Terahertz wireless networks: applications, challenges, and early solutions

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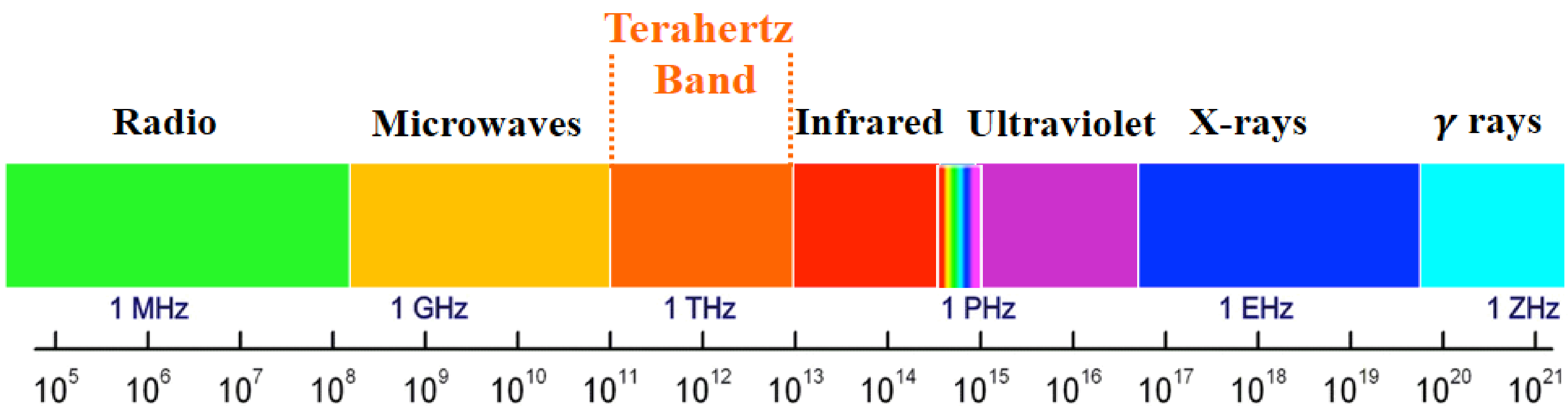
Outline

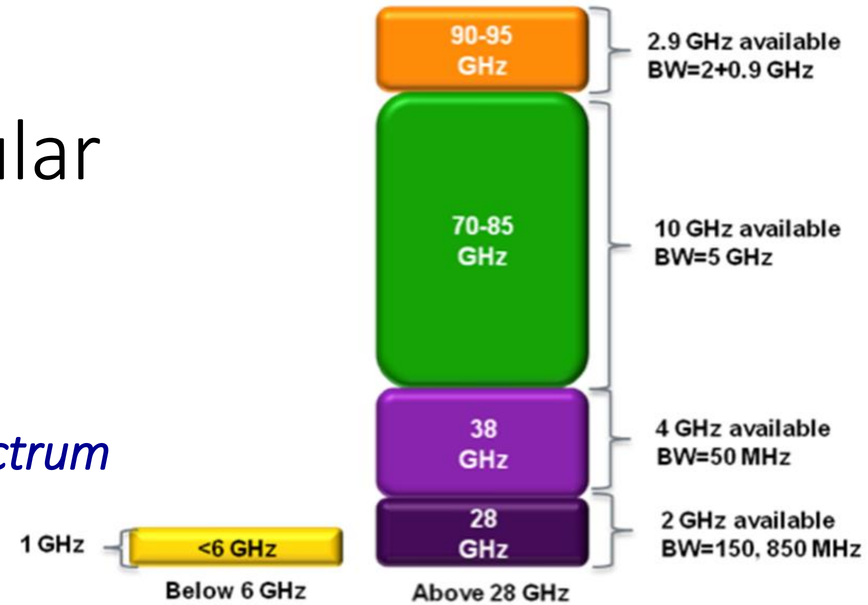
- THz band capabilities and promises
- Challenges and limitations
- Applications and use-cases
  - Macro world use-cases
  - Micro-scale applications
- Earlier solutions
  - Addressing micromobility challenges
  - Physical layer security and eavesdropping

Where is THz band? (THF)

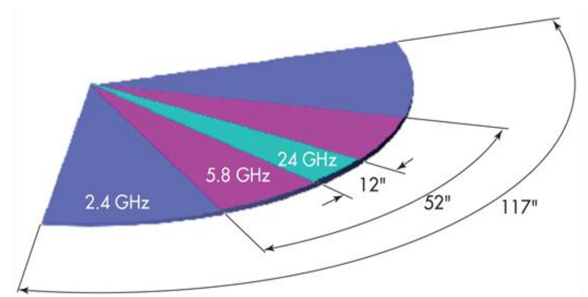


	Диапазон частот	Длина волны
Industry, IEEE	0.3 – 3 THz	1 mm – 100 µm
Academy	0.1 – 10 THz	3 mm – 30 µm
Academy	0.06 – 10 THz	5 mm – 30 µm
Early phase	**Focus: 275-325 GHz**	**Focus: ~1 mm**

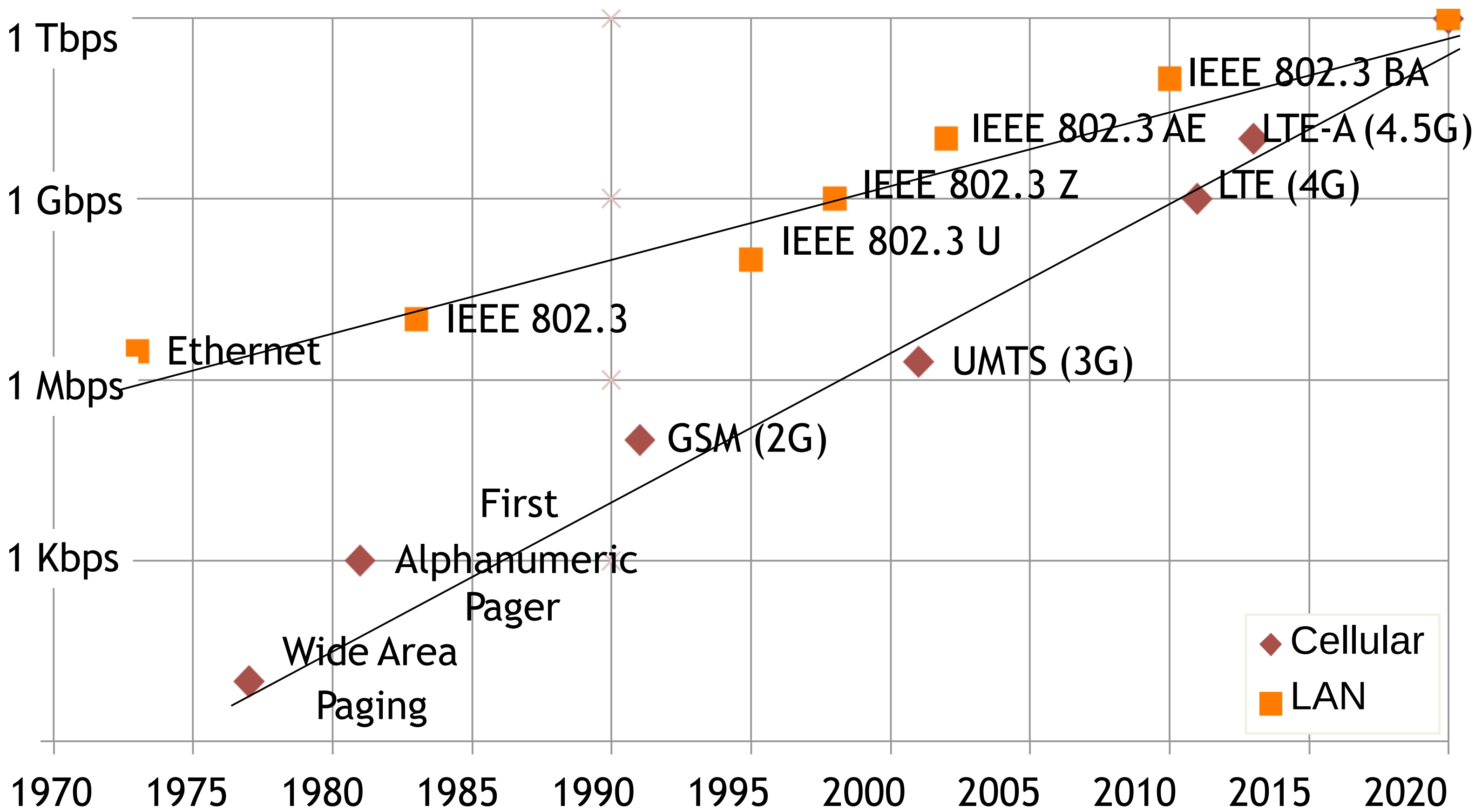
Why THz? Modern cellular



- ❑ Limitations:
  - ○ 2.4 and 5-6GHz spectrum
  - ➢ *Overcrowded: lack of "free" spectrum*
  - ○ Millimeter waves (30-100 GHz):
    - ▪ One of the major breakthroughs in 5G
    - ▪ Limited by 10 GHz of aggregated bandwdth
    - ▪ Expected rate per BS: ~10-20 Gbps
      - ➢ *Fine now, not enough for the future*
  - ○ Visible Light Spectrum (VLC), 400-790 THz
    - ▪ Giant spectrum with extreme capacity
      - ➢ *Line-of-sight communications only*

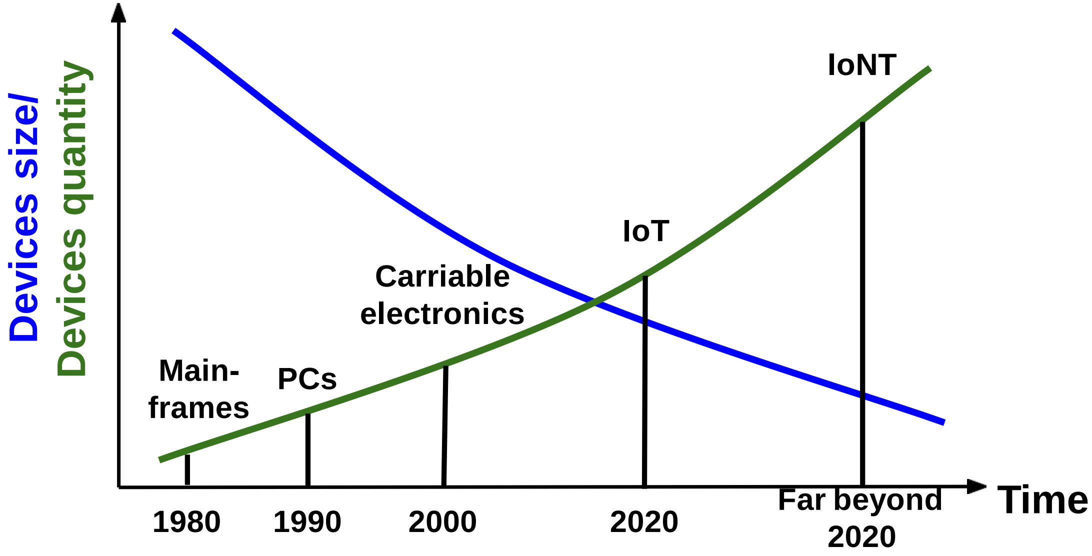


Trend: matching rates



Trend: electronics miniaturization

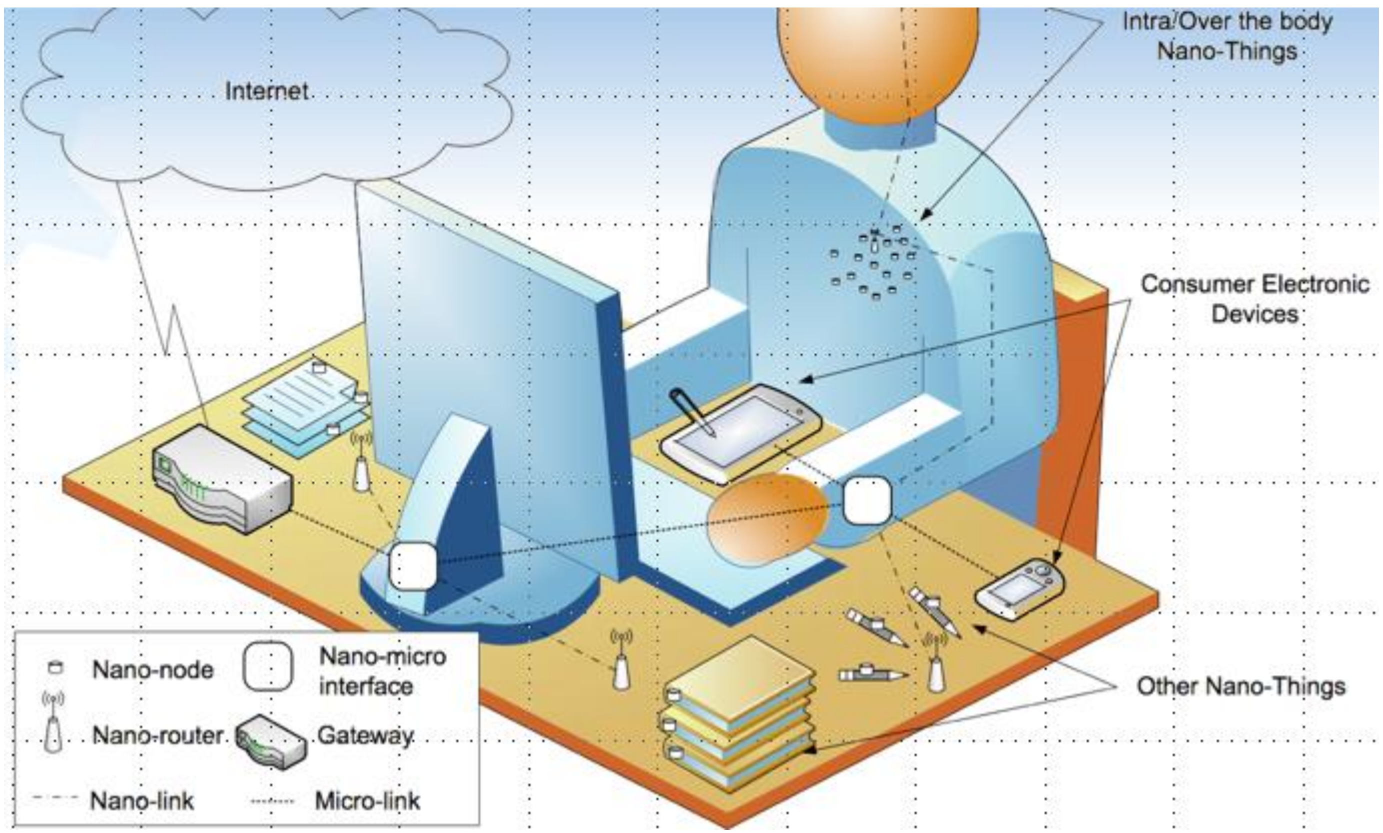
- Terahertz is interesting solution
  - Extreme throughput (Shannon law: $C=B*\log_2(1+SNR)$)
  - Perfect fit for micro/nano devices (antenna size: $\lambda/2$)



  - Needs to be adapted to communications systems
  - New challenges

Motivating example

- ❑ Ubiquitous connectivity



Advantages

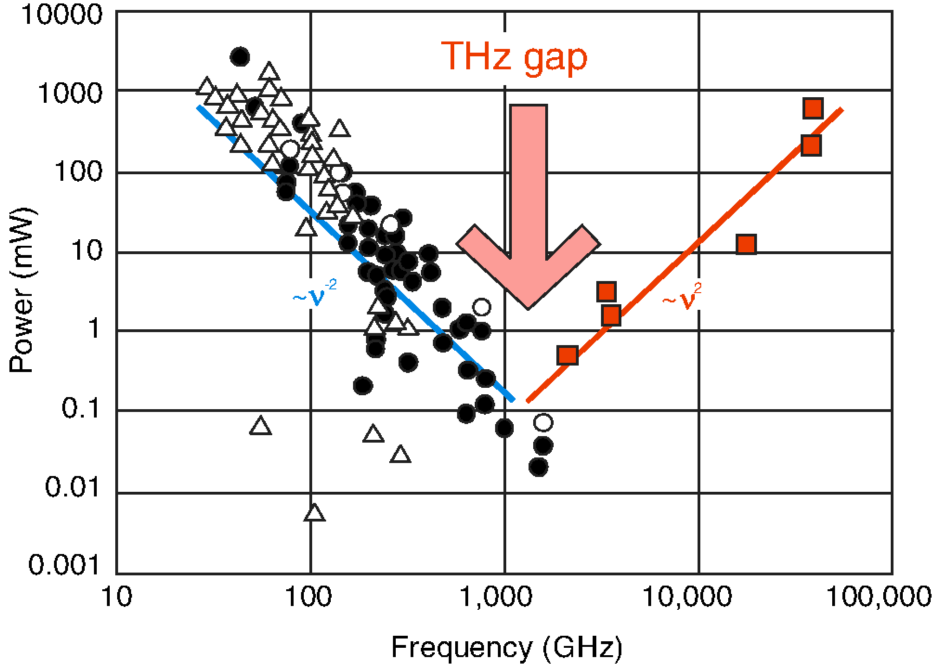
- Much higher resources (from 50 GHz and up)
  - May reach multiple Tbps if needed
  - Even with 0.1 bit/s/Hz spectral efficiency
- Miniaturized antennas (λ ~ 1mm at 300 ГГц)
  - Micro/nano applications (nanonetworks ☺)
- Retains “radio” properties up to some extent
  - Penetrates through obstacles
  - Reflects/diffuse from obstacles
- Highly directional communications
  - No interference - noise limited operation

Challenges

Electronics: "THz gap"

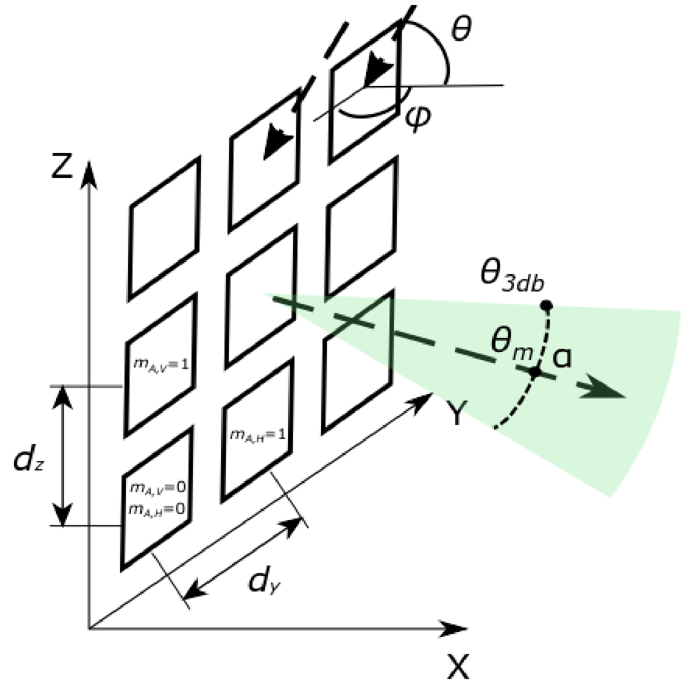
No efficient signal generation miniaturized electronics

- Too high for radio
- Too low for optics



Antenna limitations

- Too small aperture
- Isotropic radiator: $S_{эф} = \frac{\lambda^2}{4\pi} D_0$
  - Limits emitted power
  - Naturally calls for antenna arrays
- Antenna example: 1024x1024 elements
  - Gain: >100 dBm, HPBW: <1°



Akyildiz, I. F., & Jornet, J. M. (2016). Realizing ultra-massive MIMO (1024× 1024) communication in the (0.06–10) terahertz band. Nano Communication Networks, 8, 46-54.

Antenna temperature

Equating consumed and dissipated powers

Utilizing Stefan-Boltzmann law

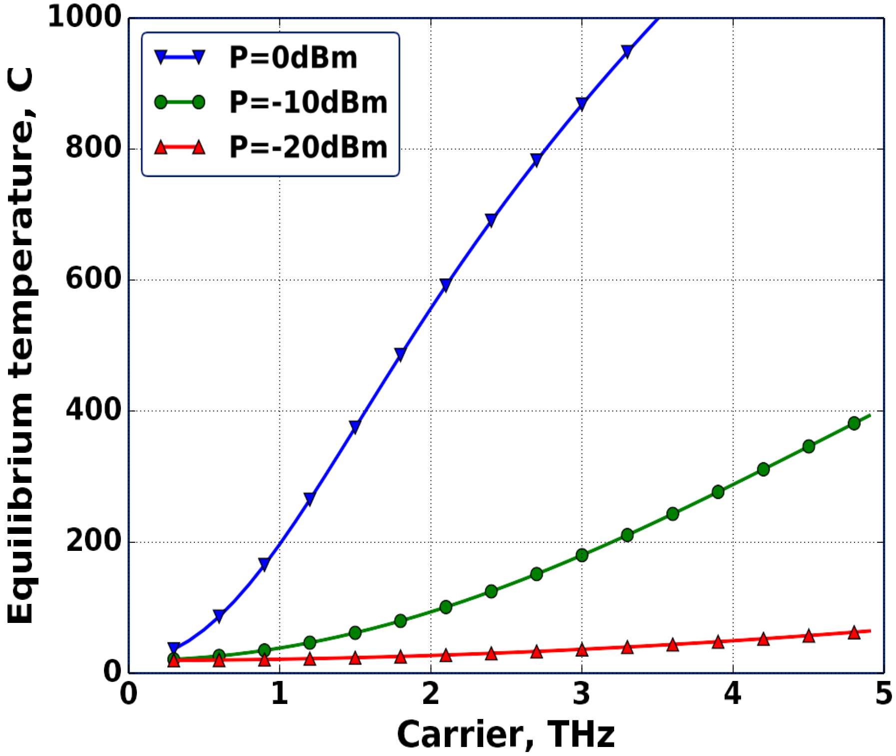
$$P_{cons} = P_{Tx}(1-\eta)$$

$$P_{diss} = \frac{\lambda^2}{36}\left(\sigma(T_a^4 - T_r^4) + h_{air}(T_a - T_r)\right)$$

- T_a – antenna temperature,
- T_r – room temperature,
- h – antenna efficiency,
- h_{air} – air heat transfer coefficient,
- σ – Stefan-Boltzmann constant

$$P_{diss} \geq P_{cons} \rightarrow \sigma \cdot (T_a^4 - T_r^4) + h_{air} * T_a - \left(T_r * h_{air} + 36 P_{Tx} * (1-\eta)/\lambda^2\right) \geq 0$$

Antenna temperature



Temperature < 50°C:

- 0dBm – up to 300GHz
- -10dBm – up to 1THz
- -20dBm – up to 3THz
- WiFi – 23 dBm

Antenna arrays needed!!!

Band up until 1 THz is ythe most promising

Propagation losses

Two cases comparison:

1) Directional Tx + Omnidirectional Rx (MxM elements + 1)
2) Directional Tx + Directional Rx (MxM + MxM)

Path losses (simple Friis model)

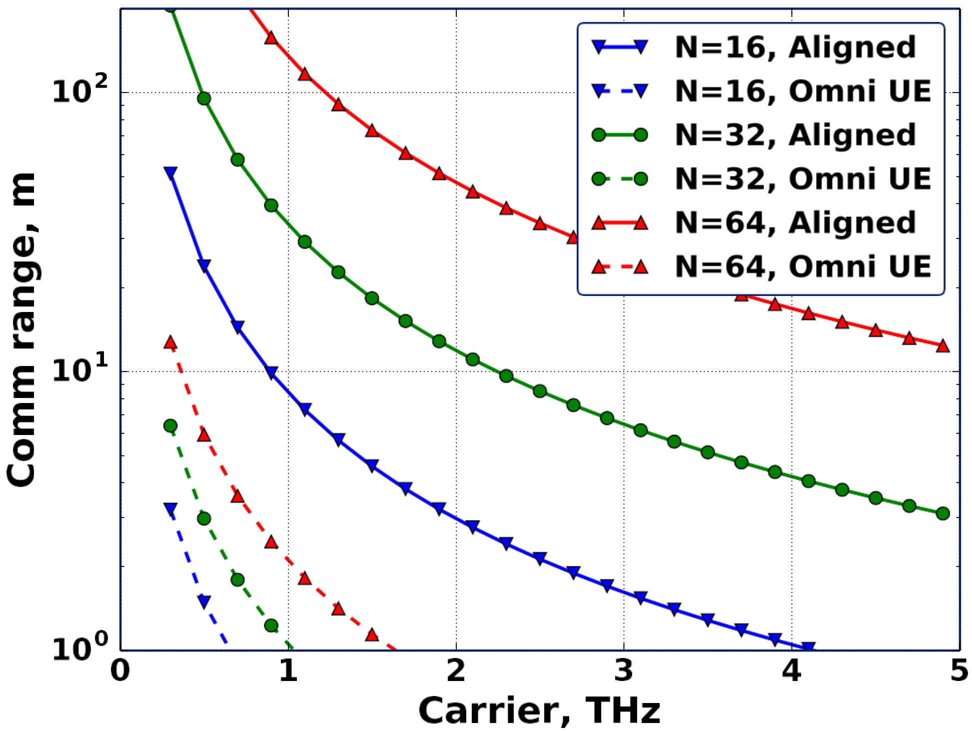
$$L = P_{Tx} + (173 - 10\log_{10}(B)) + G_{Tx} + G_{Rx} - S,$$

S – required SNR at Rx, e.g., 5 dB

Coverage radius:

$$d = 10^{L/20 + 7.38 - \log_{10}(f)}$$

Propagation losses



Parameters:

- P_{Tx} = 0 dBm
- SNR = 5 dB
- 10GHz bandwidth

Effective coverage:

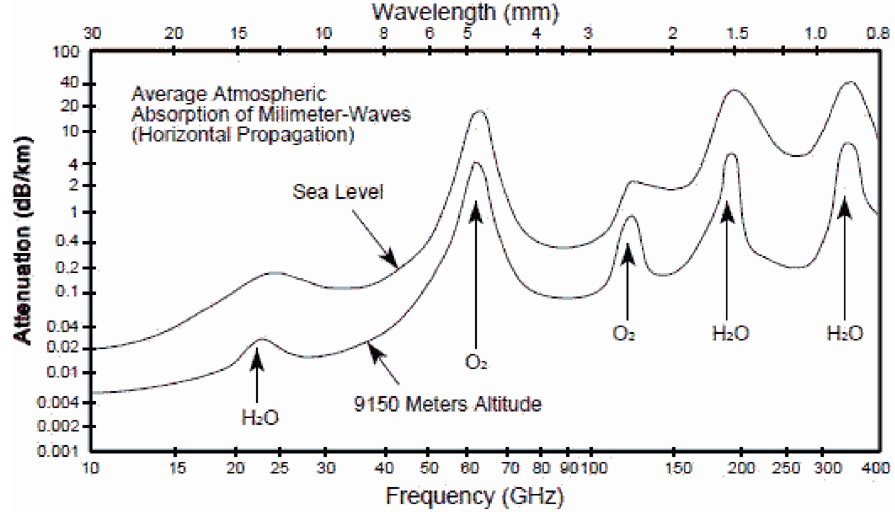
- Dir. + Omni.: <2m
- Dir. + dir.: <50m

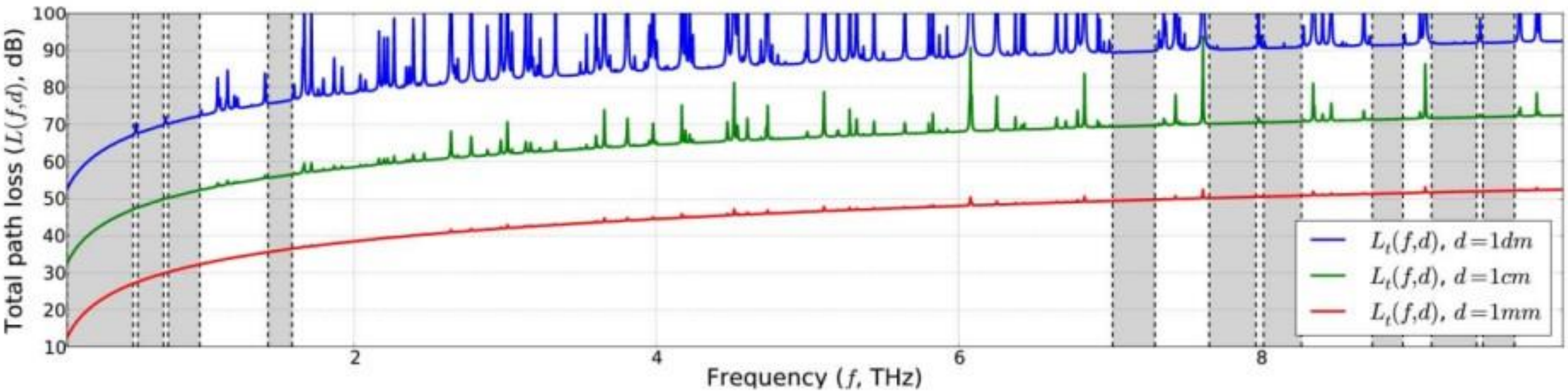
Antenna arrays needed!

Keep frequency as low as possible

Atmospheric absorption

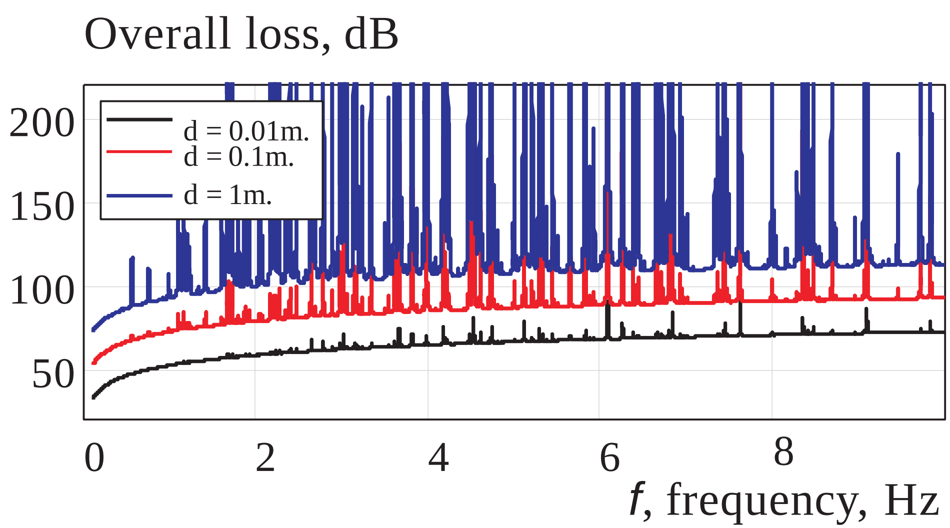
- Much higher than at millimeter wave
  - mmWave – oxygen
  - Terahertz – water vapor





➢ ***Additional losses!***

Transparency windows



First window!!!

Number	Range	Bandwidth	Pulse duration
1	0.10 – 0.54 THz	440 GHz	1.48 ps
2	0.63 – 0.72 THz	95 GHz	6.53 ps
3	0.76 – 0.98 THz	126 GHz	4.92 ps
4	7.07 – 7.23 THz	160 GHz	2.59 ps
5	7.75 – 7.88 THz	130 GHz	3.88 ps

Channel model

- Path loss

$$L_T(f,d) = L_P(f,d) + L_A(f,d)$$

First path – Friis model

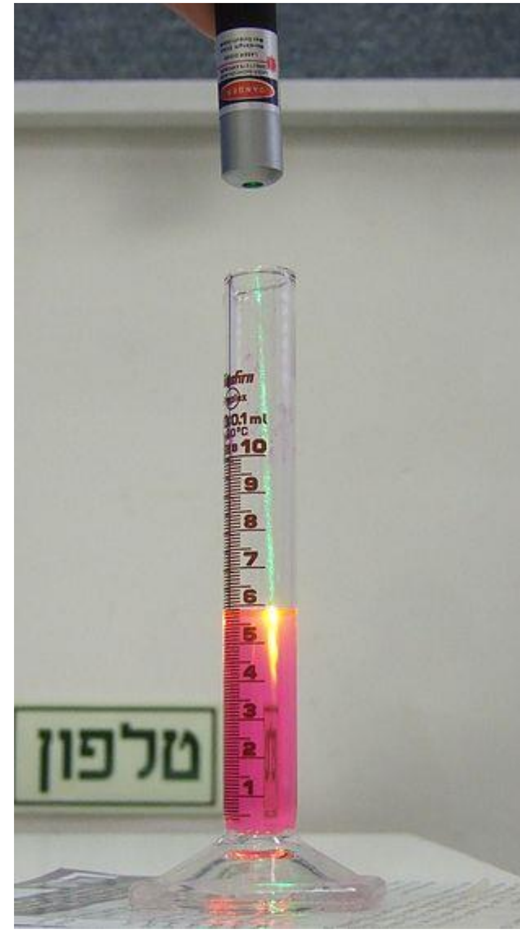
$$L_P(f,d) = \left(\frac{4\pi d f}{c}\right)^2$$

- Atmospheric absorption
  Coefficients from HITRAN database

$$L_A(f,d) = \frac{1}{\tau(f,d)} \qquad \tau(f,d) = e^{-k(f)d} = e^{-\sum_{G,I} k_{G,I}(f)d}$$

τ - transmissivity (Booger-Lambert-Beer law)

$$\boxed{P_{Rx_0} = A r_0^{-2} e^{-K r_0}}$$



Difference compared to mmWave

Common:

- ❑ Blockage

Different:

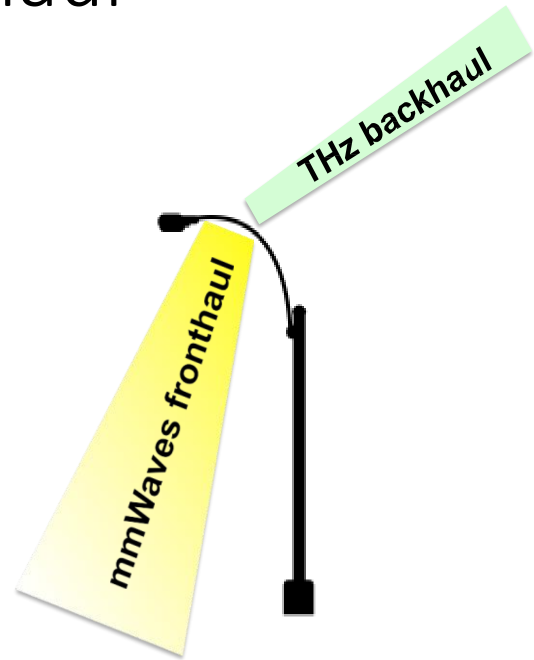
- ❑ Antenna arrays naturally required
- ❑ Extreme directivity needed ($<1^{o}$)
- ❑ Signal fades away much quicker (exponent)

What else? Extreme directivity induces additional problems…

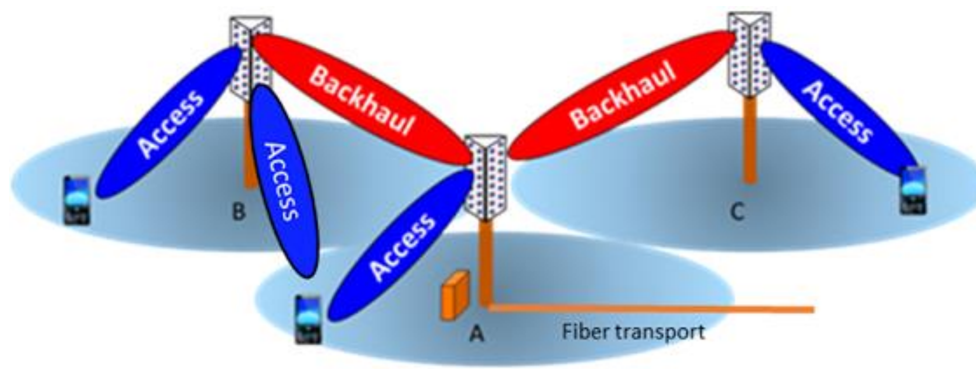
Applications

Macro: THz access and backhaul

- Backhaul rate >> access rate
  - Range 275-325GHz
  - Static channels
  - Beamalignment at installation
  - Low interference



- 3GPP Rel. 16
  - IAB technology
  - Microwave + mmWave
  - mmWave + THz



Macro: 100 Gbps access

THz last meter access in 275-325GHz

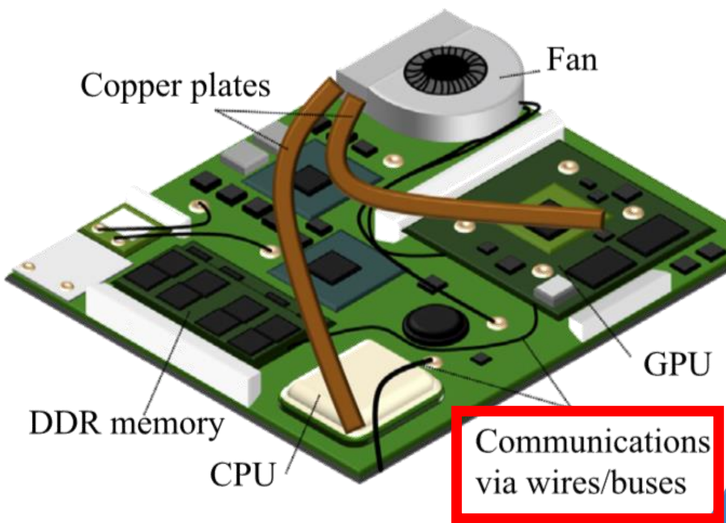
"Last Meter Indoor Terahertz Wireless Access: Performance Insights and Implementation Roadmap," to appear in IEEE Communications Magazine, 2018.

Macro: Data kiosk

- Get 1-2 Tbyte in 250ms
- Usage is similar to NFC
- Already implemented by NTT DoCoMo (IEEE 802.15.3d)

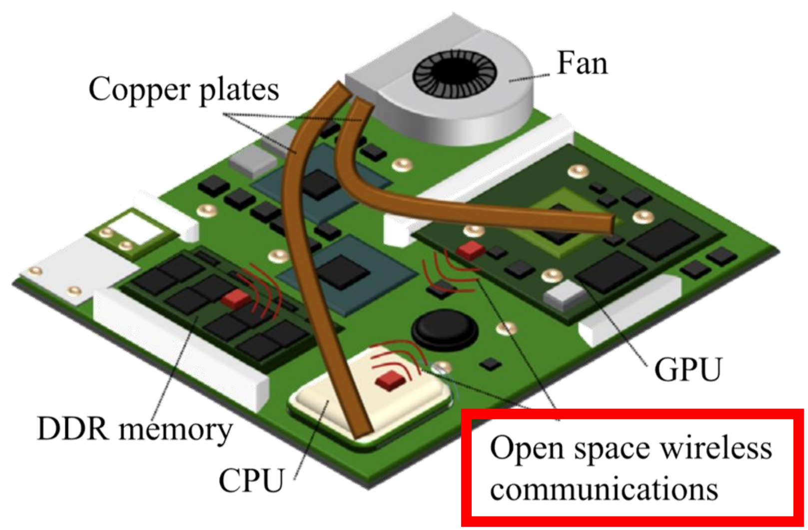
Petrov, V., & Kürner, T. (2020). IEEE 802.15. 3d: First Standardization Efforts for Sub-Terahertz Band Communications towards 6G. *arXiv preprint arXiv:2011.01683*.

Micro: board-to-board (B2B)



Classic way:

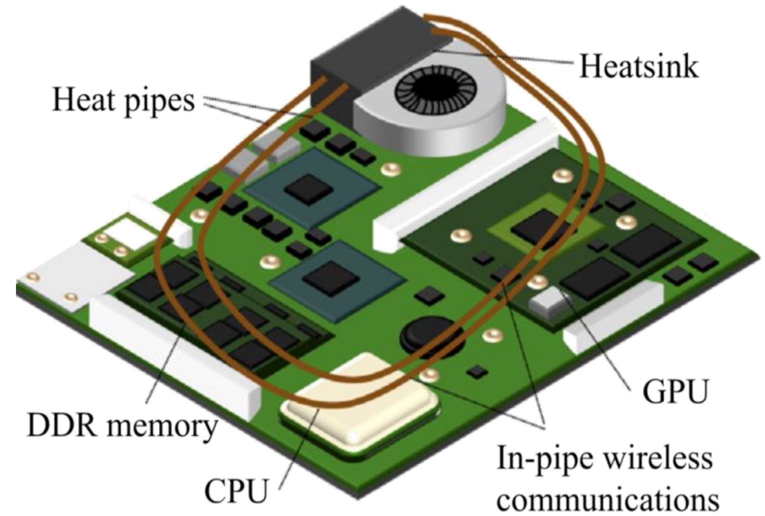
+ Simple
- Scalability
- Expensive



Alternative approach

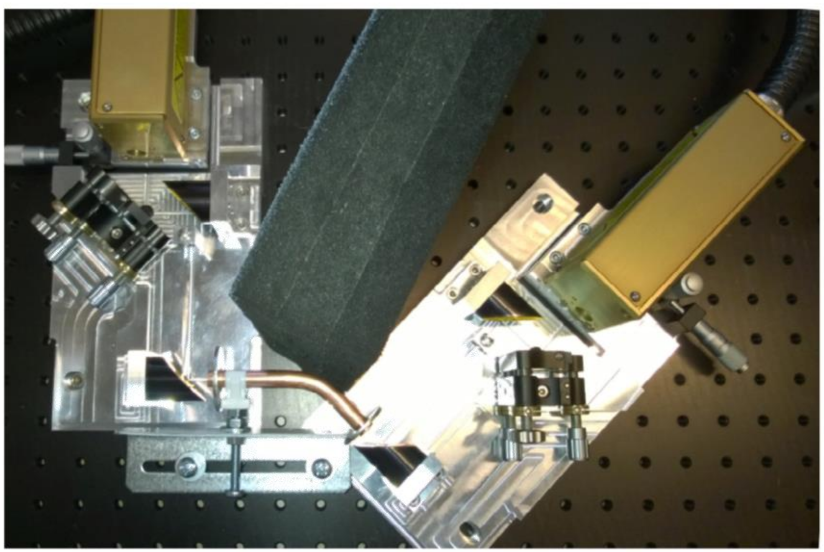
+ Scalability
+ Cheap
- Complexity
- Interference

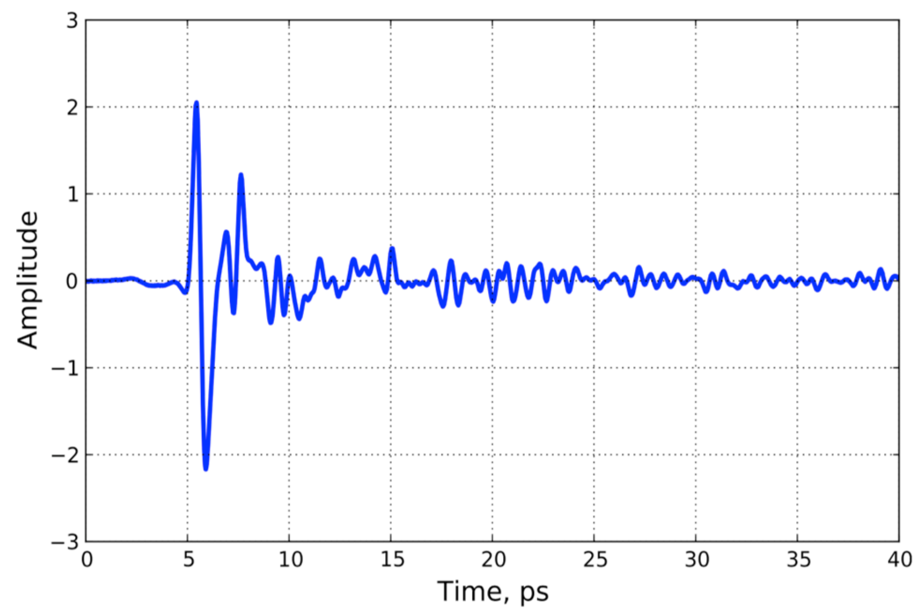
B2B: one more alternative



Mixed approach

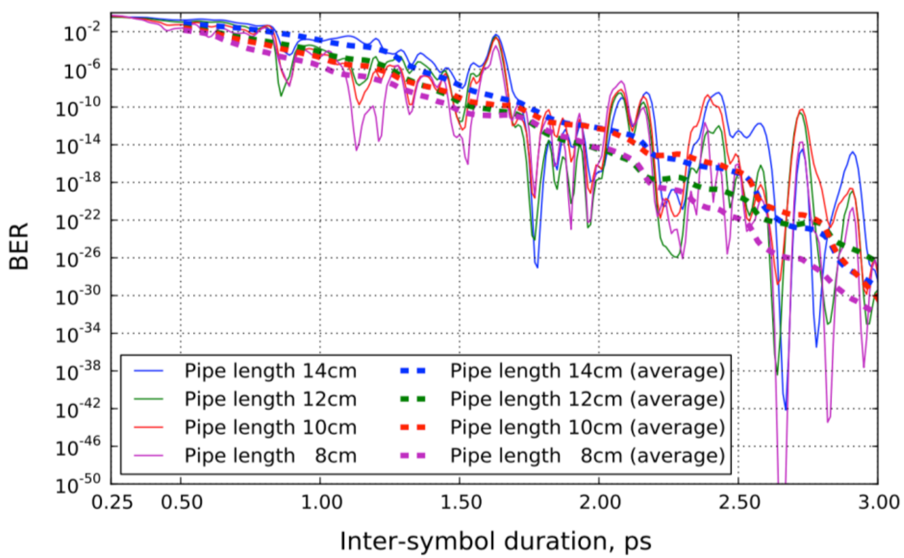
- Tubes for cooling
- Minimizing interference

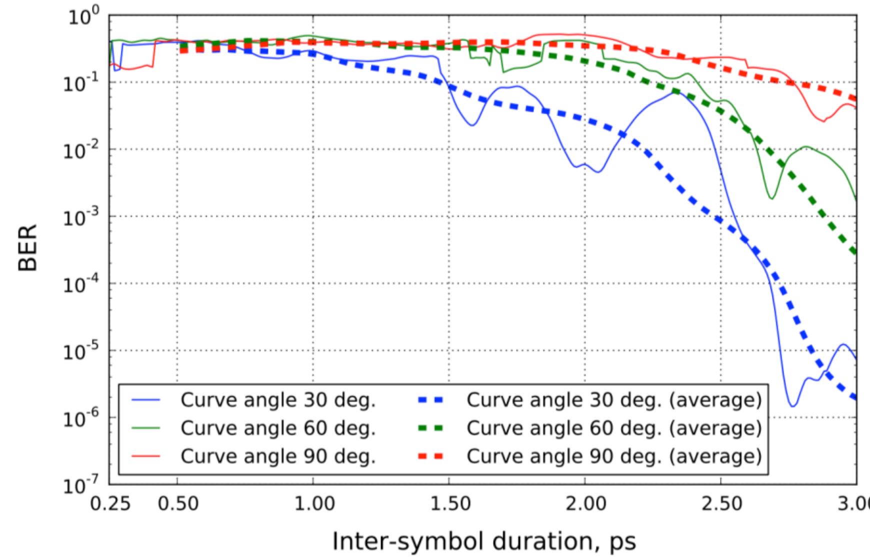


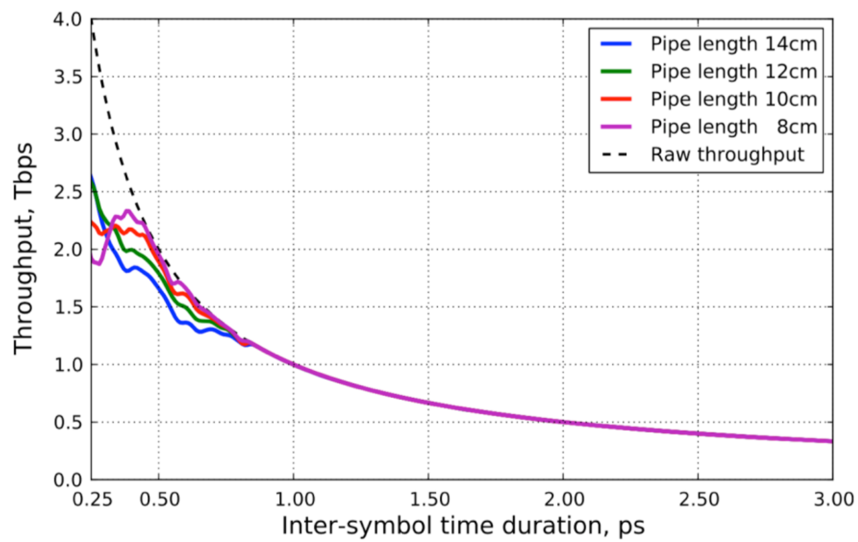


Petrov, V., Kokkoniemi, J., Moltchanov, D., Lehtomäki, J., & Koucheryavy, Y. (2017). Enabling simultaneous cooling and data transmission in the terahertz band for board-to-board communications. Physical Communication, 22, 9-18.

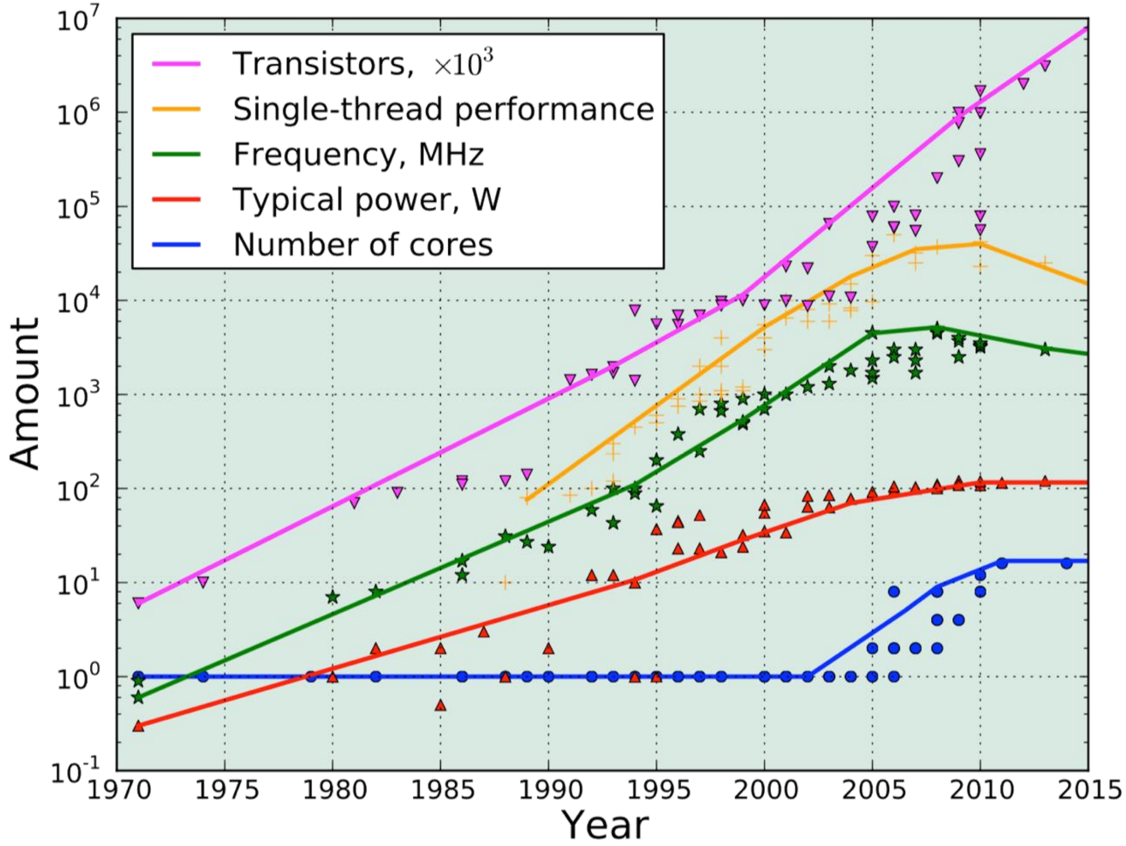
B2B: PER and rate







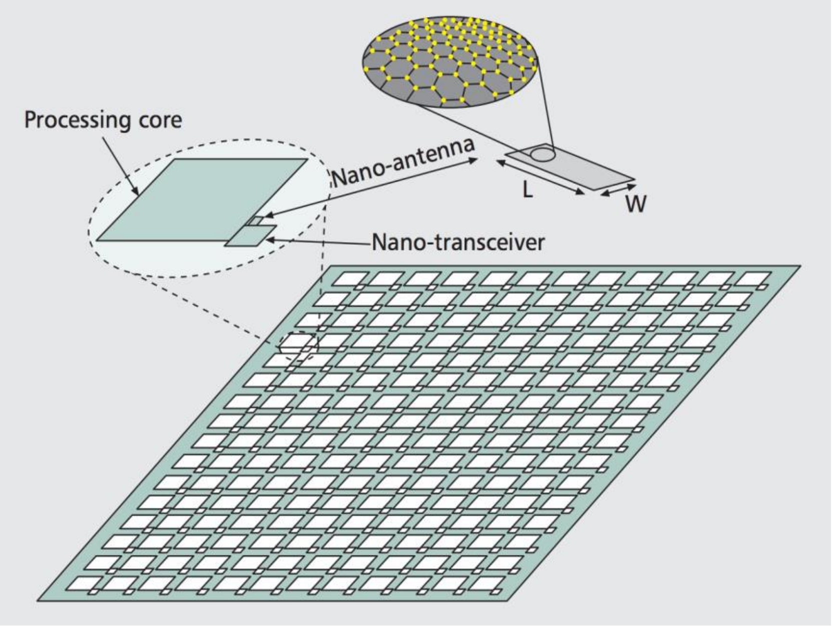
Micro: networks-on-chip (NoC)



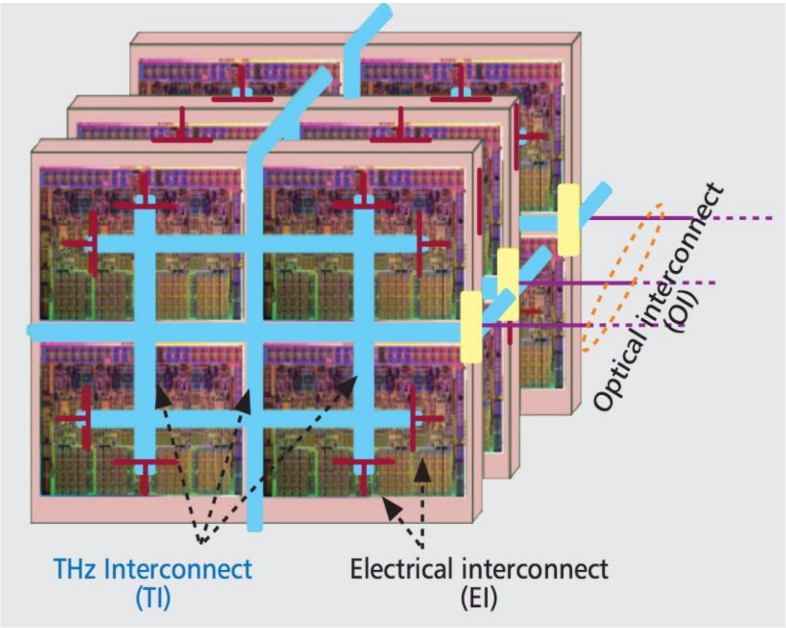
Most parameters expect for number of cores and technology plateaued

Higher performance only increasing the number of cores (AMD Zen 1/2/3 Gen.)

NoC: designs (core-cache design)



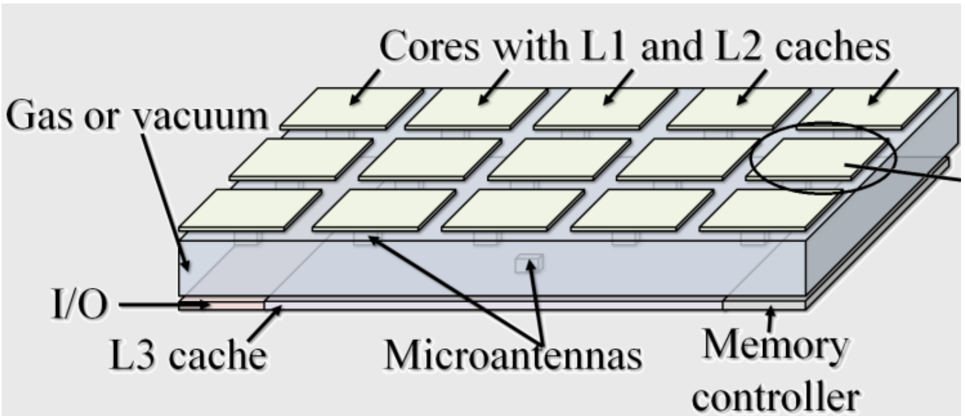
S. Abadal et al., "Graphene-enabled wireless communication for massive multicore architectures," IEEE Communications Magazine, 2013.



Q. J. Gu, "THz interconnect: the last centimeter communication," in IEEE Communications Magazine, 2015

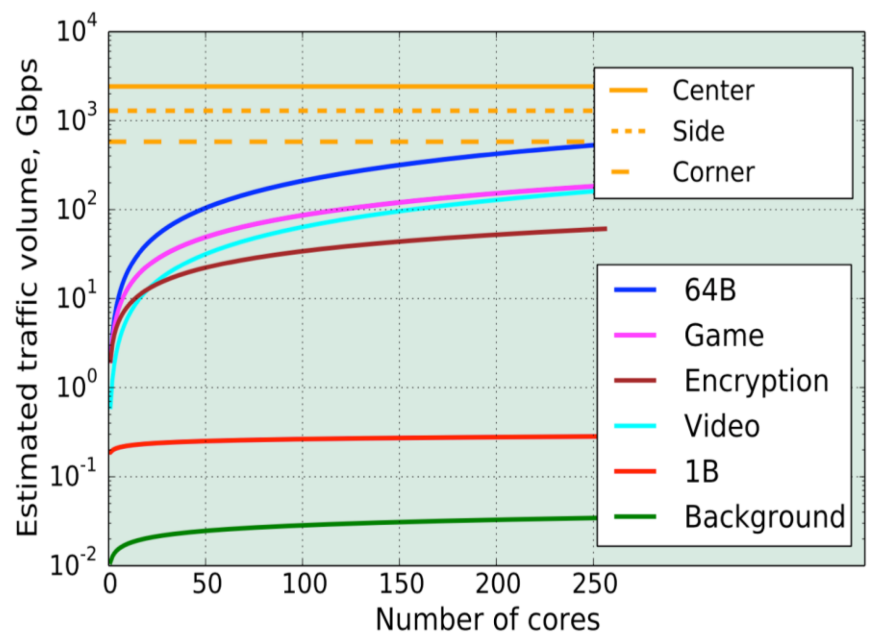
AMD Infinity Fabric….

Capacity scaling



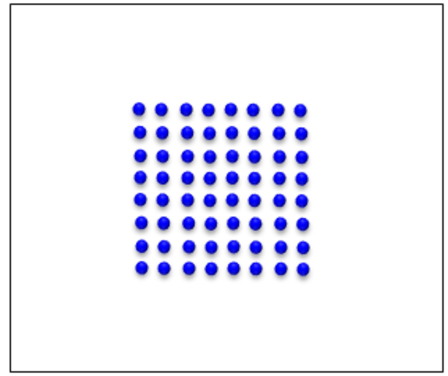
3D x86 design with external 3rd level cache and THz comm

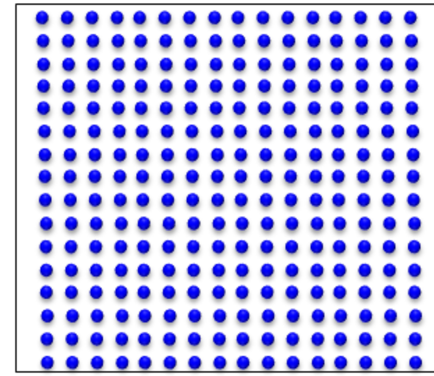
Up to 250 cores

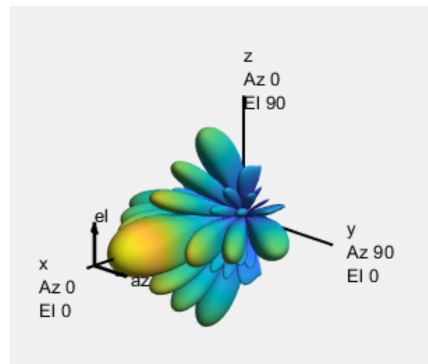


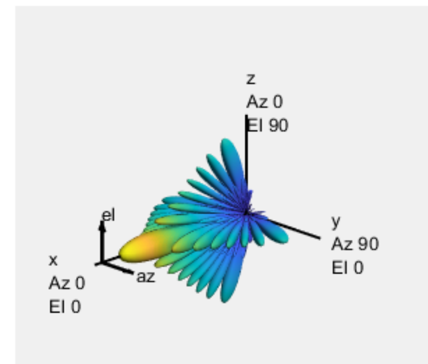
Addressing challenges: micromobility

Micromobility effects









Extra-massive antenna arrays

- Compensating for path loss
- Avoiding overheating
- Comes naturally!

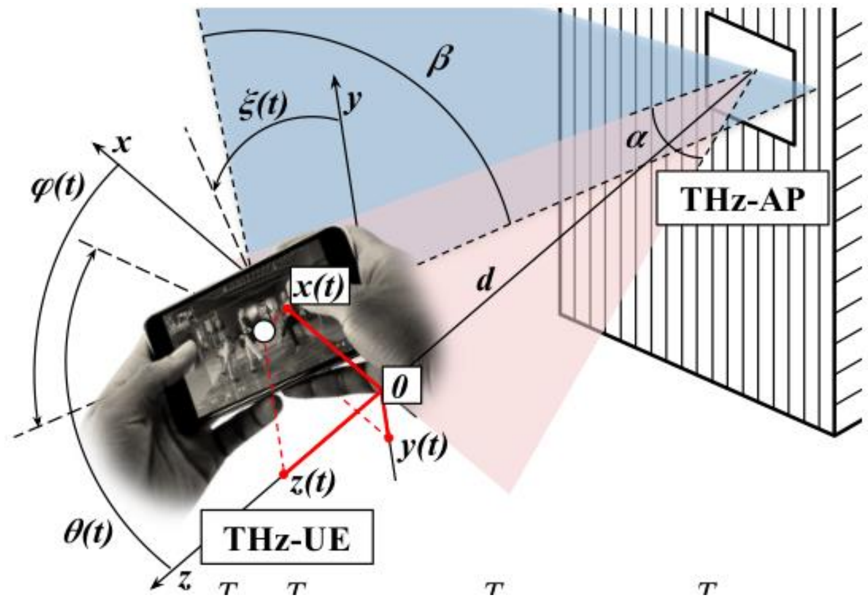
- Main lobe HPBW
  - ~120°/N
  - What if N=1024?
  - HPWB ~ 0.1° градуса

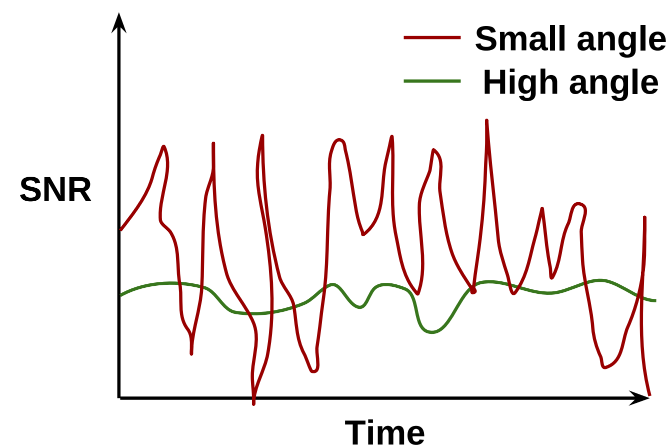
ANTENNA HPBW AND ITS APPROXIMATION

Array	**Value, direct calculation**	**Approximation**
64x1	1.585	1.594
32x1	3.171	3.188
16x1	6.345	6.375
8x1	12.71	12.75

Affecting components

- UE is mobile in nature
  - Macro-mobility
  - Micro-mobility
- Micromobility
  - Displacements along OX, OY, OZ
  - Vertical/horizontal rotations
- Small HPBW and micromobility
  - Small HPWB -> unstable
  - Large HPBW -> low rate

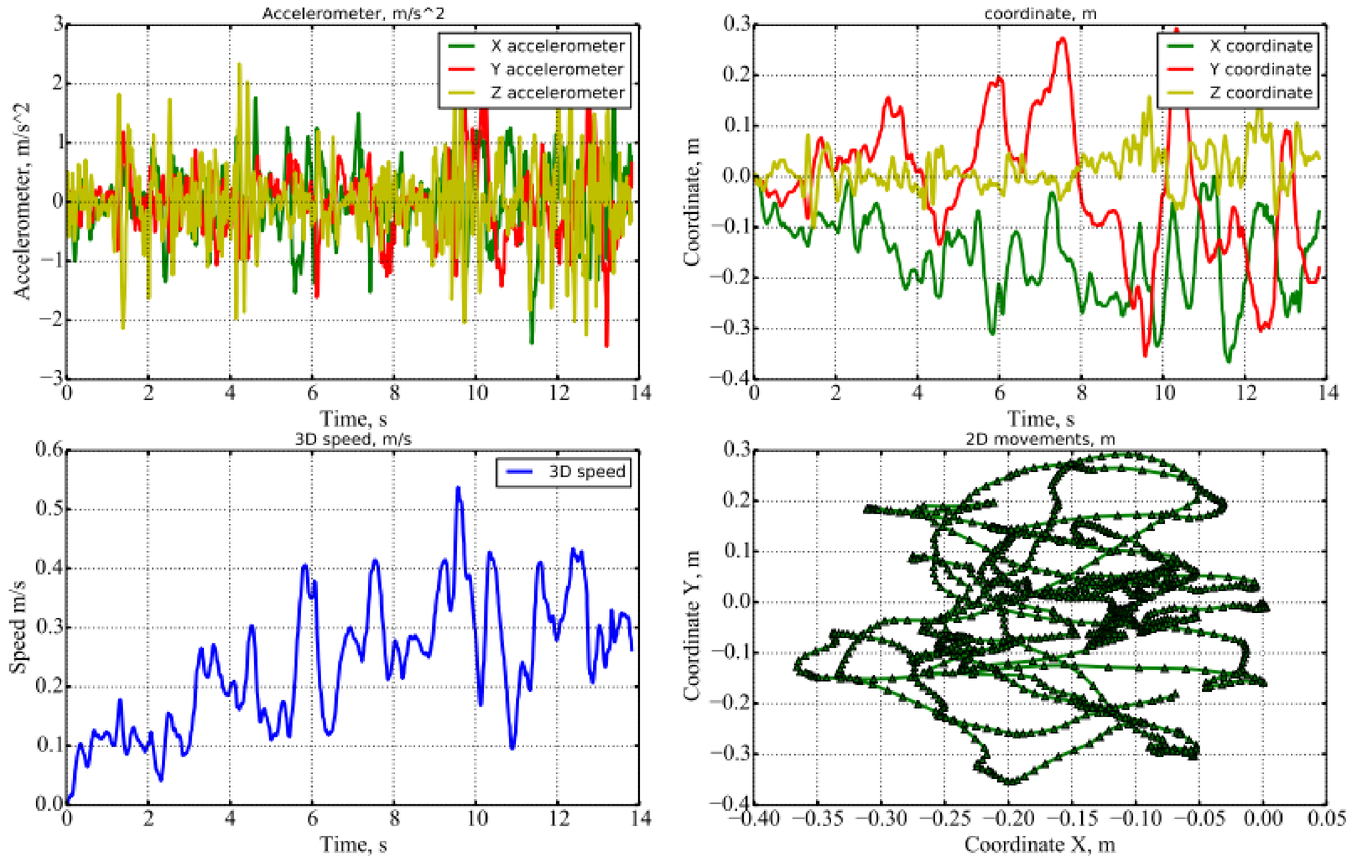




Micromobility: ball game on smartphone

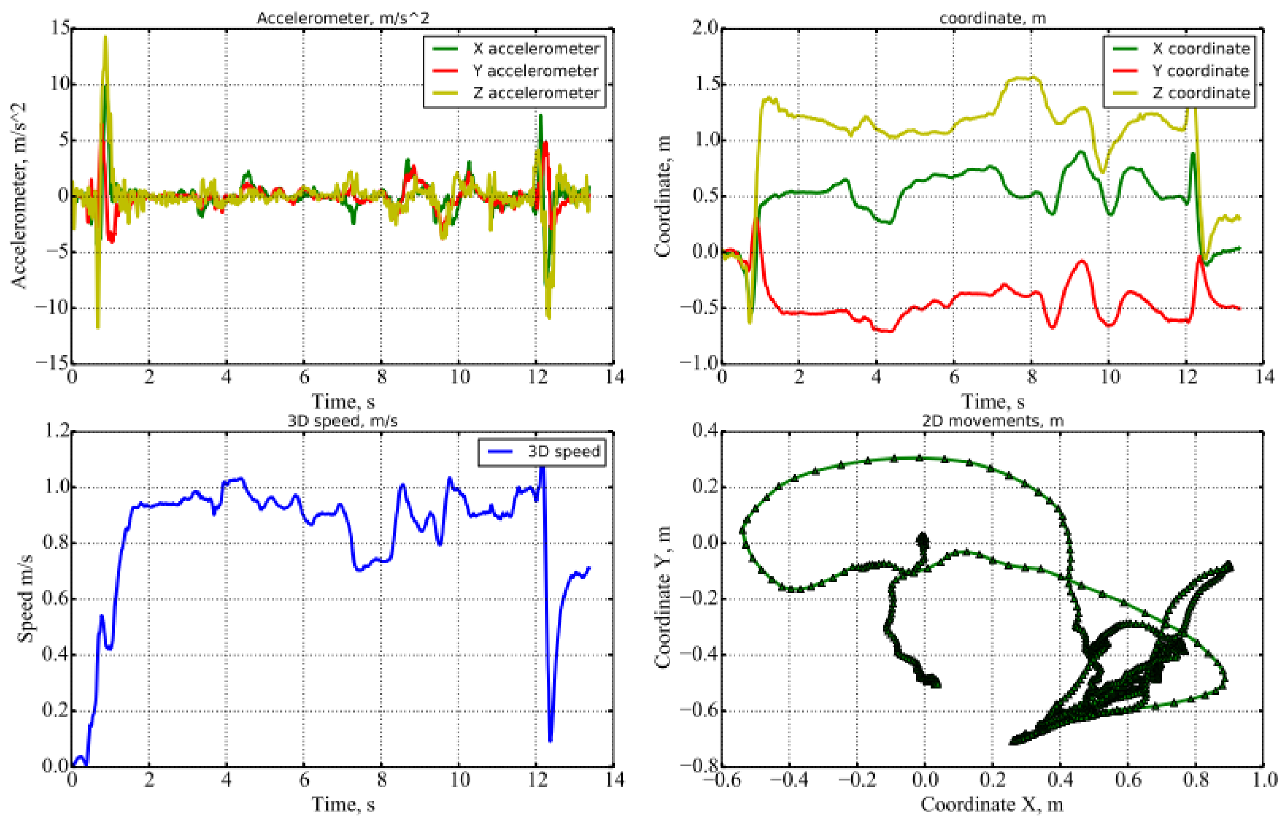
Observations

- ❑ Stochastic
- ❑ Three-dimensional

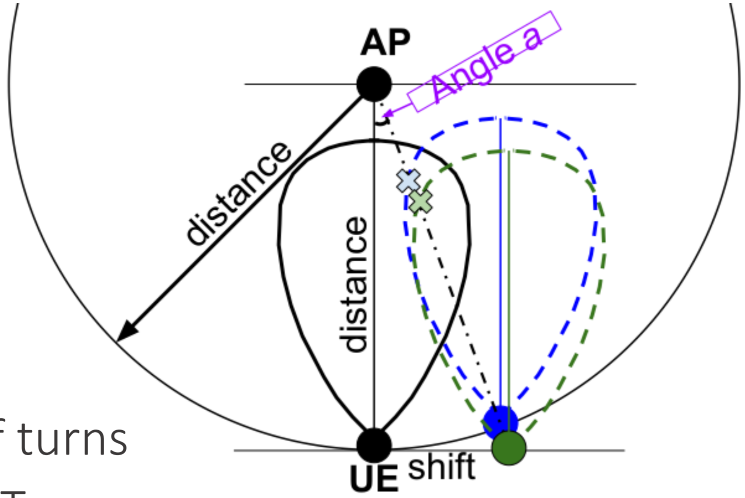


Micromobility: ongoing call

Add. observations:
- ❑ Depends on app
- ❑ Many parameters
- ❑ Complex process



Methodology

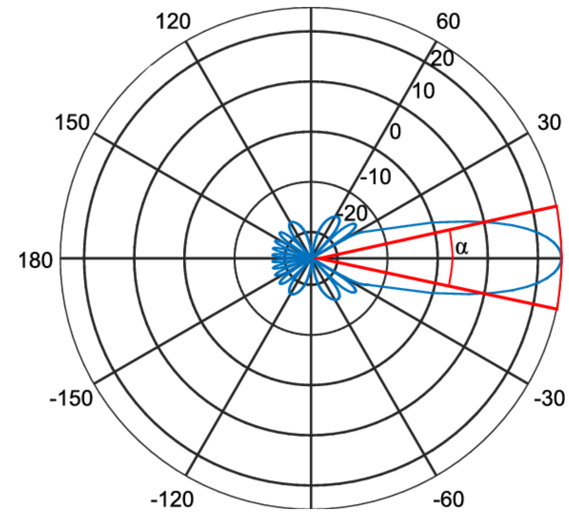


Proposal:

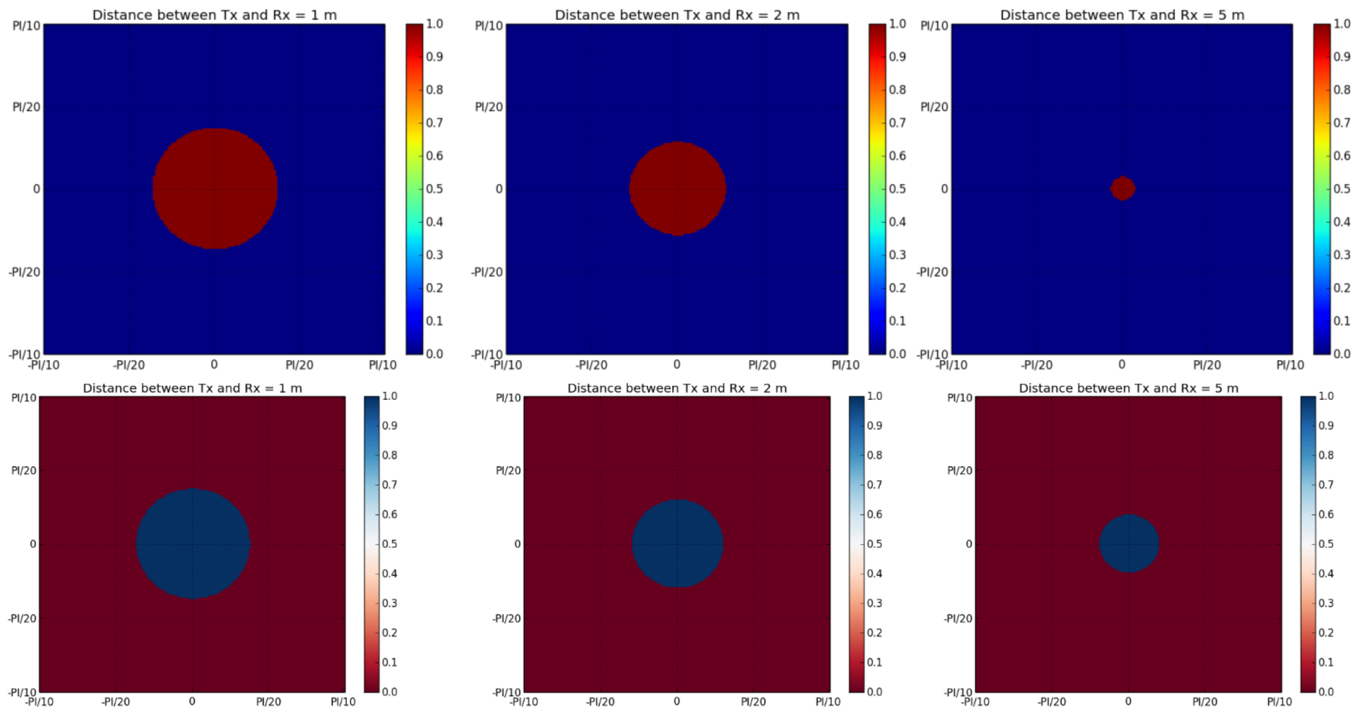
- ❑ Geometric interpretation
  - ❑ Random walk for each axis and type of turns
  - ❑ Joint them together to characterize FPT
  - ❑ Random walks are complex
  - ❑ **Reducing 3D to 2D, or even to 1D if possible**
- ❑ Determine beamsearch procedure
  - ❑ When to start searching?
  - ❑ Search regularly? How often?
  - ❑ Any other solutions?

Petrov, V., Moltchanov, D., Koucheryavy, Y., & Jornet, J. M. (2020). Capacity and Outage of Terahertz Communications with User Micro-mobility and Beam Misalignment. IEEE Transactions on Vehicular Technology.

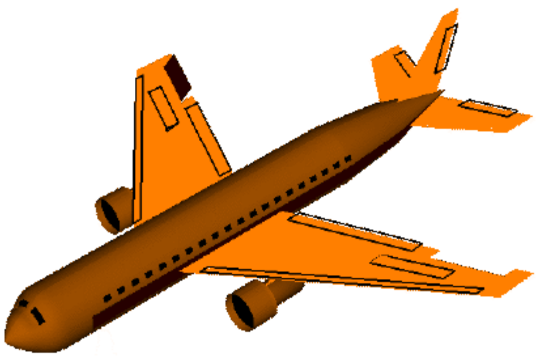
Displacements: dX, dY, dZ



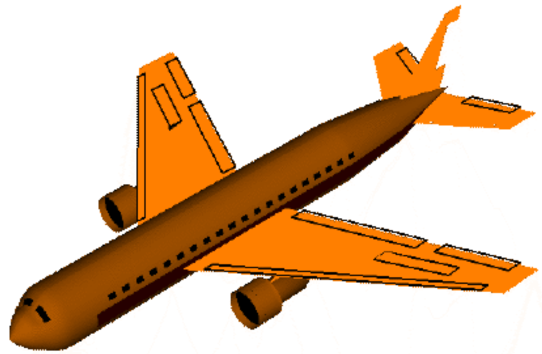
- Cone main lobe model
- Affects insignificantly
- dZ can be excluded



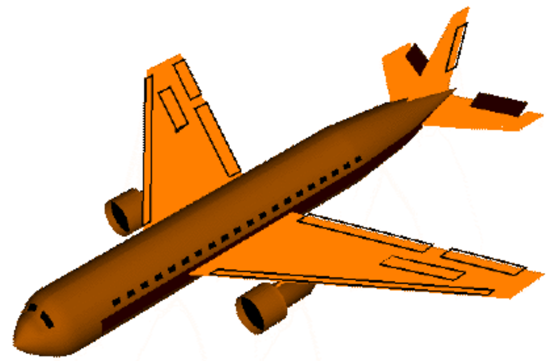
Effect of rotations: dζ, dθ and dϕ



Roll, dζ, (крен)

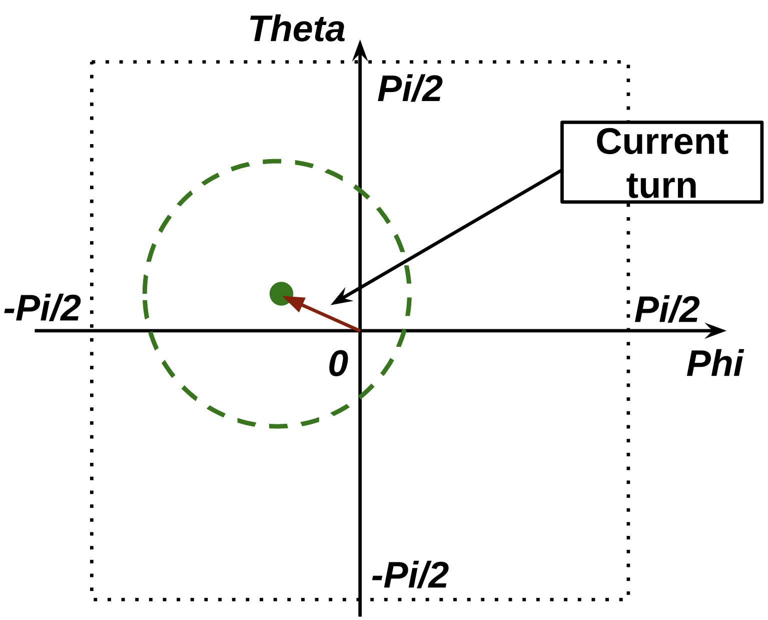


Yaw, dθ, (рыскание)



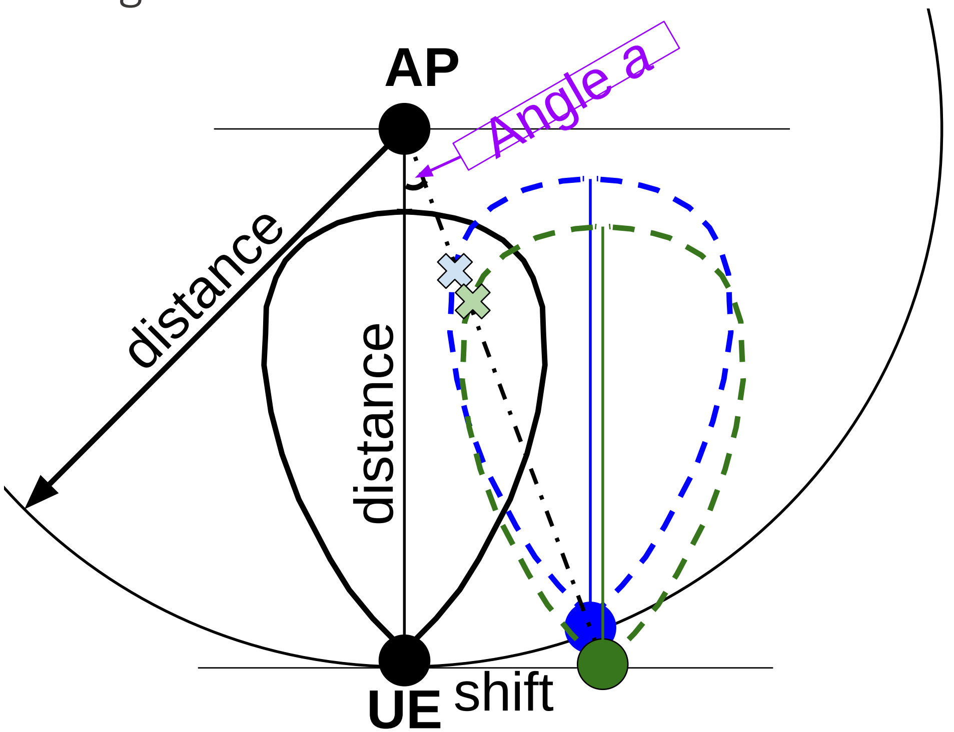
Pitch, dϕ,(тангаж)

- ❑ Interpretation of motions depends on where antenna is mounted at UE
- ❑ Roll does not affect
- ❑ Radius remains roughly the same
- ❑ Centers moves (i.e. performs random walk)



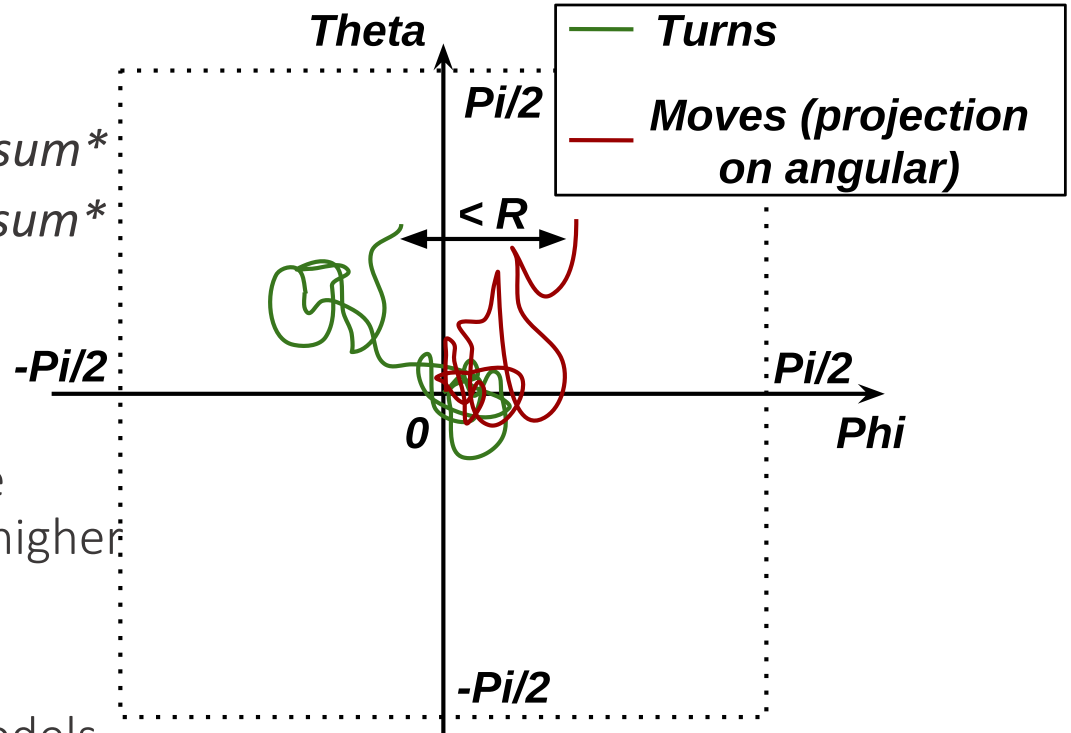
Effects of displacements: *dY*, *dX*

- Equivalent to rotations plus change of dZ
- **Observations:** moving from black dot to green one is equivalent to rotations from black dot to blue dot *and* increase of the distance (dZ displacement) from blue dot to green dot



Reducing dimensions

- From 3D to 2D
  - dθ *to dX and define its sum**
  - dϕ *to dY and define its sum**
  - Rotations (two)
  - Displacement (two)



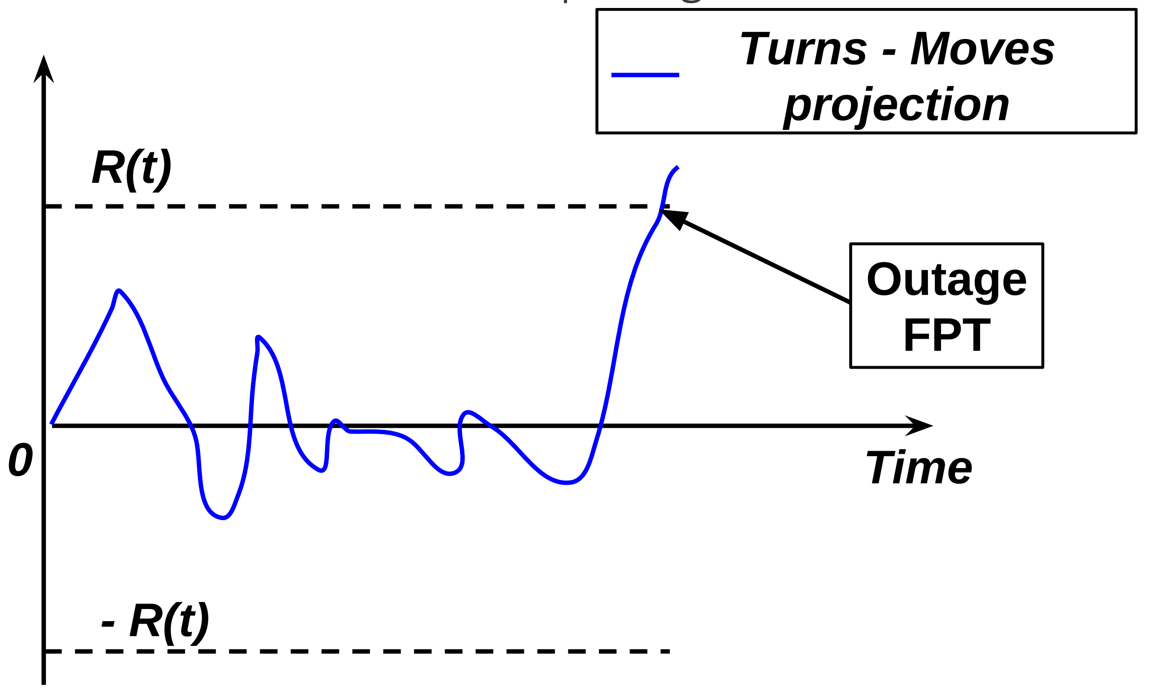
- **Outage:** when the distance between random walks is higher than *R* (*R* is half of HPBW)

- More complex antenna models can be defined (see, e.g., 3GPP TR 37.840)

*Why? sum of Brownian motions is again a Brownian motion.

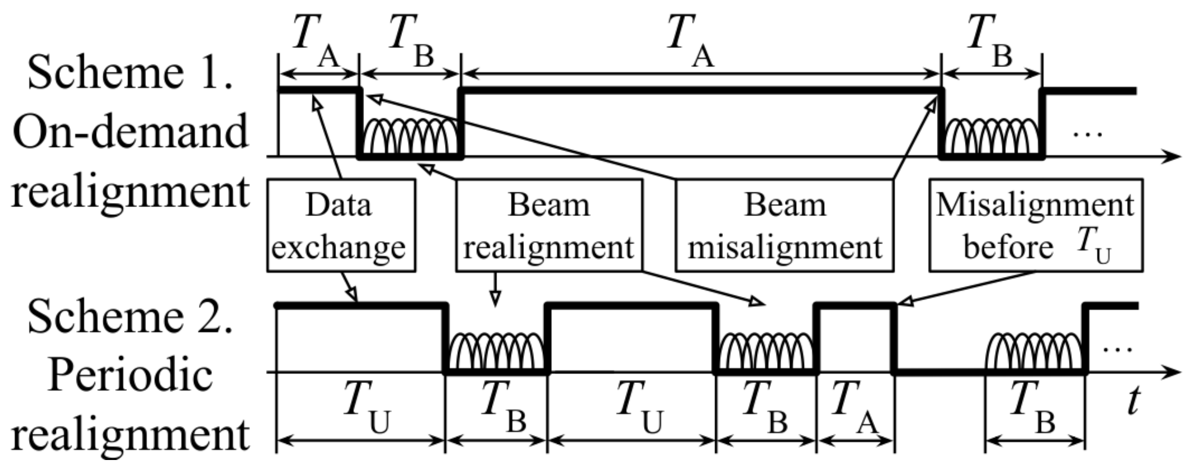
Time to outage

- From 2D to 1D
- Euclidean distance between random walks*
- We need to determine FPT – first passage time



*Distance between two 2D Brownian motions is Bessel process of order 2

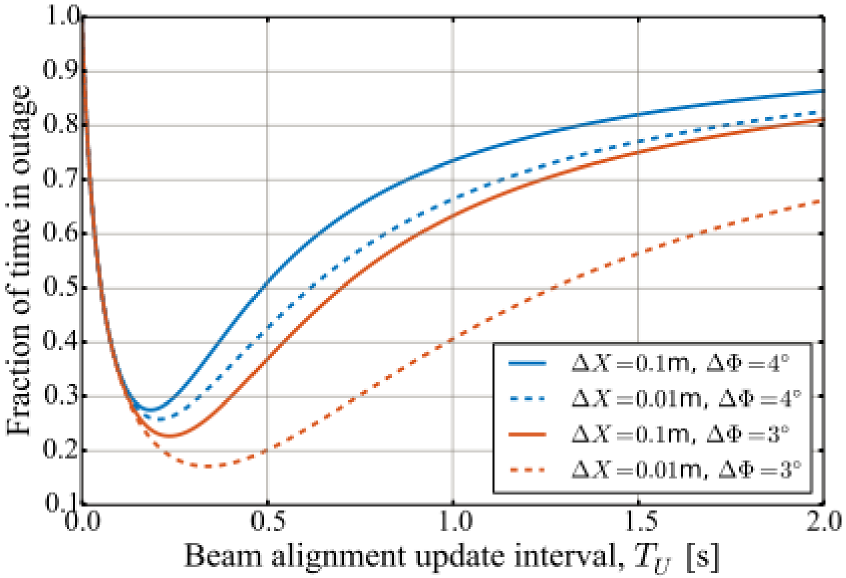
Beamforming schemes

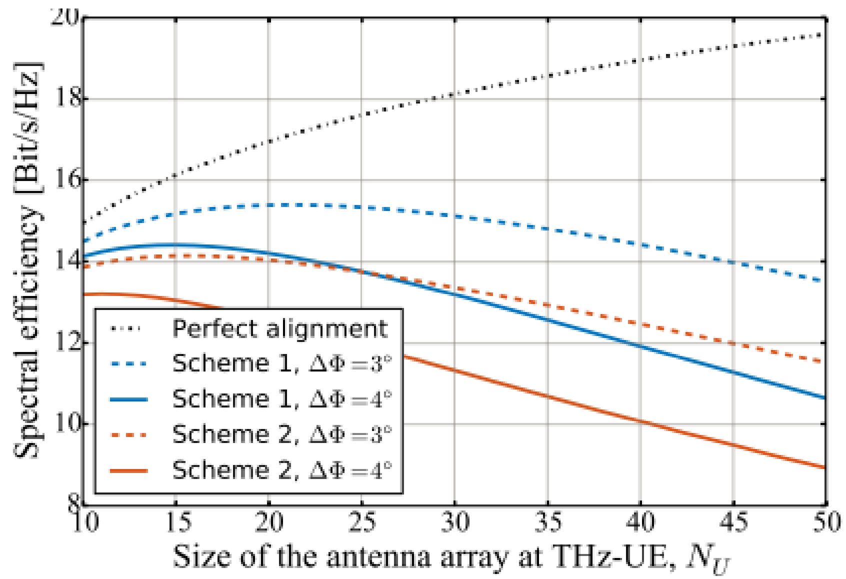


- T_A – connectivity time (time to outage)
- One-demand search (WiGig style 11ad/ay):
- Periodic search: T_U – period (searching based on min(T_A, T_U))
- T_B – time to search – depends on (i) the number of antenna configurations at both sides (antenna elements), (ii) array switching time (~2µs or less), and (iii) type of search (hierarchical, full search)

Results [1/3]

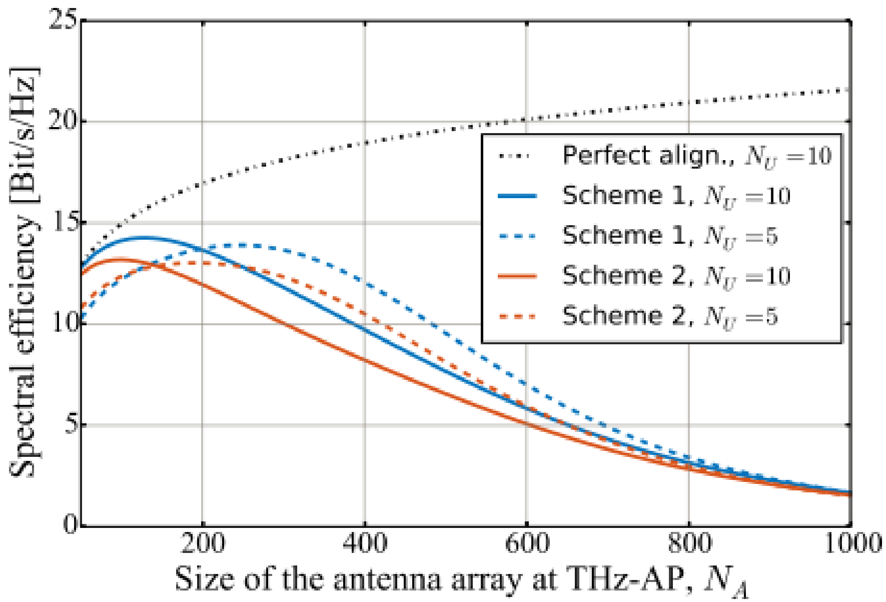
- f=0.3THz, B=50GHz, P_A=23dBm, δ=5μs

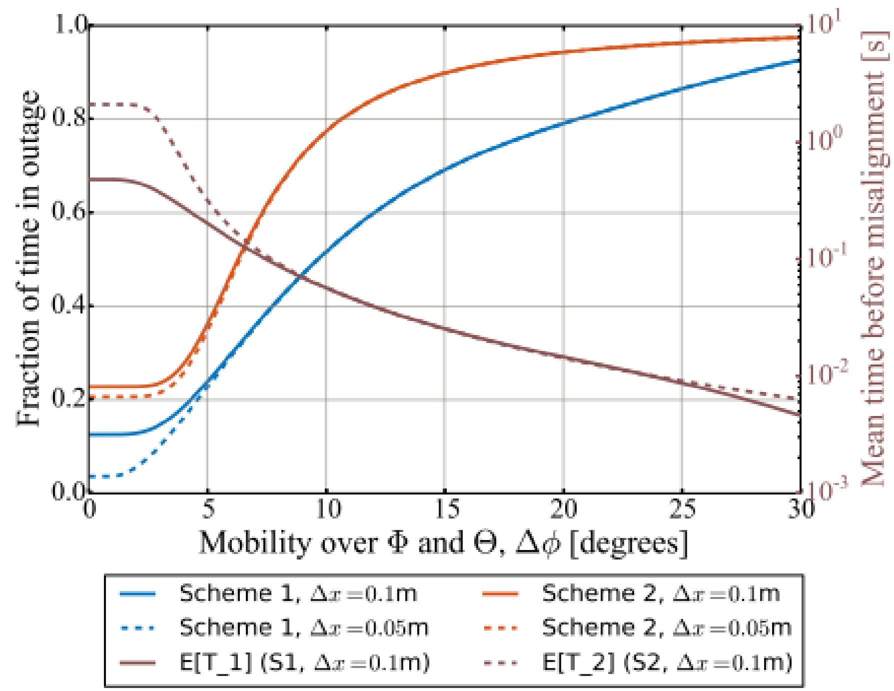




Results [2/3]

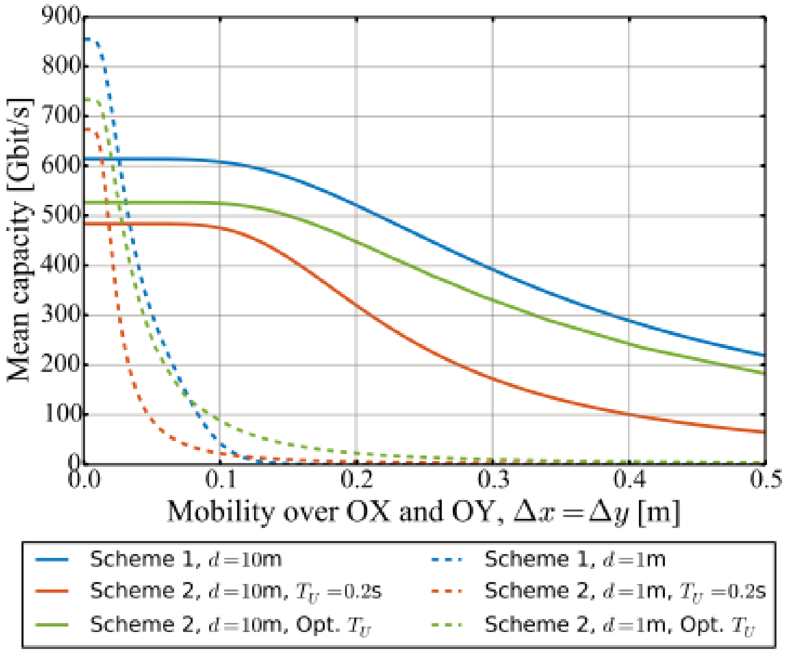
- f=0.3THz, B=50GHz, P_A=23dBm, δ=5μs

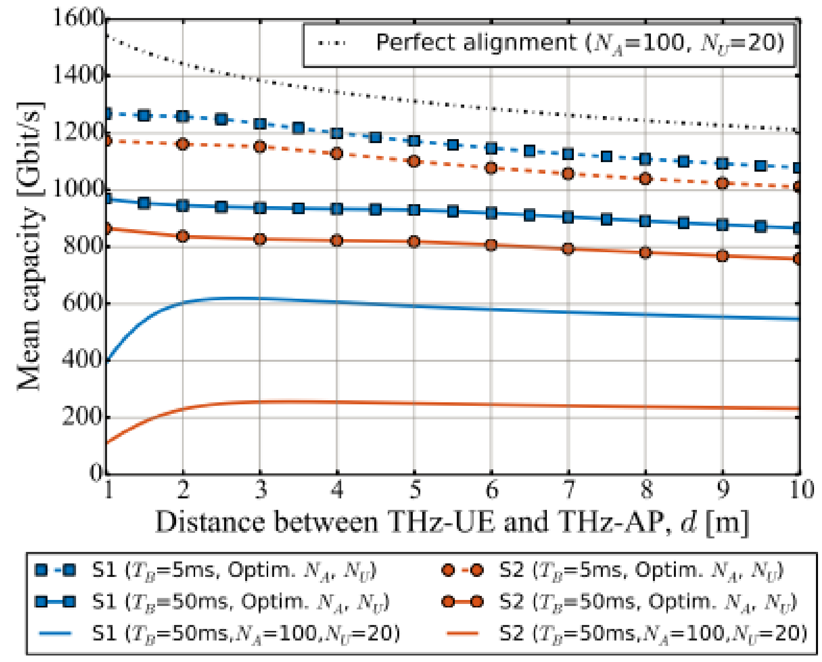




Results [3/3]

- f=0.3THz, B=50GHz, P_A=23dBm, δ=5μs





Addressing challenges: eavesdropping

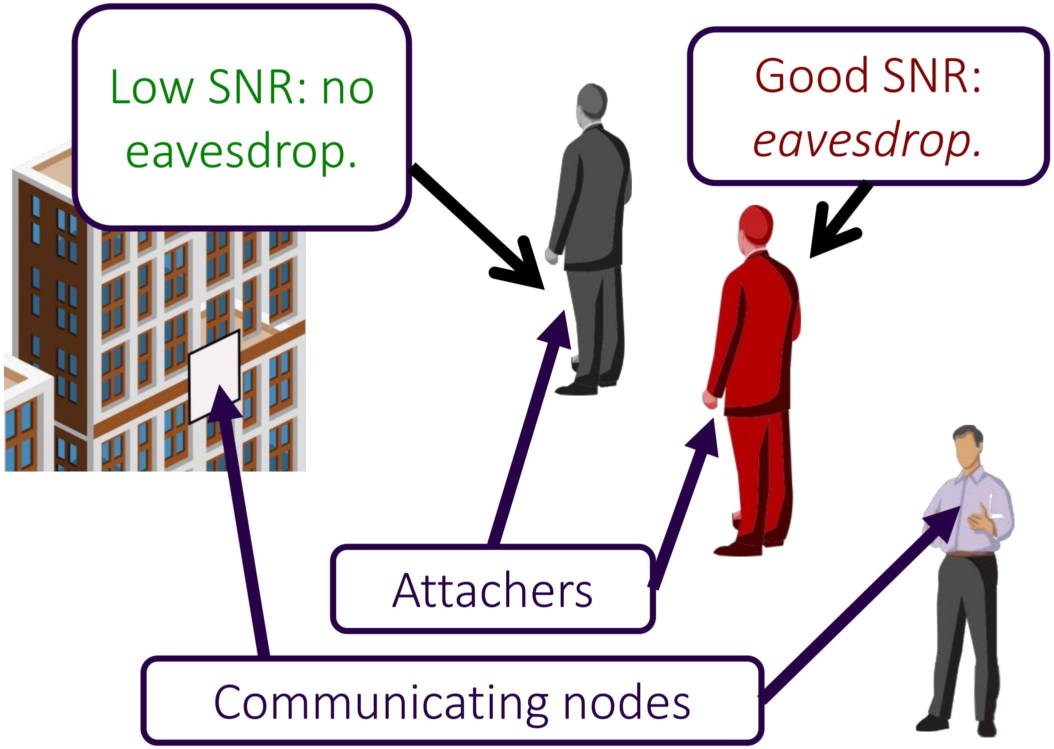
Physical layer security

Ideas at the glance:

- ❑ Secure at PHY

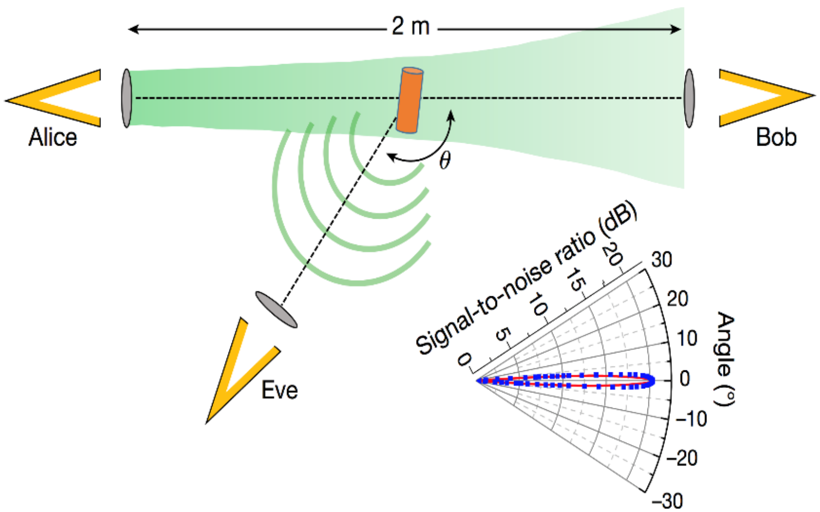
Applications:

1. Specific secure systems
2. Military systems
3. *Cellular?*



One more measure in addition to encryption!

Physical layer security in THz



Not new as a concept:

1. Directionality greatly helps
2. Still eavesdropping is possible
3. Demonstrated in [1]

[1] J. Ma, R. Shrestha, J. Adelberg, C.-Y. Yeh, Z. Hossain, E. Knightly, J. M. Jornet, and D. M. Mittleman, “Security and Eavesdropping in Terahertz Wireless Links,” Nature, November 2018.

Eavesdropping feasible in spite of high directionality!

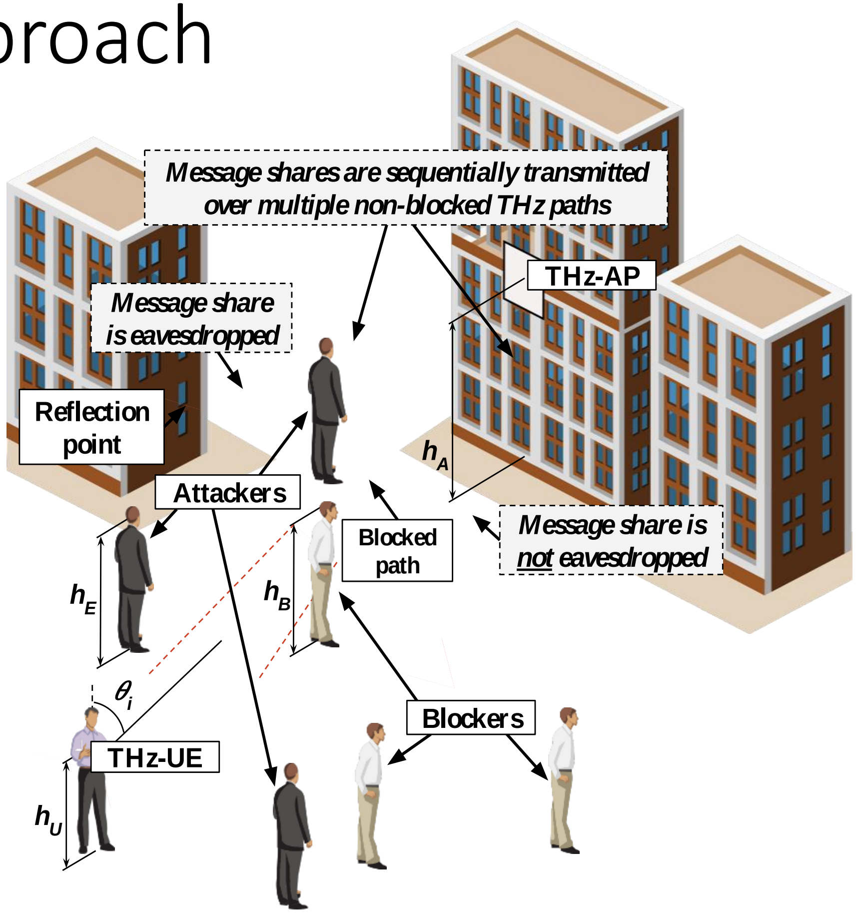
More comprehensive approach

Idea at the glance:

- ❑ Exploit multi-path
- ❑ Fragment packets

Implementation:

1. Often at least 5 paths
2. Can be decoded when all parts have been received
   - Cypher block chaining (CBC)



Difficult to eavesdrop all paths simultaneously!

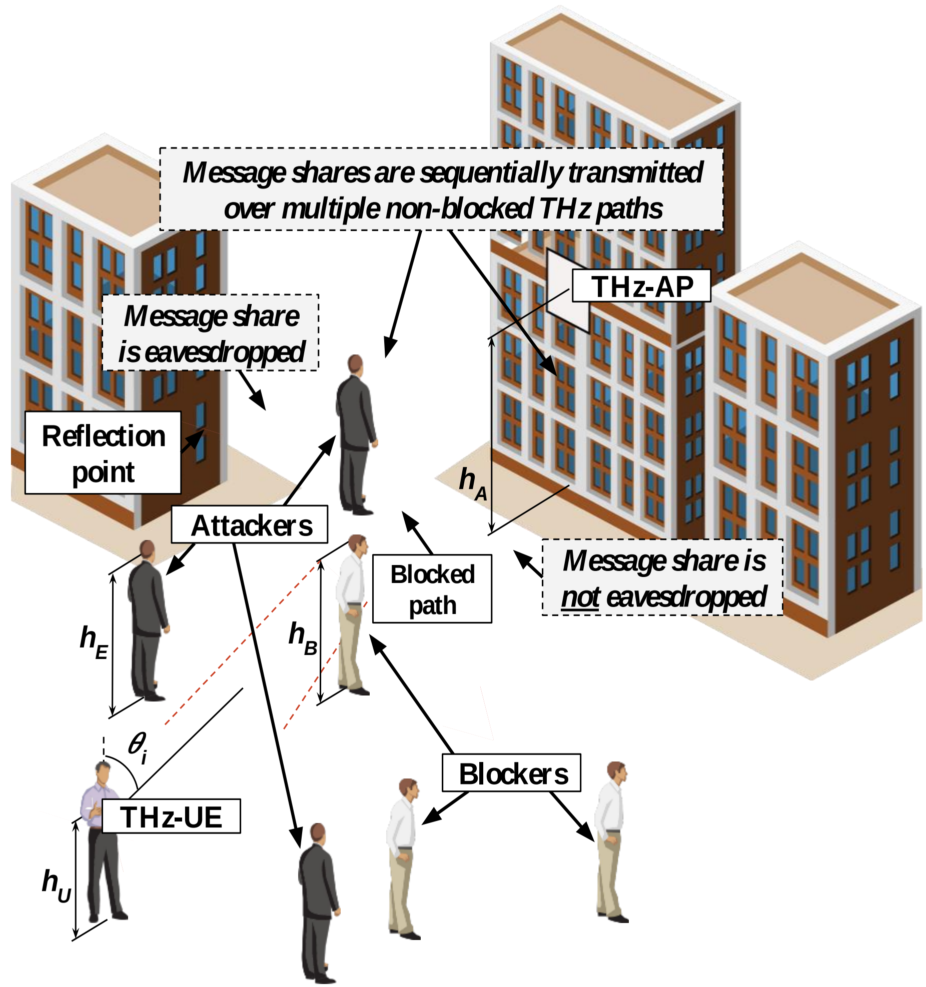
System model

The considered scenario:

1. One channel UE-AP, distance x
2. PPP UE [μ / m^2]
3. PPP of attackers [λ / m^2]

Considered schemes:

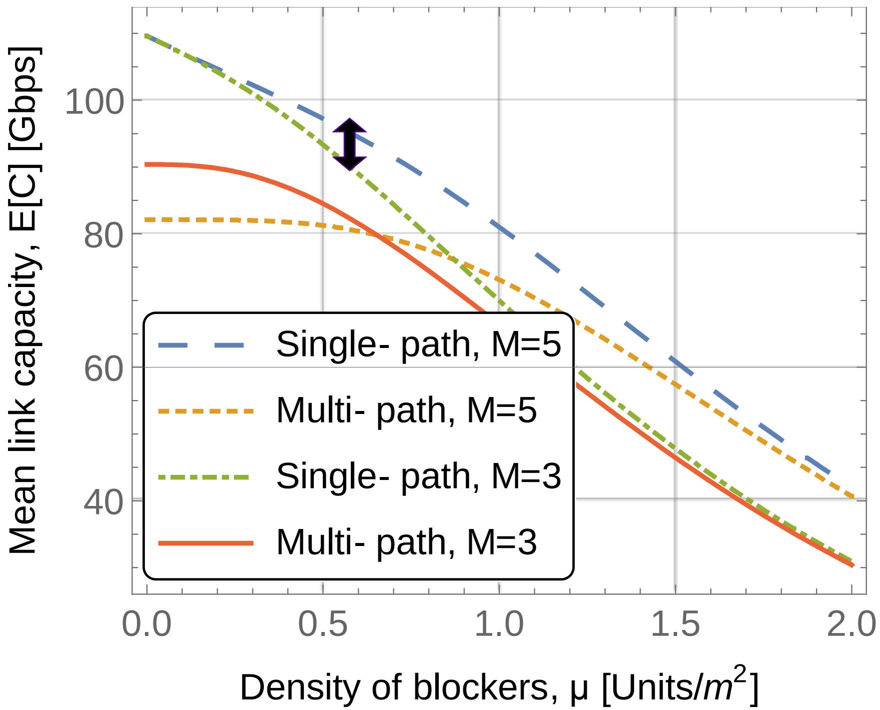
- ❑ *One path* $C\uparrow$, $p_E\uparrow$
  - Choosing the best
- ❑ *Multiple paths* $C\downarrow$, $p_E\downarrow$
  - Utilize all paths



Capacity

Observations:

1. Capacity decreases with density of blockers
2. Single path capacity gain is higher in sparse deployments
3. Multiple paths are worth from 5% to 20% (90 Gbit/s vs. 110 Gbit/s)

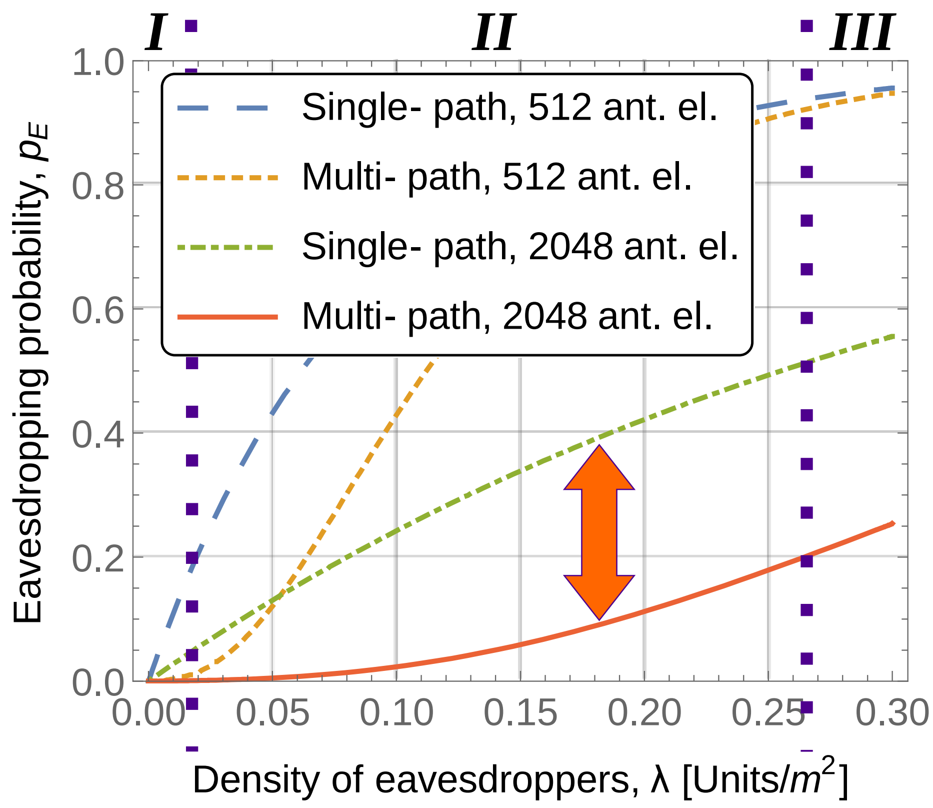


Capacity degradation is insignificant!

Eavesdropping probability

Observations:

1. Smaller HPBW ➔ smaller prob.
2. Three regimes:
   I. Both are good
   II. Multiple paths better
   III. Both are bad
3. Regime II, gives 5 times better p_E



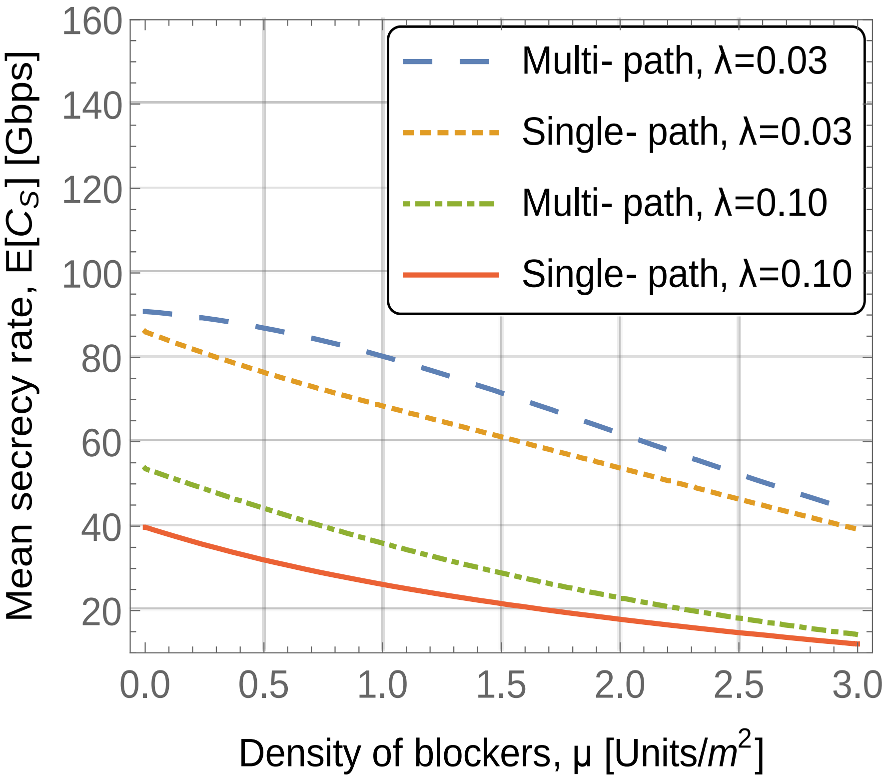
Multiple paths scheme is better!

Secrecy rate

Defined as: $C_S(x) = (1 - p_E)C(x)$

Observations:

1. More blockers ➔ smaller rate
2. More attackers ➔ smaller rate
3. Multiple paths better up to 40%



Multiple paths scheme has much better secrecy rate!