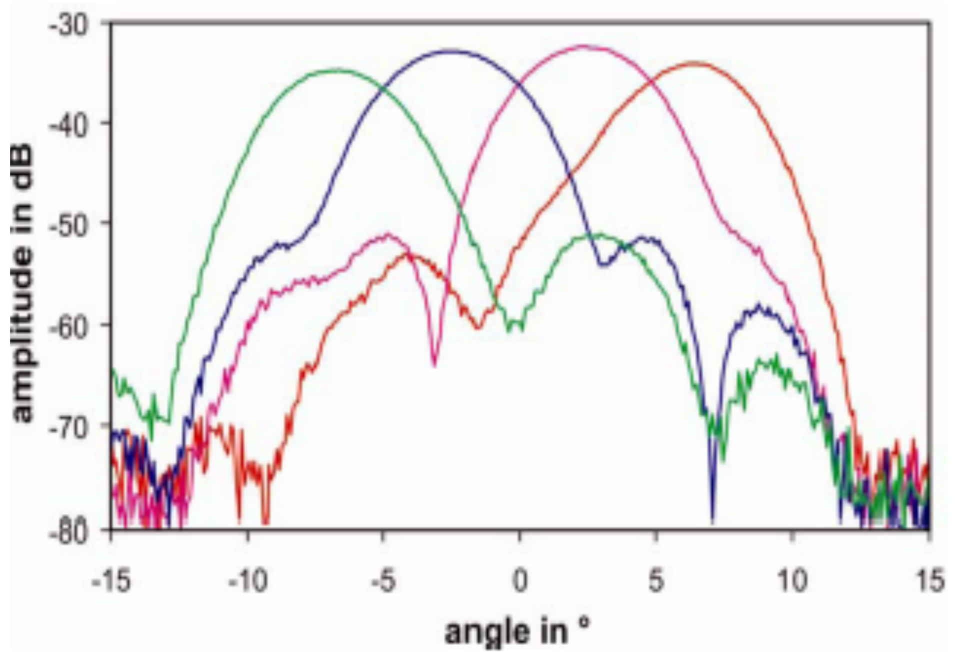
DENSO Electronically Scanning Radar (Phased Array)

Delphi Electronically Scanning Radar (Digital Beamforming)

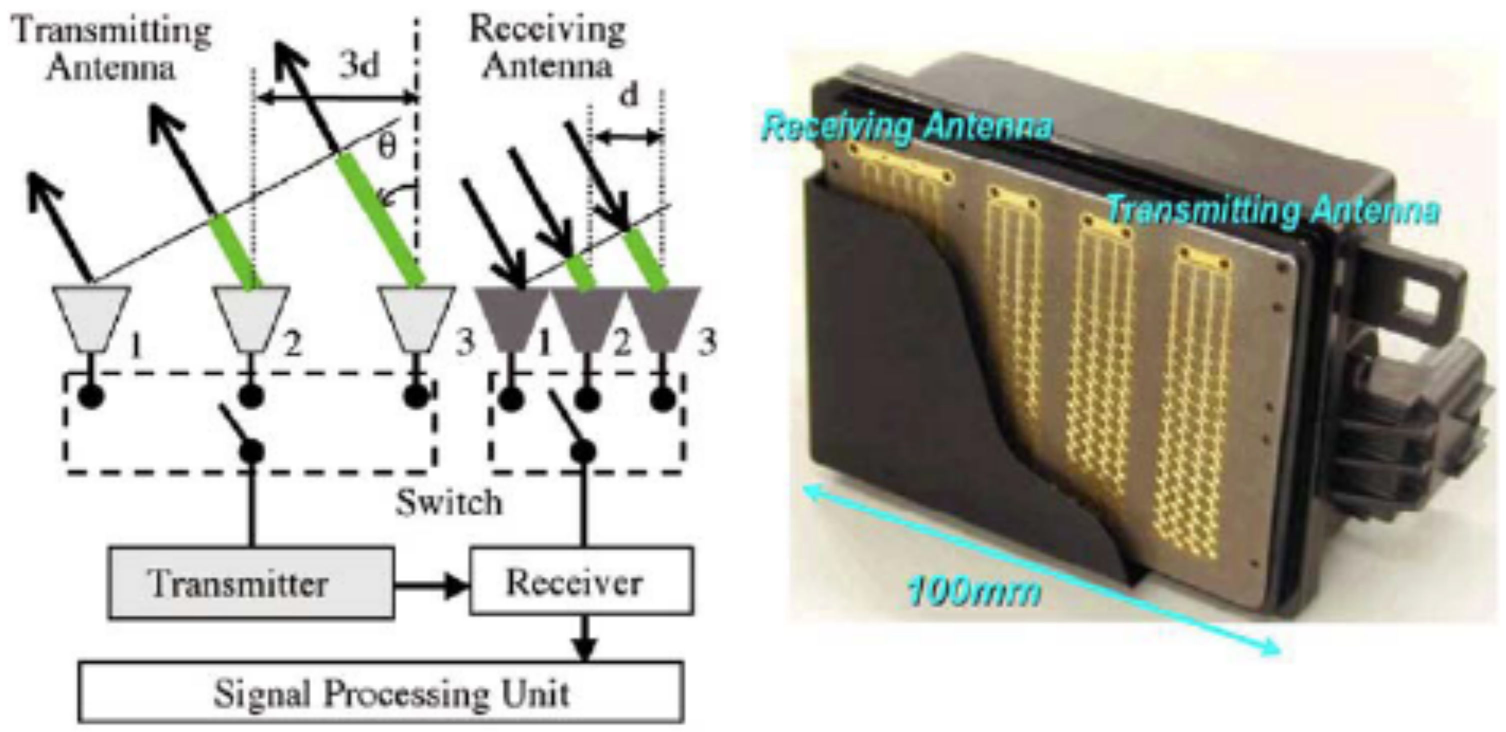


Fujitsu Ten 3D- Scan Millimeter-Wave Radar: Digital Beamforming

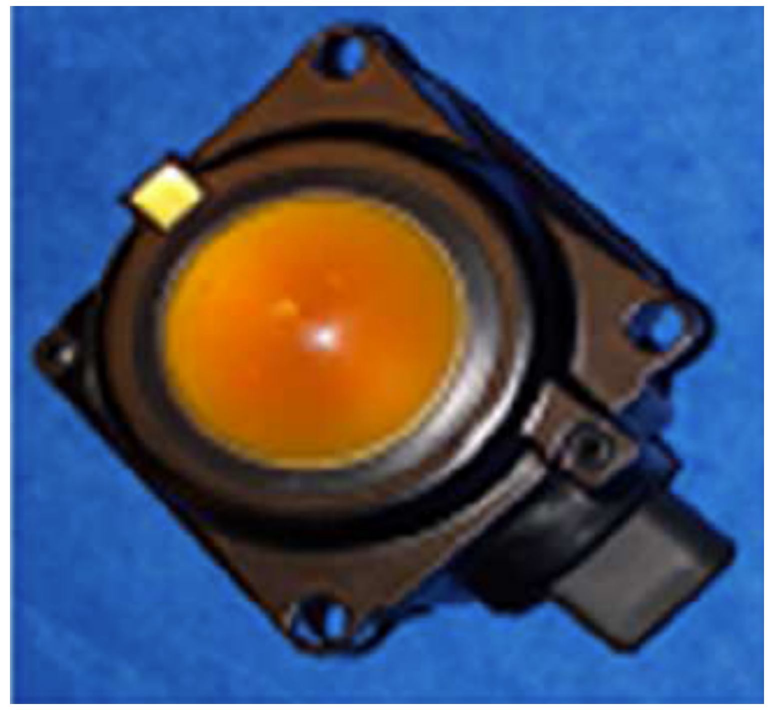
Bosch Long Range Radar (Lens Antenna)



Bosch Antenna Diagram



Toyota CRDL Radar with DBF, 77 GHz



TRW Autocruise AC20 Monopulse (Lens Antenna)

Source: Schneider, Martin. "Automotive radar–status and trends." *German microwave conference*. 2005.
Delphi, "Delphi Electronically Scanned Array", [http://delphi.com/manufacturers/auto/safety/active/electronically-scanning-radar/], Accessed on 7-2014

Research Issues in Automotive Radar

reduction in cost, weight and size

autonomous driving

surround field-of-view

improvement in 4D resolution

self-learning technology

joint vehicular communication & automotive radar

multi-sensor fusion

Research @ UT

interference, clutter and multipath mitgation

high frequency electronics

Used by consumers yet based on expensive technology

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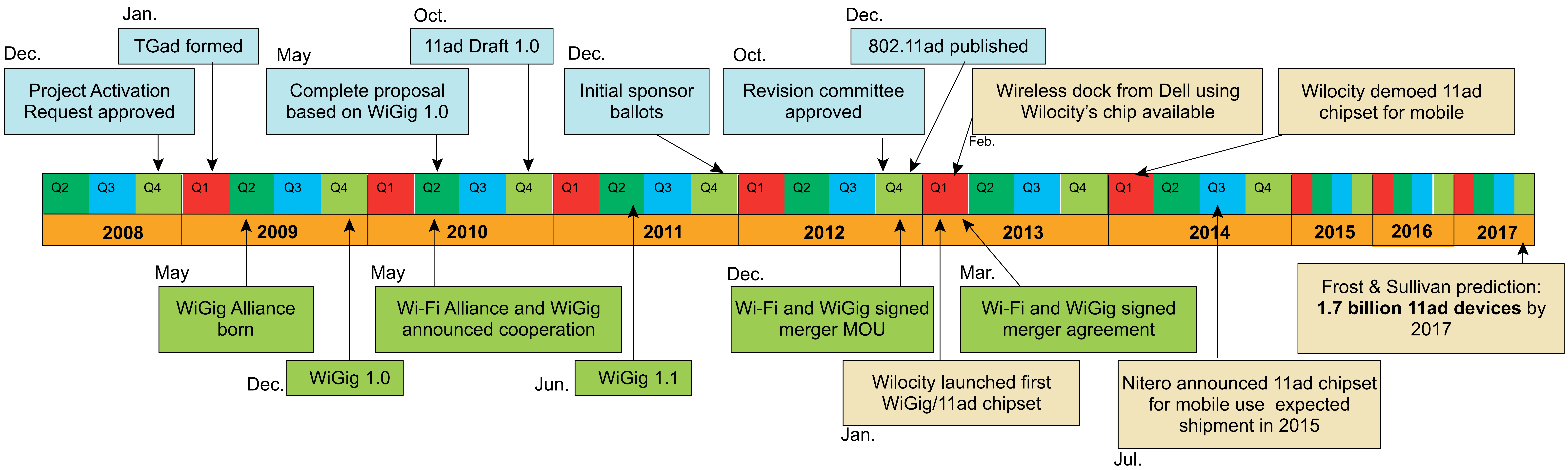
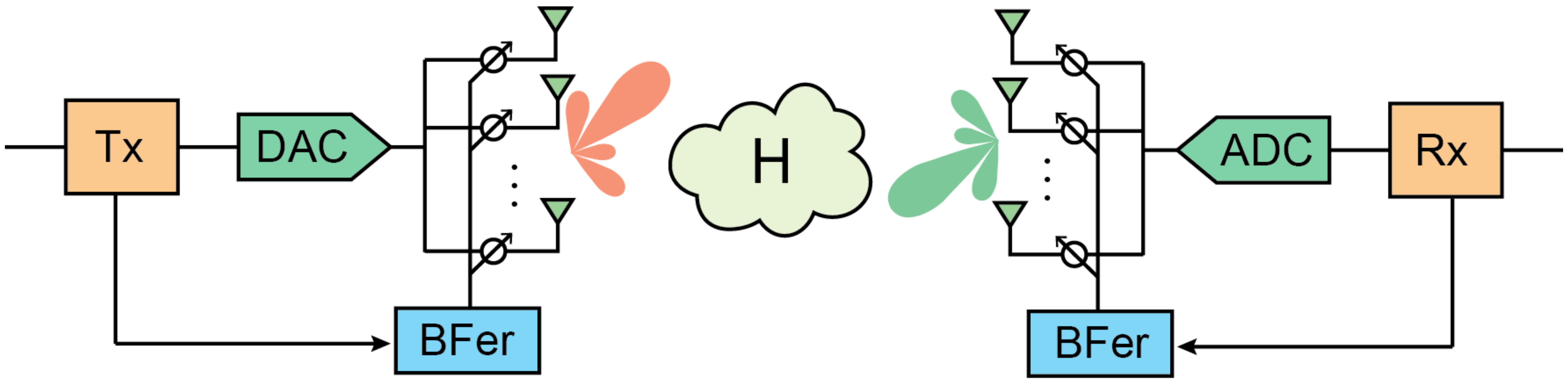
Development of IEEE 802.11ad

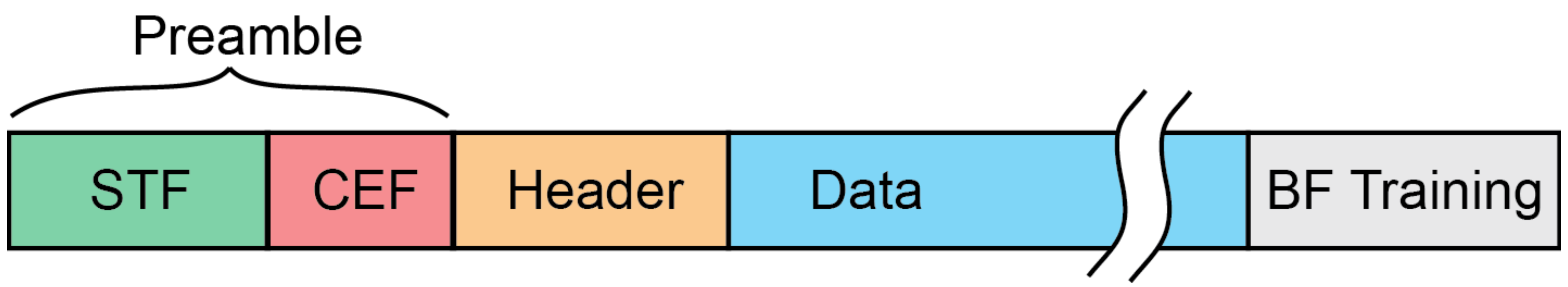


- Motivation
  - Emerging data hungry apps (e.g. HDTV streaming, rapid sync, etc.)
  - Why 60 GHz? Large unlicensed band, low co-channel interference, small form factor, etc.
- Consumer products already on market

IEEE 802.11ad



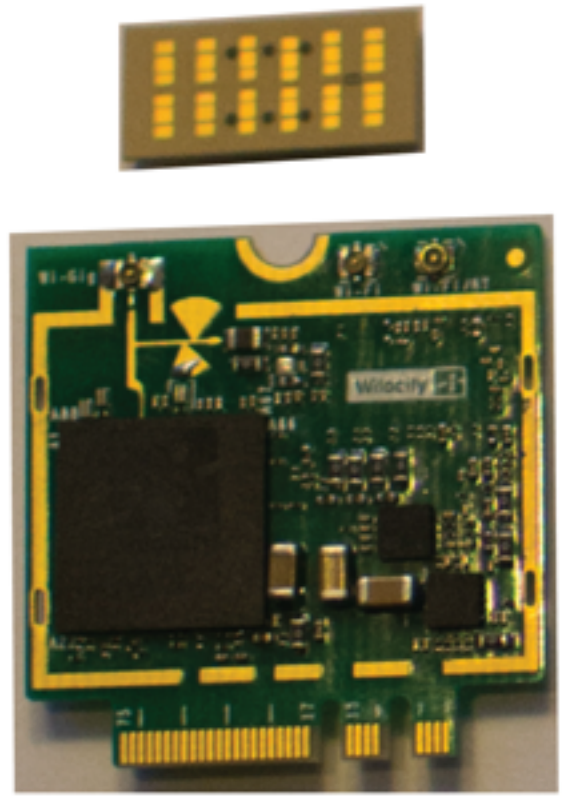
* 11ad defines four PHYs:
  - Control PHY
  - Single carrier (SC) PHY
  - OFDM PHY (optional)
  - Low power SC PHY (optional)



Frame structure

* Multiple antennas for TX and RX
  - Support only single stream MIMO
  - Analog beamforming using phase shifters
  - 16 and 32 antennas are common

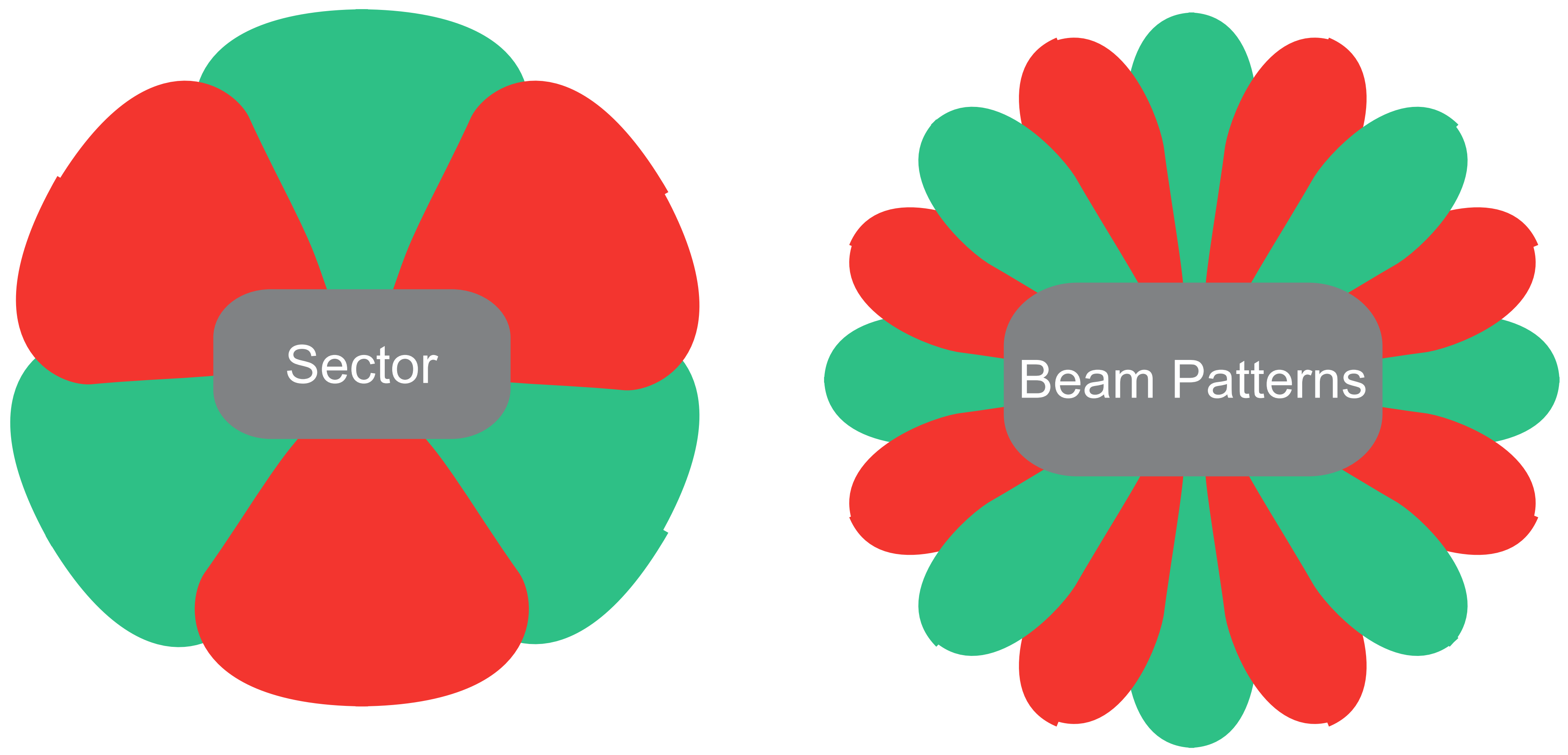
Dell WiGig docking station

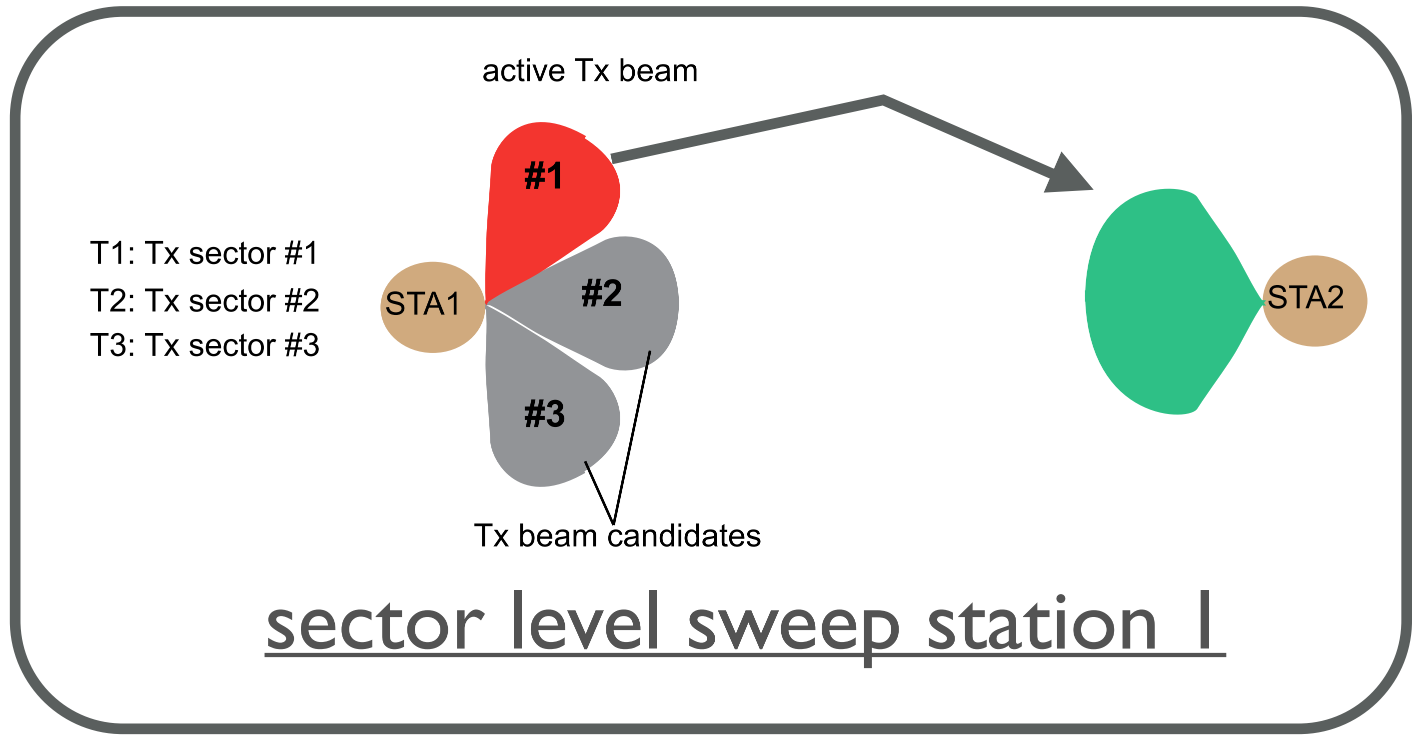


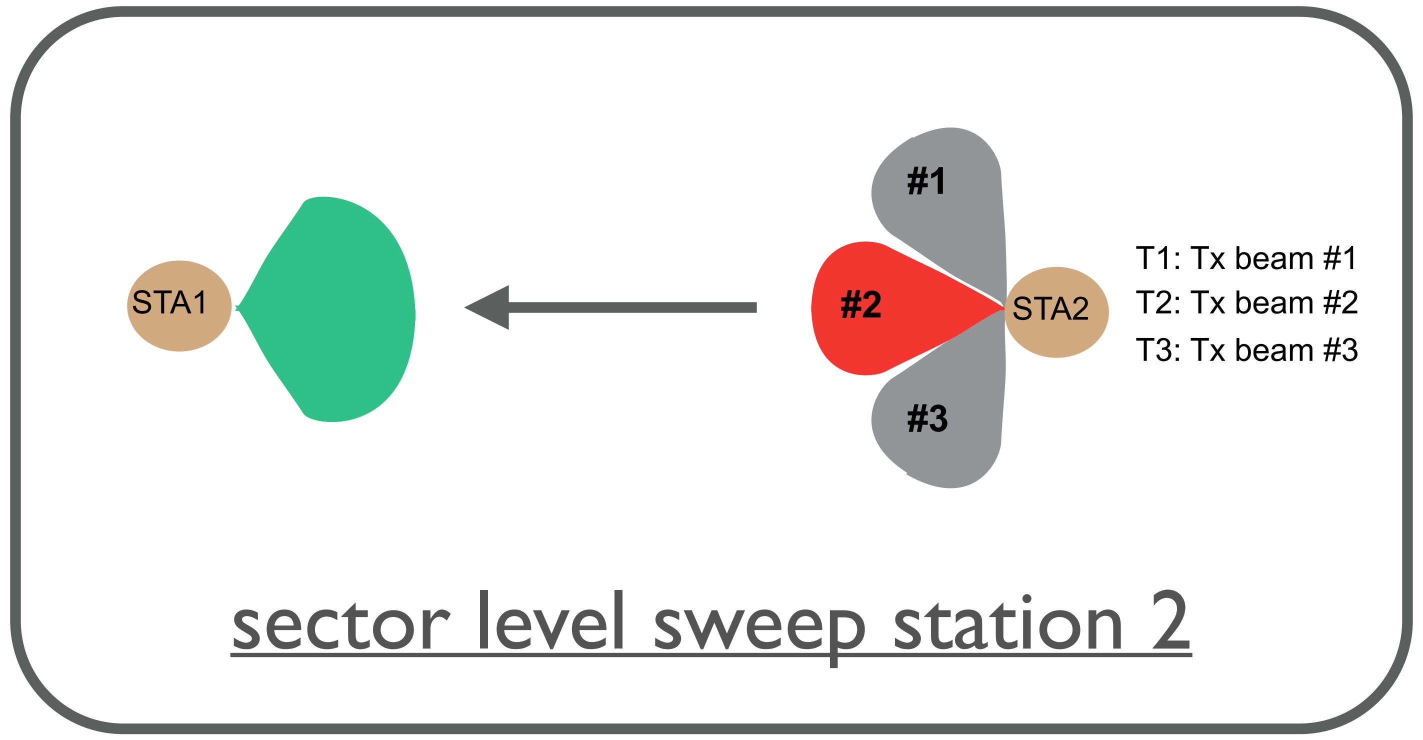
Wilocity (now Qualcomm) chip 32 antennas

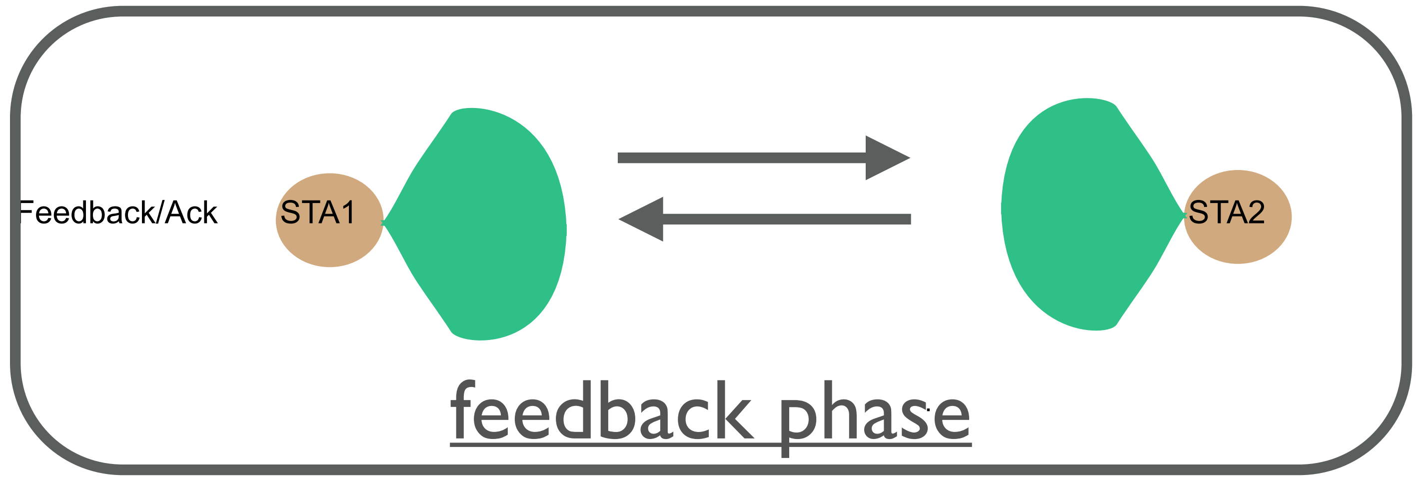
http://www.anandtech.com/show/6646/wilocity-bringing-wigig-to-your-desk-lap-home-and-office

Beam Training to Implement Single Stream MIMO









- Sector level sweep
  - Transmit sweep, receive sweep, feedback, and acknowledgement
  - Trains a combination of sector (at one end) and antenna (at the other end)
- Beam refinement
  - Training of different transmit and / or receiver antenna configurations
- Beak tracking
  - Periodic refinement over a small number of antenna configurations

Related Research Challenges in mmWave WLAN

- Better beam alignment and tracking
- Support for multi-stream MIMO
- Going towards even higher frequencies
- Co-design of circuits and signal processing algorithms
- Packaging and antenna design
- Algorithms robust to antenna arrays

Related Research Challenges in mmWave WLAN

Better beam alignment and tracking

Support for multi-stream MIMO

Going towards even higher frequencies

Co-design of circuits and signal processing algorithms

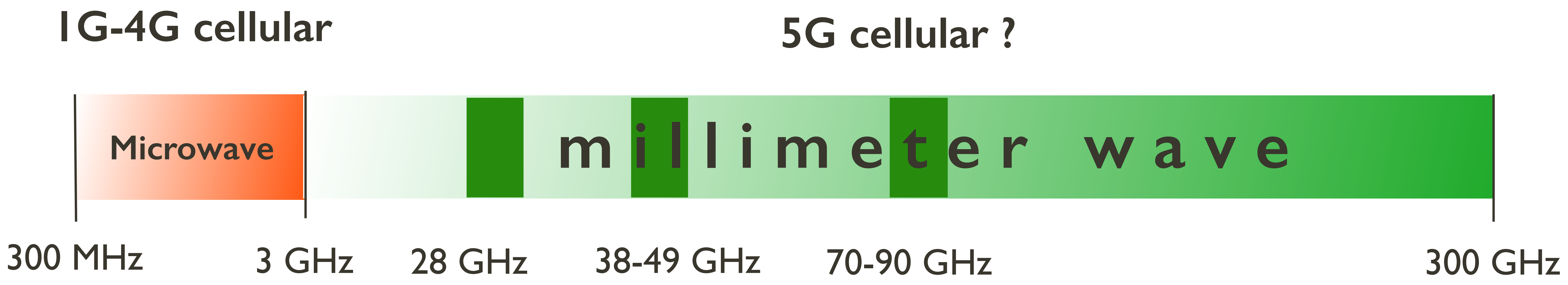
Packaging and antenna design

Algorithms robust to antenna arrays

Research @ UT

New Application: mmWave Cellular

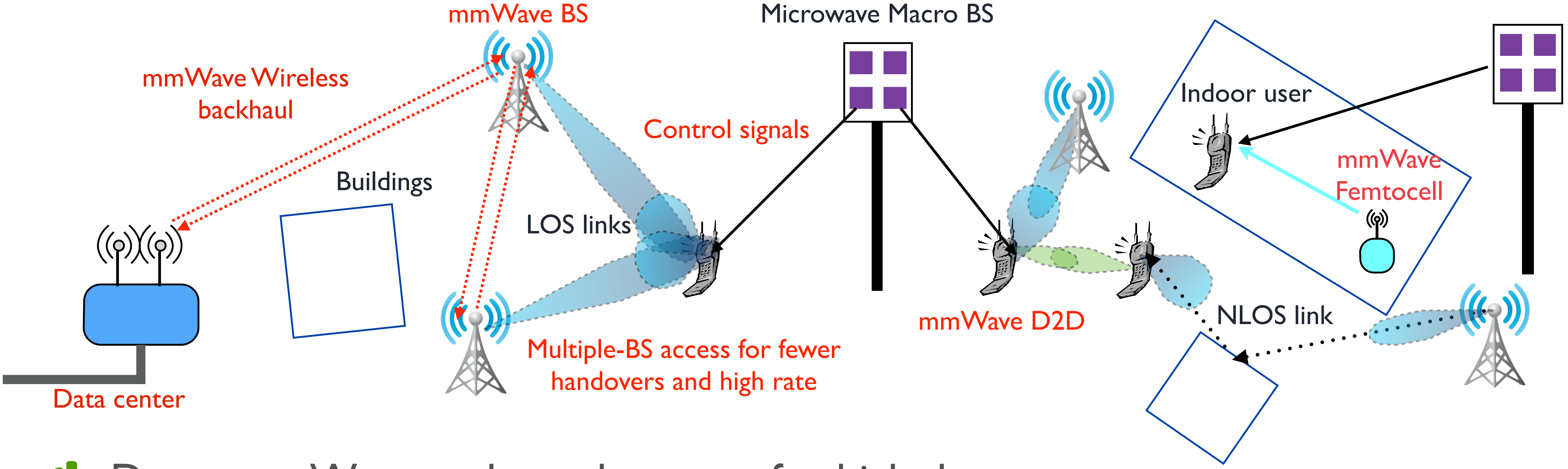
Why mmWave for 5G?



- Practical spectral efficiency limits are being reached
  - Conventional single user, multiple user, and network MIMO
  - Turbo and LDPC coding, adaptive modulation, H-ARQ
- Huge amount of spectrum in mmWave band that could be repurposed*
  - Current cellular systems live with limited microwave spectrum ~ 600 MHz
  - 29 GHz possibly available in 23 GHz, LMDS, 38, 40, 46, 47, l49, and E-band
- MmWave is the new spectral frontier for 5G cellular (or maybe 6G…)

* Z. Pi and F. Khan. "An introduction to millimeter-wave mobile broadband systems." IEEE Communications Magazine, vol. 49, no. 6, pp.101-107, Jun. 2011.
** T.S. Rappaport, R.W. Heath Jr., R. C. Daniels, and J. N. Murdock, Millimeter Wave Wireless Communication, Prentice Hall, 2014.
*** S. Rangan, T.S. Rappaport, and E. Erkip, "Millimeter Wave Cellular Wireless Networks: Potentials and Challenges", Proceedings of IEEE, 2014
**** T. Bai, A. Alkhateeb, and R.W. Heath Jr., "Coverage and Capacity of Millimeter Wave Cellular Networks," to appear in IEEE Communications Magazine 2014.

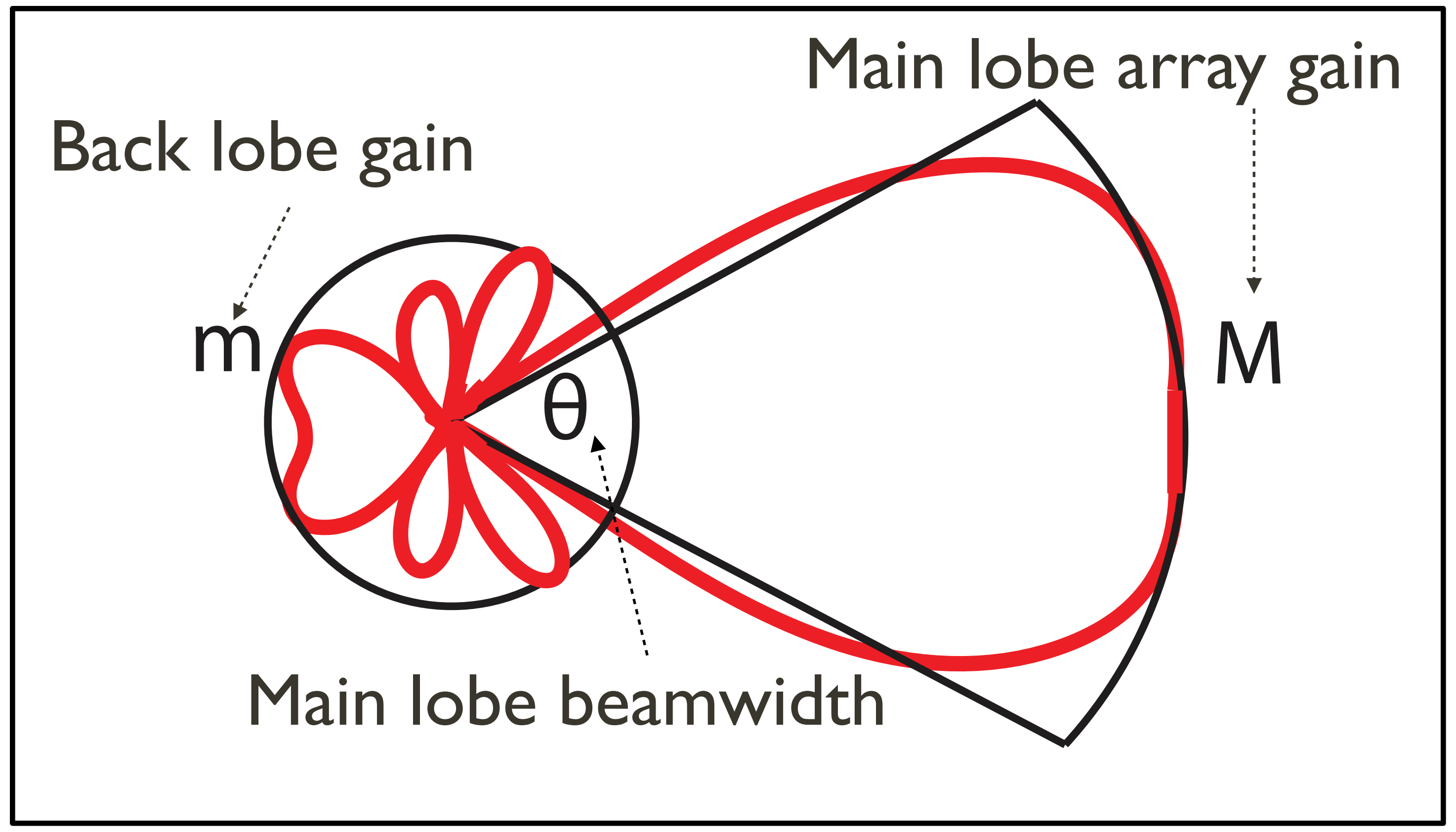
Imagining a mmWave 5G Future Network



- Dense mmWave nodes as hotspots for high data rates
  - Directional beamforming to boost signal power and reduce interference
  - Users connect to multiple-nodes for high rates and better handover
  - Coverage may suffer from blockage effects, e.g. buildings in urban areas
  - Need additional layers for indoor coverage due to large penetration losses
- Microwave BSs for coverage and control signals*

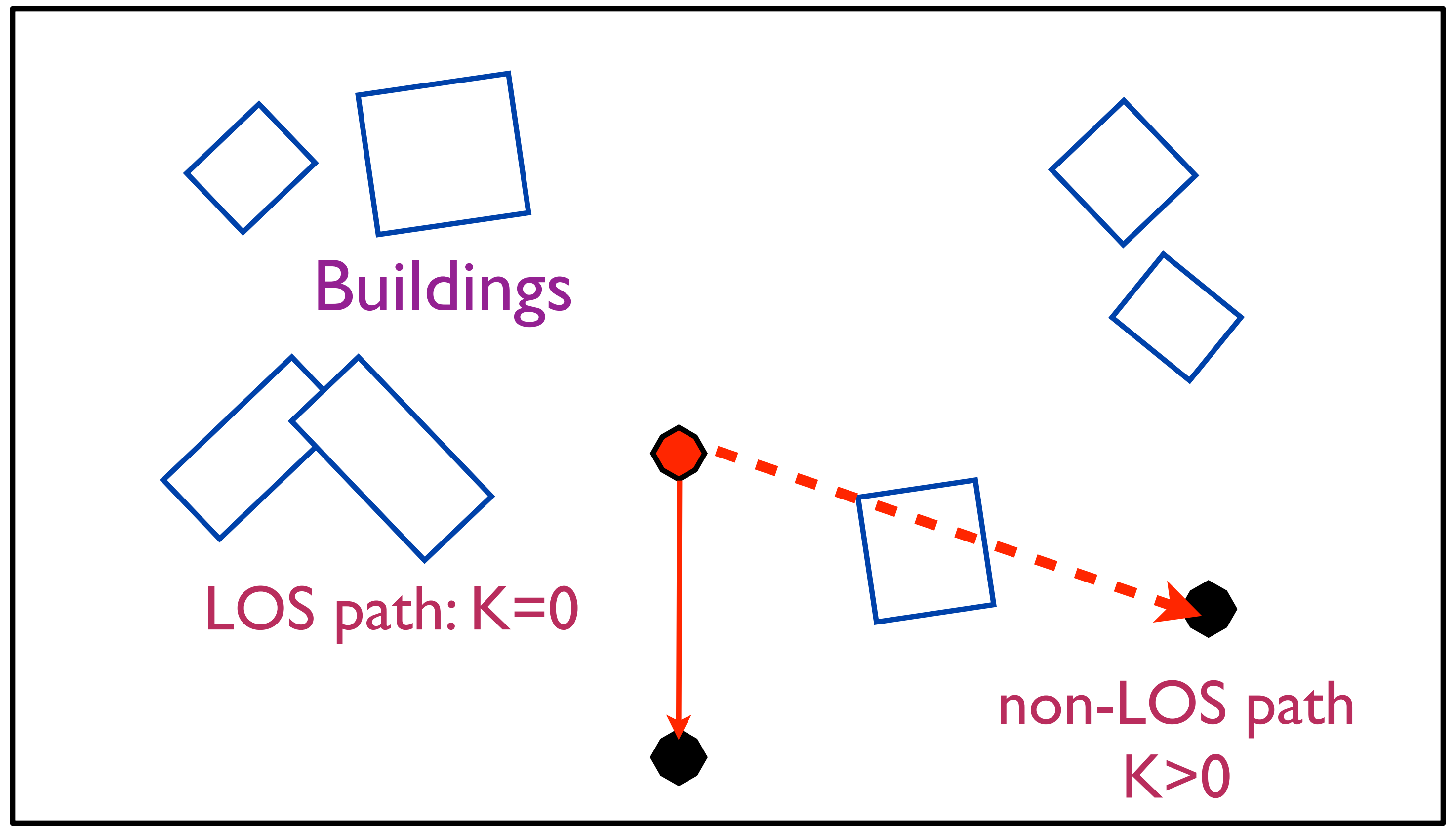
*T. Bai and R.W. Heath Jr., "Analysis of mmWave cellular networks with overlaid microwave base stations", To appear in Proc. Asilomar Conf., Nov., 2014

Network Analysis of mmWave



Sectored antenna pattern model

+



Blockages as rectangular Boolean scheme

K: # of blockages on a link

- Use "sectored antenna" to simplify analysis
  - Actual antenna patterns approximated by a sectored model
  - Sectored model captures main lobe gain, HPBW, and FBR
  - Steering orientation of interferers randomly distributed in space
- Use random shape theory to model blockages*
  - Model buildings as a rectangular Boolean scheme
  - A link of length r is LOS, i.e., unblocked, with prob. $p(r) = \mathrm{e}^{-\beta r}$
  - Different propagation laws measured in LOS/ NLOS channels**
  - Apply different path loss laws to LOS/ NLOS links

*T. Bai, R. Vaze, and R. W. Heath, Jr., ``Analysis of Blockage Effects in Urban Cellular Networks", To appear in IEEE Trans. Wireless Commun., June 2014.

** S. Rangan, T.S. Rappaport, and E. Erkip, "Millimeter Wave Cellular Wireless Networks: Potentials and Challenges", Proceedings of IEEE, 2014

MmWave SINR Coverage

Theorem [mmWave SINR Distribution]
The SINR coverage probability (CCDF of SINR) in mmWave networks is

$$P_{\mathrm{c}}(T) = A_{\mathrm{L}} P_{\mathrm{c,L}}(T) + A_{\mathrm{N}} P_{\mathrm{c,N}}(T),$$

where the conditional coverage probability by LOS BSs is evaluated as

$$P_{c,\mathrm{L}}(T) \approx \sum_{n=1}^{N_{\mathrm{L}}} (-1)^{n+1} \binom{N_{\mathrm{L}}}{n} \int_0^\infty \mathrm{e}^{-\frac{n\eta_{\mathrm{L}} x^{\alpha_{\mathrm{L}}} T\sigma^2}{C_{\mathrm{L}} M_{\mathrm{r}} M_{\mathrm{t}}} - Q_n(T,x) - V_n(T,x)} \hat{f}_{\mathrm{L}}(x) \mathrm{d}x,$$

and the conditional coverage probability by NLOS BSs is

$$P_{c,\mathrm{N}}(T) \approx \sum_{n=1}^{N_{\mathrm{N}}} (-1)^{n+1} \binom{N_{\mathrm{N}}}{n} \int_0^\infty \mathrm{e}^{-\frac{n\eta_{\mathrm{N}} x^{\alpha_{\mathrm{N}}} T\sigma^2}{C_{\mathrm{N}} M_{\mathrm{r}} M_{\mathrm{t}}} - W_n(T,x) - Z_n(T,x)} \hat{f}_{\mathrm{N}}(x) \mathrm{d}x.$$

- Use stochastic geometry to derive SINR coverage
  - Assume base stations distributed as a Poisson point process
  - Use general Nakagami distribution to incorporate small-scale fading
  - Apply for general base station density & building distributions
  - Simplified expression available in dense network case*

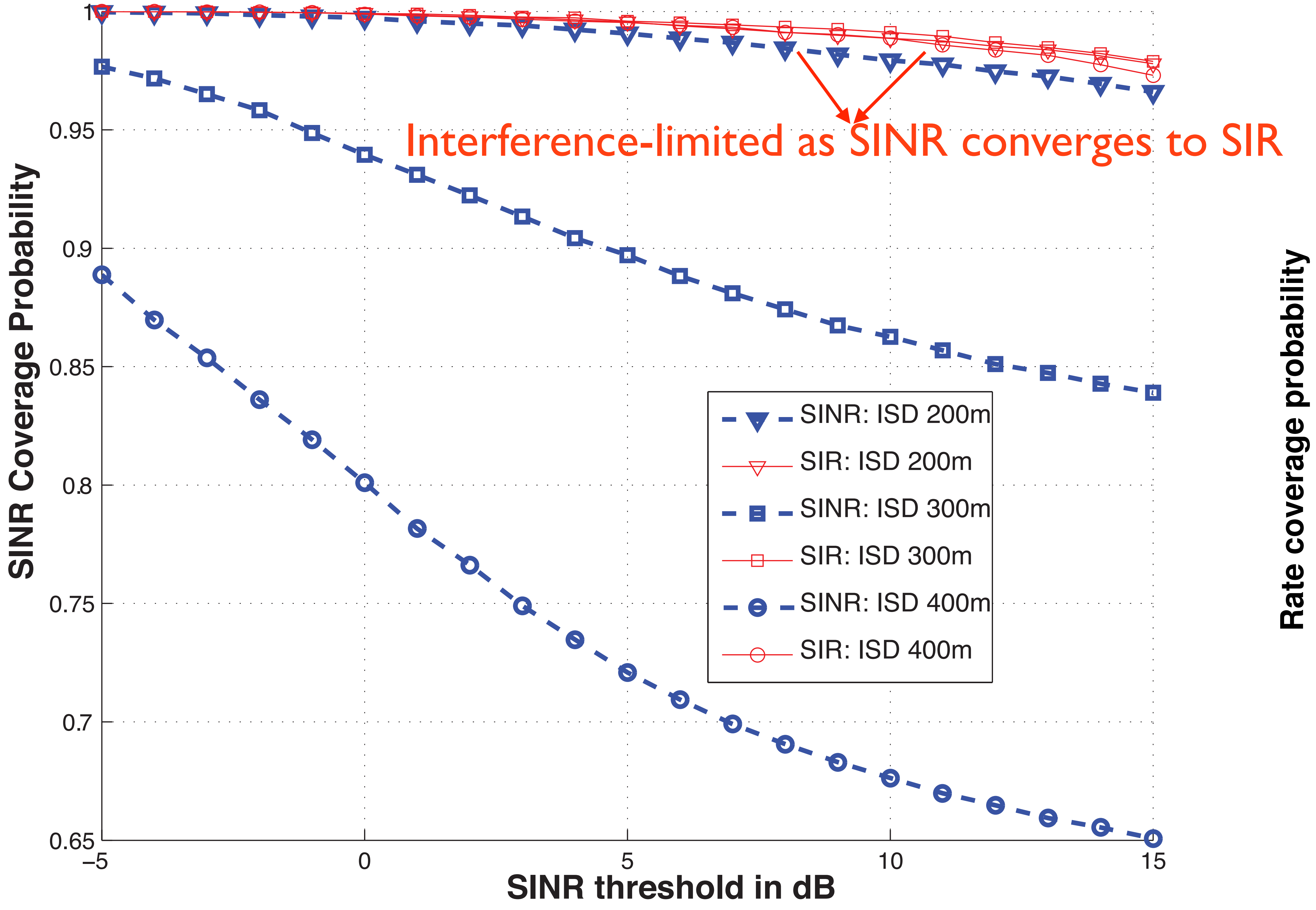
*T. Bai and R. W. Heath Jr., "Coverage analysis in dense millimeter wave cellular networks", in Proc. of Asilomar Conf., Nov., 2013

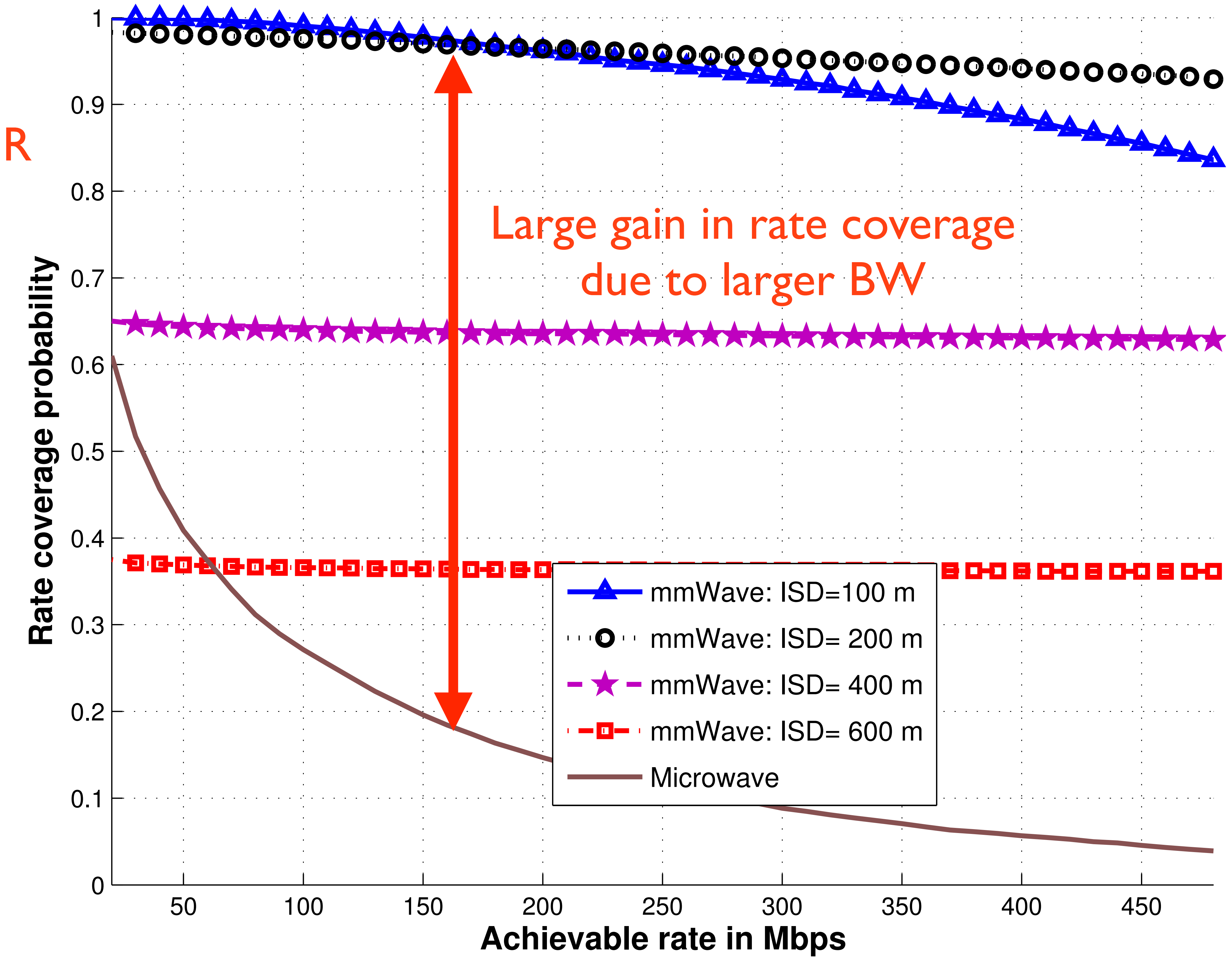
SINR & Rate Coverage With Different BS Density

MmWave:
Carrier freq. : 28 GHz
Tx power: 30 dBm
Tx directivity gain: 20 dB
Tx beamwidth: 30 degree
Rx directivity gain: 10 dB
Rx beamwidth: 90 degree
Bandwidth: 100 MHz

Microwave:
Carrier freq. : 2GHz
TX power: 46 dBm
Bandwidth: 20 MHz
4X4 SU-MIMO ZF-precoding
ISD: 1000 m

Building statistics:
the same as UT Austin campus





- Dense mmWave networks can achieve good coverage and high rate
  - mmWave SINR and rate sensitive to base station density
  - SINR improves and converges to SIR when base station is dense
  - Significant gain in data rate than microwave due to larger bandwidth and denser deployment

T. Bai and R. W. Heath Jr., "Coverage and rate analysis for millimeter wave cellular networks", submitted to IEEE Trans. Wireless Commun., March 2014.

Average Achievable Rate Comparison

	Spectrum efficiency (bps/Hz)	# of users/ cell	Bandwidth (MHz)	Cell throughput (Mbps)	ISD (m)	Rate per area (Mbps/km2)
microwave SU w\ 4X4 ZF MIMO	7.9	1	20	158	400	1257
Massive MIMO 64 antennas	1.2	10	20	240	400	1910
mmWave SU w\ analog BF	3.7	1	100	370	400	2945
mmWave SU w\ analog BF	5.8	1	100	580	200	18462
mmWave MU w\ hybrid BF	5.8	2	100	1160	200	36924

More antennas and users

(not dense enough)

Denser BS

More users and hybrid beamforming

Conclusions

MIMO at Millimeter Wave

- Millimeter wave has massive consumer potential
  - More than 1.7 billion 802.11ad devices predicted in 2017
  - LAN will be the first wide scale deployment
  - Cellular access will come in 5G, or possibly later in 6G
- MIMO and mmWave are a natural union
  - Commercial systems consider primarily single stream MIMO beamforming
  - More advanced multi-stream and multi-user MIMO is feasible
  - Research is needed on the best holistic performing technologies

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The future is bright for mmWave MIMO