Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Experimental Demonstration of Ultra-broadband Wireless Communications at True Terahertz Frequencies (1-1.05 THz)

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Abstract: In this presentation, the first experimental results for wireless Terahertz (THz) communications at 1.020 THz, the first absorption-defined window about 1 THz, are presented. After briefly describing the hardware components of the experimental test-bed, the details on the signal processing algorithms, including time, frequency and phase synchronization as well as channel estimation and equalization are described. The performance in terms of Bit Error Rate for single- and multi-carrier modulations able to support tens of Gigabits-per-second over sub-meter distances is discussed, and future directions to increase the communication distance are provided.

Purpose: Information of the Technical Advisory Group THz

EXPERIMENTAL DEMONSTRATION OF ULTRA-BROADBAND WIRELESS COMMUNICATIONS AT TRUE TERAHERTZ FREQUENCIES (1-1.05 THZ)

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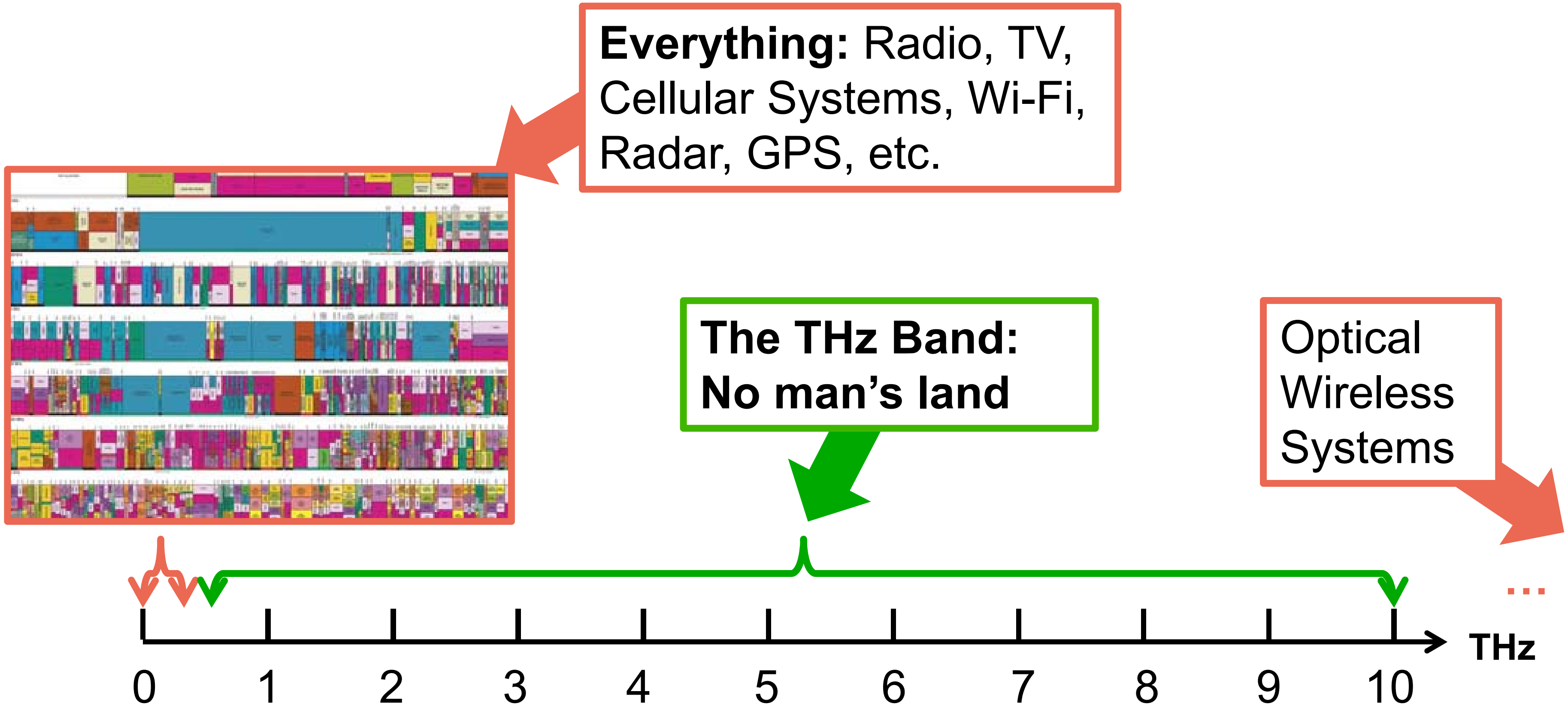
Motivation

- Over the last few years, wireless data traffic has drastically increased due to a change in the way we create, share and consume information:
  - **More devices:** 8.6 billion mobile devices connected to the Internet world wide, which generated a total of 11.5 exabytes per month of mobile data traffic in 2017 → 12.3 billion mobile-connected devices by 2022
  - **Faster connections:** Wireless data rates have doubled every 18 months over the last three decades → **Wireless Terabit-per-second (Tbps)** links will become a reality within the next 5 years

Spectrum Opportunity



Our Research: Terahertz-band Communication Networks

- **Objective:** To establish the theoretical and experimental foundations of ultra-broadband communication networks in the THz band (0.1–10 THz)

THz Materials & Devices

- THz Source/Detector
- THz Modulator/ Demodulator
- THz Antennas and Arrays

THz Channel

- Propagation Modeling (multi-path, 3D, indoor/outdoors)
- Capacity Analysis

THz Communications

- Modulation
- Coding
- Synchronization
- Ultra-Massive MIMO

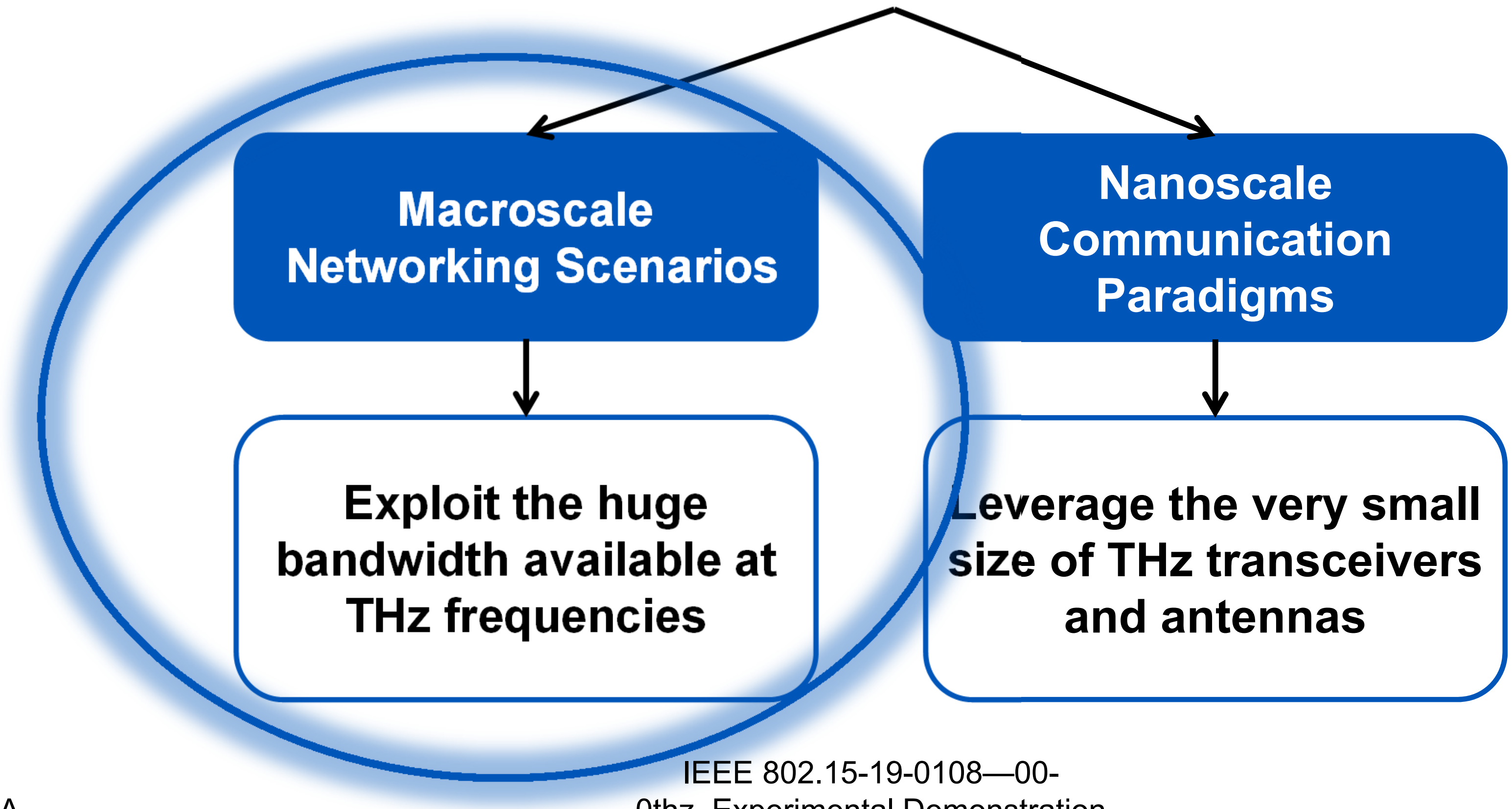
THz Networks

- Error and Flow Control
- Medium Access Control
- Relaying
- Routing

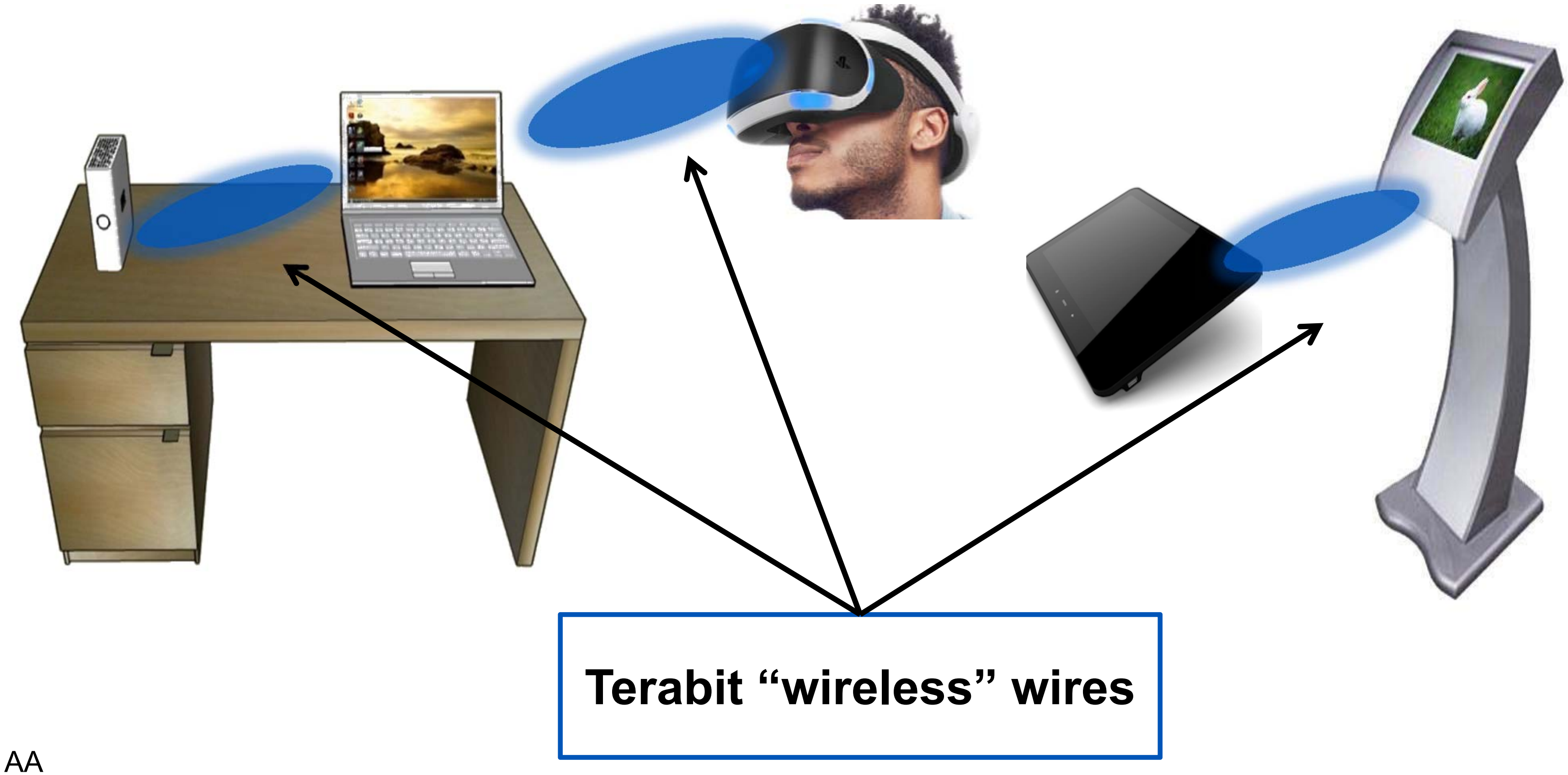
Experimental and Simulation Testbeds

Applications

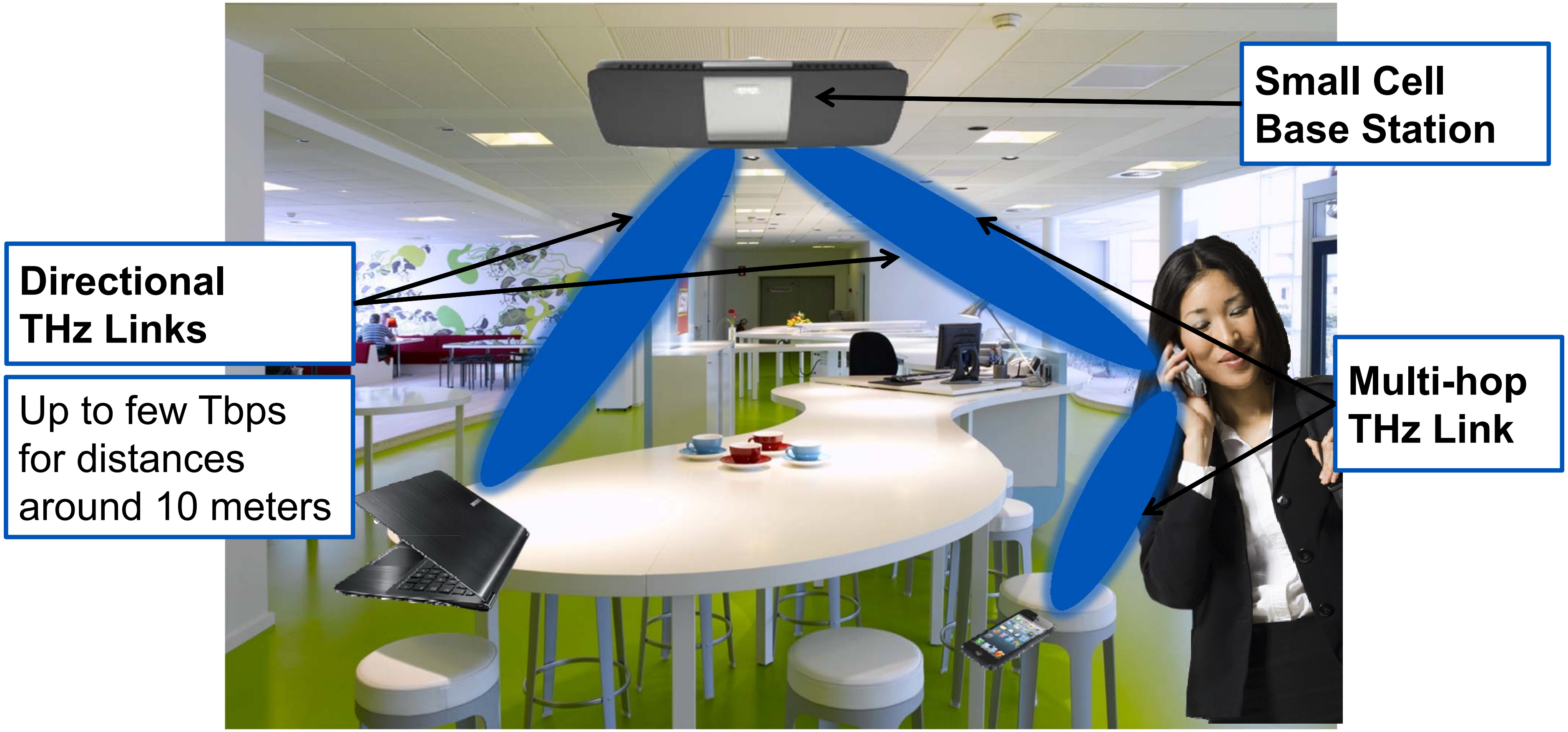
- The **huge bandwidth** provided by the THz band opens the door to a variety of applications:



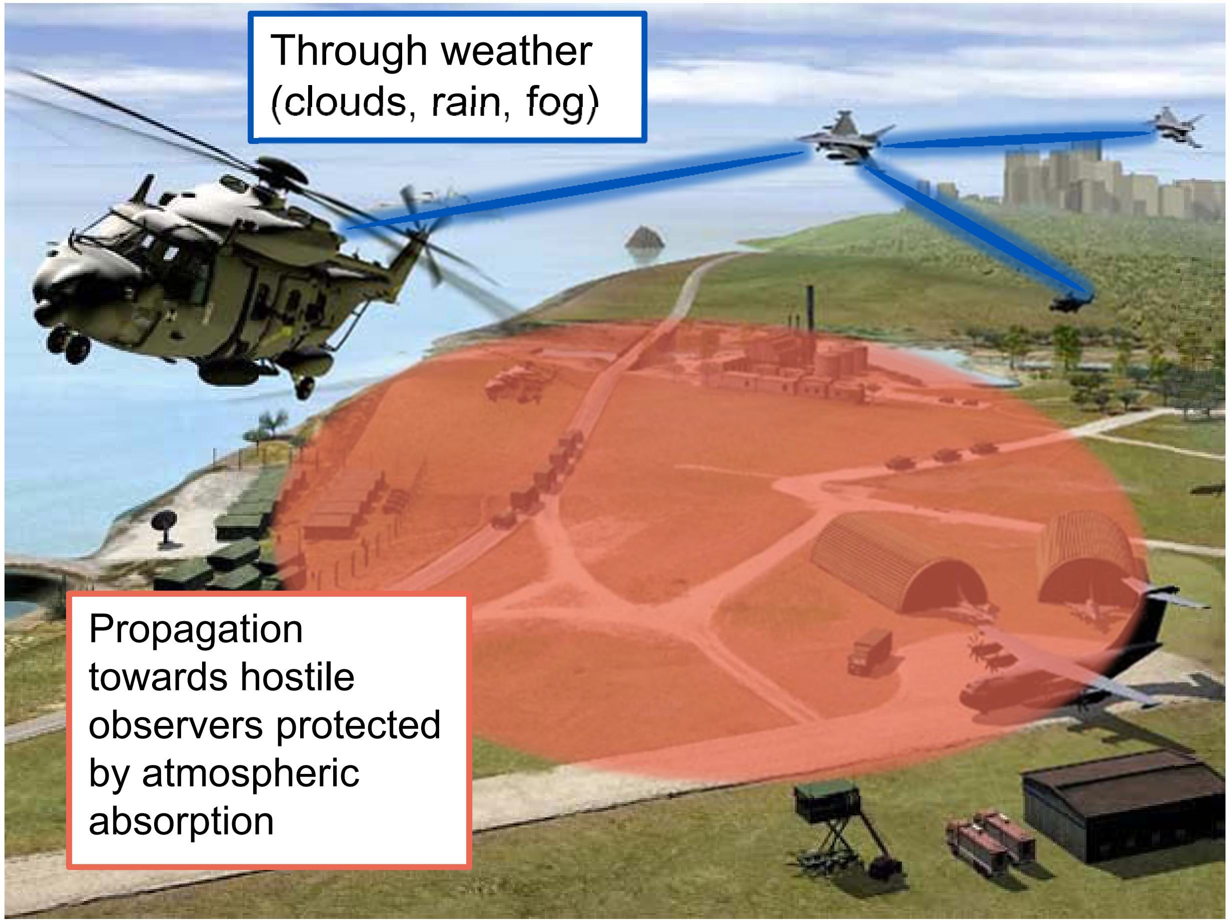
Applications:
Terabit Wireless Personal Area Networks



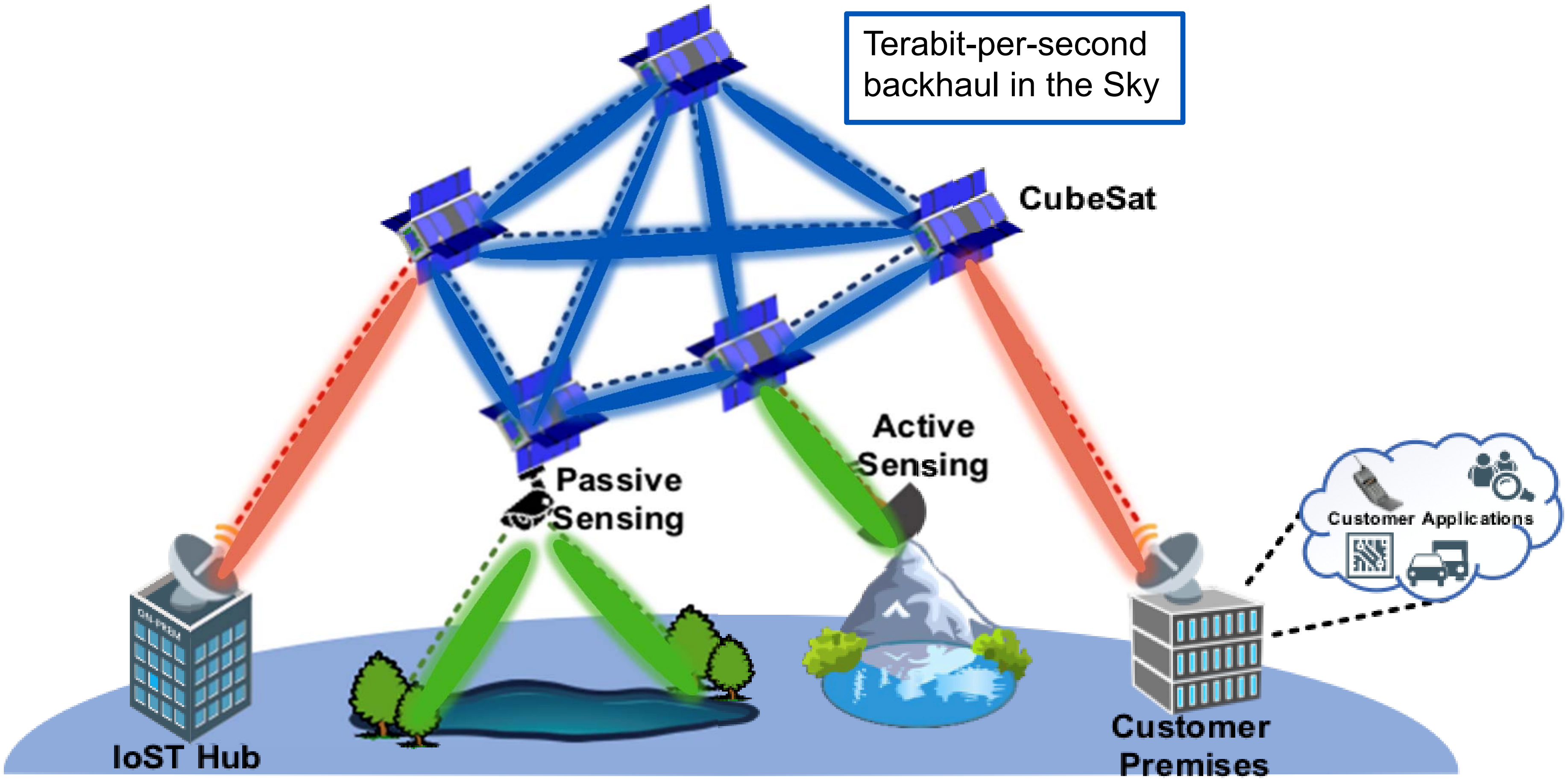
Applications:
Terabit Small Cells / WiFi



Applications:
Secure Ultra-broadband Links

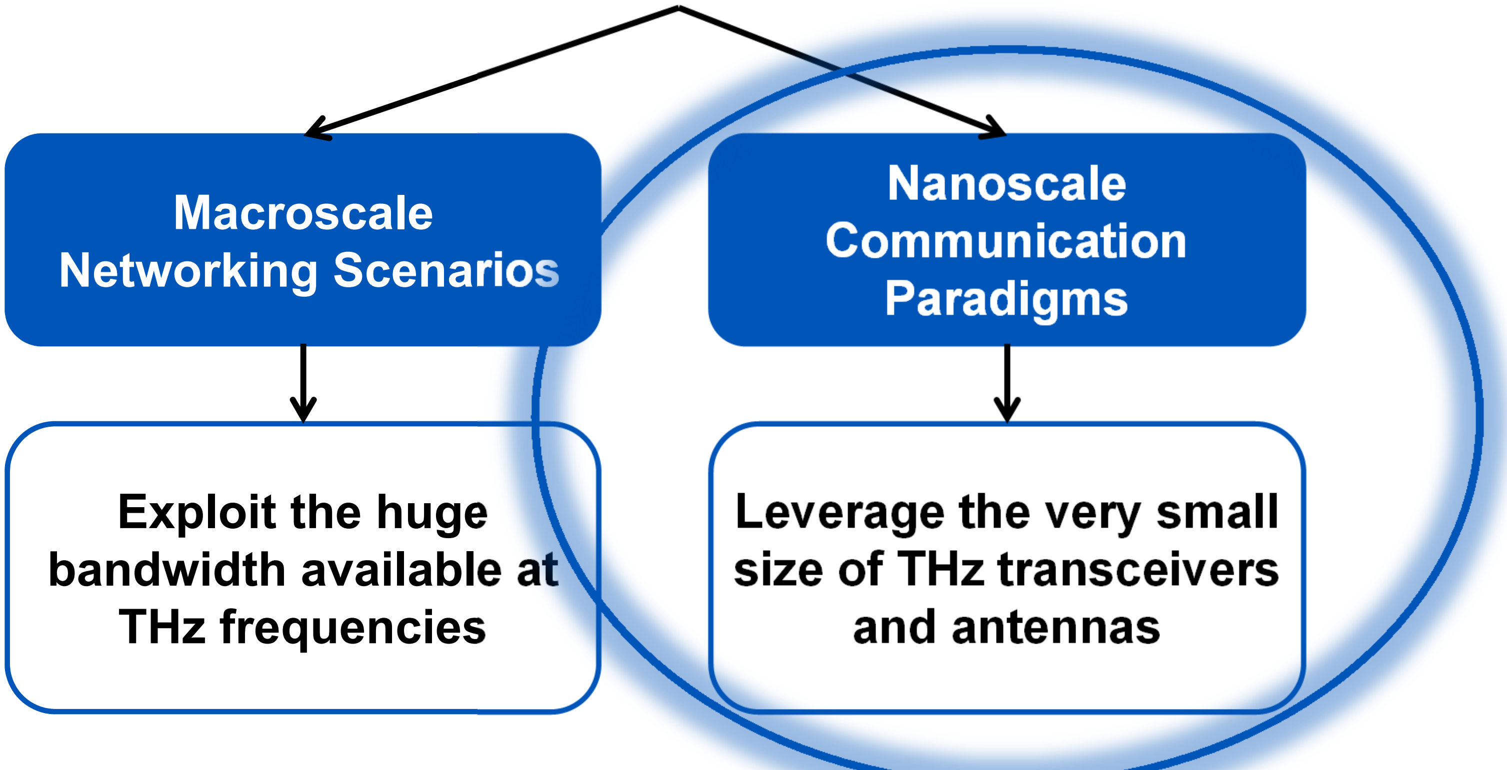


Applications: Ultra-broadband Satellite Communications

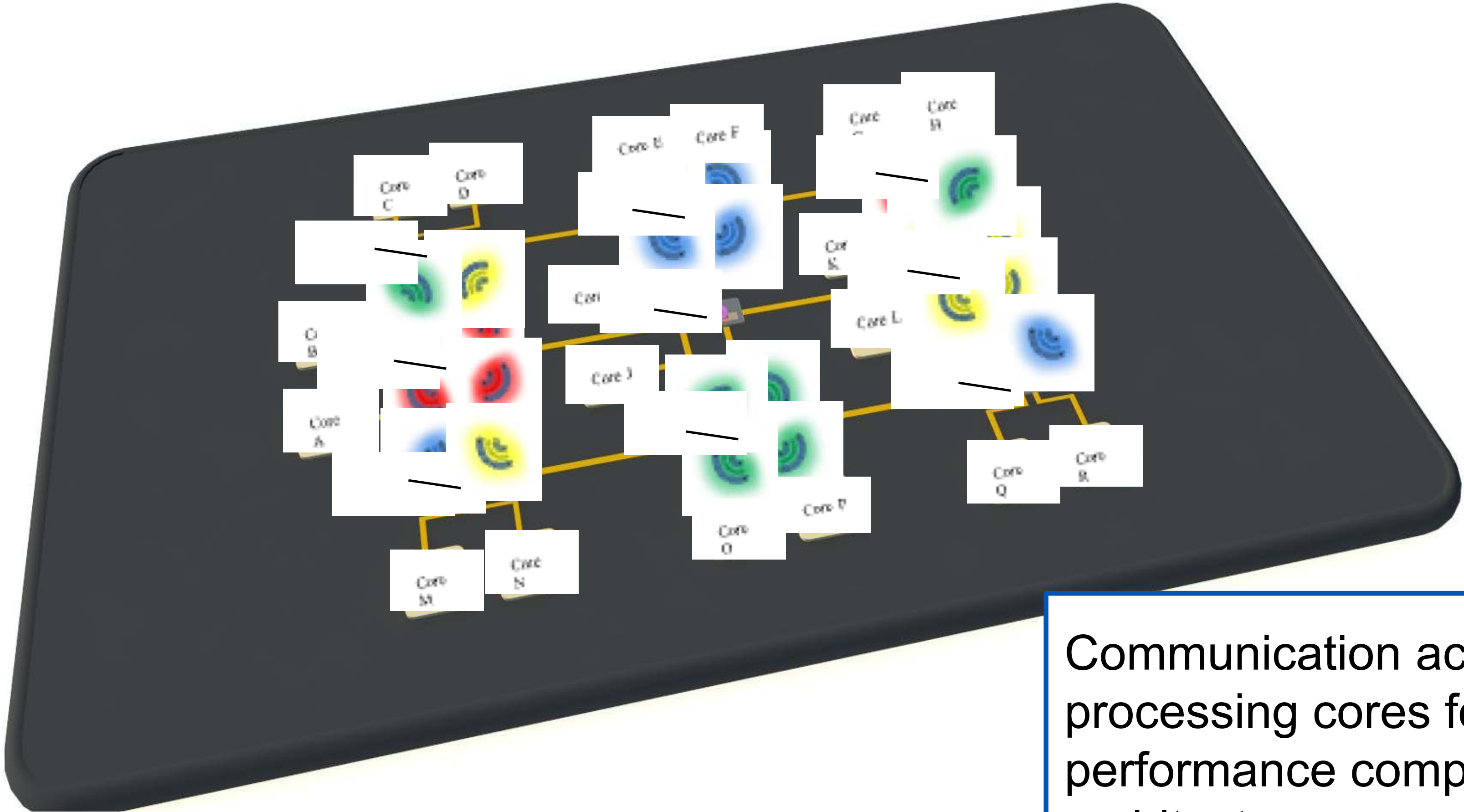


Applications

- The **huge bandwidth** provided by the THz band opens the door to a variety of applications:



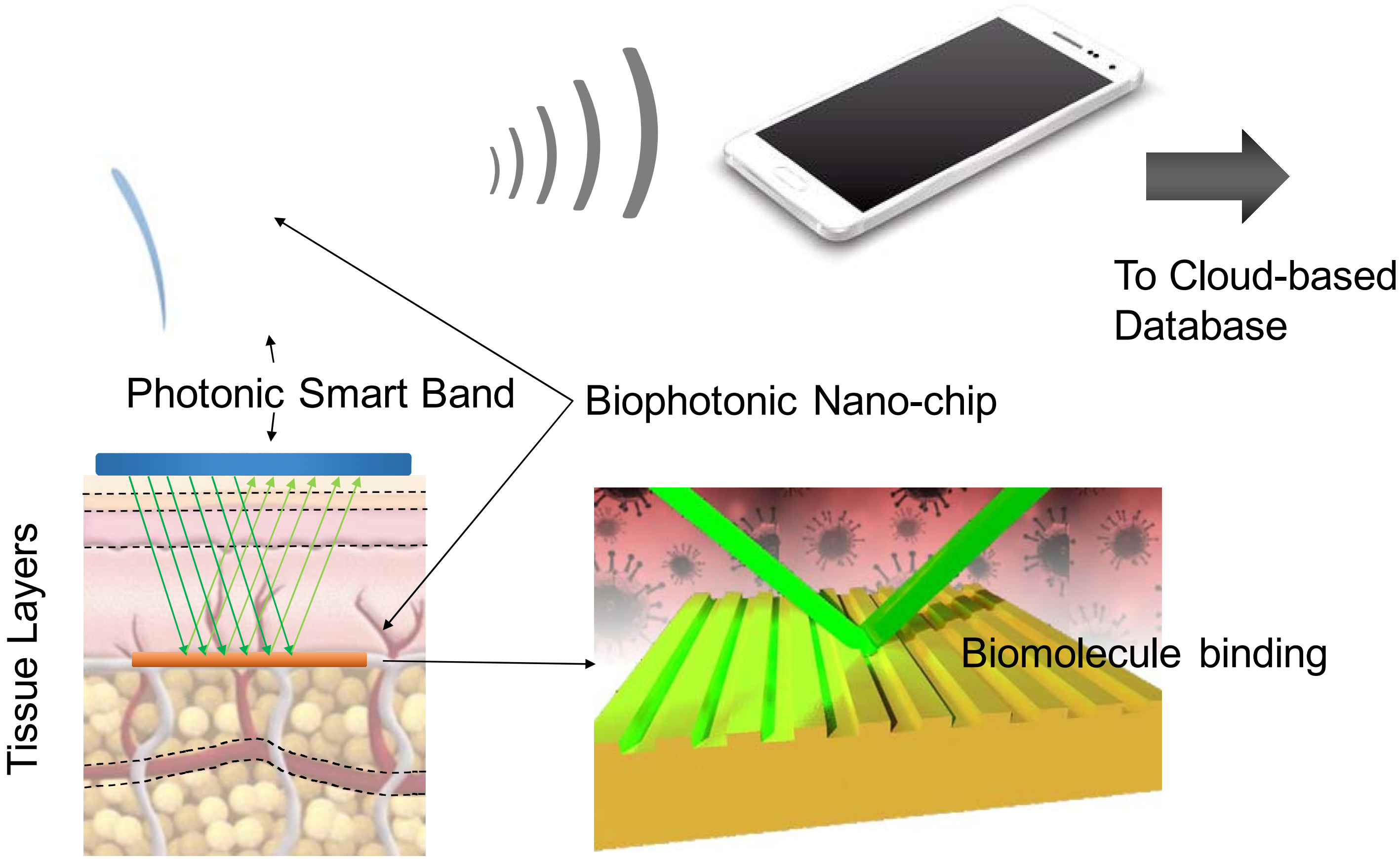
Application:
Massive Wireless Network On Chip



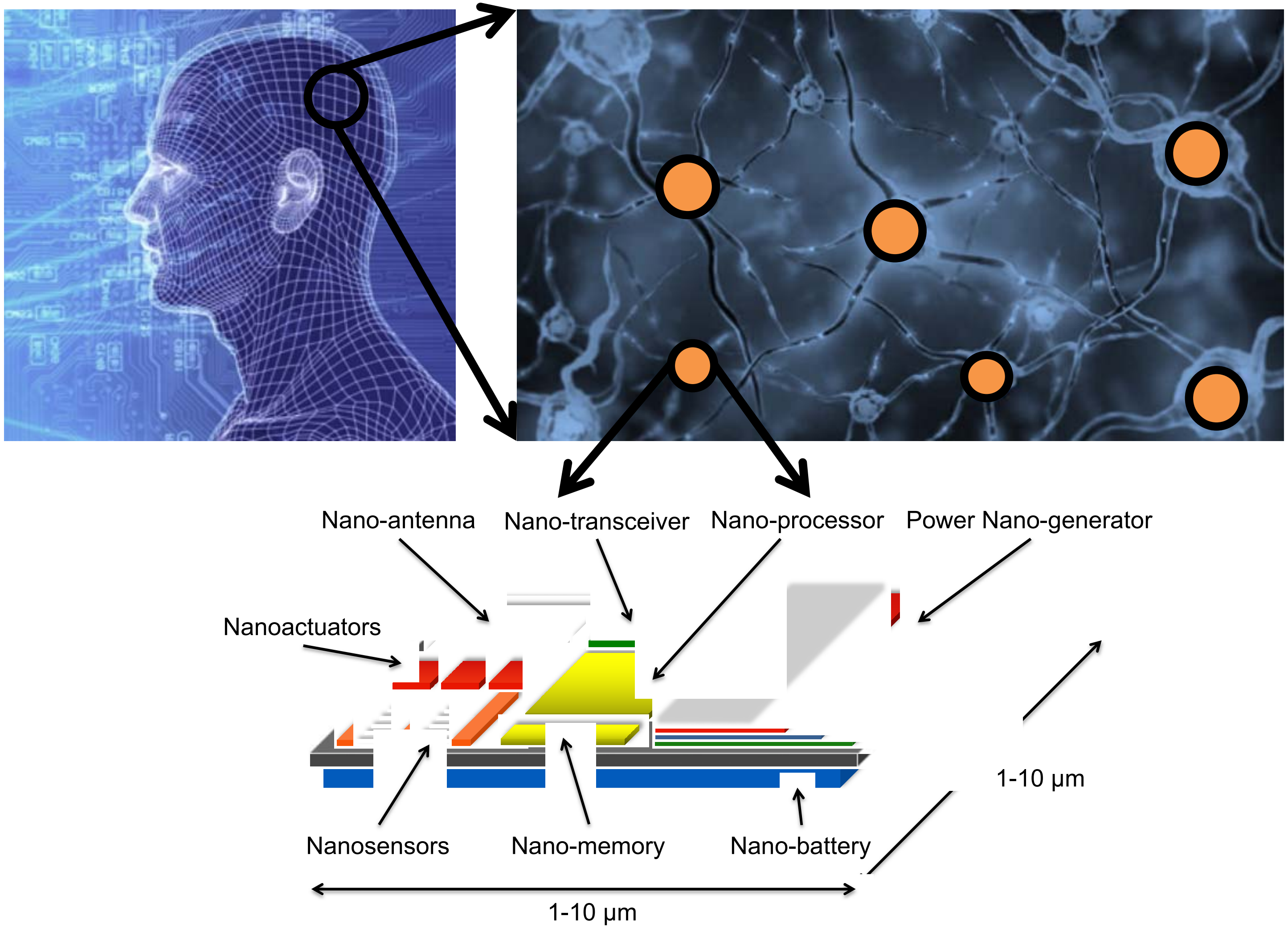
Communication across processing cores for high performance computing architectures

Applications:
Wearable Nano-bio-sensing Networks

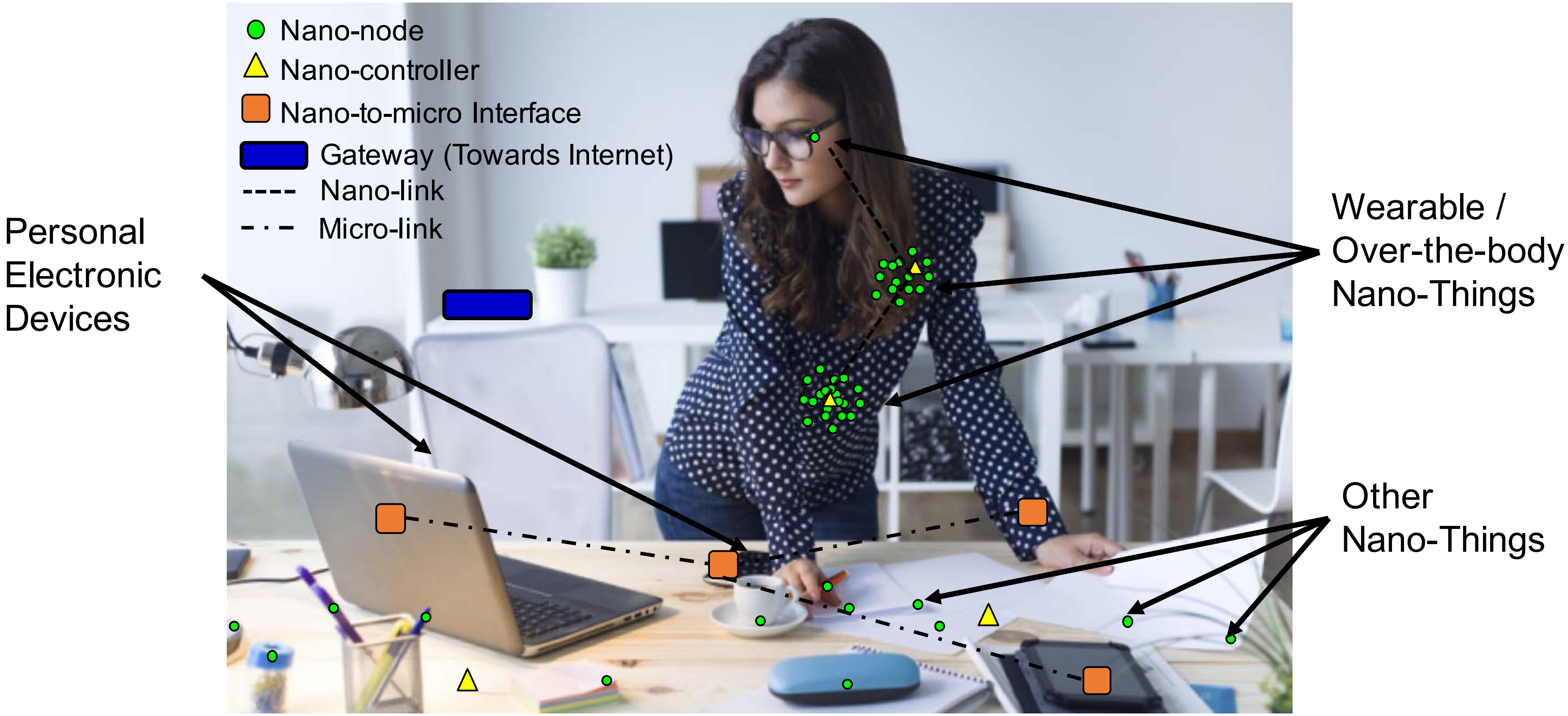
Our target: Lung cancer monitoring and early detection



Applications:
Brain Machine Nano-Interfaces



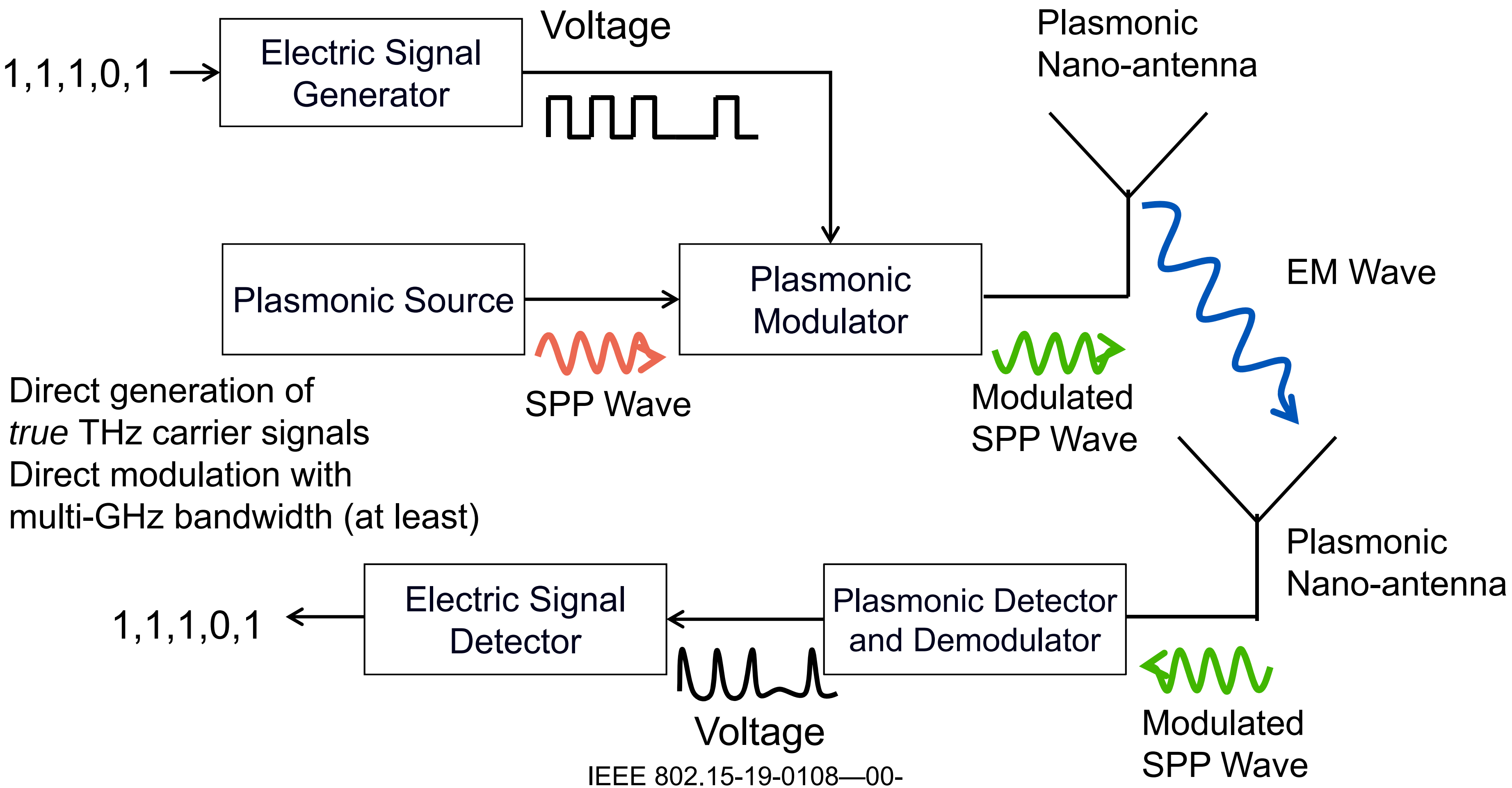
Applications:
The Internet of Nano-Things



The Terahertz Technology Gap

- **Open Challenge:**
  - Development of compact, energy-efficient systems able to generate, modulate, radiate, detect and demodulate THz signals
- **Ongoing solutions:**
  - Photonics approach:
    - Frequency-difference generation
    - Photomixing and photoconductive antennas
    - Quantum cascade lasers
  - Electronics approach:
    - Frequency multiplying chains
    - Resonant tunneling diodes
    - Traveling wave tubes (vacuum electronics)

Our Approach: Hybrid Graphene/ Semiconductor Plasmonic Technology

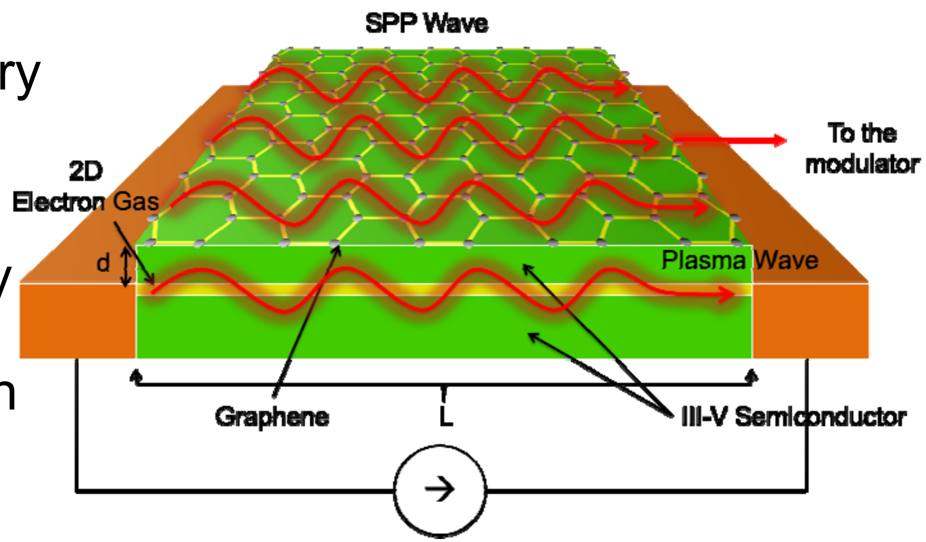


Direct generation of *true* THz carrier signals
Direct modulation with multi-GHz bandwidth (at least)

THz Plasmonic Source

J. M. Jornet and Ian F. Akyildiz, "Graphene-based Plasmonic Nano-transceiver for Terahertz Band Communication," in Proc. European Conference on Antennas and Propagation, April 2014.
U.S. Patent No. 9,397,758 issued on July 19, 2016.

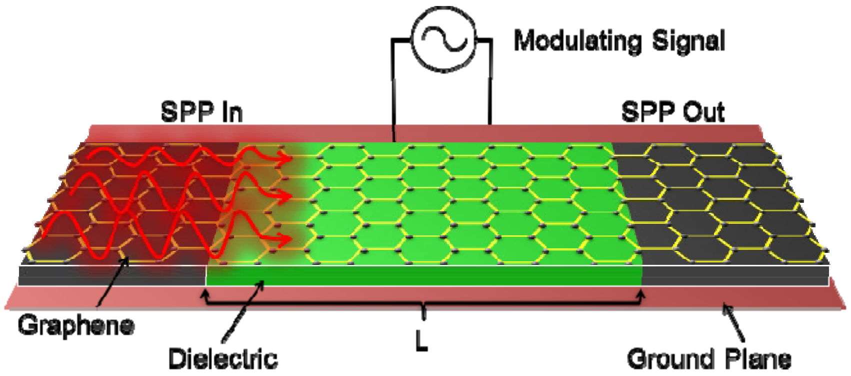
- Proposed and analytically modeled the performance of an on-chip THz signal generator and detector based on a III-V semiconductor High-Electron-Mobility Transistor (HEMT) enhanced with graphene
- **Working principle:**
  - By setting asymmetric boundary conditions at the source and drain, a THz plasma wave is excited in the channel → Dyakonov-Shur (DS) Instability
  - The plasma wave is used to launch a THz Surface Plasmon Polariton (SPP) wave on the graphene layer → SPP waves can propagate on graphene at THz frequencies



THz Plasmonic Phase Modulator

P. K. Singh, G. Aizin, N. Thawdar, M. Medley, and J. M. Jornet, "Graphene-based Plasmonic Phase Modulation for THz-band Communication," in Proc. European Conference on Antennas and Propagation, April 2016. U.S. Patent Application filed on April 9, 2018 (Priority date April 9, 2017).

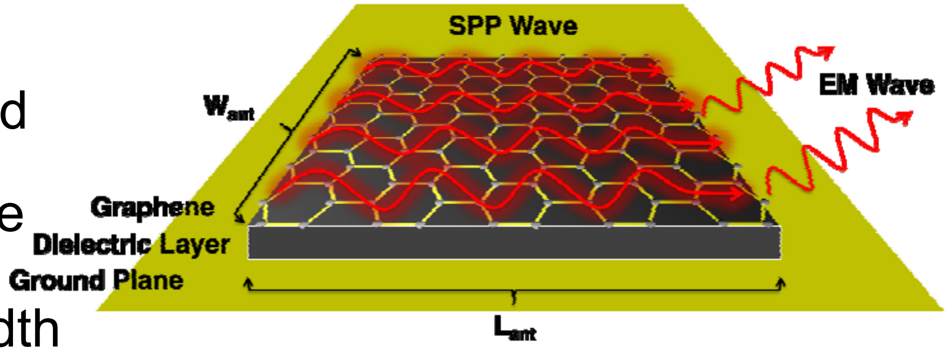
- Proposed and analytically modeled the performance of an on-chip plasmonic modulator able to based on tunable graphene waveguide
- **Working principle:**
  - By electronically modulating the Fermi energy of the graphene layer, we can accelerate or slow down the speed of a propagation SPP wave
  - The phase of an outgoing SPP wave at periodic observation times (e.g., symbols) depends only on the waveguide length and the speed → Modulating the speed == modulating phase



THz Plasmonic Antenna

J. M. Jornet and I. F. Akyildiz, "Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks," IEEE JSAC, vol. 31, no. 12, pp. 685-694, December 2013. Shorter version in Proc. of EuCAP, Apr. 2010. U.S. Patent No. 9,643,841, issued on May 9, 2017.

- Proposed and analytically modeled the performance of a graphene-based plasmonic nano-antenna able to efficiently radiate at THz-band frequencies
- **Working principle:**
  - SPP waves are *nothing but* surface EM waves → Their propagation properties depend both on the Fermi energy and on the geometry of the surface in which they propagate
  - By engineering the length, width and thickness of the plasmonic waveguide, we can design a plasmonic resonant cavity with lossy ends = a patch antenna



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- Routing

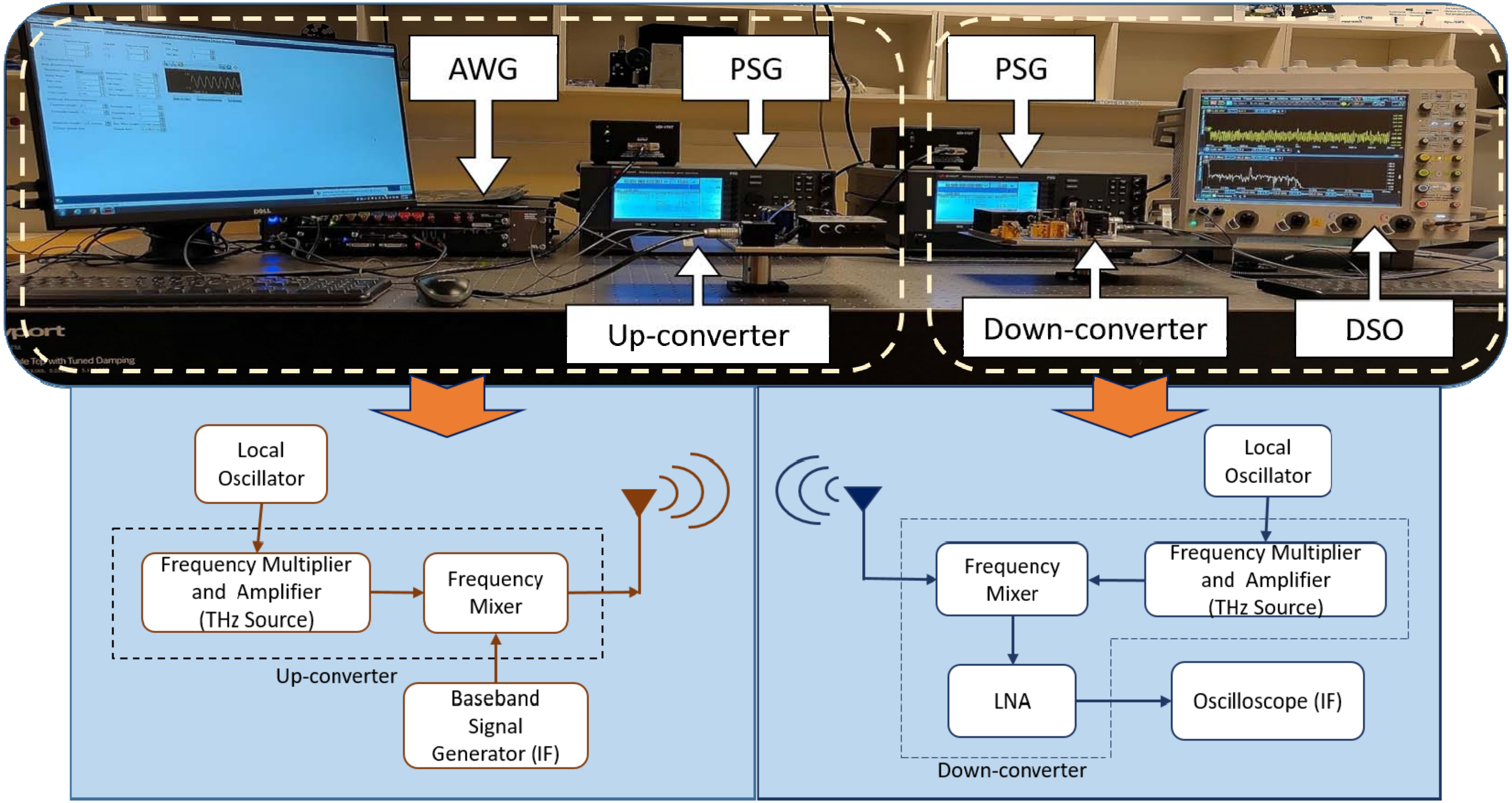
Experimental and Simulation Testbeds

The TeraNova Testbed

- The World's first Integrated testbed for ultra-broadband communication networks at *true* terahertz frequencies
  - ⌘ Hardware overview
  - ⌘ Software-defined physical layer
  - ⌘ Experimental characterization and result

J. M. Jornet, P. Sen, D. Pados, S. Batalama, E. Einarsson and J. P. Bird, "The TeraNova Platform: An Integrated Testbed for Ultra-broadband Wireless Communications at *True* Terahertz-band Frequencies," submitted for journal publication, 2018.

The TeraNova Testbed: Hardware Overview



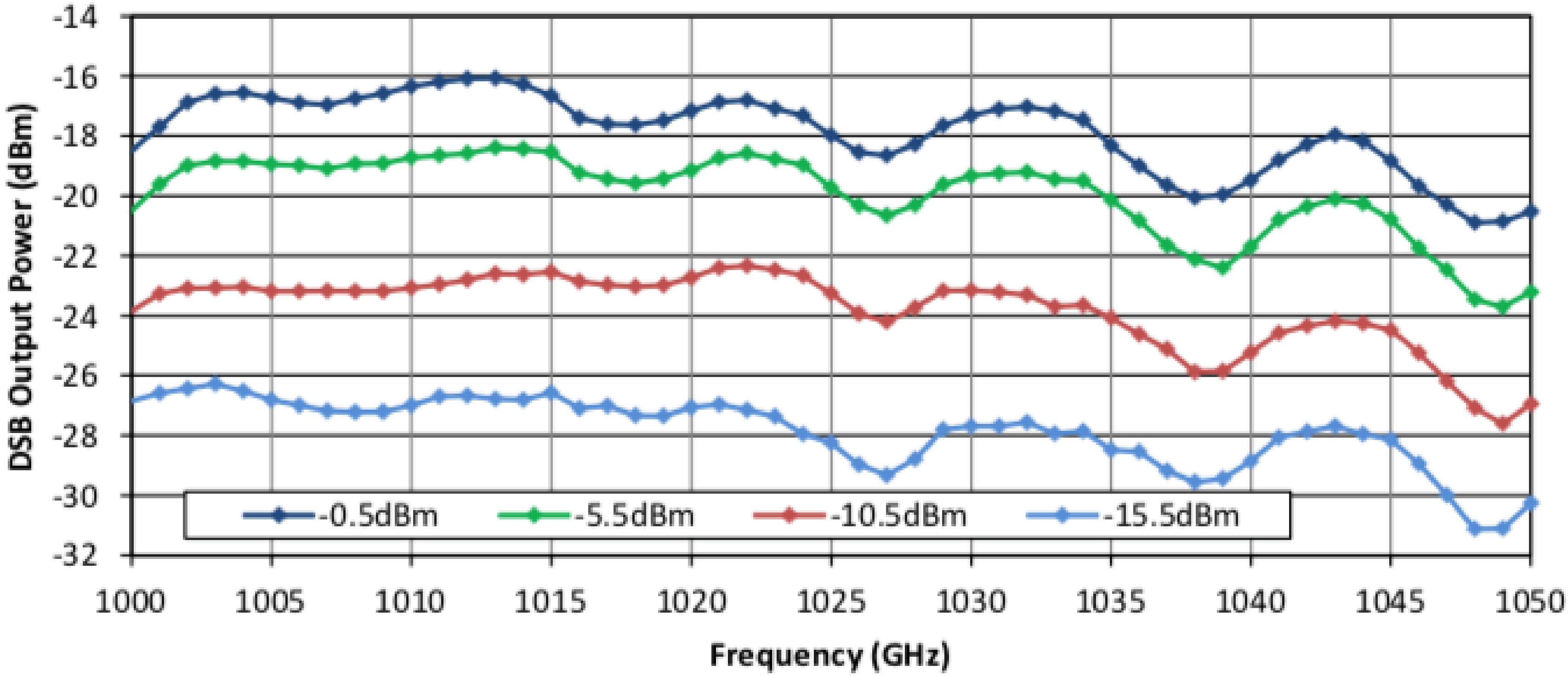
TeraNova Hardware: Key Components

- **Local Oscillator (Transmitter and Receiver side)**
  - Generate very stable sinusoids between 250 KHz to 50 GHz
  - Maximum output power 10 dBm
  - Keysight PSG E8257

- **Frequency Multipliers, Mixer and Amplifiers (MixAMC, for Up and Down converter)**
  - Based on Schottky-diode technology and custom-designed by Virginia Diode Inc. (VDI)
  - Starting point: 41.67-43.75 GHz
  - Multipliers chain: x2 x2 x2 x3 = x24
  - Mixer: 40 GHz bandwidth

- **Some specifications:**
  - **Center frequency:** tunable between 1000-1050 GHz
  - **Bandwidth:** up to 40 GHz
  - **Transmit power:** approximately 30 μW for Up-converter

Response of the Up-converter



TeraNova Hardware: Key Components

- **Baseband Signal Generator**
  - ⌘ Based on a Keysight Arbitrary Waveform Generator (AWG) M8196A
  - ⌘ Creates analog signal from the digitally described signal
    - Takes Matlab-style file as input

- **Specifications:**
  - ⌘ **Sampling Frequency:** 93.4 GigaSamples-per-second (GSas)
  - ⌘ **Bandwidth:** 32 GHz
  - ⌘ **Output power:** 10 dB single ended; 13 dBm differential
  - ⌘ **RMS jitter:** 100 fs

TeraNova Hardware: Key Components

- **Baseband Signal Recovery**
  - Based on a Keysight Digital Storage Oscilloscope (DSOZ632A)
  - One of the fastest DSO in the market
  - Creates digital signal from the received IF analog signal
    - Returns Matlab-style file as output

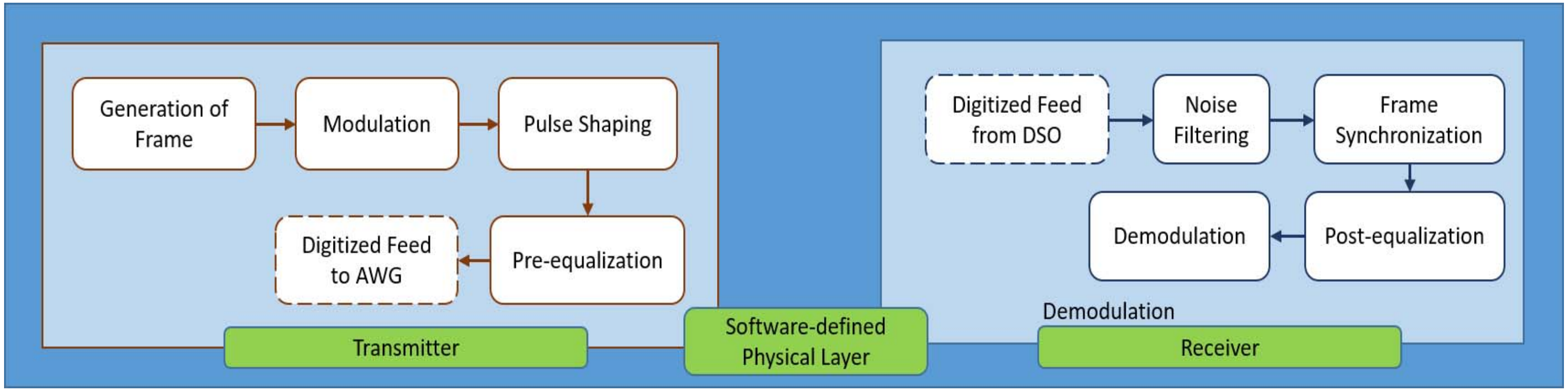
- **Specifications:**
  - **Sampling Frequency:** 80 or 160 GSas
  - **Bandwidth:** 32 or 63 GHz
  - **Resolution:** 8-bit
  - **RMS jitter:** 170 fs

TeraNova Hardware: Key Components

- **Antenna**
  - ⌘ Directional horn Antenna (VDI)
  - ⌘ 26 dBi gain
  - ⌘ 10^0 angle for 3 dB beamdwidth

- **Cables and connectors**
  - ⌘ 2.4 mm male to male coaxial cable
  - ⌘ Low insertion loss connector: VSWR rating approximately 1.2:1

The TeraNova Testbed: Software-defined Physical Layer



- Software-defined backbone for transceiver system
- Implemented on AWG and DSO

Software-defined Physical layer: Key Blocks for Transmitter

- **Generation of Frame**
  - ⌘ Header: 18 bits well-known maximal merit factor (MF) sequence
  - ⌘ Training sequence: up to 200 bits
  - ⌘ Data: 2184 bits

- **Modulation**
  - ⌘ Single Carrier: BPSK, QPSK, 8-PSK, BPAM, 4-PAM
    - Bandwidth (BW): 5-30 GHz
  - ⌘ Multicarrier: OFDM (BPSK, 10 subcarrier with 10 GHz BW)
    - serial to parallel conversion block-IFFT block- add cyclic prefix-parallel to serial conversion block to transmit
  - ⌘ Higher order modulation not used due to power limitation.

Software-defined Physical layer: Key Blocks for Transmitter

- **Pulse Shaping**
  - ⌘ Needed to limit the transmission bandwidth
  - ⌘ Raised cosine pulse filter is utilized
  - ⌘ Generated signal given by,
    - $x_m(t) = real[p(t)(I_m + jQ_m)]e^{j2\pi f_{IF} t}$
    - p is the raised cosine pulse and f_{IF} refers to the intermediate frequency

- **Pre-equalization**
  - ⌘ Utilized to compensate hardware constant frequency selective response
  - ⌘ Occur mainly due to coaxial cables and connectors
  - ⌘ Inverse of the measured frequency response is utilized as the frequency domain coefficient of the pre-equalization filter.

- Pre-equalized signal used as **Digitized feed to AWG**

Software-defined Physical layer: Key Blocks for Receiver

- **Digitized feed from DSO utilized for further processing**
  - Sampling rate is 160 Gsas
- **Noise Filtering**
  - Chebyshev bandpass (M-PSK) and lowpass (M-PAM, OFDM) filter is Utilized
  - Based on Parks-McClellan-algorithm
- **Frame Synchronization**
  - Correlator filter is utilized to get the stating point
  - Correlates the received signal with the same 18-bit-long maximal MF sequence

Software-defined Physical layer: Key Blocks for Receiver

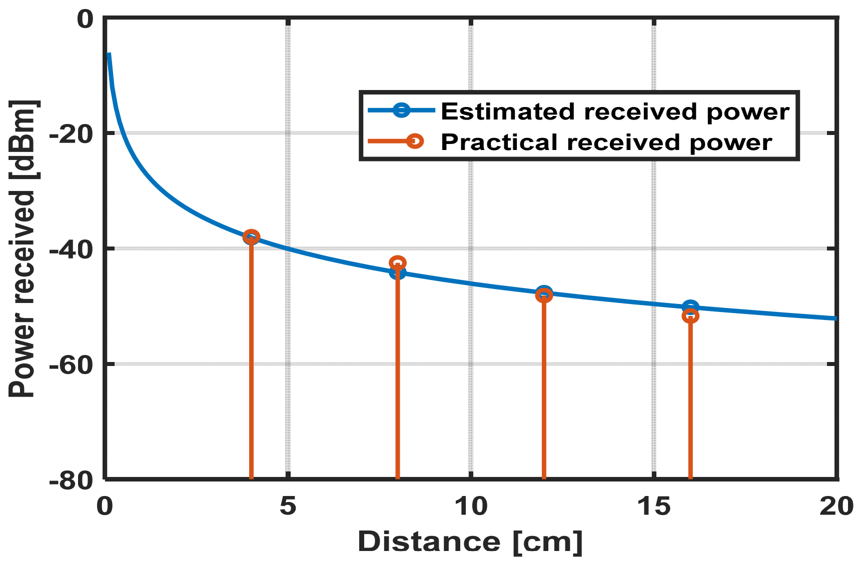
- **Post-equalization**
  - Minimum mean square error (MMSE) linear filter equalizer is utilized
  - To mitigate the effect of ISI, frequency selective nature of the channel and path loss
  - Filter coefficient vector, $\hat{f}$ is obtained by minimizing the error between the transmitted training symbols, $\hat{s}$, and the symbols of the output of the equalizer, i.e. $\mathrm{R}\hat{f}$
    - R is Toeplitz matrix with the received training symbols
  - So, objective: $min\left\|\hat{s} - R\hat{f}\right\|^2$ w.r.t $\hat{f}$
  - Solution: $\hat{f} = (R^T R)^{-1} R^T \hat{s}$

Software-defined Physical layer: Key Blocks for Receiver

- **Demodulation**
  - To detect the bits from received signal
  - Correlator type detector based on maximum likelihood criterion is utilized
    - $\hat{m} = \arg max_{1 \leq m \leq M} \left(\int_0^T r(t) x_m(t) dt - \frac{1}{2} \|x_m\|^2 \right)$
    - $\hat{m}$ denotes the maximum match with a particular symbol and m=1,2,. . . . M. M is the modulation index. $r(t)$ represents the received symbol. $x_m(t)$ is all possible symbol generated after passing through raised cosine pulse filter
  - For OFDM
    - Removed cyclic prefix- serial to parallel conversion block-FFT block- get the complex baseband signal $(I_m + jQ_m)$ - pass through detection algorithm

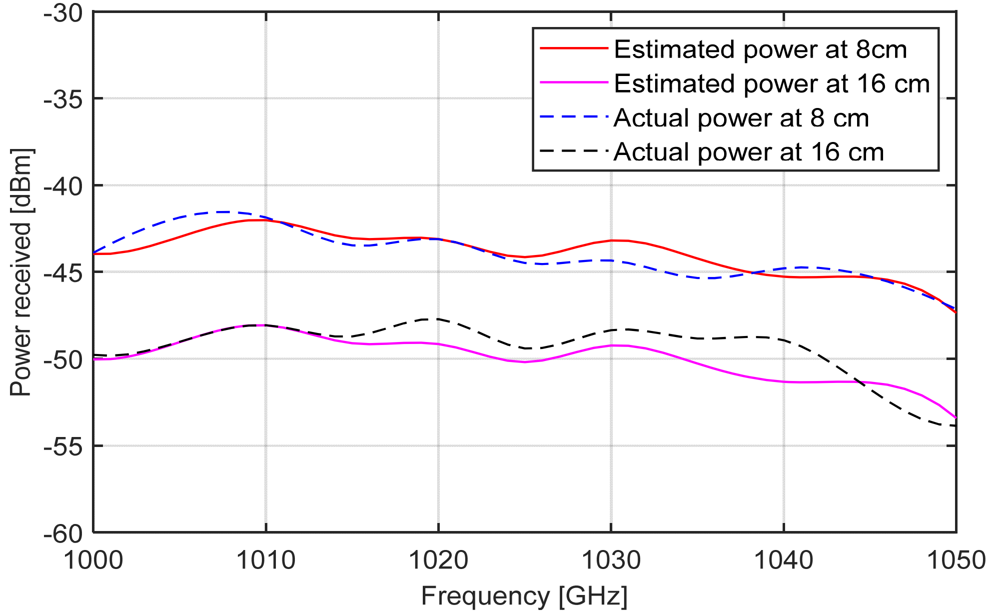
Experimental System Characterization and Result

- **Link budget analysis**
  - Match the theoretical received power and experimentally received power by taking into account the loss introduced by every element
    - $P_{rx} = P_{tx} + G_{tx} + G_{rx} + G_{LNA} - L_{spread} - L_{abs} - L_{mixer} - L_{misc}$
    - P_{tx} is transmitted signal power; G_{tx}, G_{rx} are the transmit and receive antenna gains, respectively; G_{LNA} is the LNA gain at the receiver; L_{spread} is spreading loss; L_{abs} is absorption loss; L_{mixer} is conversion loss at receiver and L_{misc} is miscellaneous losses in cables and connectors



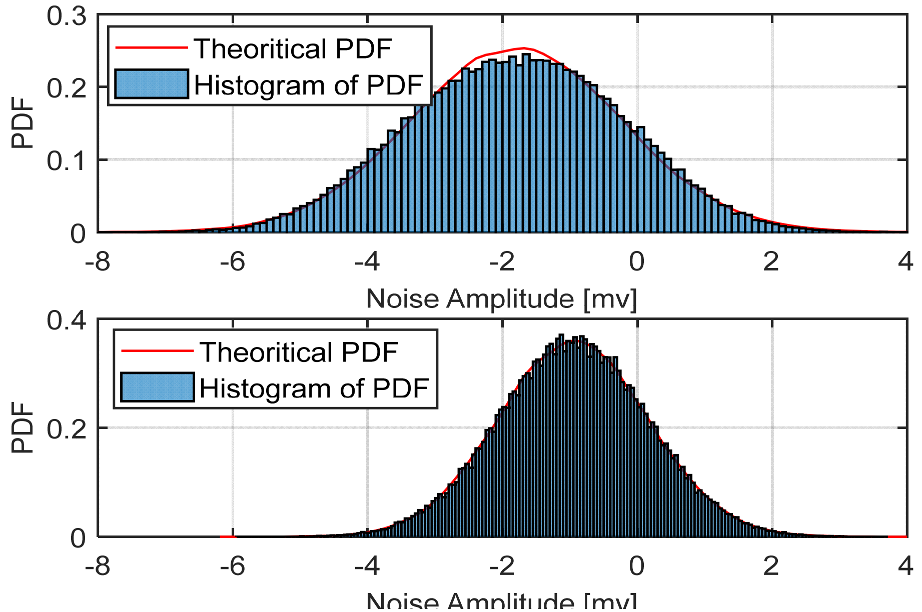
Experimental System Characterization and Result

- **Channel frequency characterization**
  - THz channel is characterized in vicinity of the first absorption-defined window above 1 THz.
  - The channel frequency characterization is done by generating a constant single tone IF of 500 MHz by AWG and sweeping the LO frequency at the transmitter and the receiver in fixed steps of 5 GHz, from 1 THz to 1.05 THz.
  - Simultaneous change the two LOs help to separate the impact of the up & down converters and mixers from the actual channel response.



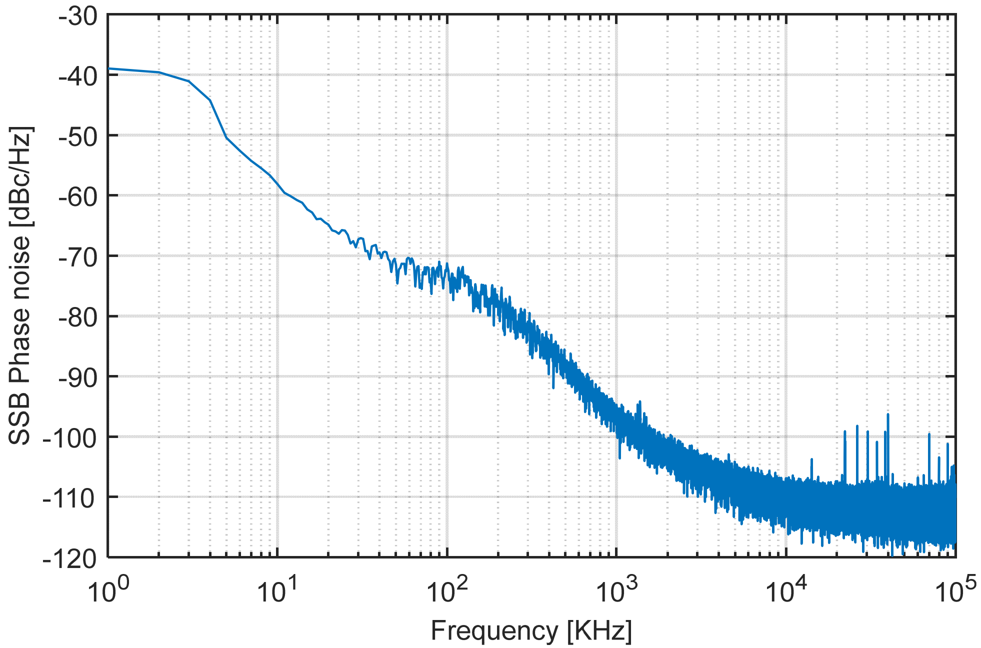
Experimental System Characterization and Result

- **Noise amplitude characterization**
  - Main source: thermal noise in the receiving chain, the absorption noise introduced by water vapor molecules, low frequency noise due to the power supply and the transmission chain.
  - It is an essential step to determine detection algorithm and further processing of the signal for detection of the bits
  - Noise follows a Gaussian distribution:
    - Mean -1.7 mv, variance 2.4 μw for the system with the down-converter added
    - Mean -0.95 mv, variance 1.2 μw for the system without the down-converter added



Experimental System Characterization and Result

- **Noise phase characterization**
  - Rapid, short-term, random fluctuations in phase due to time-domain instability
  - Measured by comparing the carrier power with the power of phase leakage for 1 Hz bandwidth at the different phase offset from the carrier frequency.
  - Very low single side band (SSB) phase noise at RF, -100 dBc/Hz at 1 MHz



Experimental System Characterization and Result

- **Data communication**
  - 10 frames of 2184 data bits consider for bit error rate (BER)

BPSK

BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
10/5	6	10	0
10/5	12	6	9.1×10^{-5}
20/10	6	4	1.8×10^{-4}
30/15	6	1.8	2.5×10^{-2}

QPSK

BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
10/10	6	10	0
10/10	12	6	9.1×10^{-4}
20/20	6	4	1.2×10^{-3}
30/30	6	1.8	8.7×10^{-2}

8-PSK

BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
10/15	6	10	9.1×10^{-5}
10/15	12	6	2.7×10^{-2}

Experimental System Characterization and Result

- **Data communication**
  - 10 frames of 2184 data bits consider for bit error rate (BER)

BPAM

BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
5/5	6	15.5	0
5/5	12	13	5.2×10^{-3}

4-PAM

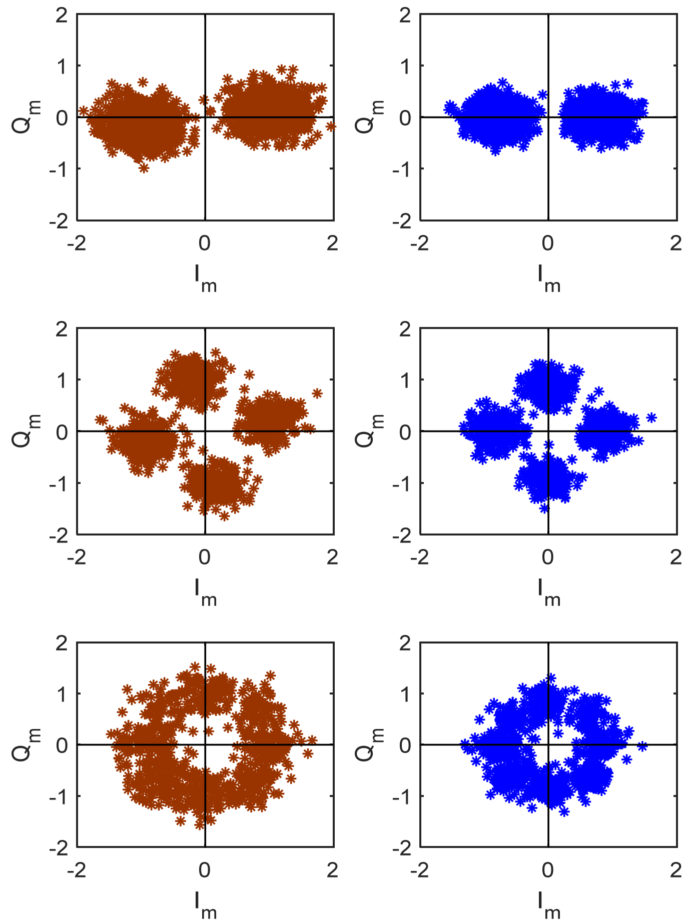
BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
5/10	6	12.3	3.7×10^{-2}

OFDM

BW (GHz)/ Rate (Gbps)	Distance (cm)	SNR (dB)	BER
10/9	6	16	7.3×10^{-4}
10/9	12	8	5.6×10^{-2}

Constellation diagram

- Constellation diagram of BPSK, QPSK and 8-PSK modulation at 13 cm distance with 10 GHz bandwidth
- After and before equalization
- Before equalization, the constellations are wide scattered
- Equalization corrects the phase of the modulation



Conclusion

- Link budget analysis and channel characterization experimental results closely match with the theoretically computed values.
- The results reinforce the system design and demonstrate the ultra-broadband response of the channel.
- Noise amplitude follows the Gaussian distribution and allows us to utilize ML type detectors.
- Low phase noise eases the design and implementation of single and multi-carrier modulations.
- BER results encourage the use of phase modulations with the current technology available.
- Wireless communications in the THz band (and beyond) will be a major part of 5G+/6G systems.