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SIGNET

# Main features of Millimeter Waves

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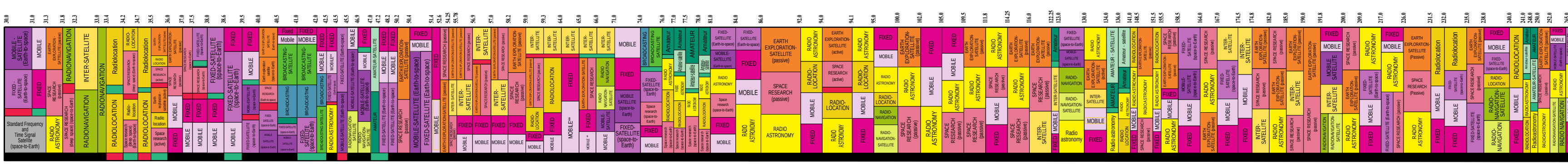
## Spectrum is a key resource for any radio access network.

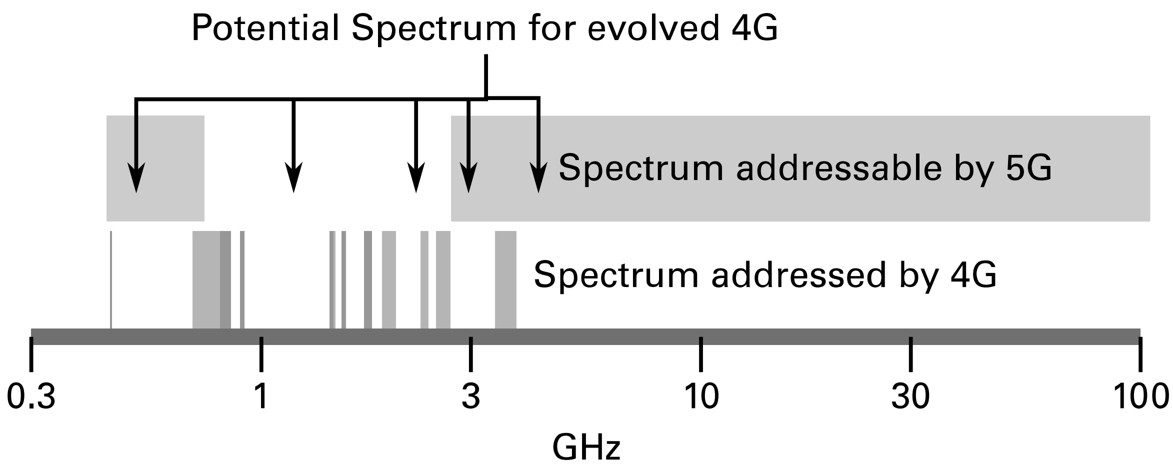
- The drivers for high network capacity are:
  - **Availability** of spectrum.
  - **Demand** in terms of the traffic that is driven through the network.
  - **Diversity** of services that can maintain load in a network across all hours of a day.
  - **Multiplexing** capability of the Internet Protocol (IP).



# 5G Spectrum Challenges



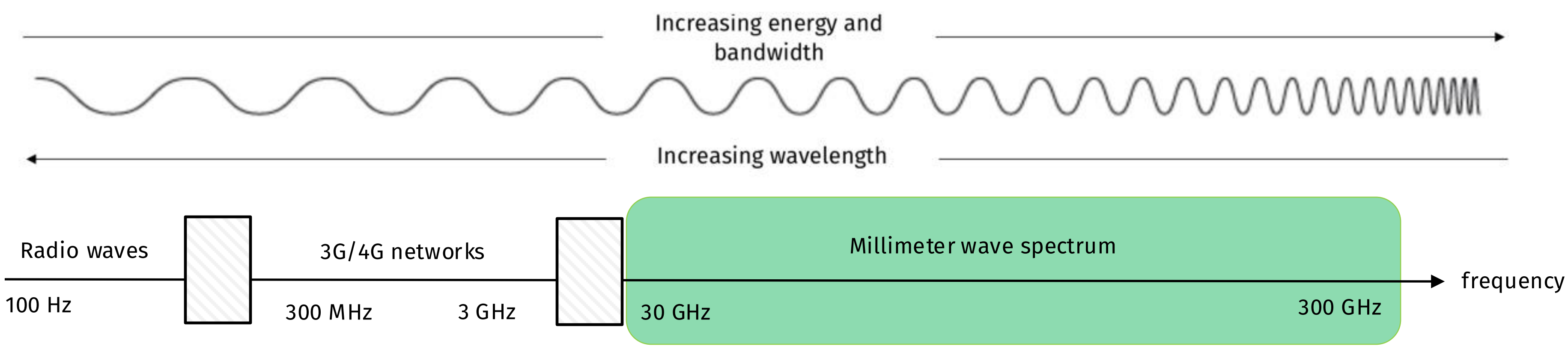
- Data volumes to be supported by 5G mobile access will dramatically **increase**, and requirements on coverage, reliability and low latency will be strengthened.
  - 1000x higher traffic capacity and 10÷100x higher typical user data rate.
  - SOLUTION: more spectrum and wider contiguous bandwidths.




**Source**: Osseiran, Afif, et al., "5G mobile and wireless communications technology". Cambridge University Press, 2016.

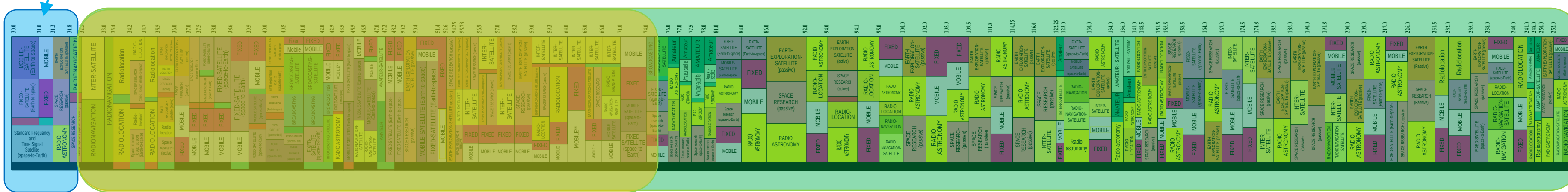
## The Millimeter Waves

- The millimeter waves include frequencies **between 30 and 300 GHz**.
- Industry has loosely defined it to include any frequency above 6 GHz, to better distinguish it from the legacy sub-6GHz spectrum.
- Distinguished from the so-called **legacy spectrum below 6 GHz** where previous network generations (3G, 4G) have been operating.
- At mmWaves, the wavelength is in the order of **millimeters**



# Why Millimeter Waves?

Current cellular and WiFi spectrum (BANDWIDTH: up to **40 MHz**)



0.3 GHz

300 GHz

Candidate 5G spectrum: BANDWIDTH up to **2 GHz**

## Higher frequency, higher bandwidth, higher throughput

- **Potential of Gbps data rates**
- NR will boost the 5G performance by supporting frequencies in the mmWave range

I. A. Hemadeh, K. Satyanarayana, M. El-Hajjar, and L. Hanzo. “Millimeter-Wave Communications: Physical Channel Models, Design Considerations, Antenna Constructions, and Link-Budget”. In: IEEE Communications Surveys & Tutorials (2018), pp. 870–913

# Challenges of Millimeter Waves



## Very high path loss

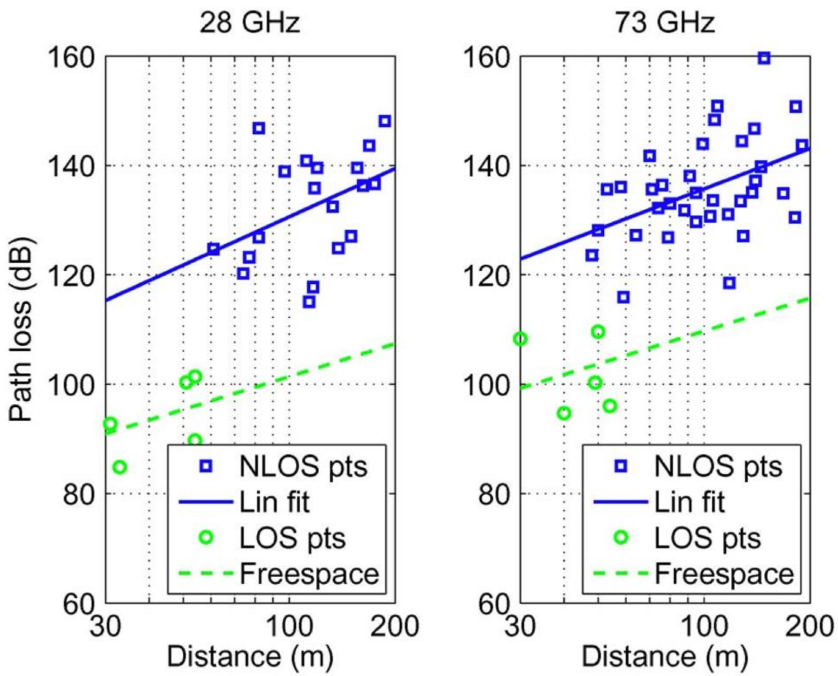
- Quadratically with carrier frequency
- Quadratically with the distance

**Source:** M. Akdeniz, et al. "Millimeter wave channel modeling and cellular capacity evaluation." *IEEE journal on selected areas in communications* 32.6 (2014): 1164-1179.

$$P_{RX} = P_{TX}\left(\frac{\lambda}{4\pi R}\right)^2 = \frac{P_{TX}}{4\pi R^2}\frac{c^2}{4\pi f_c^2}$$

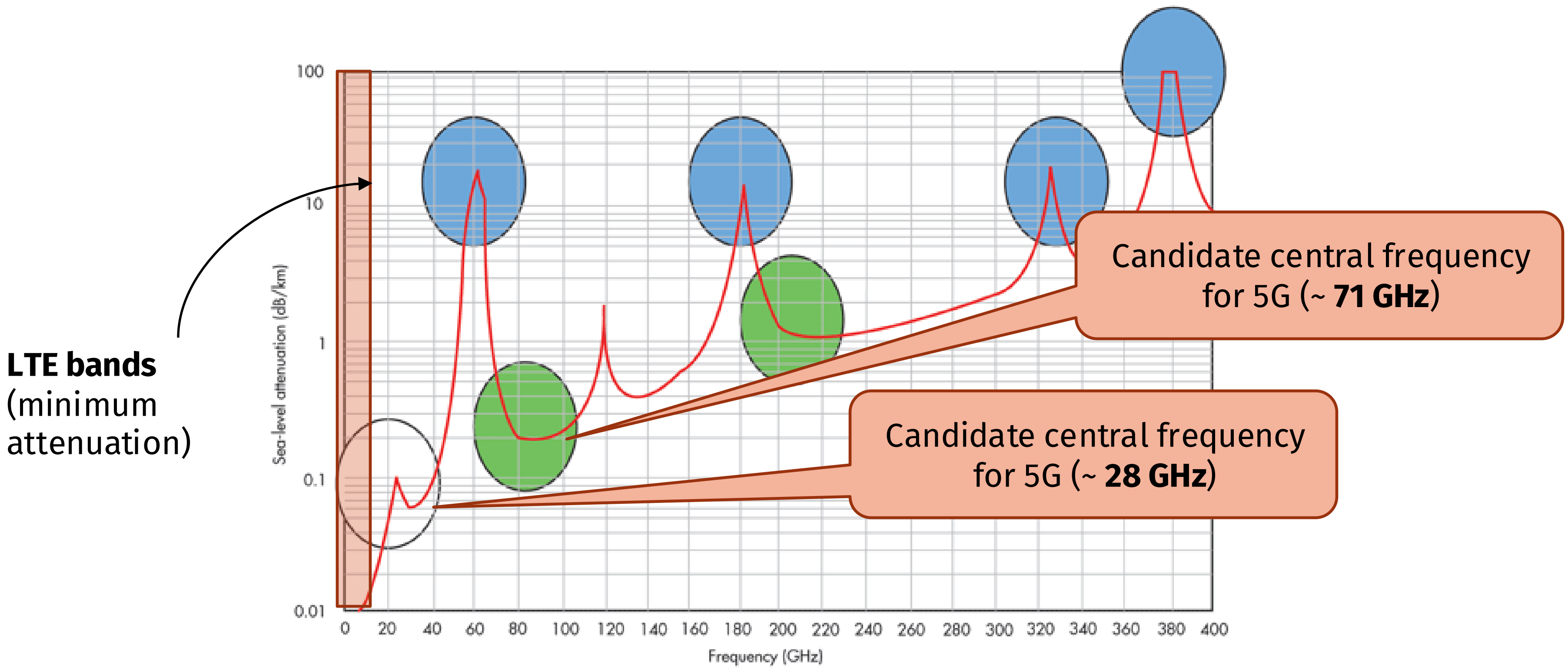
*Communication **distance** must be reduced to have acceptable received power*

*Carrier **frequency** (orders of magnitude higher than for 4G/LTE networks)*



## Atmospheric attenuation

- Caused by the nature $H_2O$ and $O_2$ molecules in the air



## Material penetration

- mmWaves cannot propagate through obstacles and solid material

*Small wavelength (in the order of **millimeters**)*

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \left( \frac{\lambda}{4\pi R} \right)^2 = \frac{P_{\mathrm{TX}}}{4\pi R^2} \frac{c^2}{4\pi f_c^2}$$

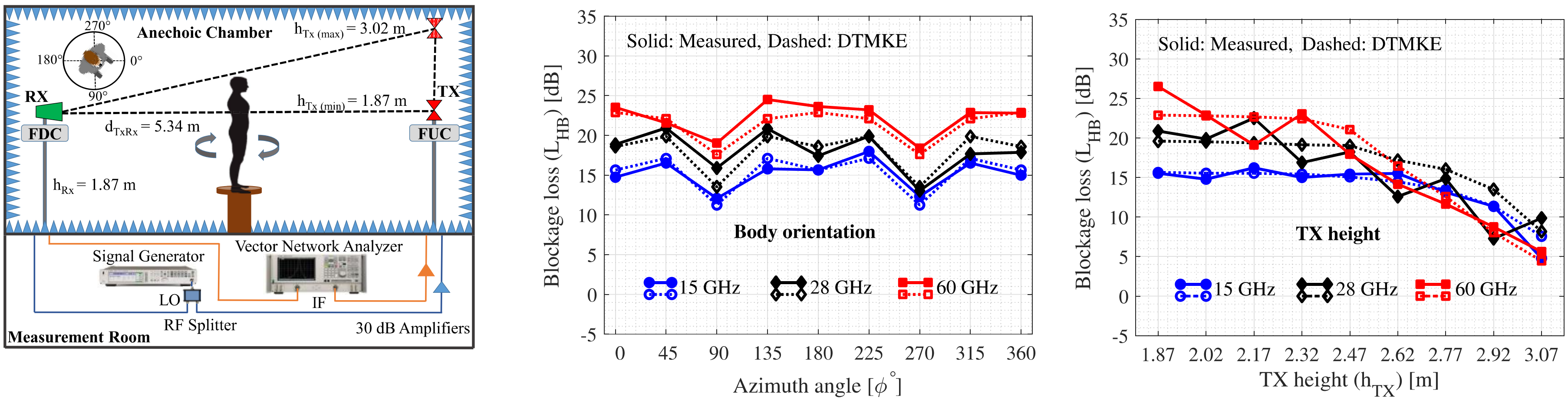
| Material | Penetration loss [dB] |
|---|---|
| Standard multi-pane glass | $L_{\text{glass}} = 2 + 0.2f$ |
| IRR glass | $L_{\text{IIRglass}} = 23 + 0.3f$ |
| Concrete | $L_{\text{concrete}} = 5 + 4f$ |
| Wood | $L_{\text{wood}} = 4.85 + 0.12f$ |
| Note: f is in GHz | |


- 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 38.901, 2020.
- J. Hansryd, et al., "Long term path attenuation measurement of the 71–76 GHz band in a 70/80 GHz microwave link". In: Proceedings of the European Conference on Antennas and Propagation. 2010.
- S. Ranvier, et al., "Millimeter-Wave MIMO Radio Channel Sounder". In: IEEE Transactions on Instrumentation and Measurement (2007), pp. 1018–1024.

# Challenges of Millimeter Waves

## Human’s attenuation

- It depends on the “characteristics” of the occluding blocker and the antenna configurations (additional loss of up to 25 dB)



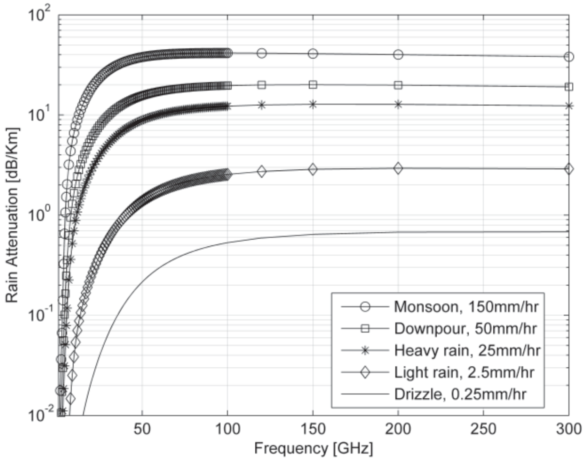

U. T. Virk and K. Haneda. “Modeling Human Blockage at 5G Millimeter-Wave Frequencies”. In: IEEE Transactions on Antennas and Propagation (2020), pp. 2256–2266

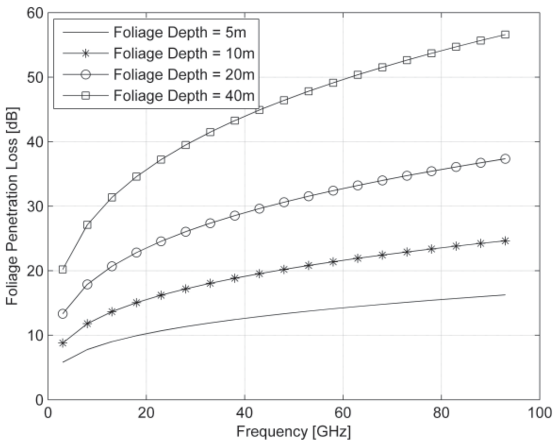
# Challenges of Millimeter Waves

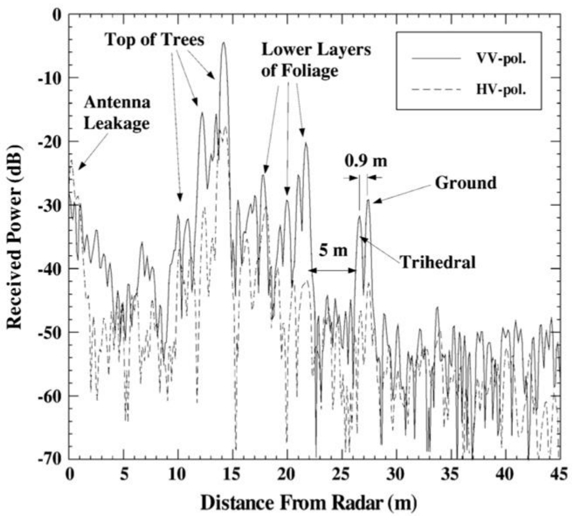


## Rain and foliage attenuation

- Proportional to the density and depth of the foliage
- Proportional to the rain rate (mm/hr)



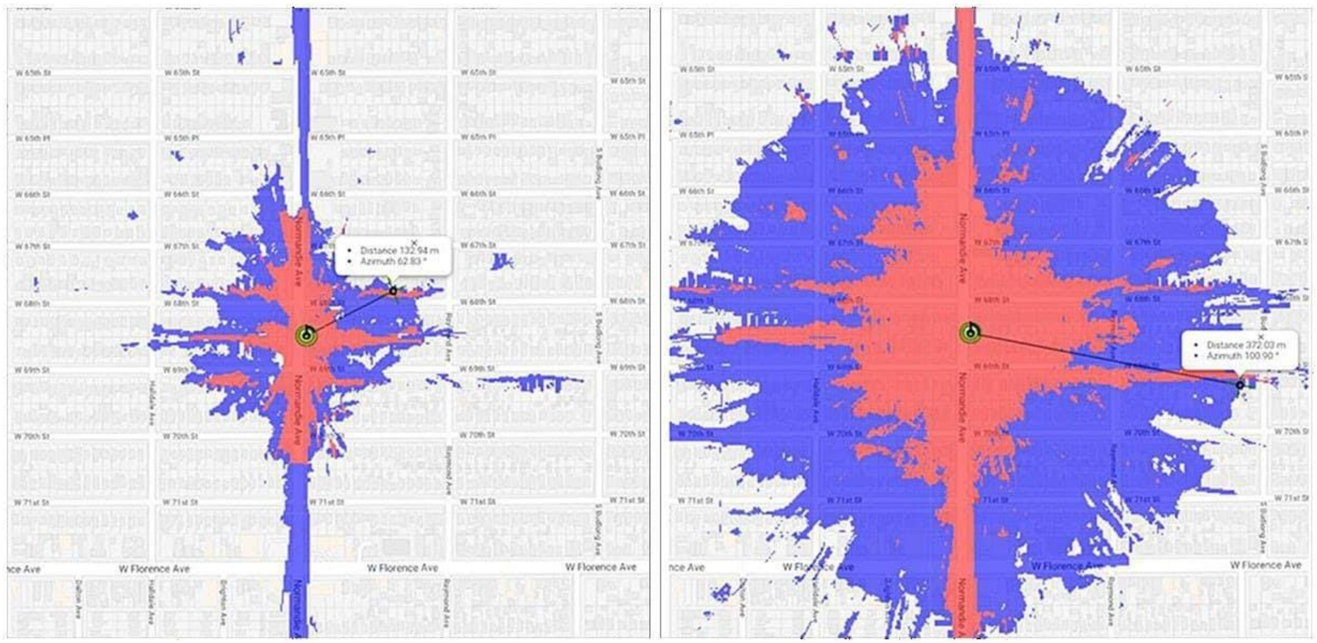

- F. Khan and Z. Pi. “mmWave mobile broadband (MMB): Unleashing the 3– 300GHz spectrum”. 2011.
- Nashashibi, Adib Y., et al. "Millimeter-wave measurements of foliage attenuation and ground reflectivity of tree stands at nadir incidence." IEEE Transactions on Antennas and Propagation52.5 (2004): 1211-1222.

## Indoor/outdoor coverage

- Achieving seamless indoor coverage via an outdoor transmitters is not possible → spatial reuse through **relays**

100 Mbps

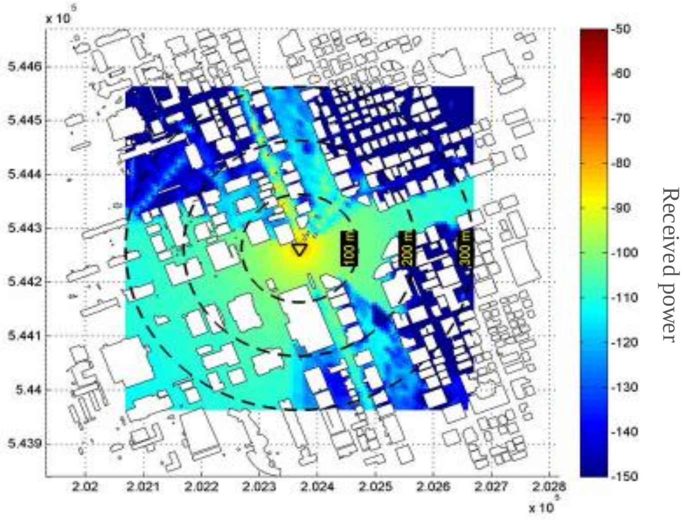
1 Gbps



**Source:** https://spectrum.ieee.org/tech-talk/telecom/standards/how-america-can-prepare-to-live-in-chinas-5g-world

## Reflection and diffraction

- **Mobility** of the mobile terminals causes multi-path components to arrive at the RX with different incident angles
- **Diffraction** impacts on indoor environments
- **Reflection** impacts on outdoor scenarios



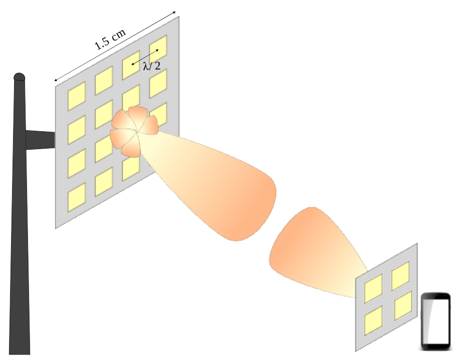
# How to Overcome Limitations of Millimeter Waves?

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \left( \frac{\lambda}{4\pi R} \right)^2$$

*Increasing the transmission power is NOT a valid option due to* ***regulations on electromagnetic emissions*** *and because of* ***interference***

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} \left( \frac{\lambda}{4\pi R} \right)^2 G_{\mathrm{TX}} G_{\mathrm{RX}}$$

***ANTENNA GAIN:*** *if designed correctly, we can overcome high-frequency propagation issue*

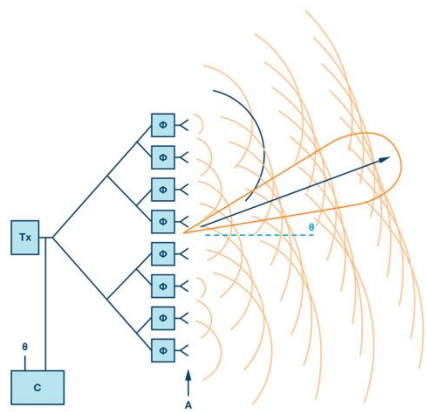


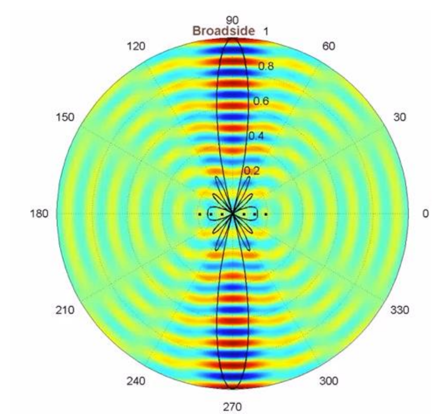

**MIMO**: Multiple Input Multiple Output

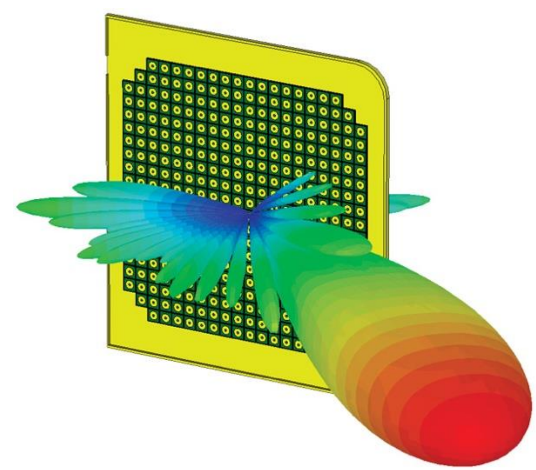
Use **multiple transmit and receive antennas** to exploit multipath propagation, so that a 3D beam can be synthesized → <u>DIRECTIONAL</u> COMMUNICATION

## Coherent superposition of wavefronts

- By appropriately shaping the signal, all wavefronts collectively emitted by all antennas add up constructively at the locations of the intended terminals, but randomly (i.e., destructively) almost everywhere else.
- Typical MIMO installations use few (i.e., less than 10) antennas
- At mmWaves, it becomes practical to build large antenna arrays (e.g., with 100 or more elements) → **MASSIVE MIMO**



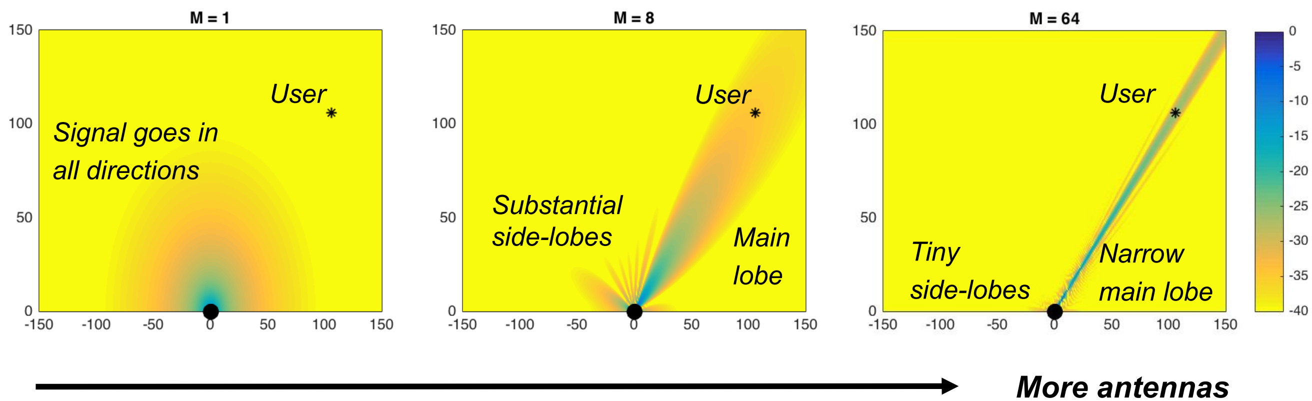



## Beamforming gain

- Multiple antenna elements are adaptively phased to form a concentrated beam pattern towards a specific direction.
- Partially overcome the severe path loss experienced at mmWaves

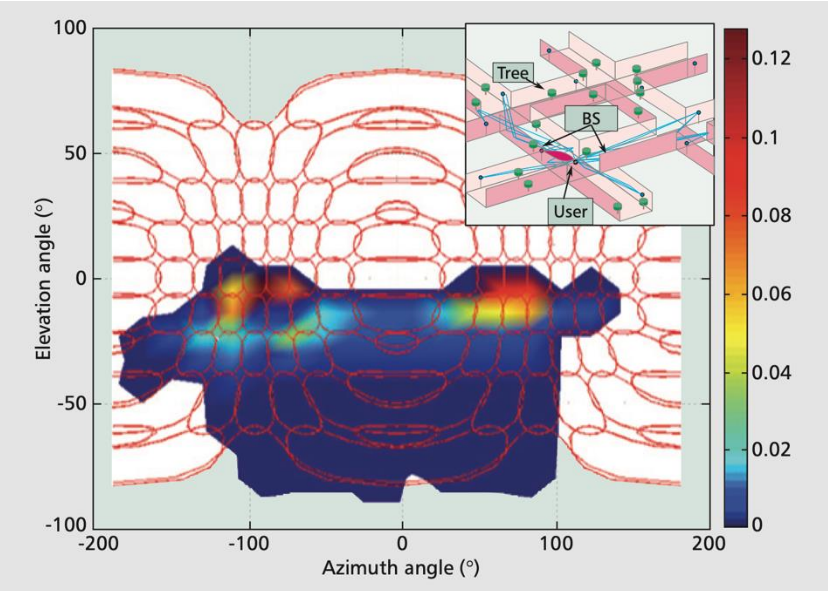
$$G = 10\log_{10}(N_{\mathrm{TX}} N_{\mathrm{RX}})$$



# The Potential of MIMO

## Spatial diversity

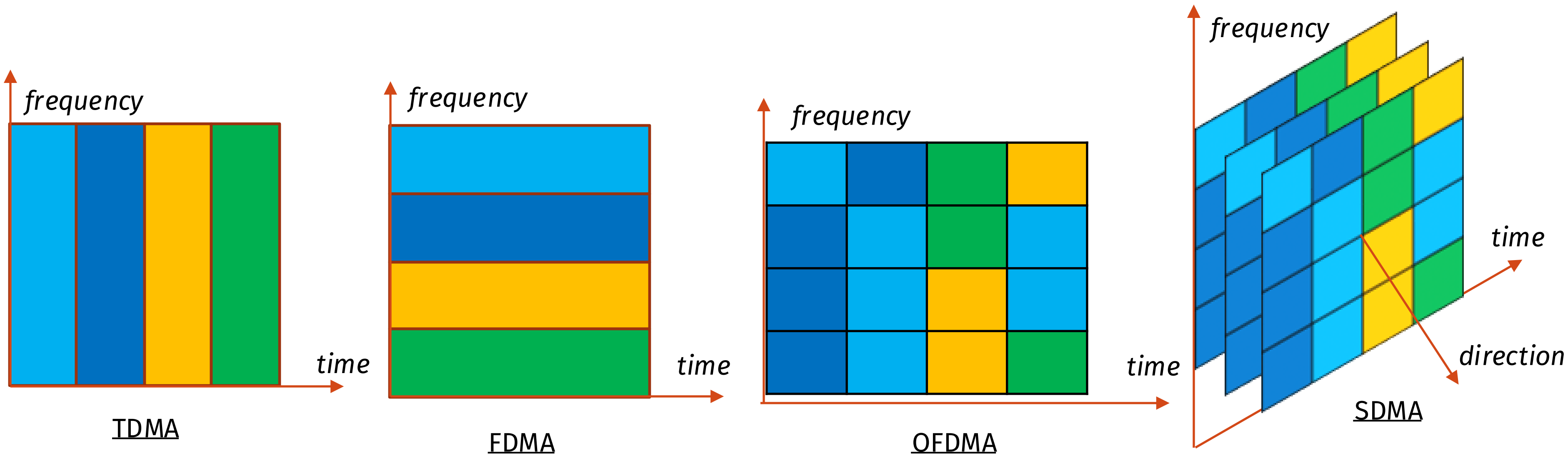
- Sufficiently separated antennas are used to transmit redundant versions of the same message over multiple paths.
- The quasi-independent fading characteristics of the mmWave channel are exploited to make links more robust and decrease the outage.




Sun, Shu, et al. "MIMO for millimeter-wave wireless communications: Beamforming, spatial multiplexing, or both?." IEEE Communications Magazine 52.12 (2014): 110-121.

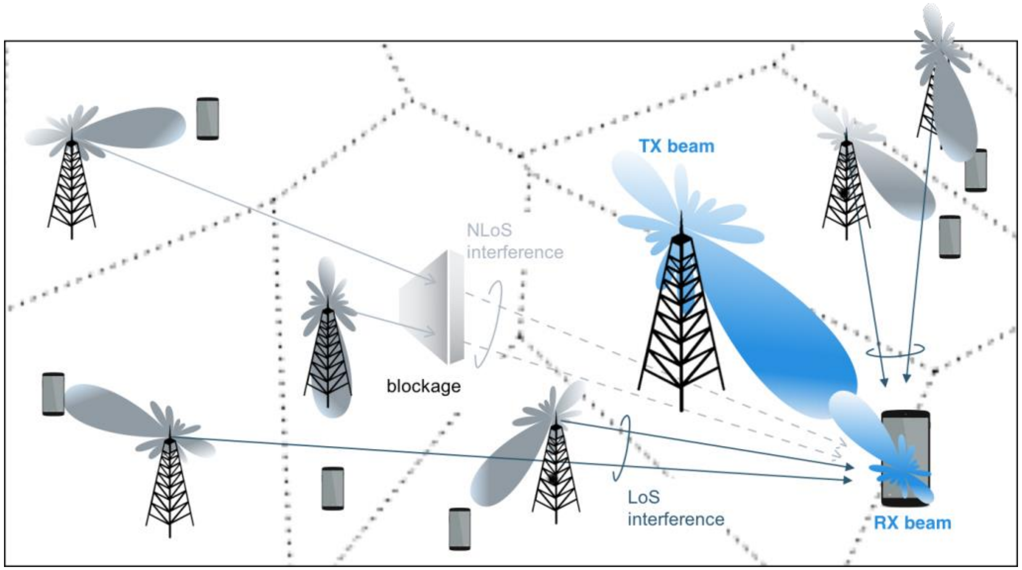
## Spatial multiplexing and SDMA

- Signal is split into multiple independent streams, transmitted **simultaneously** and **in parallel** on the same channel via different antennas.
- The multipath proprieties of the channel can be used to **multiplex users** in the spatial dimension while operating in the same time-frequency resource.
  - Another degree of freedom given by the **spatial dimension**.



## Reduced interference and improved privacy

- Dominant paths from interferers are blocked
- Side lobes do not create interference
- Towards noise-limited regime
- Inherent security and privacy (user is isolated from external attacks)




M. Rebato et al. "Stochastic geometric coverage analysis in mmWave cellular networks with realistic channel and antenna radiation models." IEEE Transactions on Communications 67.5 (2019): 3736-3752.

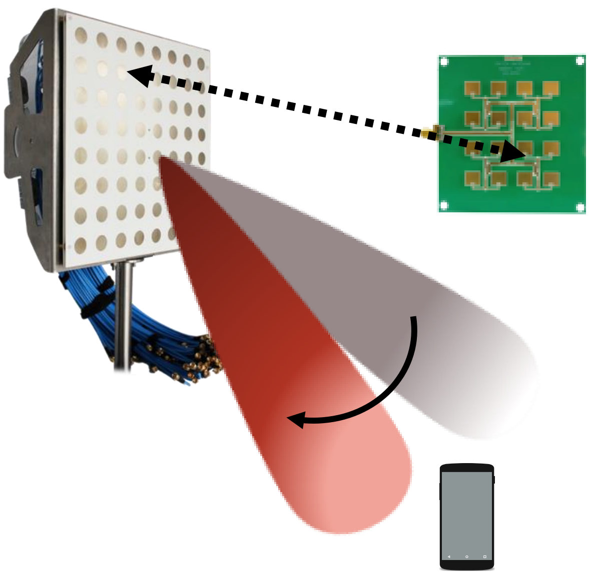
# The Challenges of MIMO

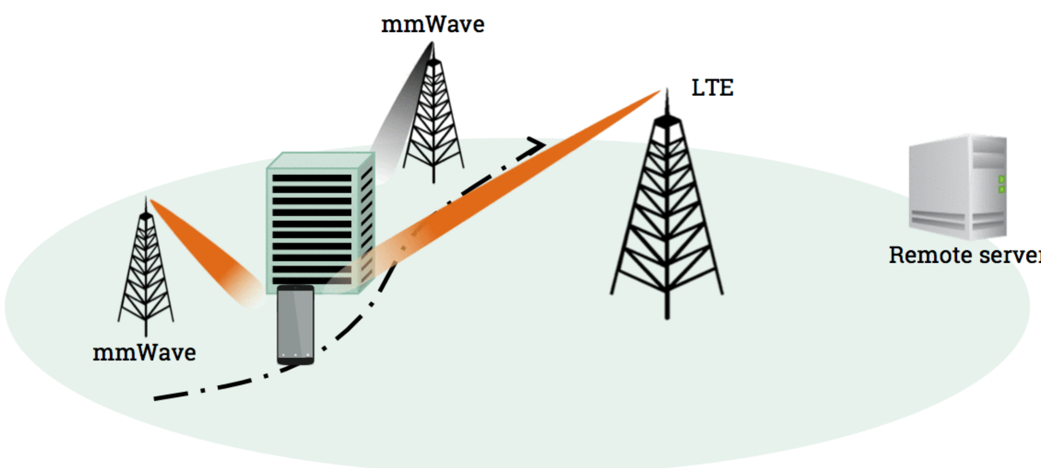
## Hardware impairments

- Massive MIMO exploits channel reciprocity to estimate the channel responses on the uplink and use such information for both uplink and downlink transmissions.
- Since the transceiver hardware is generally not reciprocal, calibration is needed to exploit the channel reciprocity in practice.


## Beam management

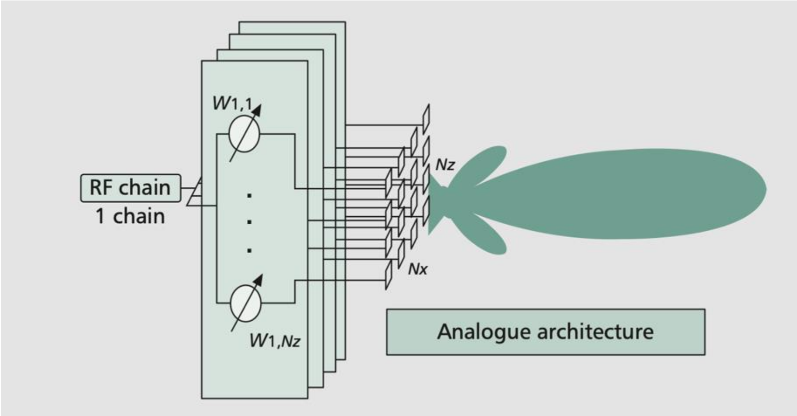
- Directionality requires precise beam alignment at the transmitter and the receiver, and implies increased control overhead (especially in MASSIVE MIMO).





## Energy-consumption vs. flexibility trade-off

### ANALOG BEAMFORMING




**Source**: S. Sun, et al., "Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," in *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110-121, December 2014

### CONS

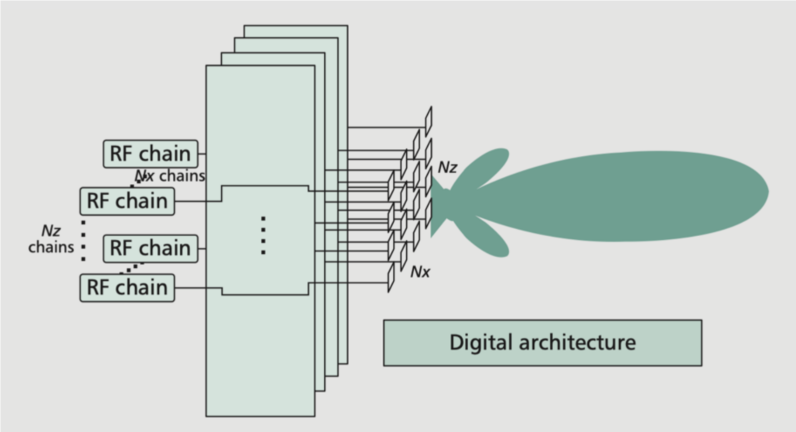
- Processing in the **analog** domain
- TX/RX in only **one direction** at a time

### PROS

- Single Radio Frequency (RF)
- Single pair of Analog to Digital Converters
- Consumes low power

## Energy-consumption vs. flexibility trade-off

**DIGITAL BEAMFORMING**




**Source**: S. Sun, et al., "Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?," in *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110-121, December 2014

**CONS**

- One RF chain per antenna element
- Reduced $P_{TX}$ available to each direction
- **Power consuming (OK only @ RX)**

**PROS**

- Processing in the digital domain
- Beams at **infinite** directions
- Powerful/flexible signal process

# Summary of mmWave

## In conclusion:

- mmWaves have the potential to provide very high throughput
- However, they suffer from more severe propagation conditions (higher path loss, blockage)
- The smaller wavelength makes it possible to pack many antennas in a small physical space, thereby compensating for the path loss
- Network deployment needs to account for blockage effects and to provide proper diversity
- Several practical issues still to be fully addressed

- How about THz?