mmWave communications for 5th generation cellular networks

Paul Ferrand (Huawei Technologies)

Why mmWave?

Image ©Ericsson

Why mmWave?

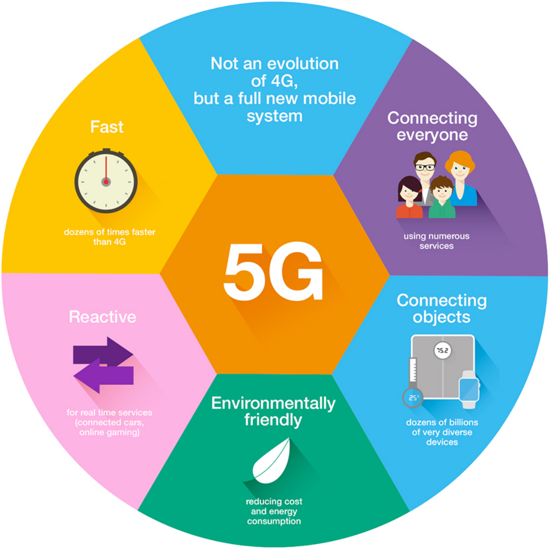


Image ©Orange

Why mmWave?

Other possibilities for mmWave:

- Data center interconnects
- Circuit junctions
- Information showers
- Vehicular communications
- . . .

Why mmWave?

The 1000$\times$ throughtput objective of 5G (among others)

Density $\times$ Spectral Efficiency $\times$ Bandwith

Why mmWave?

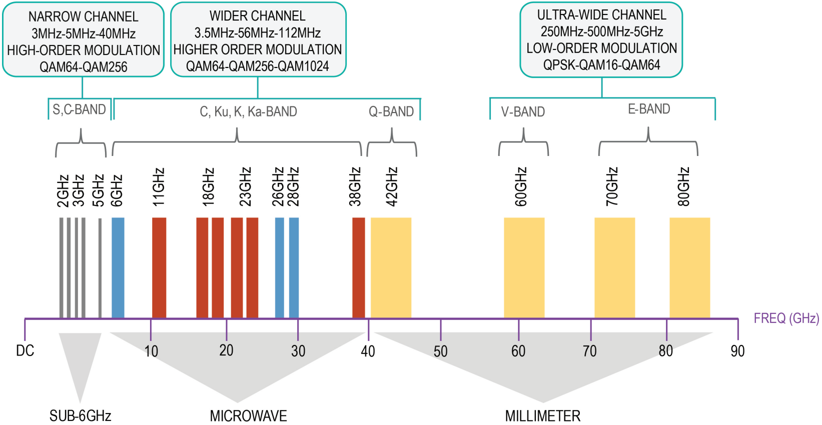


Image ©MWRF

Why mmWave?

$$C = W \log_2 \left(1 + \frac{\alpha P}{W N_0}\right)$$

mmWave characteristics

- Friis free-space equation:

$$P_r = \frac{\text{Effective Power}}{4\pi d^2} \times \text{Effective Aperture} = P_t G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2$$

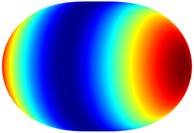
- Antenna gain:

$$G \propto 4\pi \frac{D^2}{\lambda^2}$$

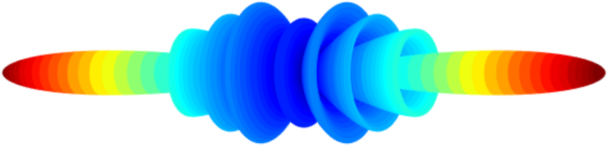
- Actual pathloss depends on the line-of-sight situation

mmWave characteristics

Circular antenna array (5cm at 6 GHz)

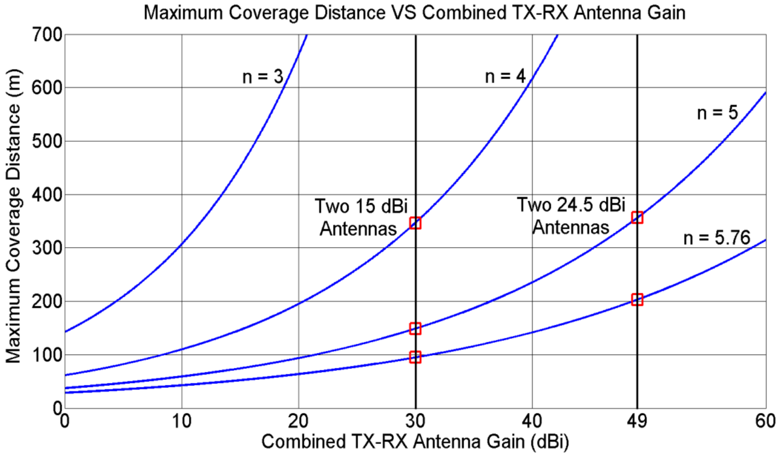


Circular antenna array (5cm at 60 GHz)



mmWave characteristics

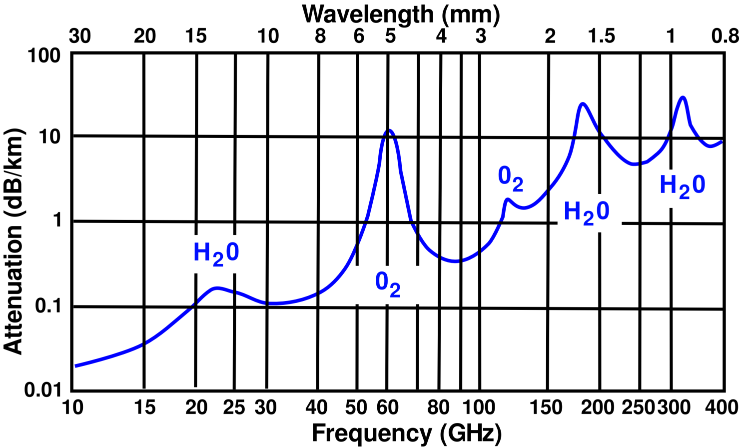
Coverage distance w.r.t. antenna gain, for a pathloss exponent *n*



From Rappaport *et al.*, "mmWave mobile communications for 5G cellular: it will work!", 2013.

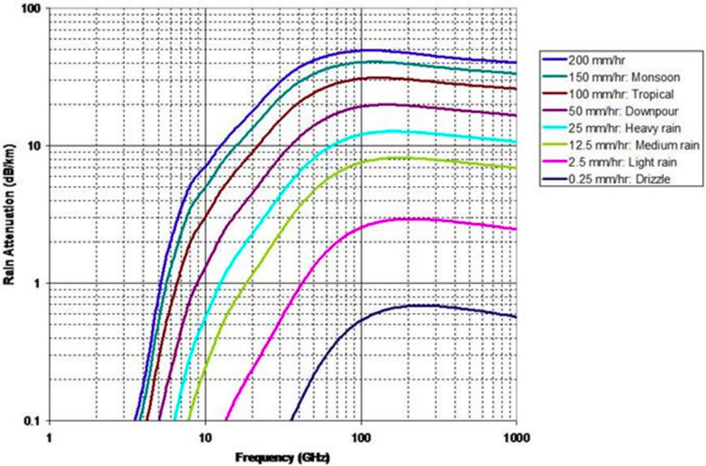
mmWave characteristics

Atmospheric absorption occurs due to oxygen and water molecules



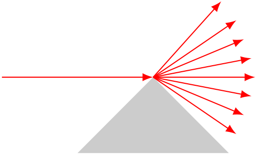
mmWave characteristics

Rain attenuation effects are more prominent

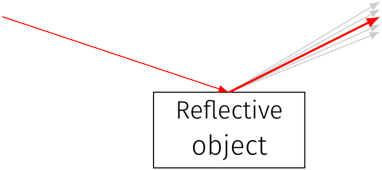


mmWave characteristics

- Diffraction effects are not a good propagation mechanism (unlike sub-4G cellular)



- Reflection and scattering tend to be more specular



mmWave characteristics

Reflection and transmission losses.

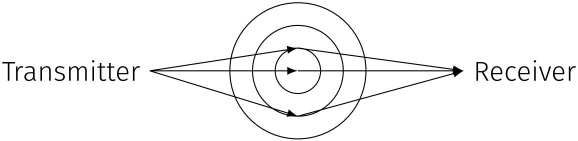
Environment	Material	Angle (°)	Reflection Loss (dB)
Outdoor	Tinted Glass	10	0.5
	Concrete	10	0.9
		45	2.1
Indoor	Clear Glass	10	1.3
	Drywall	10	1.5
		45	2.2

Environment	Material	Thickness (cm)	Penetration Loss (dB)
Outdoor	Tinted Glass	4	40.1
	Brick	185	28.3
Indoor	Clear Glass	1	3.6
	Tinted Glass	1	24.5
	Drywall	38	6.8

mmWave characteristics

Diffraction and Fresnel zones.

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$



mmWave characteristics

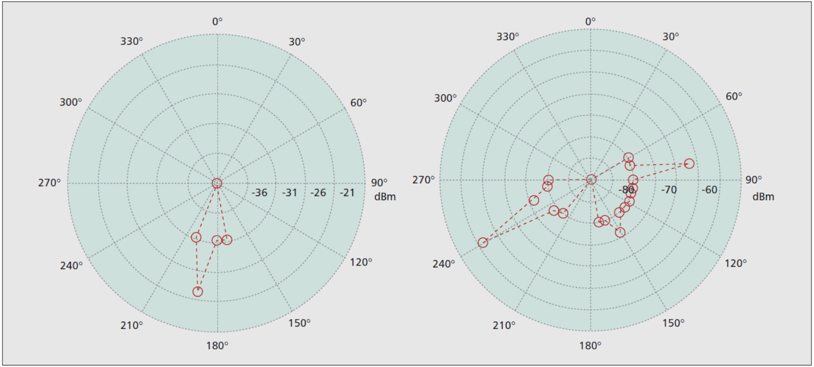
Doppler effect

$$f_d = f_c \left(\frac{c + \|\vec{v}_t\|}{c - \|\vec{v}_r\|} + 1 \right)$$

- Channel stability depends heavily on beamwidth and bandwith
- Channels are expected to change roughly 10 times faster than in current cellular bands!

mmWave characteristics

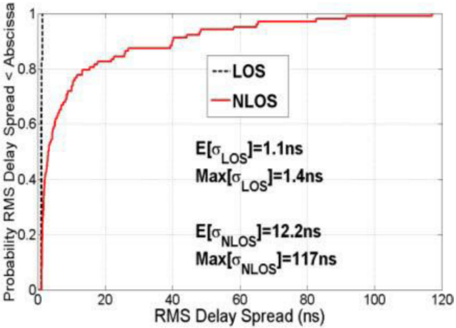
Angular power profile (azimuth) for a LoS and NLoS link



From Sun *et al.*, “MIMO for mmWave communications: beamforming, spatial multiplexing or both?”, 2014.

mmWave characteristics

R.M.S. delay spread for a 38 GHz link in LoS and non-LoS conditions



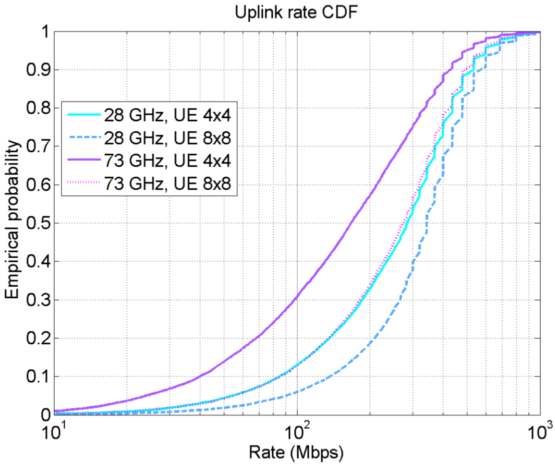
From Rappaport *et al.*, "mmWave mobile communications for 5G cellular: it will work!", 2013.

mmWave characteristics

	μWave	mmWave
Bandwith	1.4-150 MHz	100-2000 MHz
# antennas (BS)	1-8	16-256
# antennas (UE)	1-2	4-32
Delay spread	0.1-10 μs	10-40 ns
Angle spread	60 deg.	60 deg.
Scatterers	4-9	<4
Fading	Rayleigh	Rician
Pathloss exponent	2-4	2-4
Penetration loss	small	high
Spatial correlation	less	more

mmWave projected capacity

Channel capacity from measurements, at 28 GHz and 73 GHz

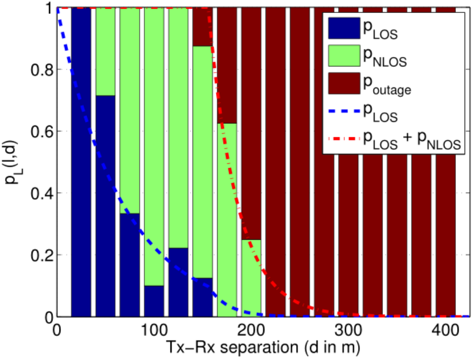


From Rangan *et al.*, “Millimeter-Wave Cellular Networks: Potentials and Challenges”, 2014.

mmWave projected capacity

The relatively sparse channel leads to a 3-level outage behavior:

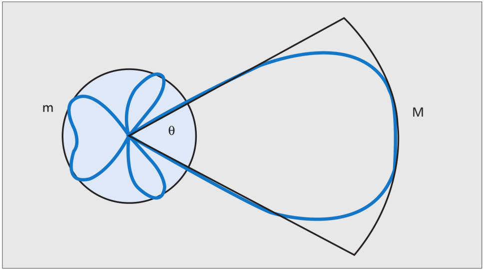
$$p_{out}(d) = \max\{0, 1 - \exp(-\beta_0 d + \beta_1)\}$$
$$p_{LOS}(d) = (1 - p_{out}(d)) \exp(-\beta_2 d)\}$$
$$p_{NLOS}(d) = 1 - p_{out}(d) - p_{LOS}(d)$$



From Adkeniz *et al.*, 2013

mmWave projected capacity

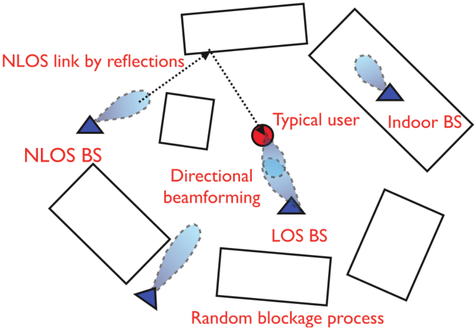
Stochastic geometry approach ; extending Poisson point processes



From Bai *et al.*, “Coverage and capacity of mmWave cellular networks”, 2014

mmWave projected capacity

Introducing random “shape” processes



From Bai *et al.*, “Coverage and capacity of mmWave cellular networks”, 2014

mmWave projected capacity

Projected spectral efficiency using the SG model

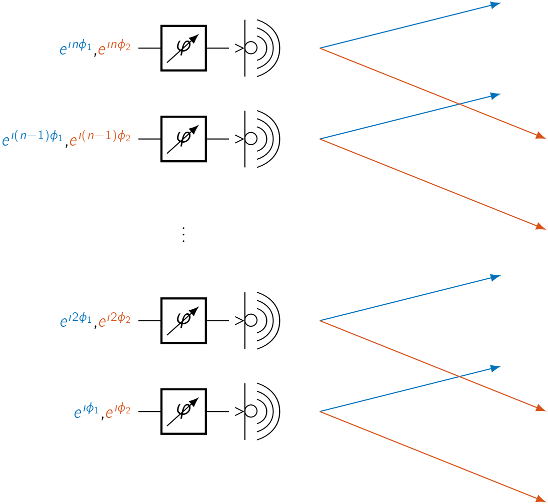
Architecture	Avg.	5%
SISO (μWave)	31	1.2
SU-MIMO (μWave)	77.2	1.4
Massive MIMO (μWave)	432.2	124.1
SU-beamsteering (mmWave)	451.2	294.4
MU-beamsteering (mmWave)	901.7	576

From Bai *et al.*, "Coverage and capacity of mmWave cellular networks", 2014

Antennas and arrays for mmWave

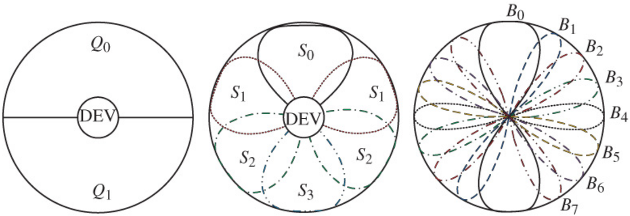
- Short wavelength : more potential for high gain antennas and arrays
- Even packaging antennas with other transceiver parts
- Compared to traditional antennas, efficiency is more of an issue than gain
- Joint behavior of other metal elements in the near-field
- Difficulties in measuring and characterizing the antenna patterns

Beamforming/beamsteering basics



Antennas and arrays for mmWave

- Beam-steering is required to get the benefits of antenna arrays and mmWave
- Issue : how to discover the angles of arrival? How to estimate then and feed them back?
- One solution : beam codebooks

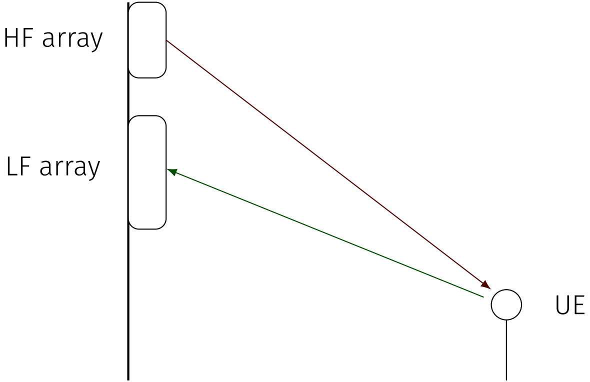


(a) Quasi-omni pattern (b) Sector (c) Beam

From Lan *et al.*, "Beam codebook based beamforming protocol for multi-Gbps mmWave networks", 2009.

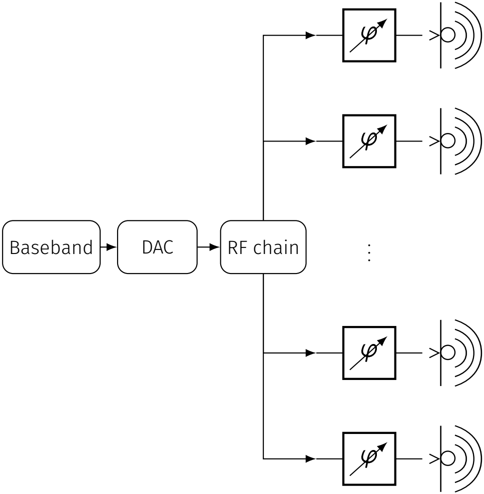
Antennas and arrays for mmWave

- Another solution: low-frequency assisted beamsteering
- But you can use classical phased array techniques on the massive MIMO low-frequency array!

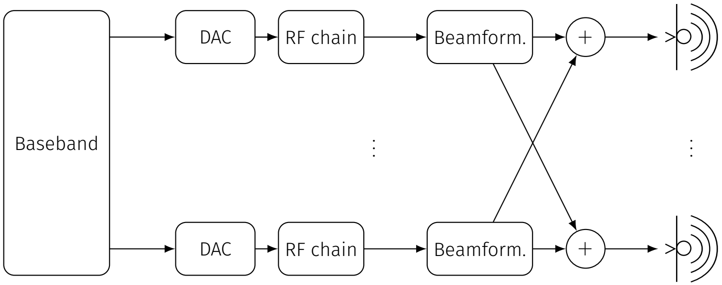


Antennas and arrays for mmWave

Analog beamforming (high ADC consumption)

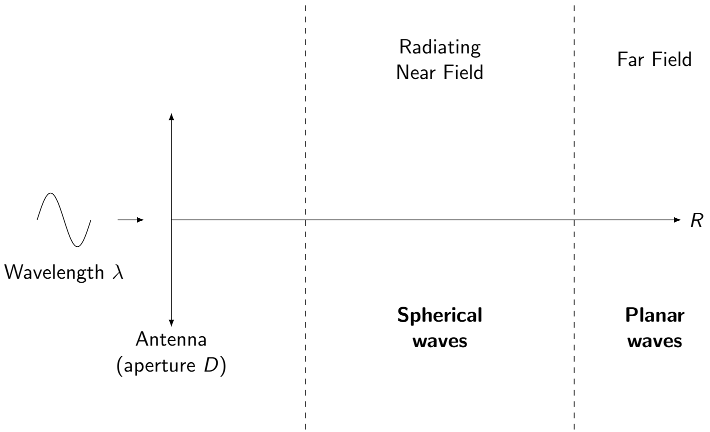


Hybrid beamforming : aims at enabling multiple users and/or streams on the same band



Antennas and arrays for mmWave

Multiple streams in a mainly LoS link: the reality

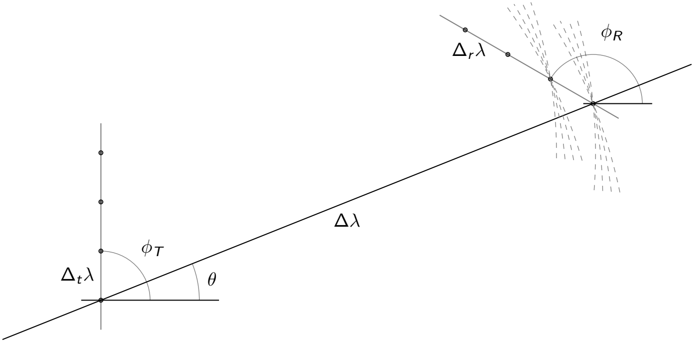


$$R = 0.62\sqrt{\frac{D^3}{\lambda}}$$

$$R = \frac{2D^2}{\lambda}$$

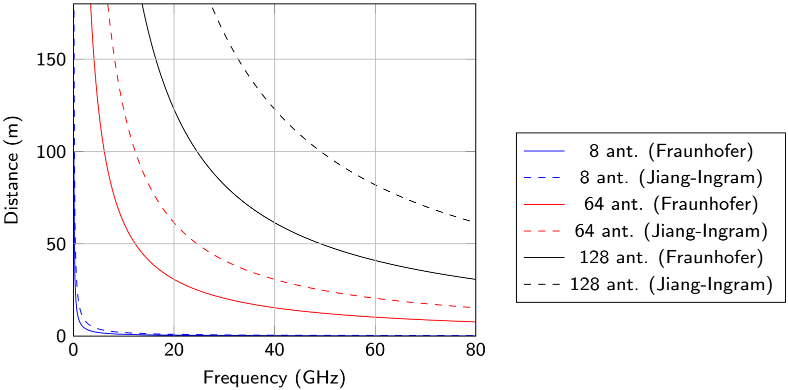
Antennas and arrays for mmWave

At a close range, spherical wave inputs some diversity in the channel → capacity gains from multi-stream MIMO

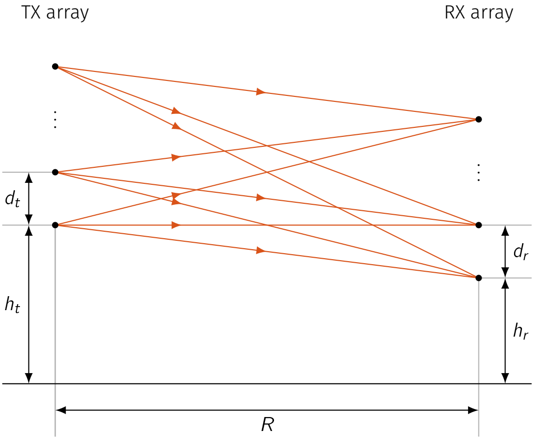


Antennas and arrays for mmWave

Distance limits to see tangible effects on the channel capacity (Jiang-Ingram bound)



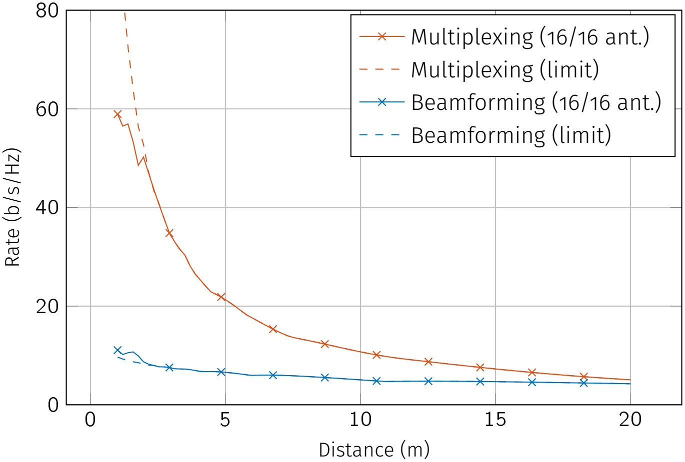
Line-of-sight MIMO: harnessing spherical waves



Optimal array distance: $d^2 = \lambda R$

Antennas and arrays for mmWave

Comparing beamforming and static precoding at 60GHz with LoS MIMO

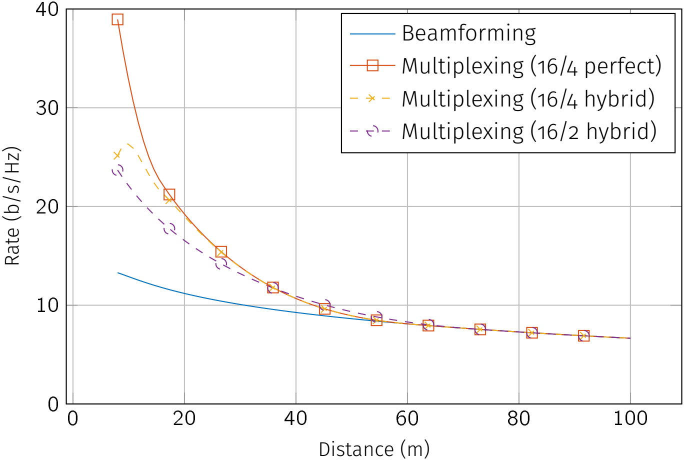


TX/RX diameter : 1m/5cm   60 GHz band, 40 dB at 1m

16/16 means 16 TX antennas and 16 RX antennas

Antennas and arrays for mmWave

Performance of hybrid beamforming approaches on LoS MIMO



TX/RX diameter : 1m/5cm   28 GHz band, 60 dB at 1m

16/4 means 16 TX antennas and 4 RX antennas

mmWave industrial and academic opportunities

- Massive wideband architectures
  - Single-carrier or OFDM/filter-banks?
- Precoding and multiplexing architectures
  - Low power, low cost, low resolution
  - Issues of channel estimation and quantization
- Dirty RF and non-optimal components
  - Phase noise, frequency offsets, oscillator pulling...
- MAC layer issues
  - Network discovery and beam scanning
  - Hidden nodes
  - Handovers, ...
- Waveform design for communications, and hybrid radar/communication transceivers