Feasibility Study of the THz Band for Communications between Wearable Electronics

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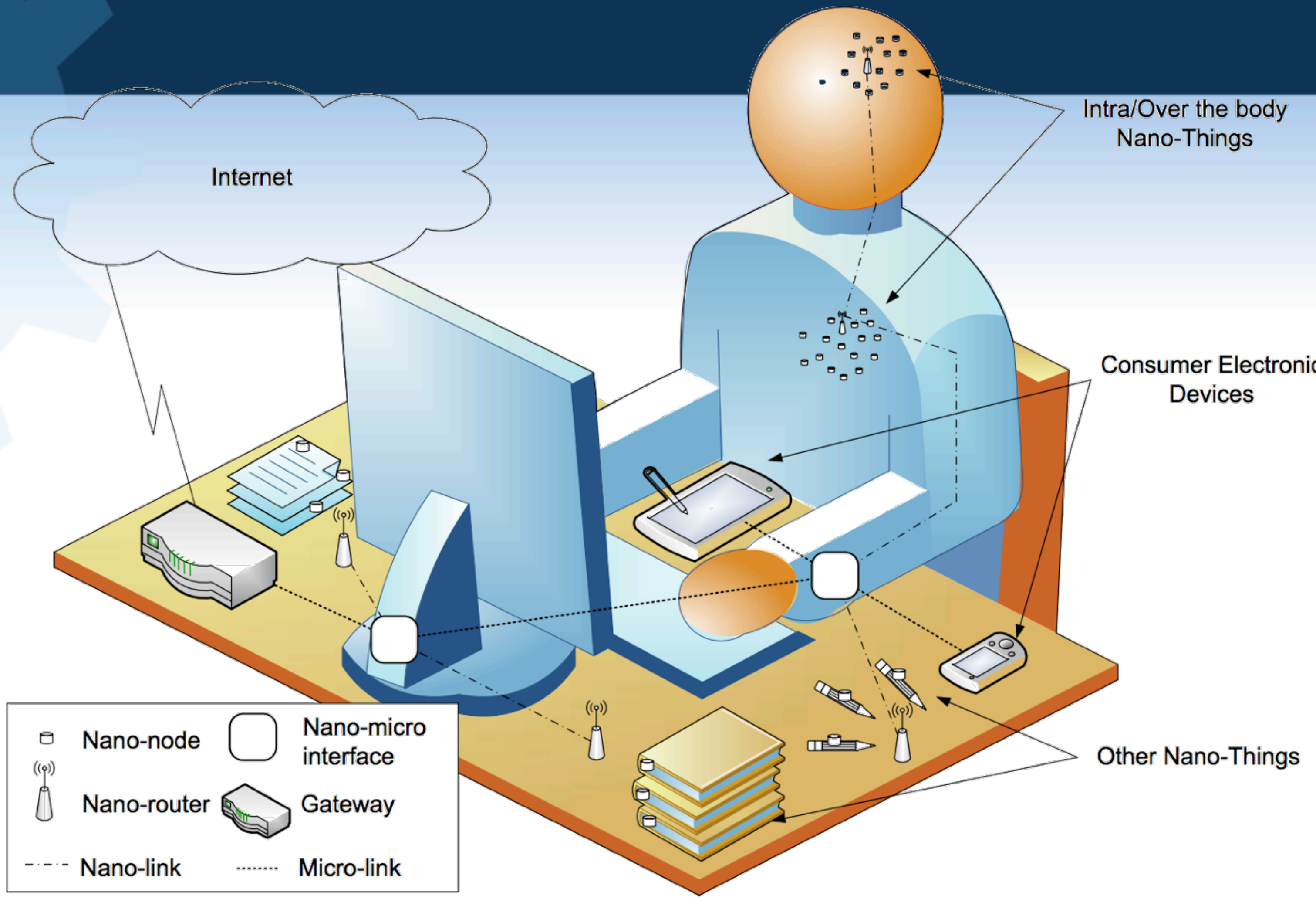
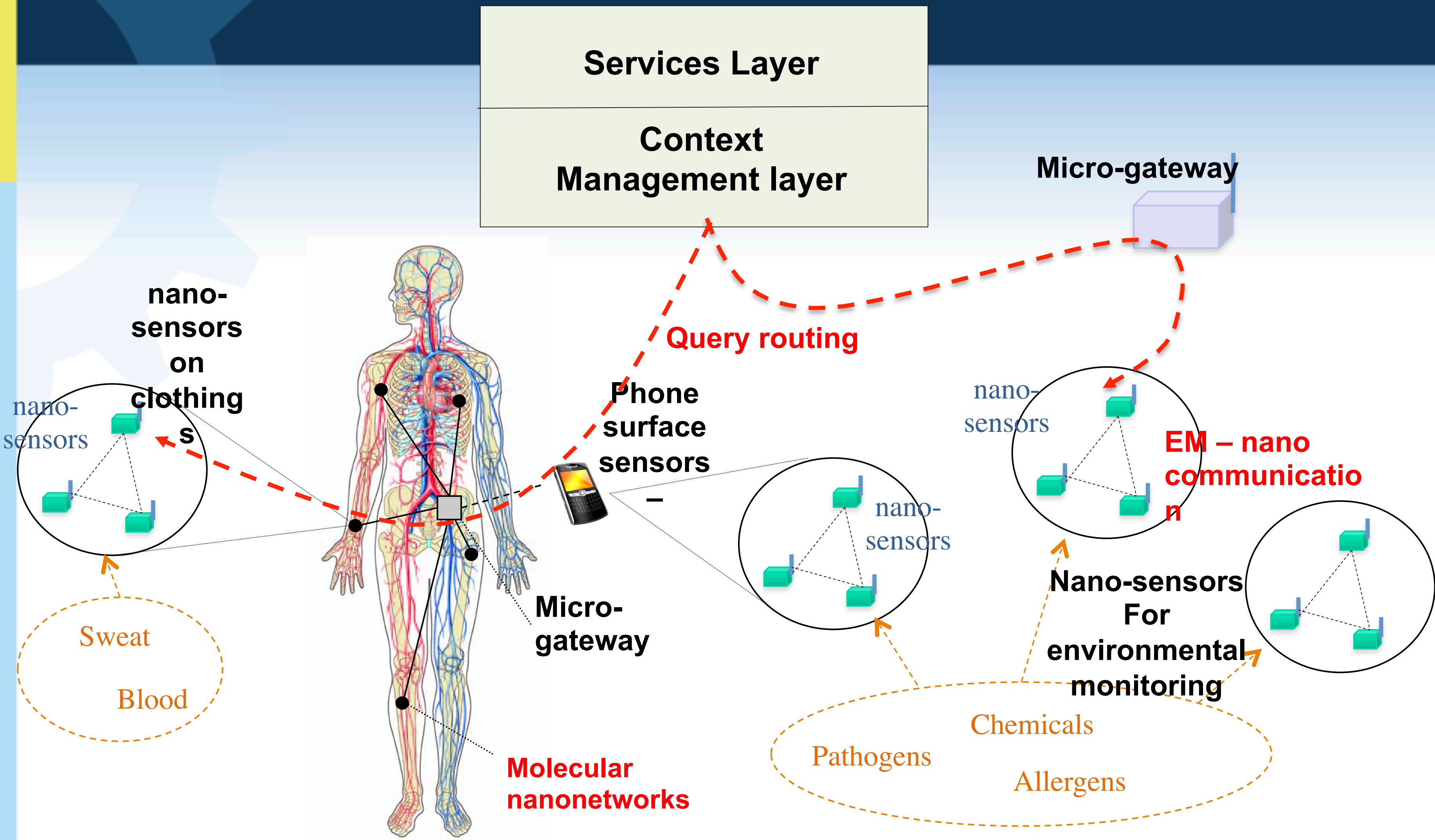
Ubiquitous connectivity



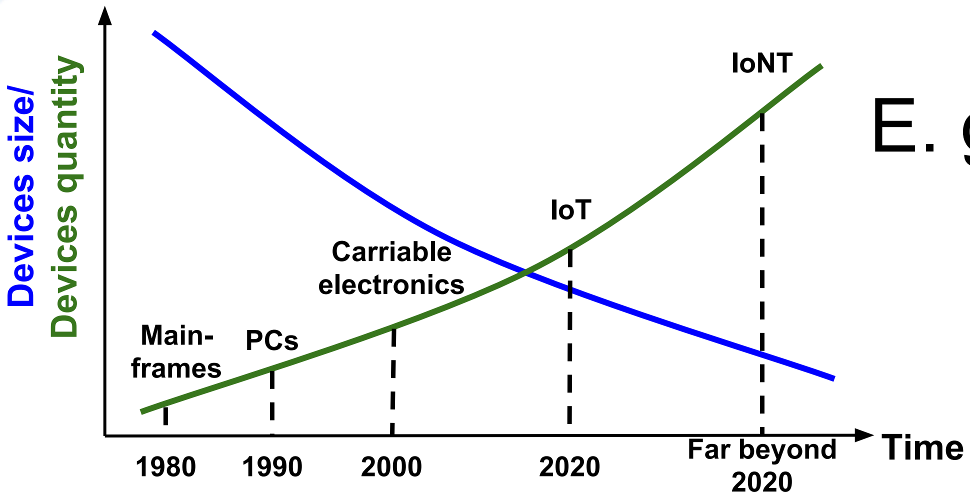
Converged infrastructure for Personal Area Networking

IoNT – Internet of Nano Things



Devices miniaturization trend

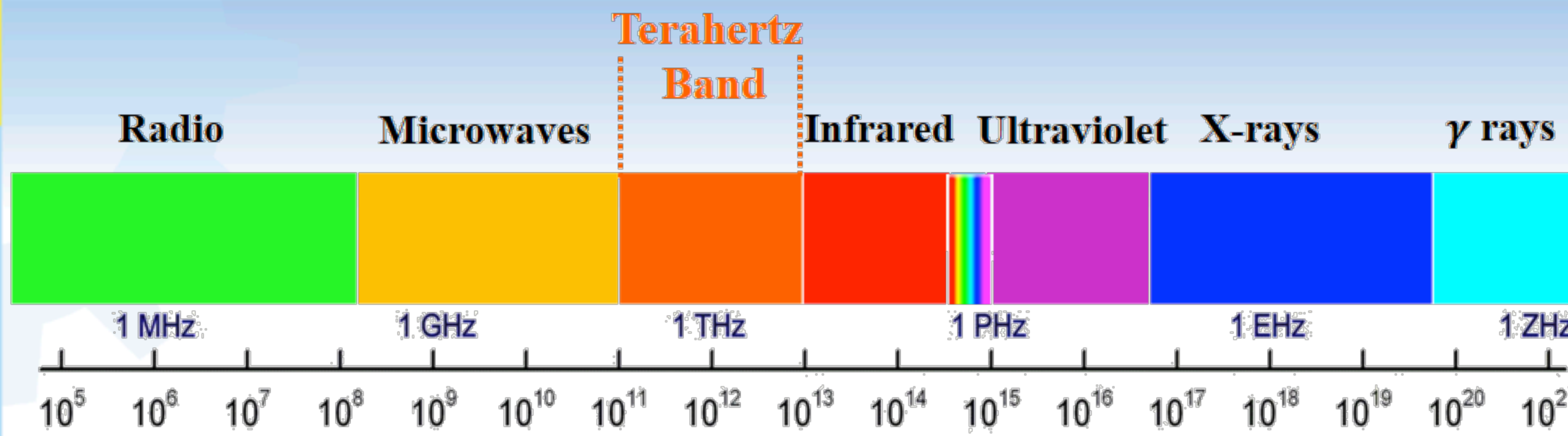
- Growing interest towards the THz band
  - Feasible for micro- and nano-scale devices
  - Smaller devices ➔ smaller Tx/Rx ➔ smaller antennas ➔ higher frequencies



E. g. 1 THz ➔ 0.3 mm wavelength

- *Adaptation of communication techniques is required*
  - *Novel research challenges raise*

Definitions of the THz band



	Frequency range	Wavelengths
Industry, IEEE 802.15.3d	0.3 – 3 THz	1 mm – 100 μm
Academia	0.1 – 10 THz	3 mm – 30 μm
Smart academia	0.06 – 10 THz	5 mm – 30 μm
Current presentation	**Major focus: 0.1 – 3 THz**	**Primary: 3 mm – 100 μm**

Interest growth in numbers

Industry

2008: IEEE 802.15 THz Interest Group (IG)

2013: IG upgraded to a Study Group on 100G

2014: Task Group .3d has been established

Over 300 contributions

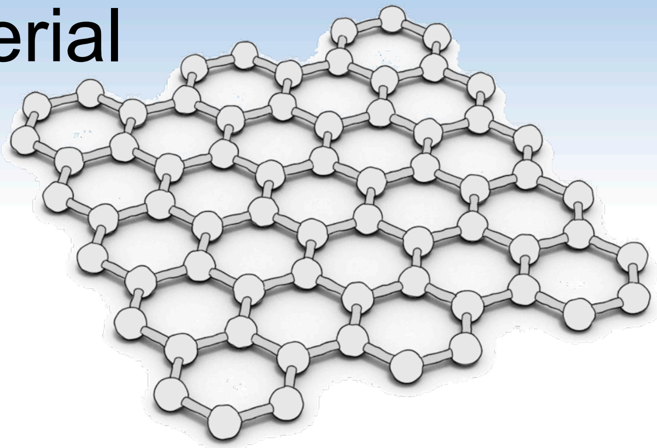
Academia

- Workshops at INFOCOM and ICC
- Symposiums at GLOBECOM and ICC
- IEEE Transactions on THz, 2 Special Issues in JSAC

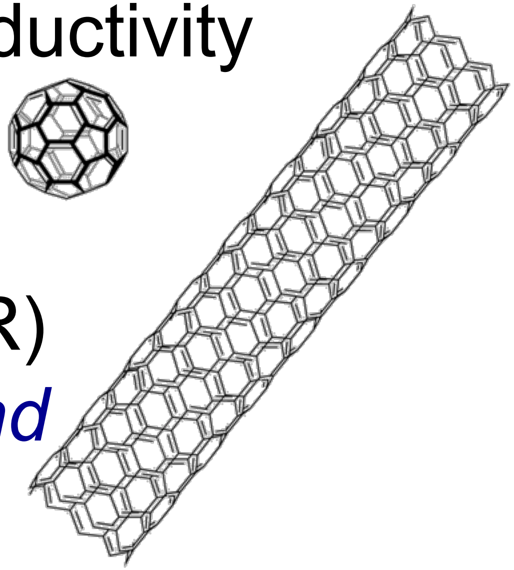
More than 500 articles

Several proofs of concept for elements

Enabling technologies
Graphene and Carbon Nano Tubes (CNTs)



- ❑ One atom thick carbon material
- ❑ Produced by Andre Geim,
  K. Novoselov in 2004
  - ***Nobel prize 2010***
- ❑ Major electrical property:
  - Extremely high electrical conductivity
- ❑ Derivatives:
  - Carbon Nanotubes (CNT)
  - Graphene Nanoribbons (GNR)



Feasibility of micro- and nano-scale antennas

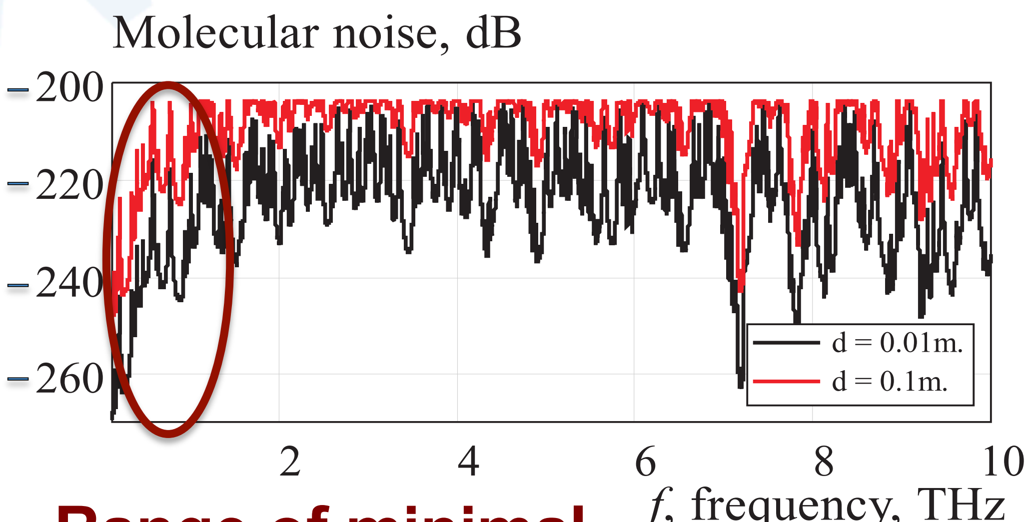
THz channel properties (1) Propagation and path loss

- **Spatial loss** $L_T(f,d) = L_P(f,d) + L_A(f,d)$
  - E.g. free-space loss for omnidirectional antennas $L_P(f,d) = \left(\frac{4\pi fd}{c_0}\right)^2$
- **Molecular absorption loss**
  - *Frequency-selective channel (!!!)*
  - Due to internally vibrating molecules on frequencies similar to signal ones
  - Feature of the THz Band
  - Abs. coefficients ➔ from HITRAN database

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

THz channel properties (2)
Molecular absorption noise

- Feature of the THz band
  - Molecules convert part of the absorbed energy into kinetic energy



$$P_N(f,d) = k_B N_M(f)$$
$$= k_B T\left[1-\tau(f,d)\right] =$$
$$= k_B T\left[1-e^{-k(f)d}\right]$$

Range of minimal noise level

Noise highly fluctuates through the frequencies

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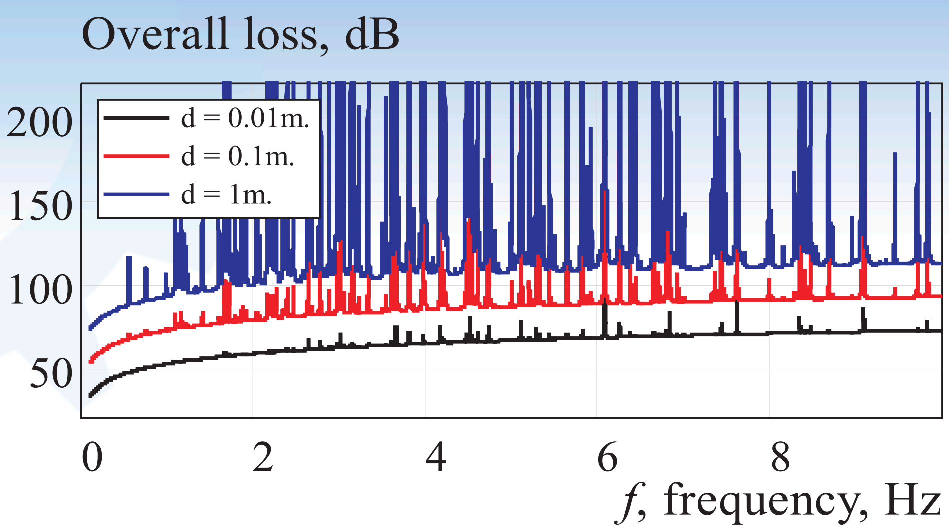
THz channel is frequency-selective



- First transparency window is the most promising

Window	Frequency range	Bandwidth	Half 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

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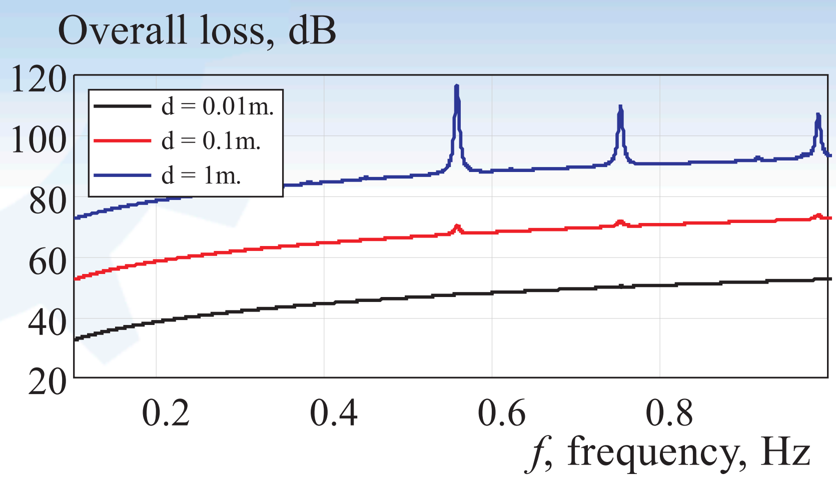
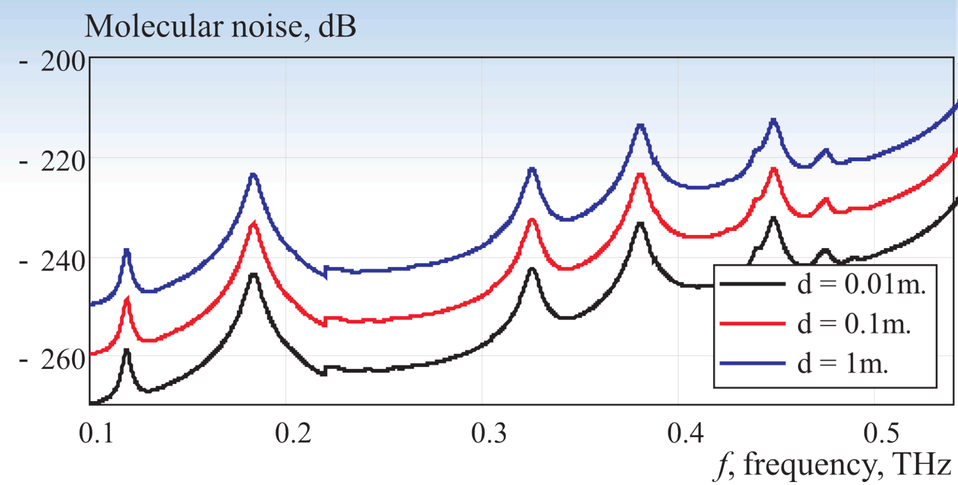
Study 0.1 – 0.54 THz in-depth

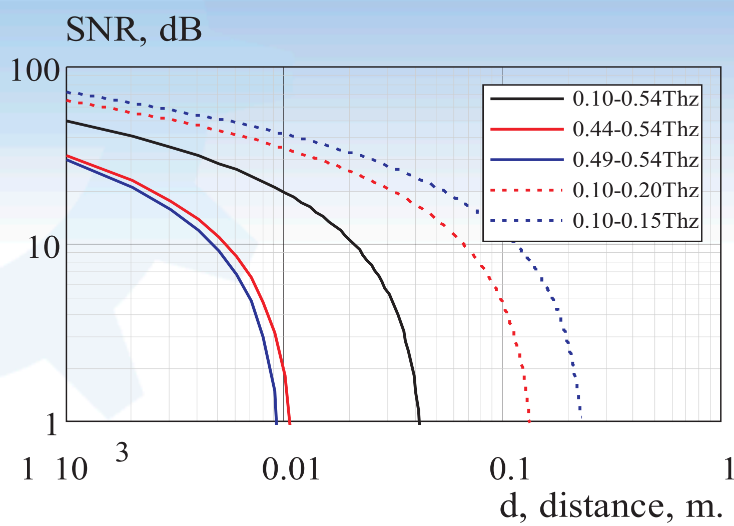
First transparency window, 0.1 – 0.54 THz

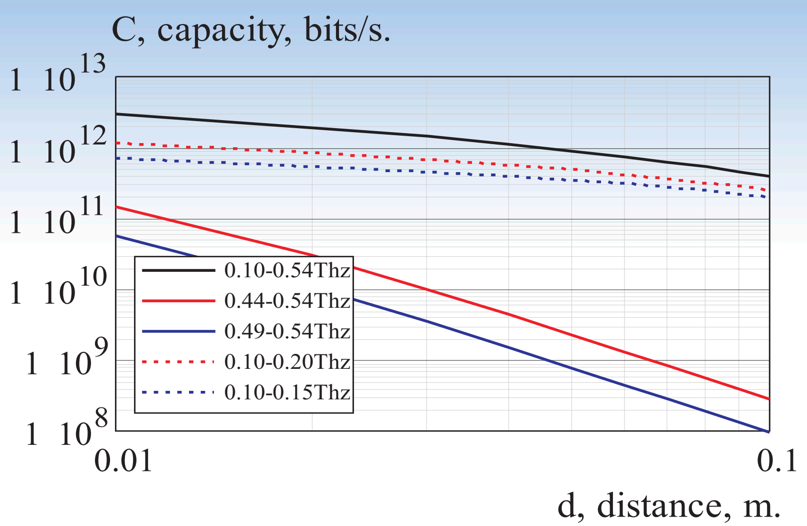




- ~20dB gain over 0.1 – 3 THz (!)
  - (10 times in amplitude, 100 in power)
  - Sufficient for decoding with major MCS
  - Suggested for transmission over "longer" distances: ≥1 cm

Range/capacity trade off
Small channels



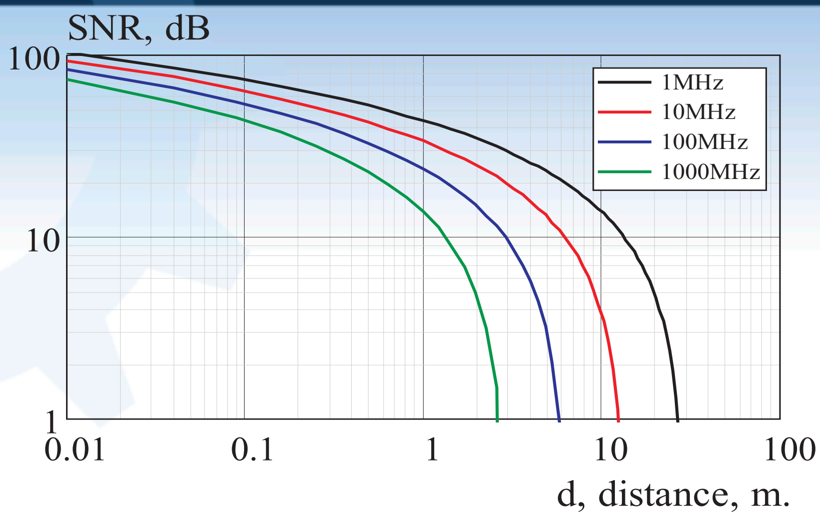


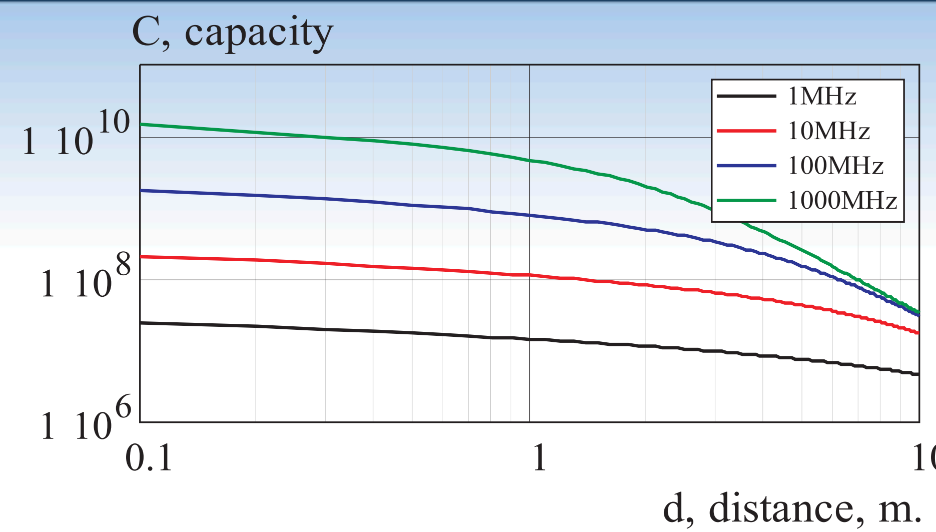
- For 10 cm distance:

Frequency range (bandwidth)	SNR	Capacity
0.1 – 0.54 THz (440 GHz)	20 dB	500 Gbps
0.1 – 0.2 THz (100 GHz)	33 dB	300 Gbps
0.1 – 0.15 THz (50 GHz)	35 dB	200 Gbps

Enabling complex MCSs

Range/capacity trade off
Tiny channels





- For SNR = 10 dB, Smart metering case

Frequency range (bandwidth)	Range	Capacity (at 1 m)
~0.1 THz (1000 MHz)	2 m	8 Gbps
~0.1 THz (10 MHz)	6 m	0.1 Gbps (100 Mbps)
~0.1 THz (1 MHz)	15 m	0.01 Gbps (10 Mbps)

Applicable for sensing applications

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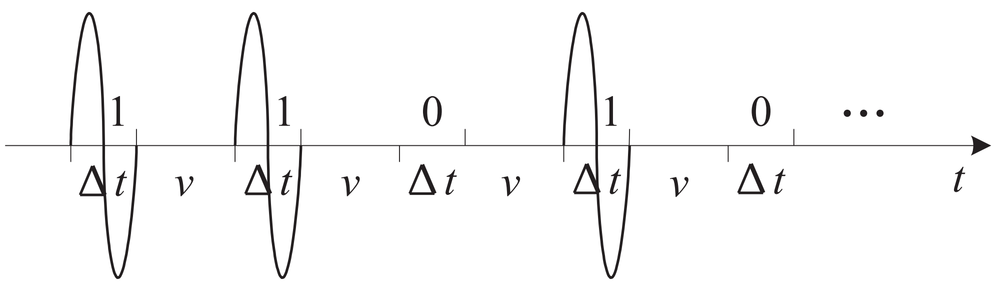
Modulation and Coding
On/Off Keying simple MCS

- Limitations of continuous-wave MCS:
  - Generating carrier at 1-2THz and higher
  - Filtering at higher frequencies
  - Energy efficiency

Advances in physics are needed

- On/Off keying
- Transmitting s(t):
  - s(t)=1 ➔ Pulse
  - s(t)=0 ➔ Silence



"Low-complex" hardware

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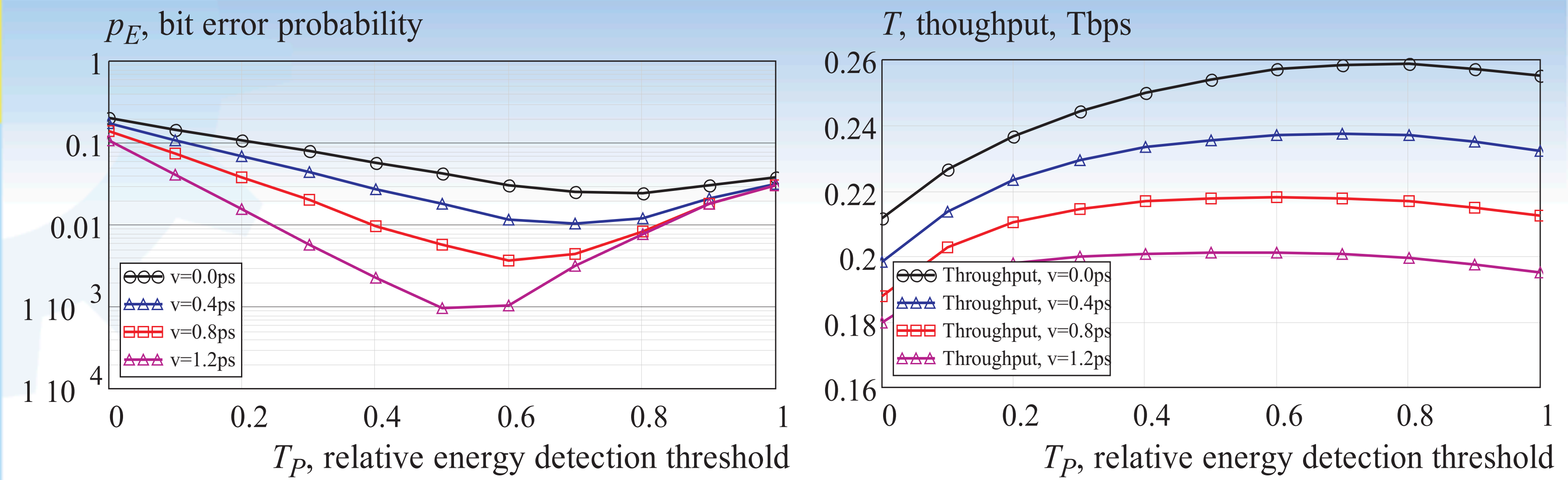
BER and throughput estimation for OOK



- ❑ Asymmetric channel: $p_{E1} \neq p_{E0}$
- ❑ Set of threshold ➔ optimisation problem
- ❑ BER can be lower than 0.001

FEC codes are applicable

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Summary
Primary research challenges (1)

- **Fundamental PHY**: *Feasibility of miniaturised components design and manufacturing*
  - THz signal generators
  - Tx/Rx
  - Antennas
- **Advanced PHY:** *Rapid improvements study*
  - Feasibility of carriers-based communications
  - Directivity is vital and needed soon (mitigation of high propagation losses)
  - Antenna arrays and (massive) MIMO

Summary
Primary research challenges (2)

- **Lower link**: *Principal selection of MCS type*
  - Limitations of On/Off keying modulation
  - Applicability of IEEE 802.11ac-based signaling (minimize time-to-market)
  - Suitability of full-duplex MAC
- **Upper link and higher layers:** *System level*
  - Peers discovery (especially, with directional antennas), angle of arrival, etc.
  - Addressing for massive amount of devices
  - Security and Privacy issues

Applicability assessment for certain user scenarios