Towards Terabit Wireless Communications

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Outline

- Wireless Communication Evolution
- Integrated Space and Terrestrial Networks
- Millimetre Wave RF Backbone
- Other Enabling Techniques
- UTS Terabit Roadmap
- Conclusions

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What Is Beyond 5G

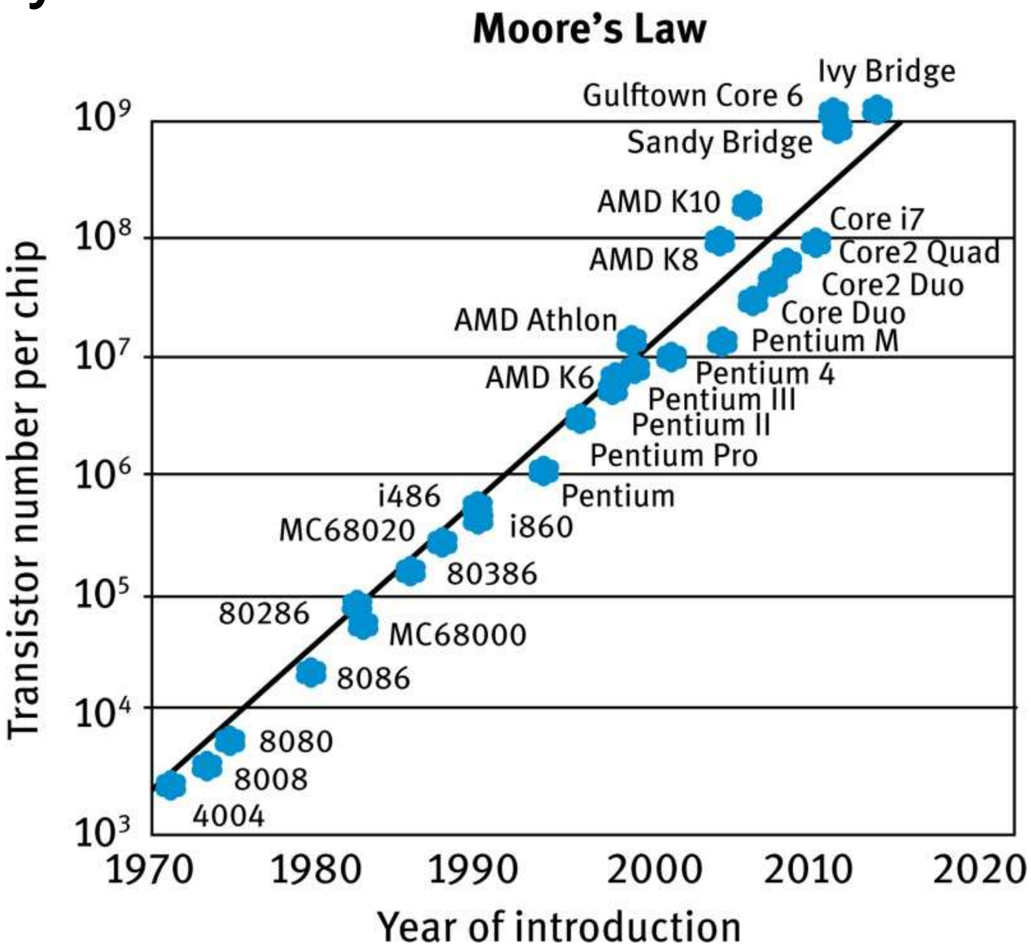
- The 5th generation mobile system aims at 1000 time capacity increase and enables more connections and new applications such as Internet of Things.
- However, 5G system is still ground based and its coverage is limited.
- With the 5G system to be deployed within one or two years by 2020, what will be the next move?

6G ?

ISTN ?

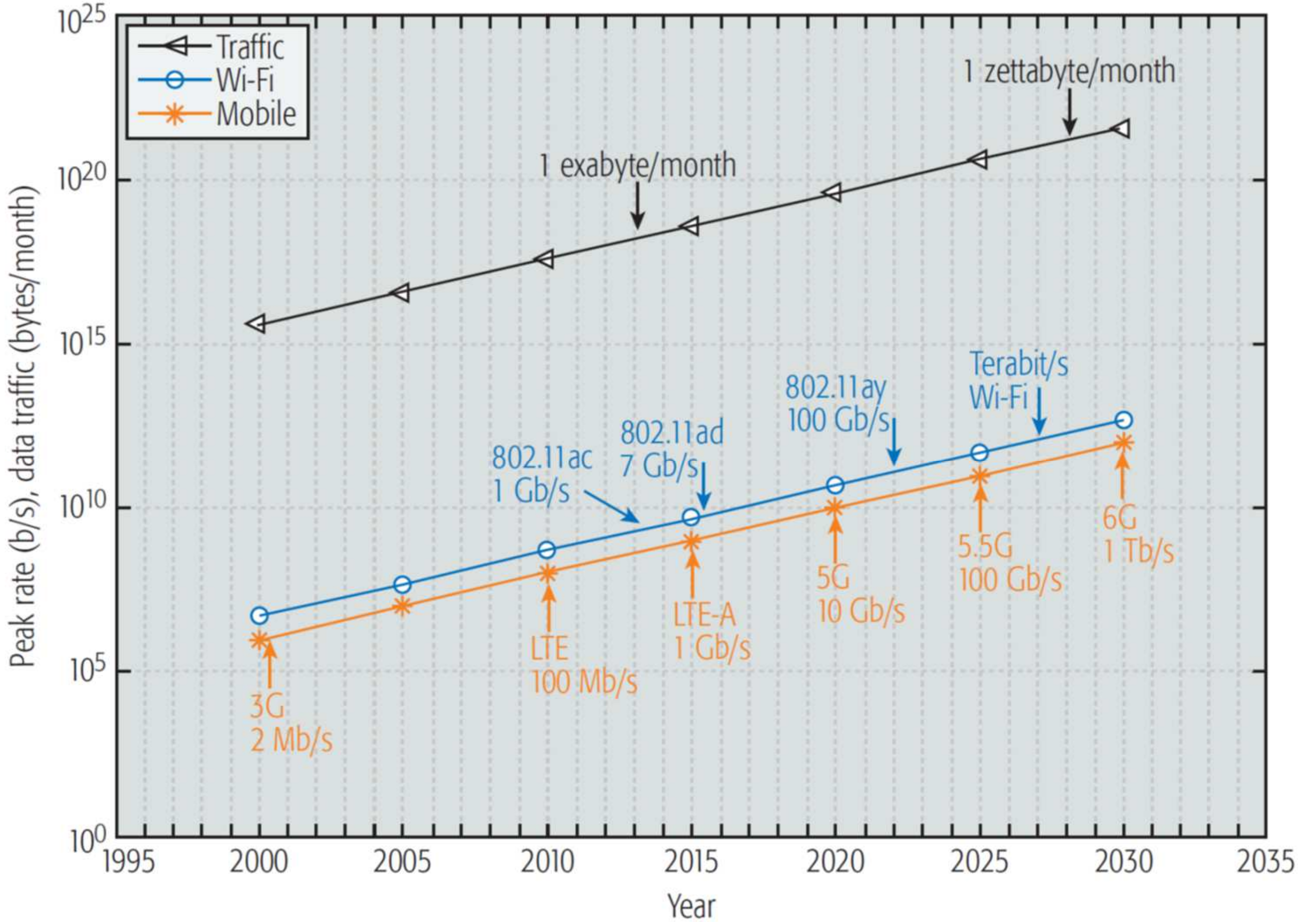
The Moore's Law

- Moore's law is the observation that the number of transistors in a dense integrated circuit doubles about every two years.



The "Omnify" Principle

- *Omnify* stands for ***O**rder of **m**ag**n**itude **i**ncrease every **f**ive **y**ears*. This means that demand for data increases 10 times every 5 years.



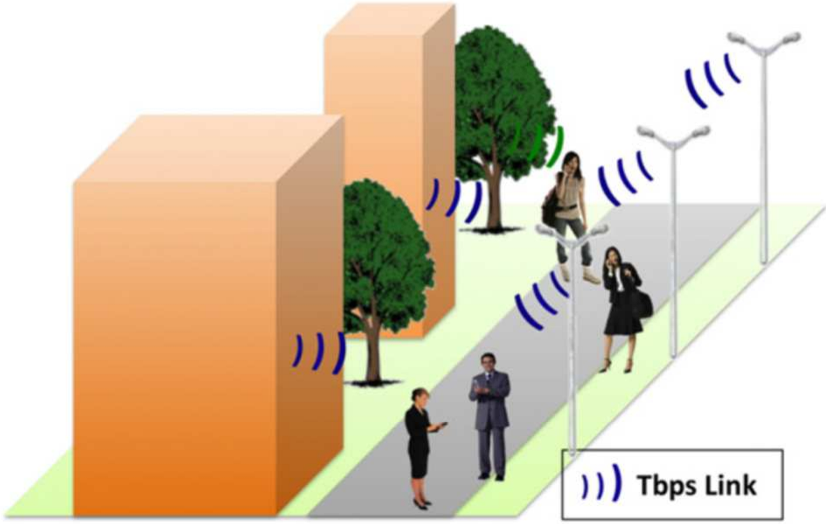
How to Achieve Tbps Data Rate?

- Terahertz (THz) band communication is envisioned as a key wireless technology to satisfy this demand.
- The THz band is the spectral band that spans the frequencies between 0.1 THz and 10 THz which is still one of the least explored frequency bands for communication.
- The THz band offers a much larger bandwidth, which ranges from tens of GHz up to several THz bandwidth, enabling Tbps data rate even with lower level modulation.

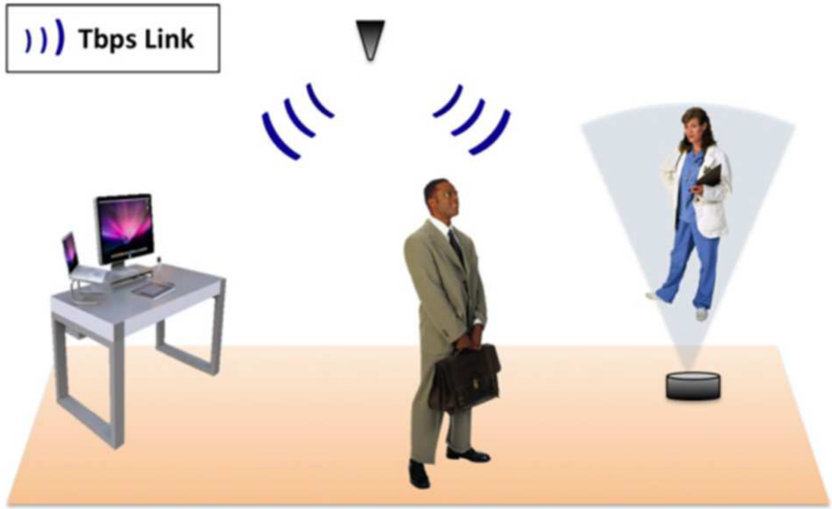
Challenges of THz Band Communication

- One of the main challenges is imposed by the very high path loss at THz band frequencies, which poses a major constraint on the communication distance.
- Additional challenges:
  - Implementation of compact high power THz band transceivers
  - Development of efficient ultra-broadband antennas at THz band frequencies,
  - Characterization of the frequency-selective path loss of the THz band channel,
  - Development of novel transmission schemes and communication protocols
  - ……

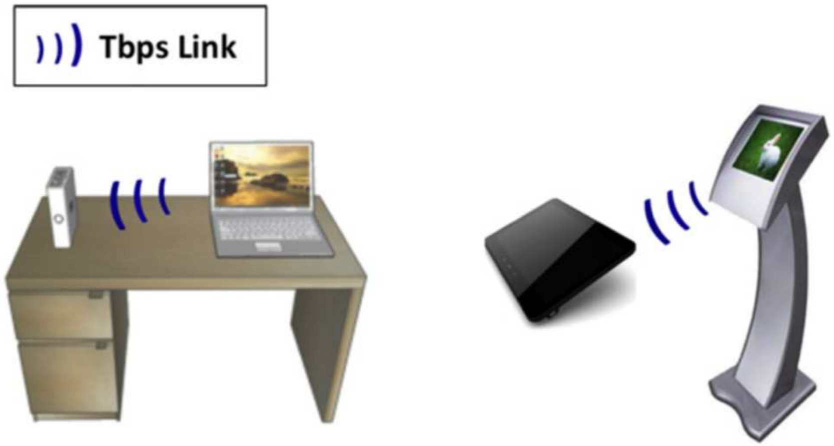
Application Scenarios of Tbps Wireless



(a) 5G cellular networks.



(b) Terabit wireless local area networks.



(c) Terabit wireless personal area networks.

(d) Secure wireless communication for military applications.

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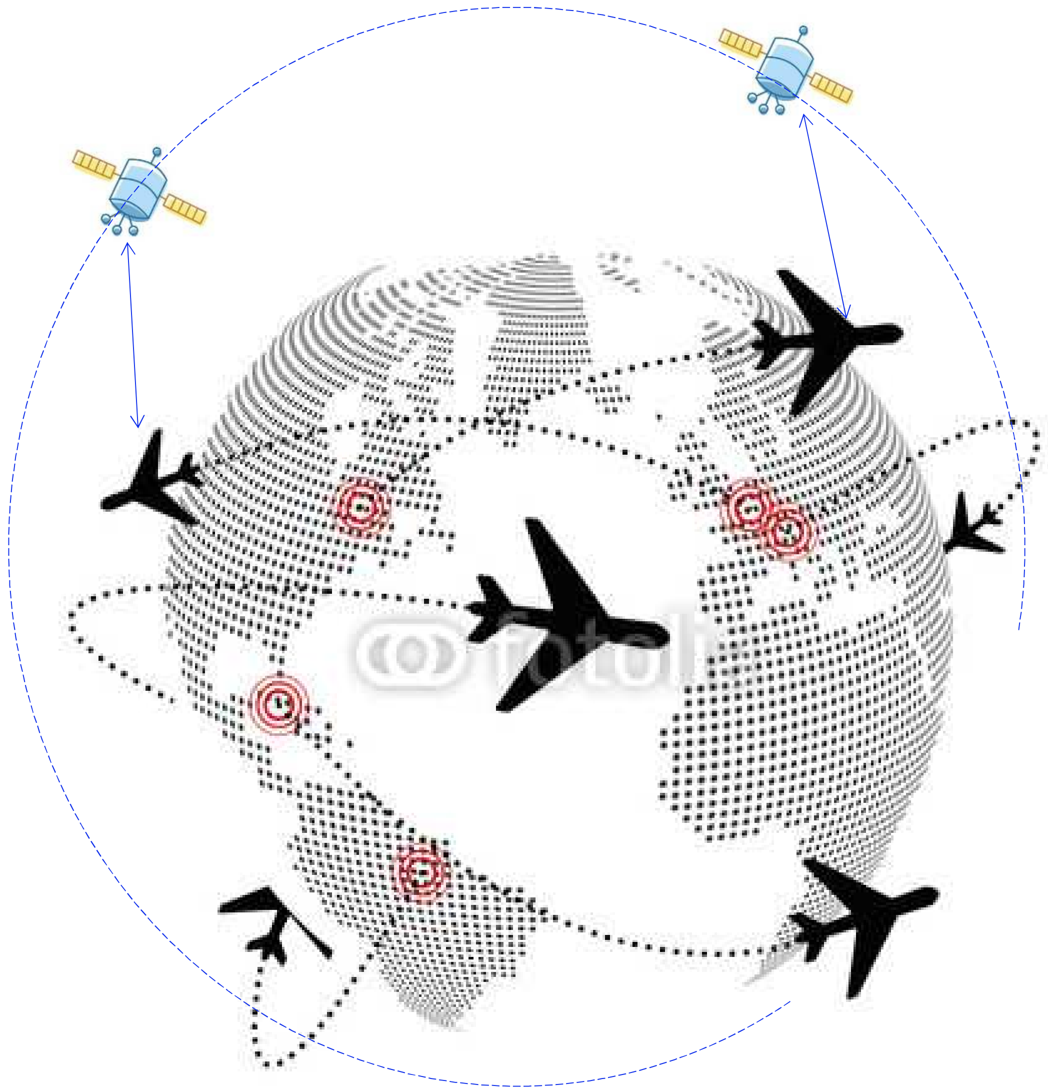
How to Extend Wireless for Coverage

- In parallel with the development of terrestrial mobile systems such as 5G, another major international effort in wireless communications is the development of space communications networks.
- Space communications networks enable global wireless connectivity at any time and from anywhere… on the sea, in rural and remote areas, over the air and space.

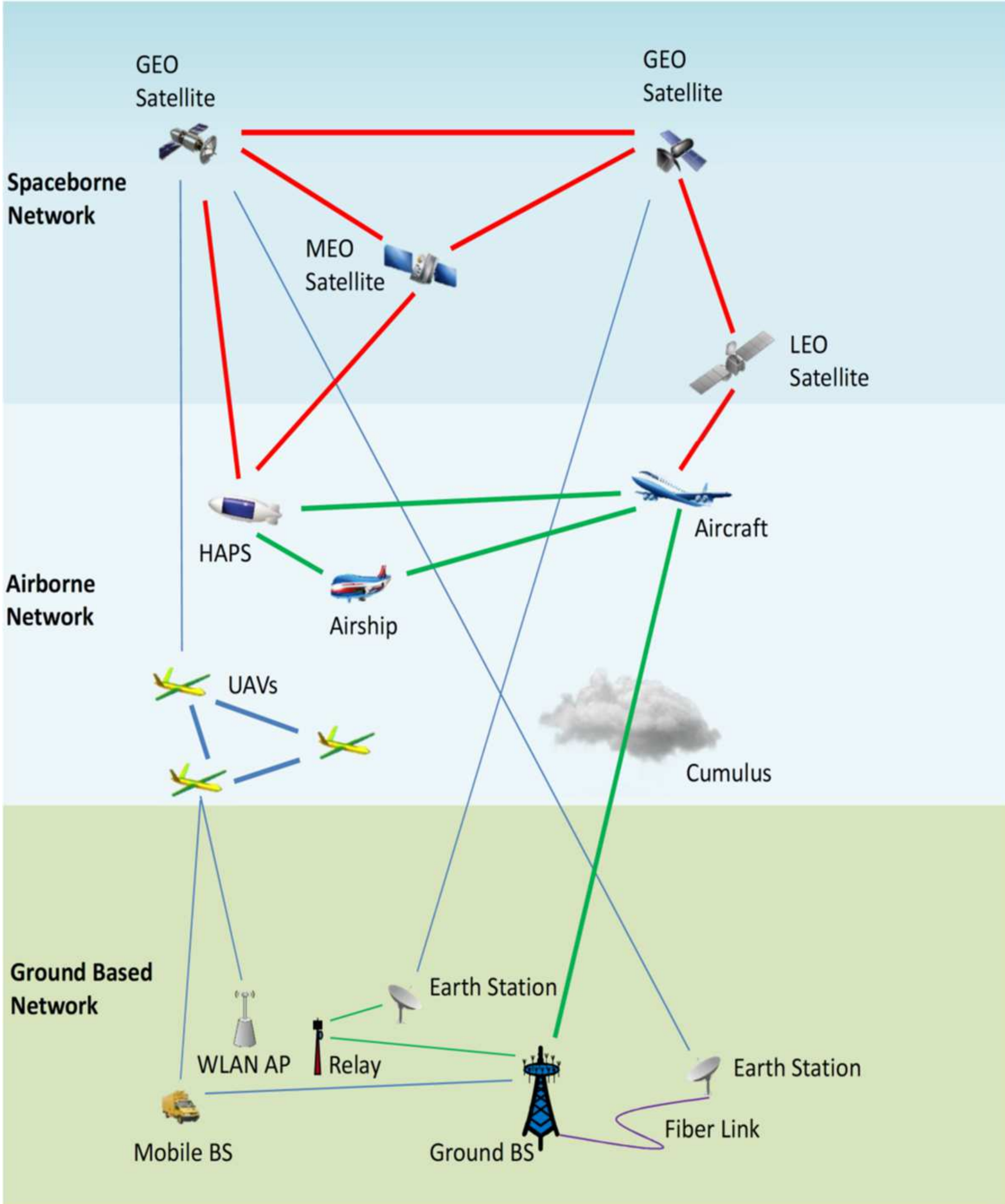


History of Space Network

- The concept of using various space platforms to perform data acquisition, transmission and information processing has been around for several tens of years.
- Such space platforms include Geosynchronous Earth Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites, Low Earth Orbit (LEO) satellites, as well as high-altitude platform stations (HAPSs).
- Evolution: Narrowband satellite communications systems (Iridium and Globalstar) → Wideband satellite communications systems (not implemented) → Space Internet (O3b Networks)

Integrated Space and Terrestrial Network

- Interconnecting spaceborne, airborne and ground based transmission platforms to form a global seamless communications system.
- This will be one of the future directions of communications technology research and development.



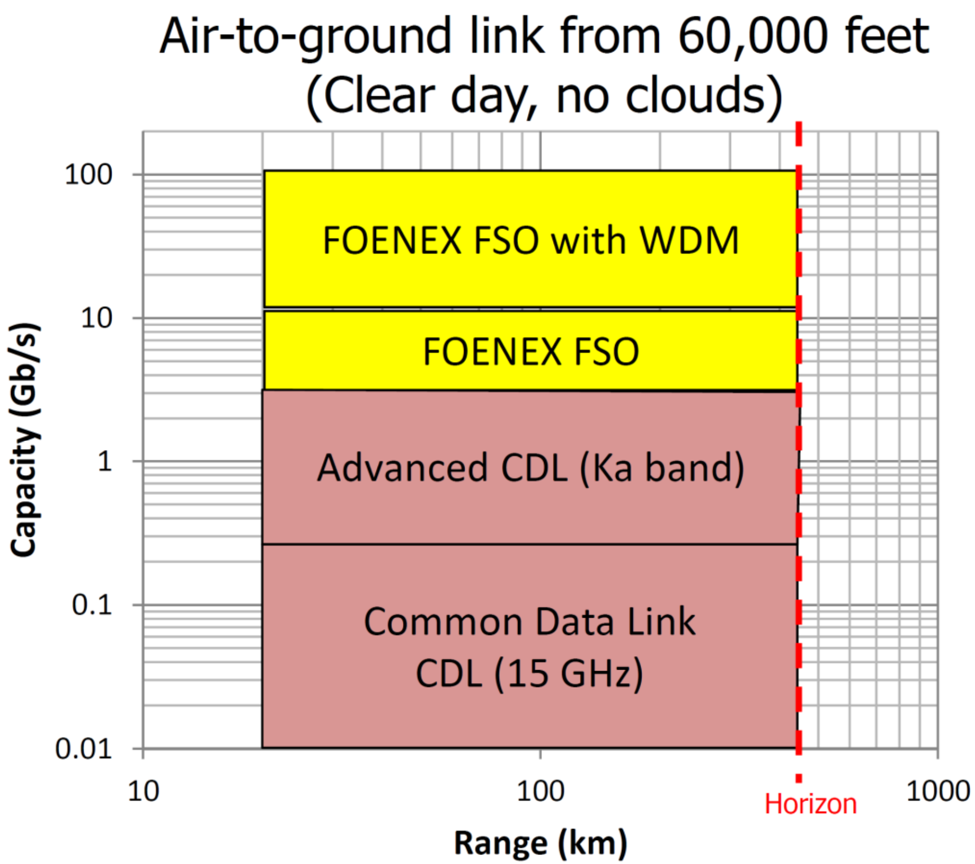
Importance of High-Speed Backbone

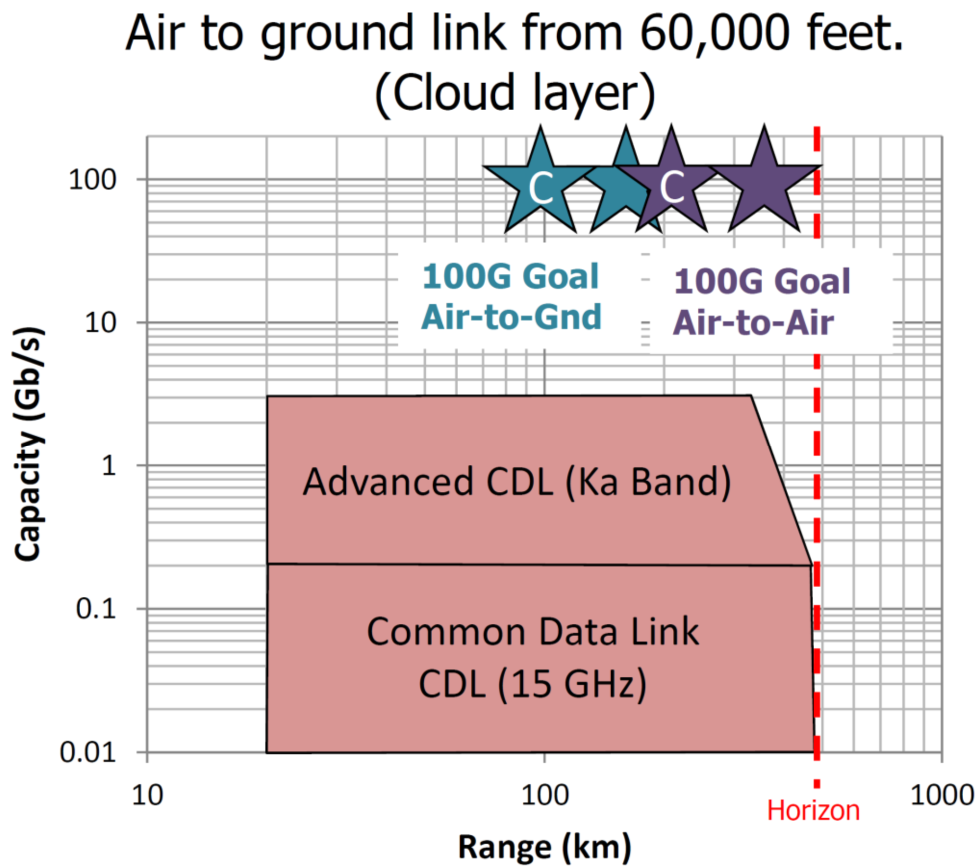
- Backbone communications networks consist of various high-capacity links to interconnect the major nodes of the information network and to handle the aggregated voice, video, Internet, and enterprise data flows.
- Conventional telecommunication infrastructure relies heavily on single-mode optical fiber as the data backbone.
- However, the air-space-ground integrated information network can't rely on a fixed infrastructure and instead needs a means of projecting fiber-optic-equivalent capacity anywhere and anytime.

Free-Space Optical (FSO) Links

- A logical approach is to use FSO links to achieve the required capacity.
- FSO links have been shown to have fiber-optic-equivalent capacity at long ranges and are expected to play a significant role in the airborne-based backbone.
- However, FSO links can’t propagate through clouds, which are present 40% of the time in some regions and lead to unacceptable network availability.

State-of-the-Art of Airborne-Based Backbones





Excerpted from DARPA Free Space Optical Experimental Network Experiment (FOENEX) Program(2011-213)

DARPA 100G RF Backbone Program

- The goals of 100 G RF Backbone program:
  - To design, build and test an airborne-based communications link with fiber-optic-equivalent capacity and long reach that can propagate through clouds and provide high availability.
  - To provide 100 Gbps capacity at ranges of 200 km for air-to-air links and 100 km for air-to-ground links from a high-altitude (e.g. 60,000 ft.) aerial platform.
  - To provide an all-weather (cloud, rain, and fog) capability while maintaining tactically-relevant throughput and link ranges.
  - Size, weight, and power (SWaP) will be limited by the host platforms, which will primarily be high-altitude, long-endurance aerial platforms.

How to Achieve 100 Gbps Capacity

$$\text{Capacity} = M\ B \log_2(1 + S/N)$$

- Increase the system bandwidth, which usually requires moving to higher frequencies where atmospheric losses can reduce link performance.
- Apply spectrally-efficient modulation, such as quadrature amplitude modulation, which requires increasing the signal power in order to achieve the signal-to-noise ratio required to demodulate the signal.
- Use multiple independent channels, such as spatial multiplexing, polarization multiplexing, and/or orbital angular momentum; some of which require multiple antenna apertures.

mm-Wave is the best choice

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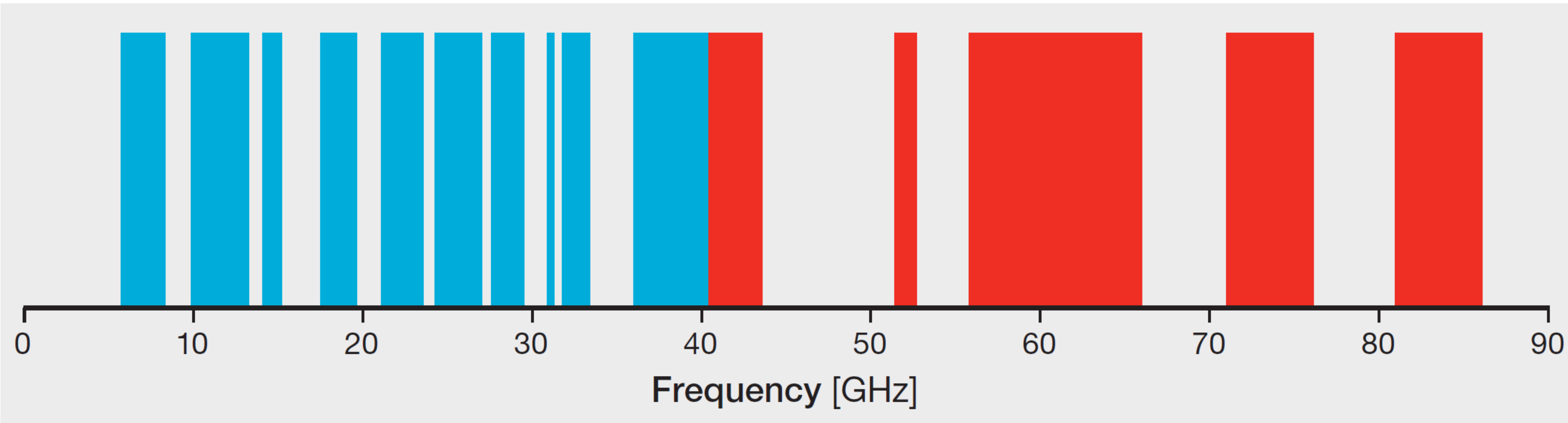
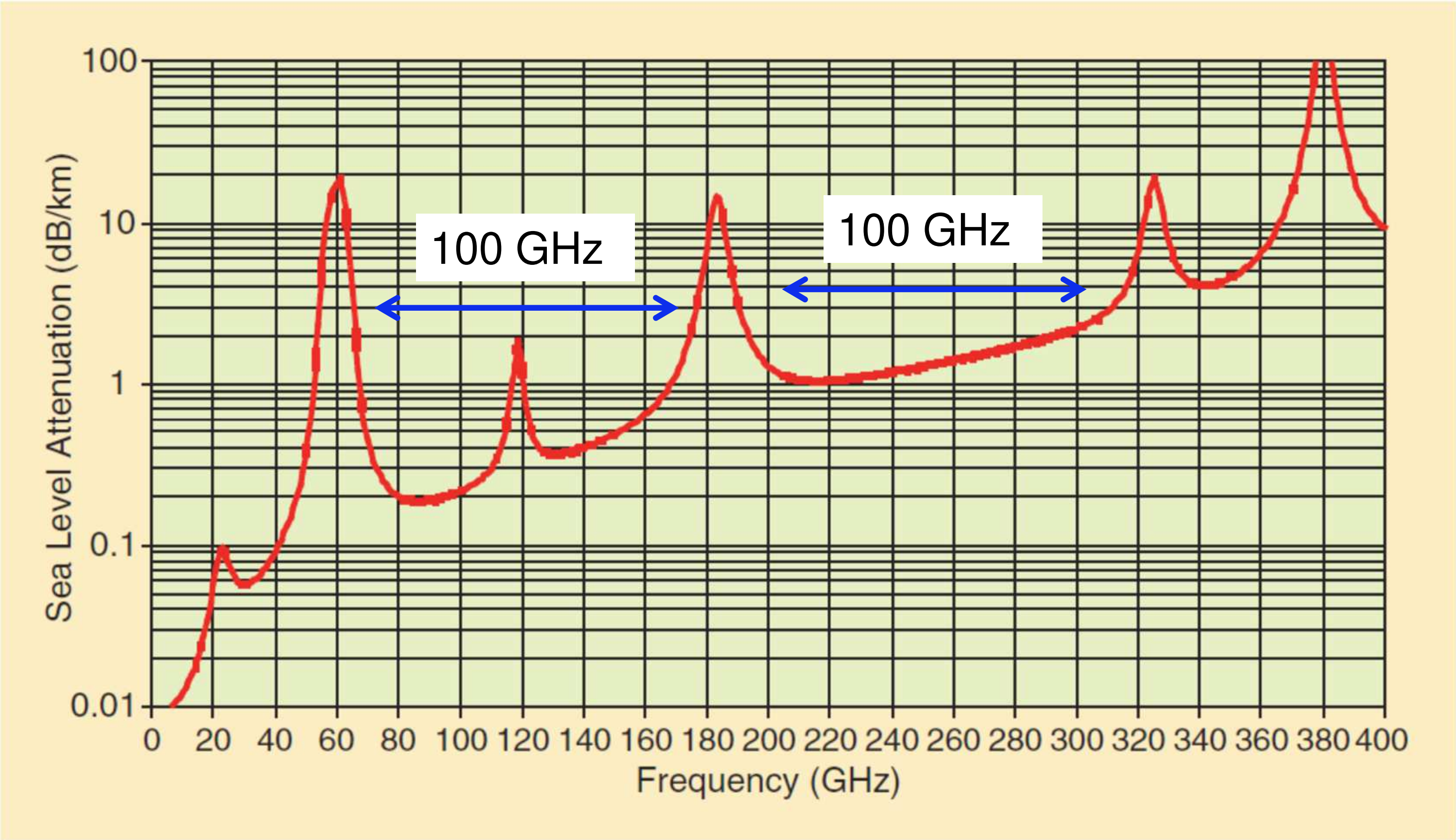
A Natural Shift to Higher Frequencies

- More bandwidth is available in upper microwave frequency bands and millimeter wave (mm-Wave) frequency bands.
- However, larger path loss will reduce the communication range.



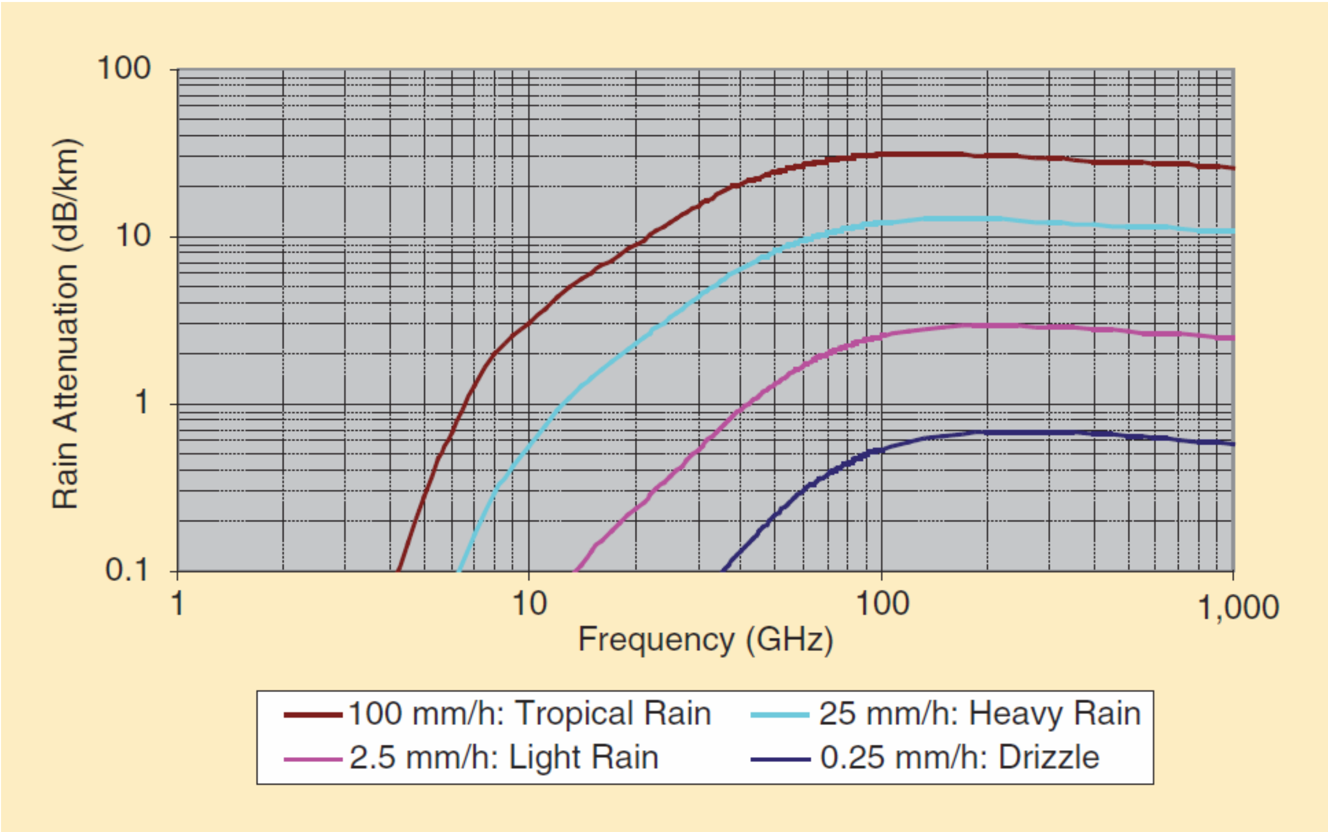
Atmospheric Absorption

- Within so-called atmospheric windows (35, 90, 140, 220 GHz and upwards), attenuation due to atmospheric absorption is minimized, allowing superior wireless transmission.

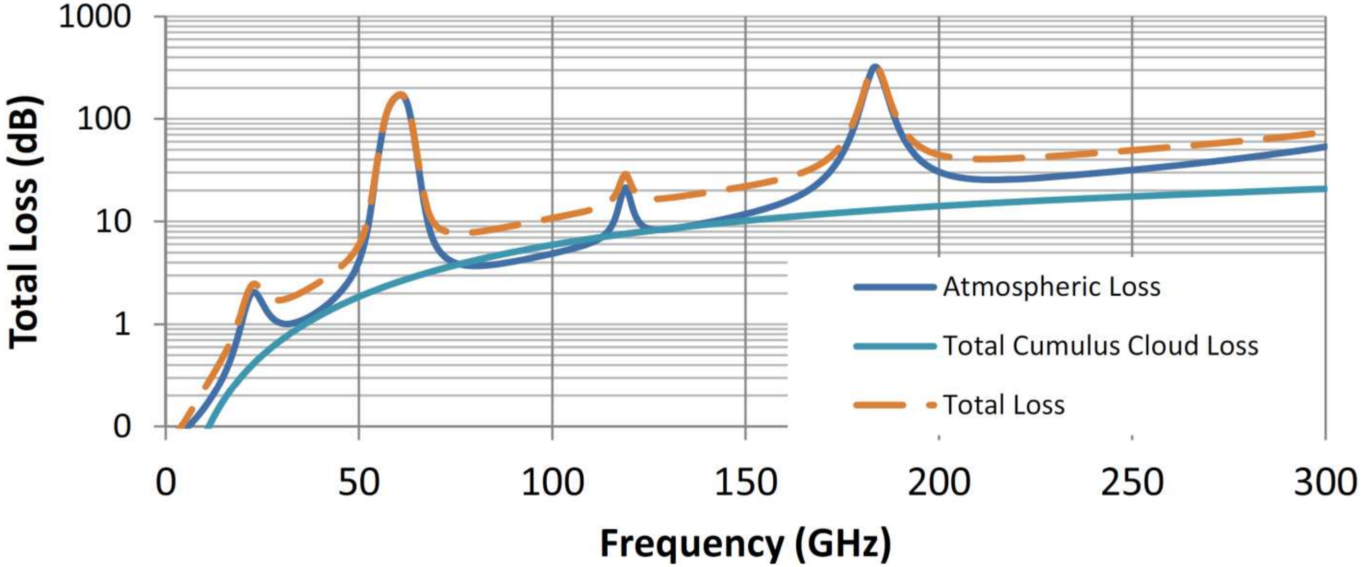


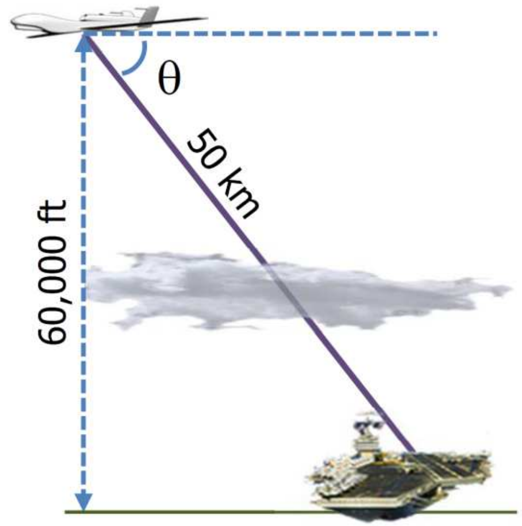
Rain Attenuation

- The main factor that limits available communication range at the upper microwave and mm-wave frequencies is the rain attenuation.



Total Loss Through Cloud



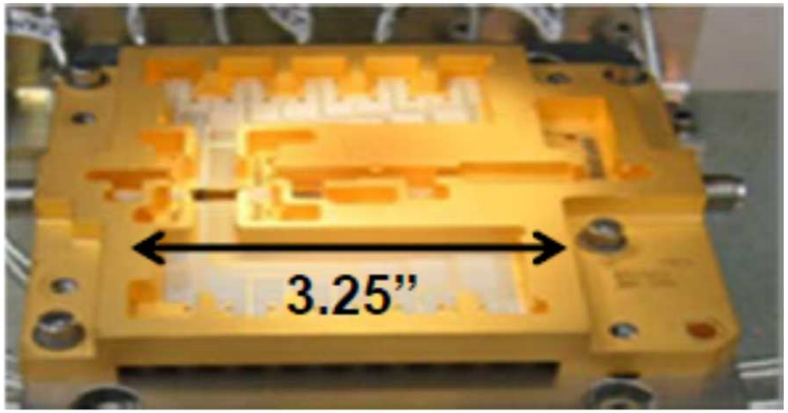


Assumptions:
Air-to-ground link
Height: 60,000 feet
(18 km)
Tx Aperture: 12″
Rx Aperture: 12″

Excerpted from DARPA 100 Gb/s RF Backbone (100G) Proposers' Day Briefing

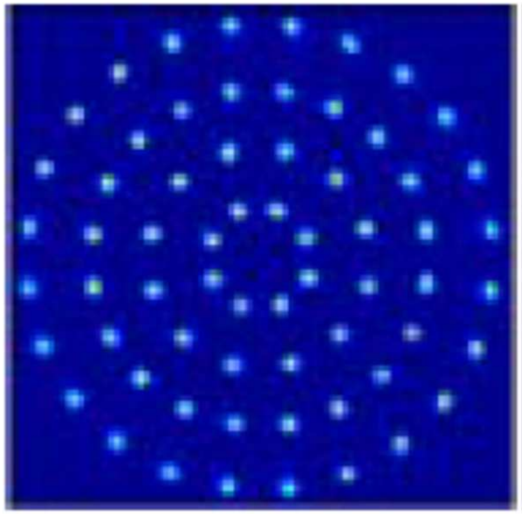
DARPA's 100G Solution

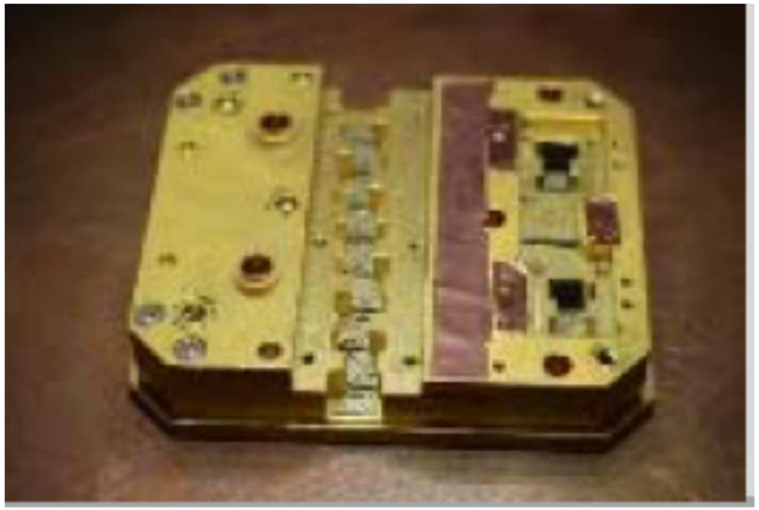
- Phase 1 of the program has been completed, in which the fundamental techniques and building blocks are developed
- Phase 2 of the program is the system design and integration completed by the end of 2017.
- Some highlights of Phase 1 achievements are
  - Direct digital to RF conversion using Indium Phosphide (InP) modulator at data rate in excess of 25 Gbps within 5 GHz bandwidth



Some Highlights of Phase 1 Achievements

- Direct digital to RF conversion using Indium Phosphide (InP) modulator at data rate in excess of 25 Gbps within 5 GHz bandwidth
- Nyquist Cyclic Modulation with 32APSK and 64APSK to achieve low PAPR
- 20 dBW power amplifier
- Photonic approaches to generate millimetre-wave signals
- ADC and DAC sampling rate in excess of 10 Gsps





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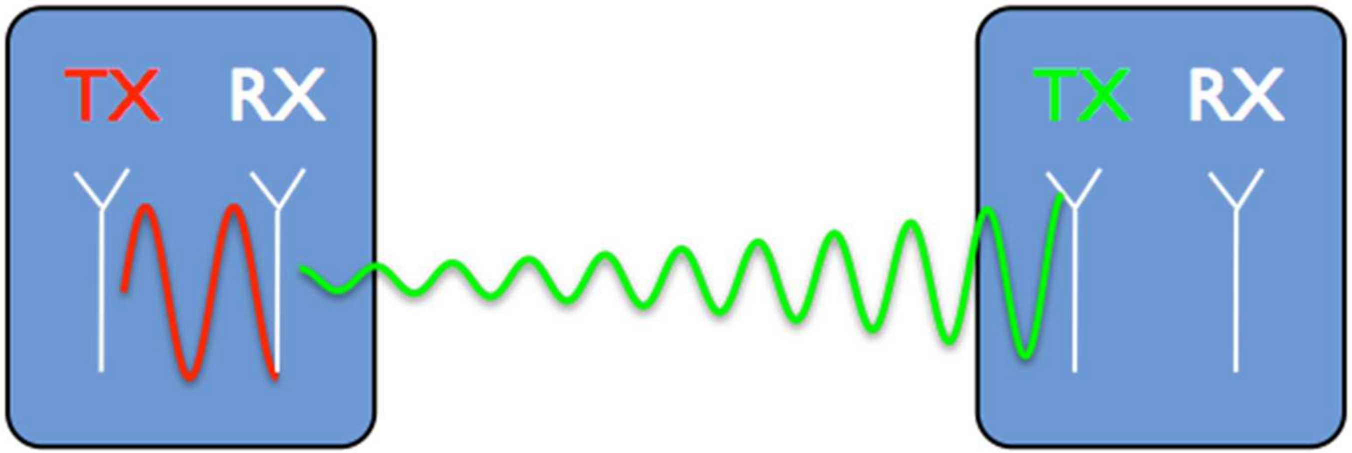
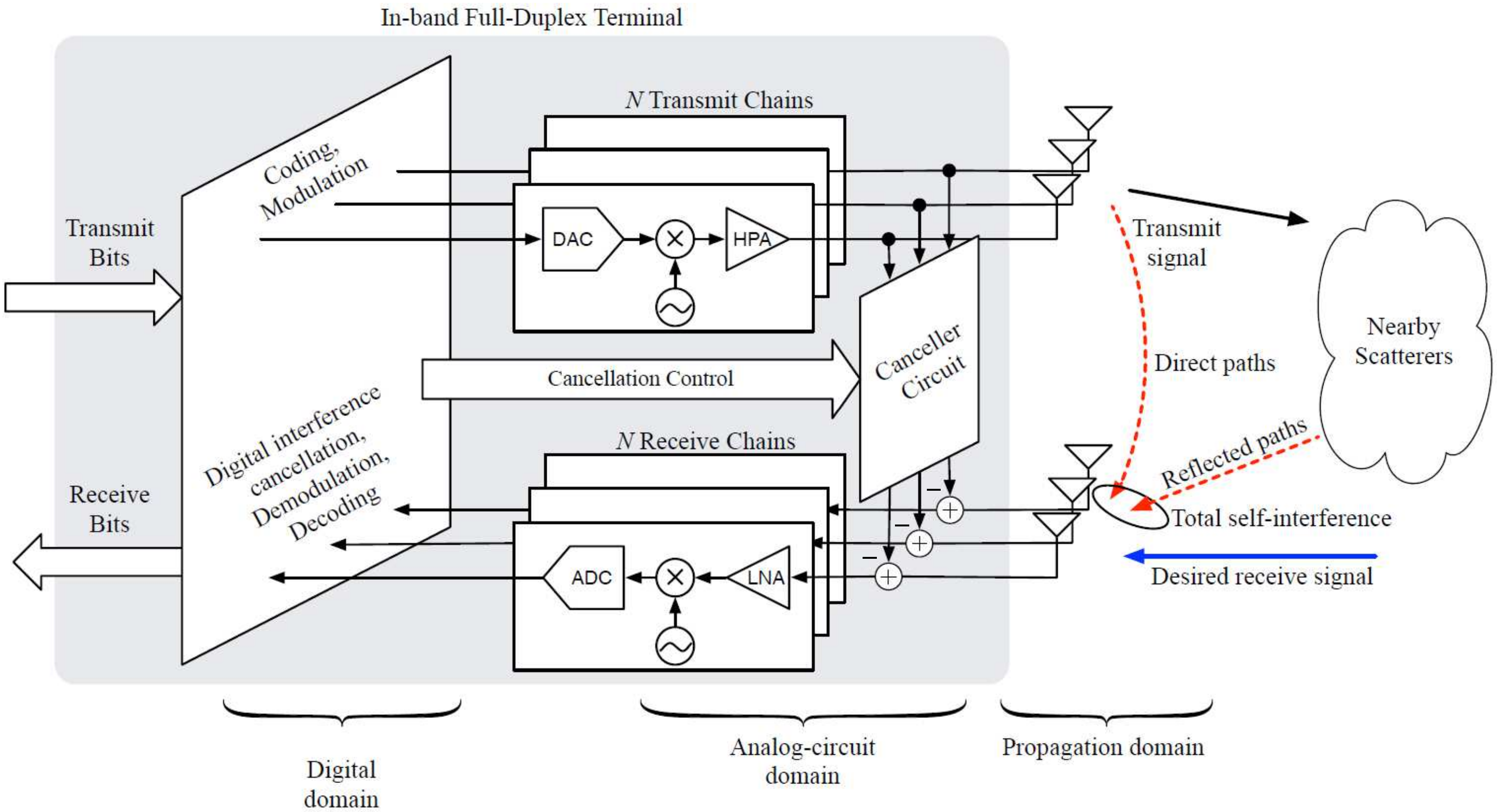
In-Band Full Duplex

- In-band full duplex (IBFD) can be used to further improve the spectral efficiency in mm-Wave frequencies.
- Among the various challenging issues which need to be solved before the full duplex radio becomes a reality, self-interference from the transmitter to the co-located receiver is the most fundamental one.



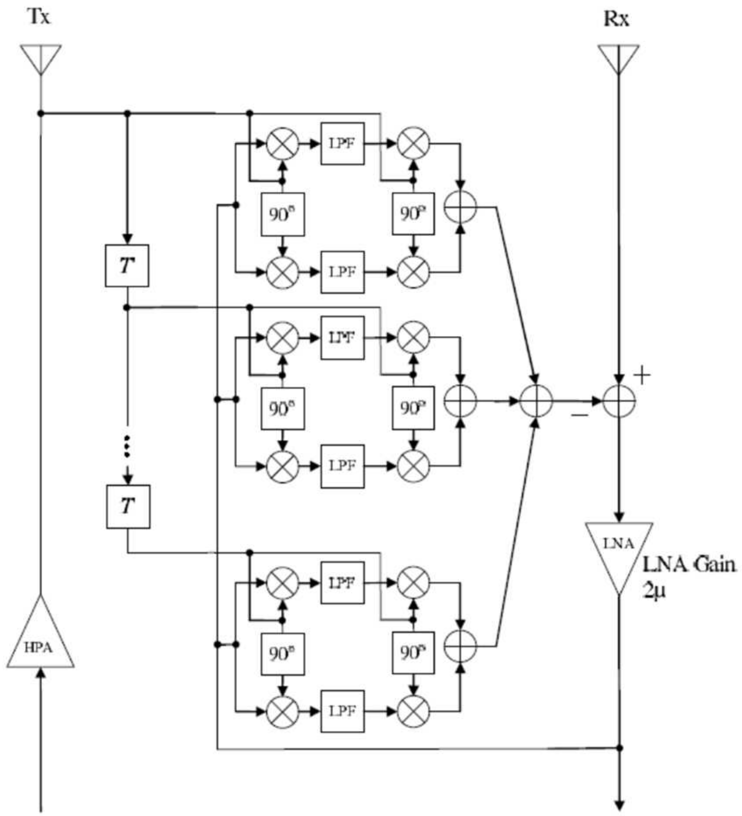
Sources of Self-interference

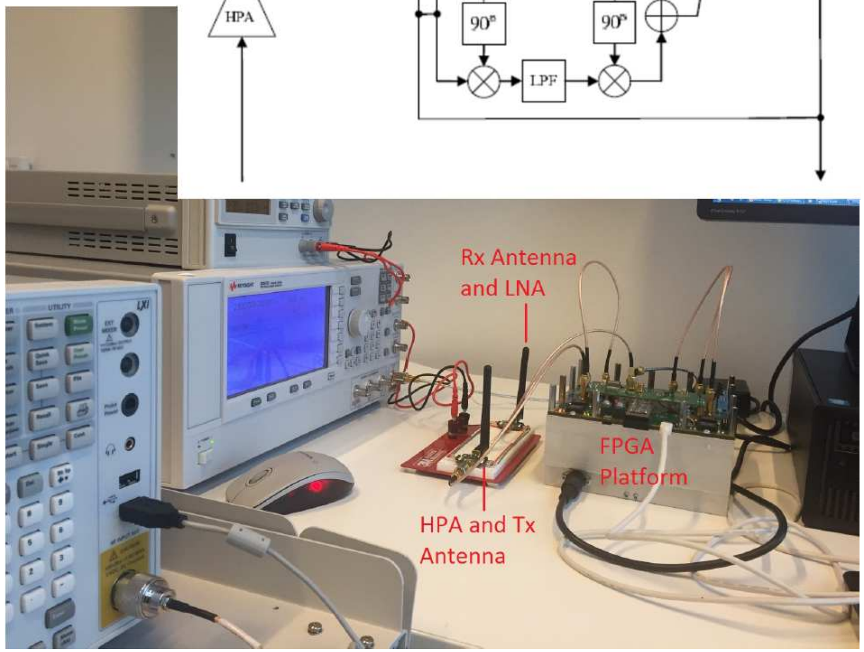
- Internal Interference: quantization noise, phase noise, amplifier distortion, …
- Direct path self-interference or leakage
- Near field reflected path self-interference



Novel SIC by ALMS Loop

- Weighting coefficients are automatically adapted by ALMS loop with simple RC circuits.
- Implemented directly at RF not baseband.
- We have proved that the interference suppression ratio (ISR) is determined by the loop gain (including LAN gain) and transmitted signal power (given the multiplier dimensional constants).

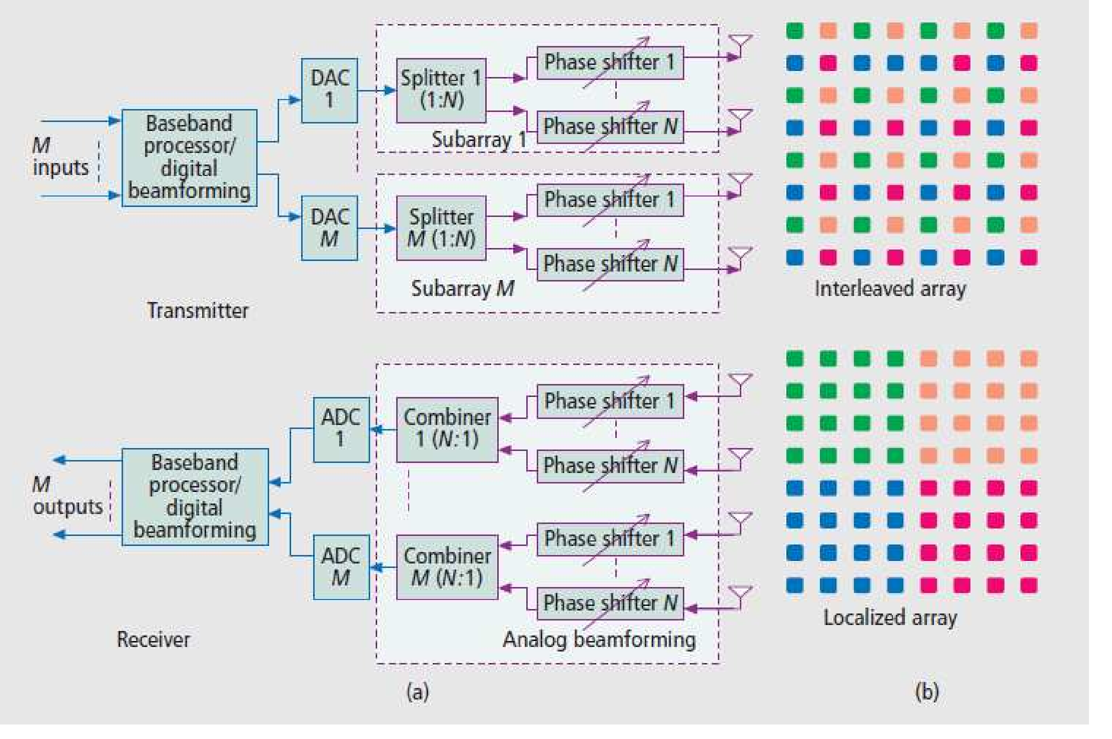




Xiaojing Huang and Y. Jay Guo, “Radio Frequency Self-Interference Cancellation with Analog Least Mean Square Loop,” IEEE Transactions on Microwave Theory and Techniques, Vol. 65, No. 9, September 2017, pp. 3336 – 3350.

mm-Wave Hybrid Antenna Array

- A full digital implementation of wideband antenna array at mm-wave frequencies is unrealistic due to the space constraint and digital signal processing cost.
- Advantages of hybrid array solution:
  - Reduced RF and digital cost
  - High transmit power for longer range operation
  - Optimized system performance
  - SDMA for Direct air-to-Ground (DA2G) communications



X. Huang, et. al., "A hybrid adaptive antenna array," IEEE Trans . on Wireless Communications, Vol. 9, No. 5, May 2010, pp. 1770-1779.

Patent, Publications, and Prototyping

- Y. Jay Guo, John Bunton, Val Dyadyuk, and **Xiaojing Huang**, "Multi-stage Hybrid Adaptive Antennas," filed on 2 February 2009, AU2009900371, PCT published on 20 August 2010, WO 2010/085854 A1.
- **Xiaojing Huang**, Y. Jay Guo, and John Bunton, "A Hybrid Adaptive Antenna Array," *IEEE Transactions on Wireless communications*, Vol. 9, No. 5, May 2010, pp. 1770-1779.
- **Xiaojing Huang** and Y. Jay Guo, "Frequency-Domain AoA Estimation and Beamforming with Hybrid Antenna Array," *IEEE Transactions on Wireless Communications*, Vol. 10, No. 8, August 2011, pp.2543-2553.
- Jian (Andrew) Zhang, **Xiaojing Huang**, Val Dyadyuk, and Y. Jay Guo, "Massive Hybrid Antenna Array for Millimeter Wave Cellular Communications," *IEEE Wireless Communications Magazine*, Vol. 22, No. 1, February 2015, pp. 79 – 87.
- Hang Li, Thomas (Qian) Wang, **Xiaojing Huang**, and Y. Jay Guo, "Adaptive AoA and Polarization Estimation for Receiving Polarized mmWave Signals," to appear in *IEEE Wireless Communications Letters (Accepted on 26 October 2018).*

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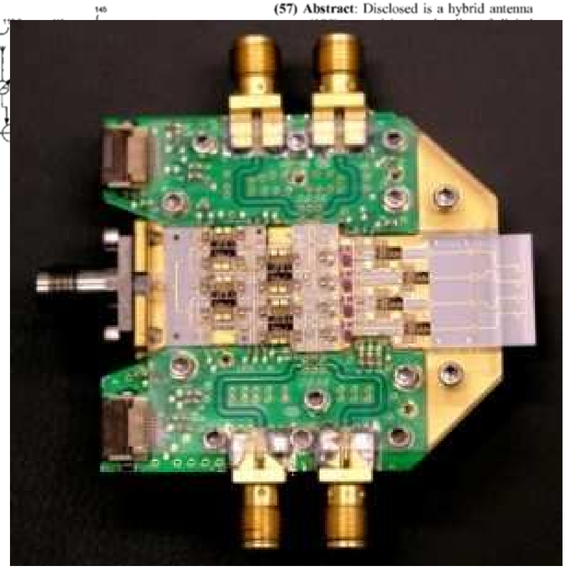
Published:
— *with international search report (Art. 21(3))*

(54) Title: HYBRID ADAPTIVE ANTENNA ARRAY

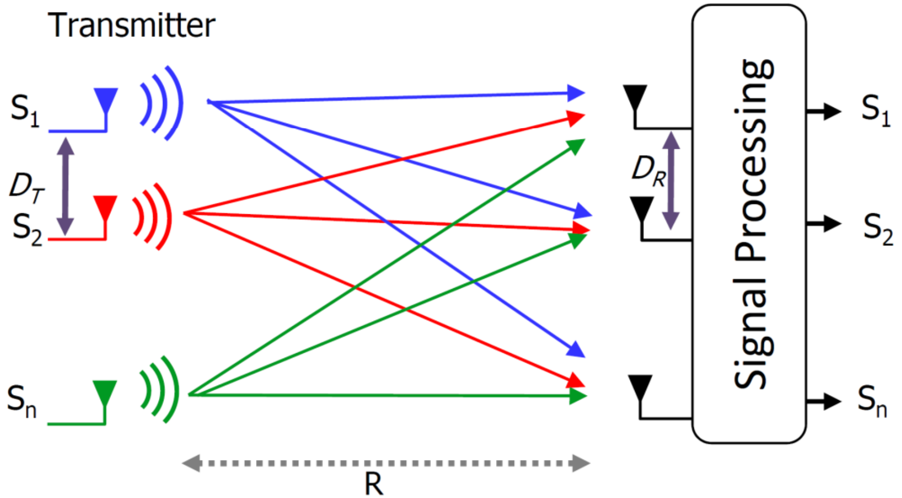
(57) Abstract: Disclosed is a hybrid antenna

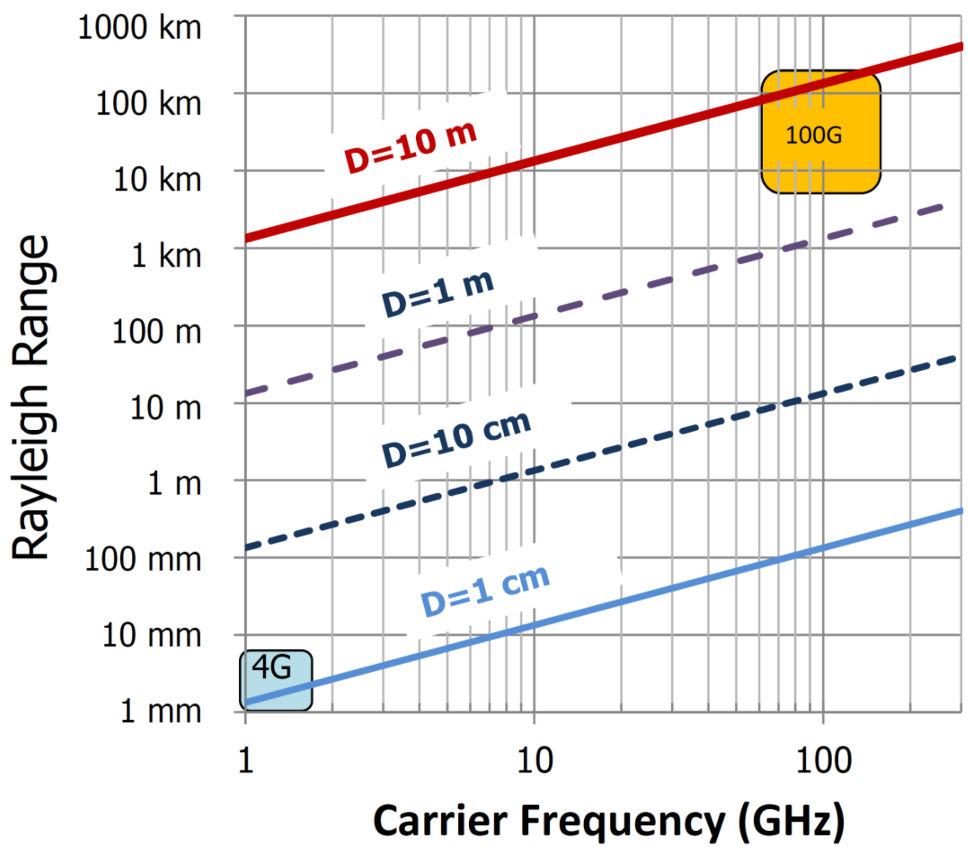


LOS-MIMO

- Use Spatial Multiplexing, operating at or near the Rayleigh Range to form multiple independent channels

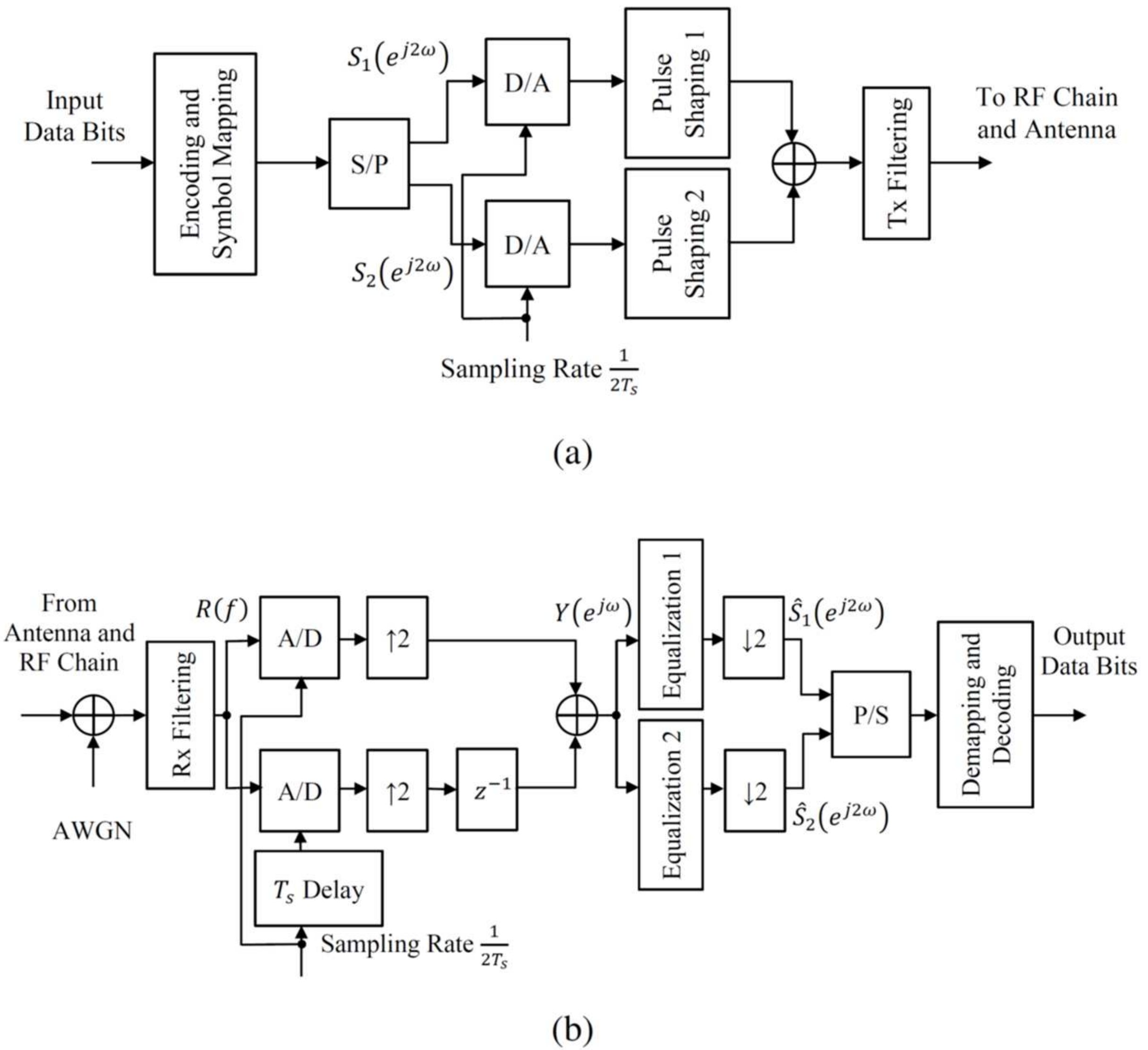
$$R \leq \frac{nD_T D_R}{\lambda}$$





Low Cost Analog-to-Digital Conversion

- UTS patented technology called dual pulse shaping (DPS) transmission
- It enables a mm-wave system with commercially available and affordable data conversion devices.
- With DPS, the system can achieve full Nyquist rate transmission with only half of the sampling rate required by conventional Nyquist pulse shaping.



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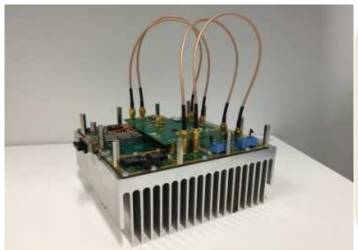
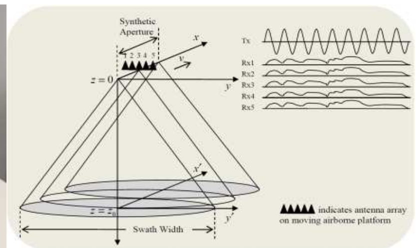
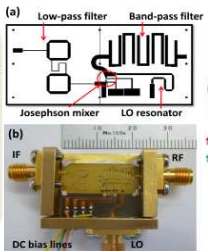
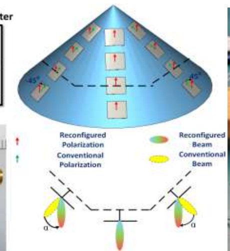
UTS Track Record on High Speed Systems

- Our capabilities:
  - Reconfigurable and multiband antennas
  - Image radar and radio holography
  - Full duplex wireless communication
  - Coding, modulation, signal processing for wireless systems
  - Real-time implementation of communication protocols and standards
  - Prototyping of high speed microwave, millimetre wave and terahertz systems
- Our track record:
  - 10 Gbps microwave system using band and channel aggregation
  - 5 to 20 Gbps millimetre wave and terahertz systems
  - Successful technology transfer to telecommunication industry

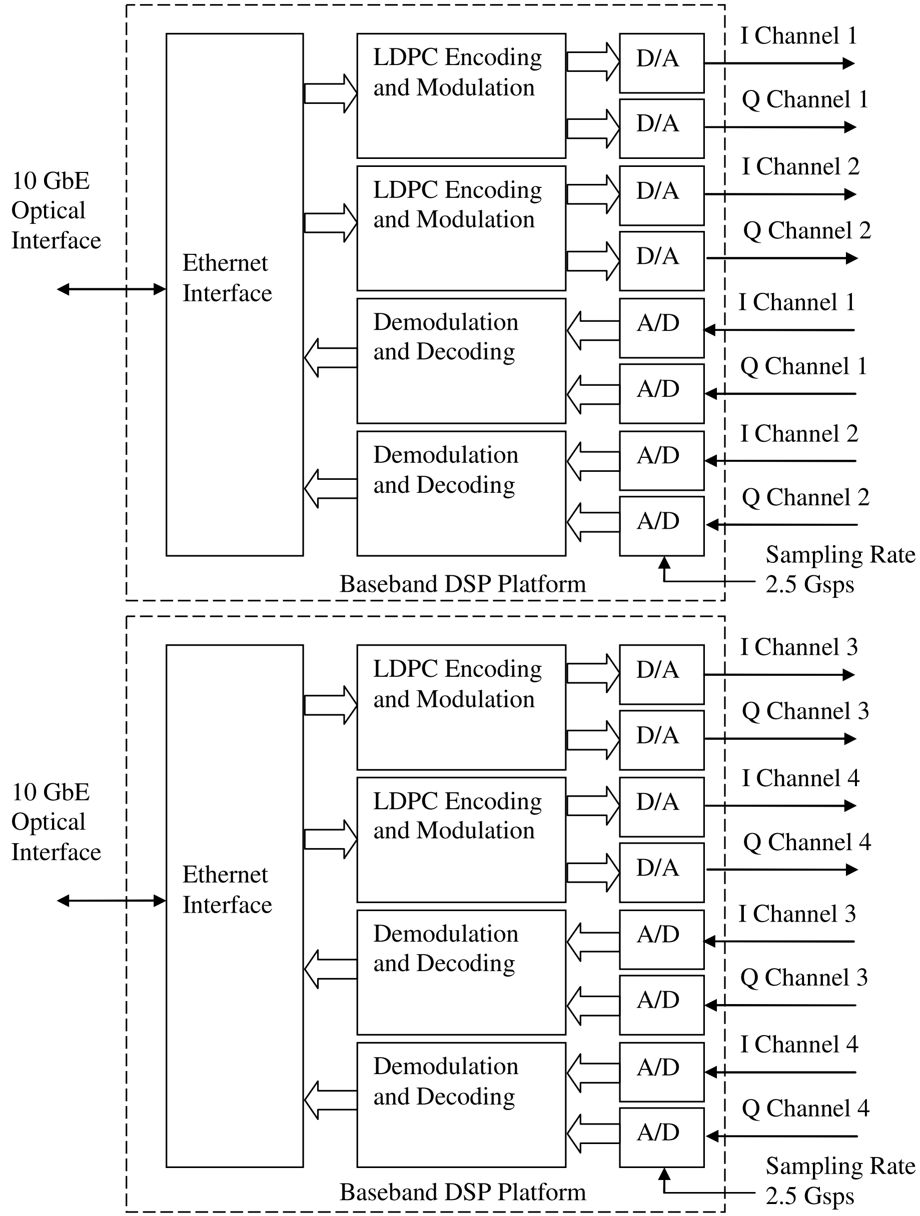







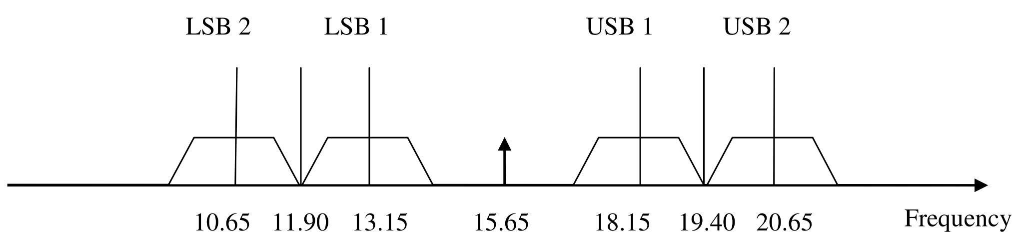

Current 20 Gbps Modem: DSP Platform

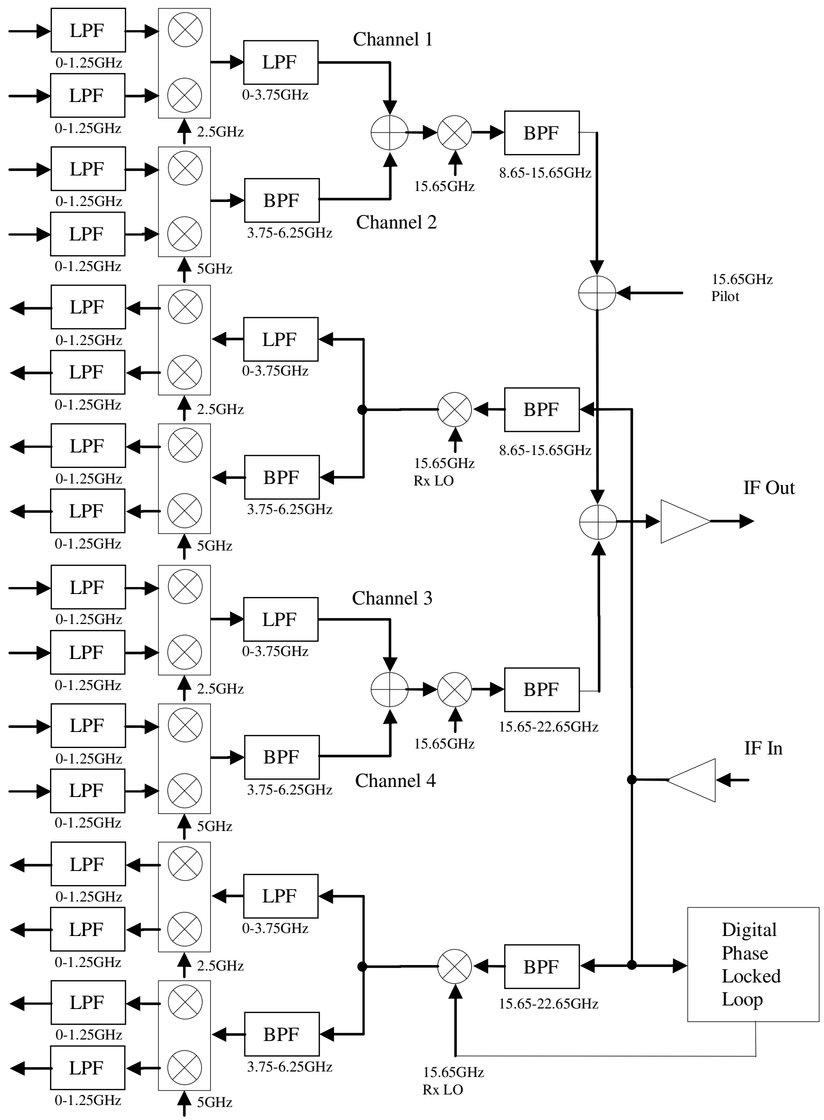
- The platform has one 10 GbE interface, a FPGA signal processing module and four D/As and A/Ds to generate/receive two I/Q baseband signals
- D/A and A/D sampling rate = 2.5 Gsps
- FPGA uses Xilinx Virtex 7 with clock 312.5 MHz
- Each I/Q channel provides 5 Gbps data rate
- Total data rate = 20 Gbps in two directions



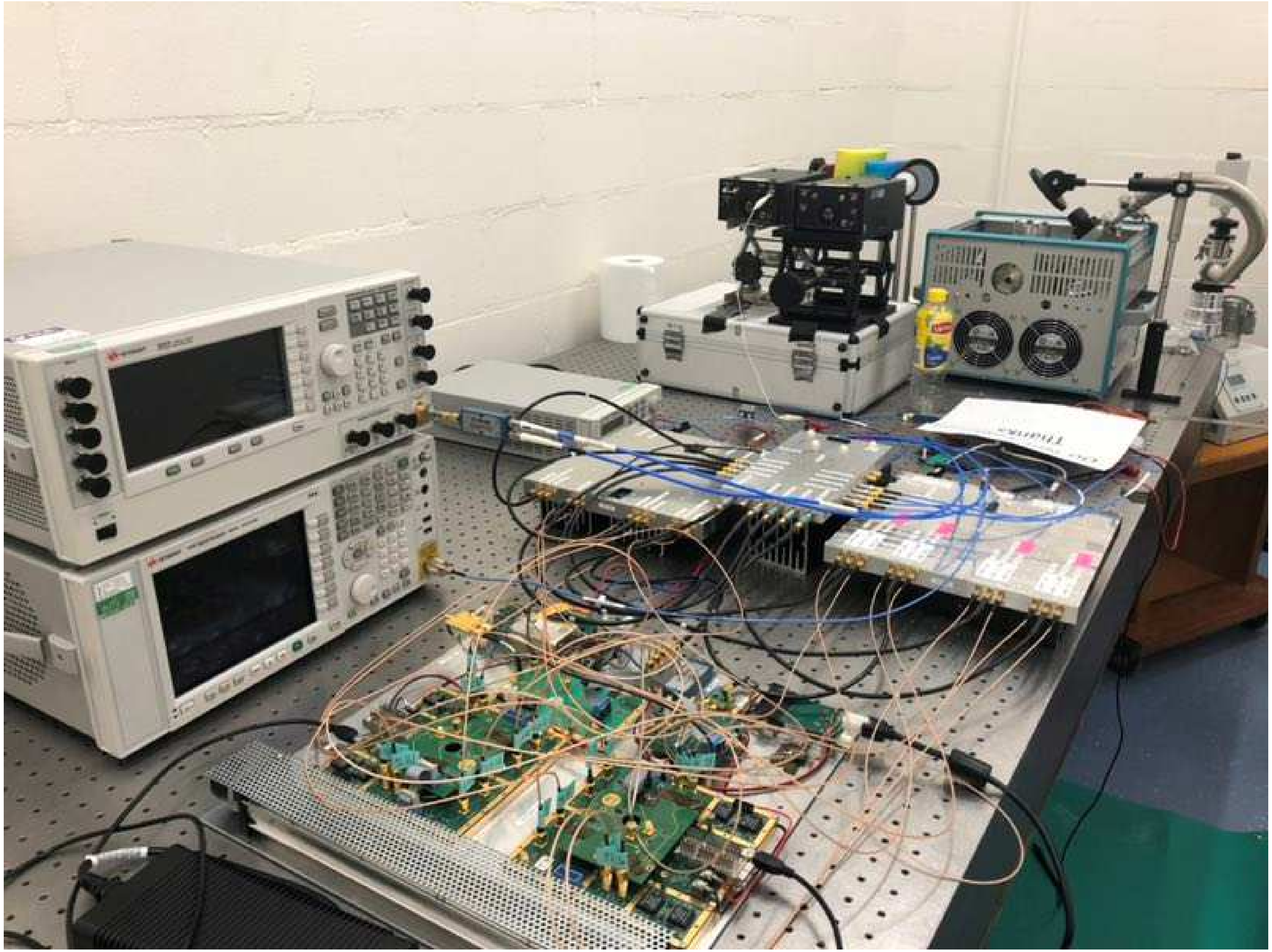
Current 20 Gbps Modem: IF Module

- Two I/Q channels in each DSP platform are up-converted to 15.65 GHz IF (lower or upper sideband)
- The lower and upper sidebands are combined to form a 12.5 GHz IF signal with center frequency 15.65 GHz
- A 15.65 GHz pilot is also added for carrier frequency tracking
- Digital phase locked loop is also implemented for large tracking range

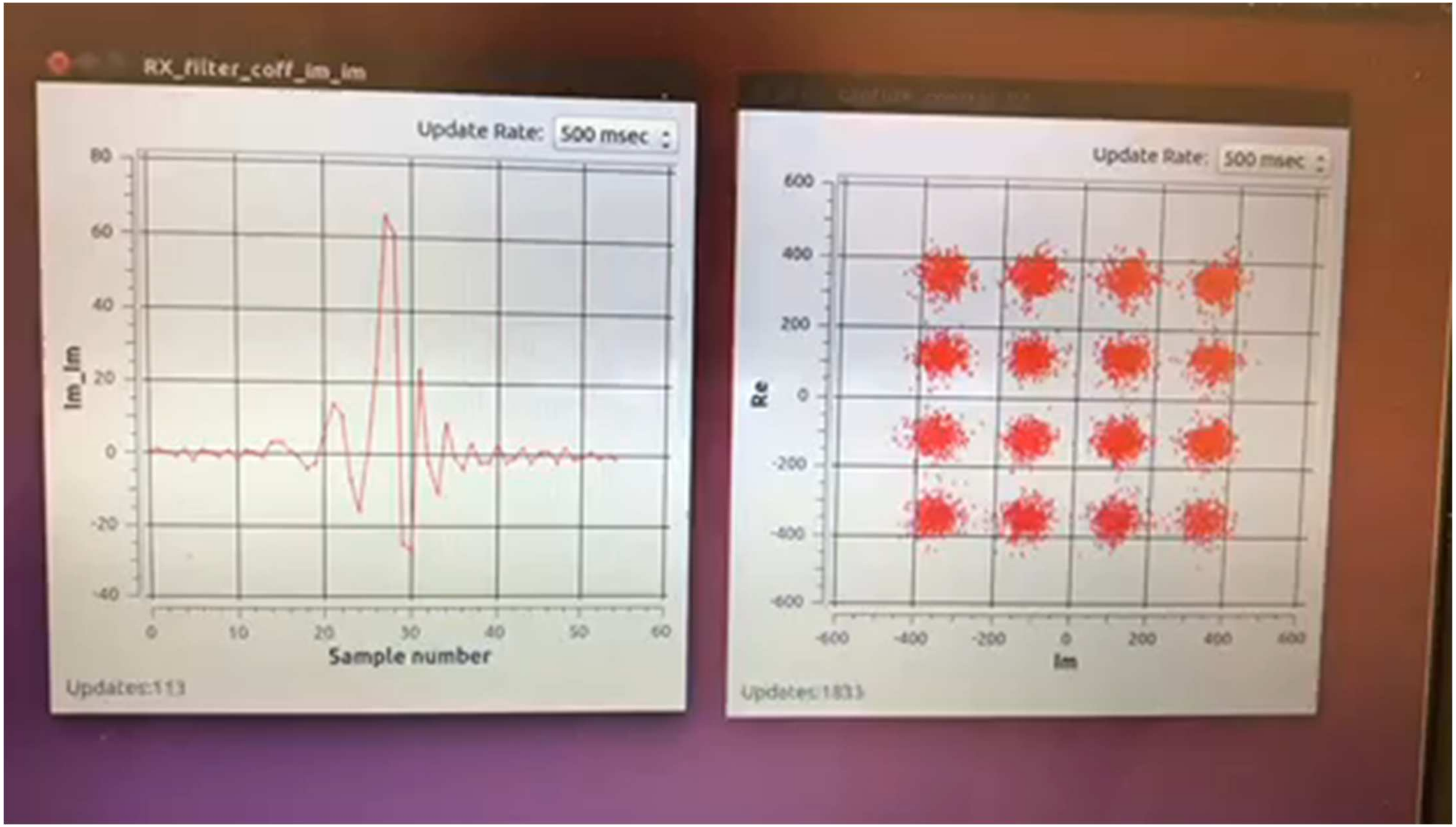




UTS 20 Gbps THz System Test Setup

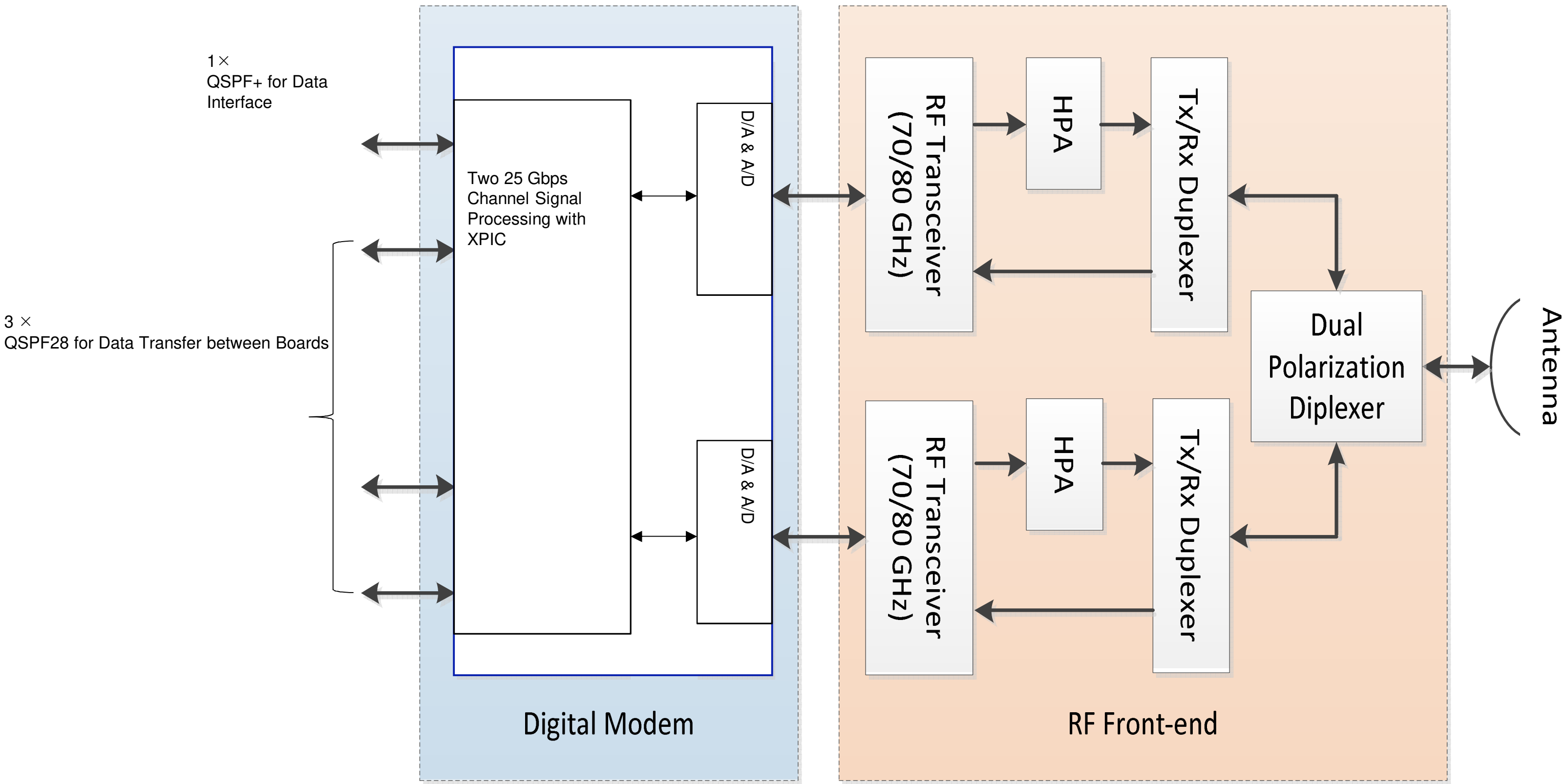


UTS 20 Gbps THz System Live 16QAM Test



Current 50 Gbps E-band Project: System

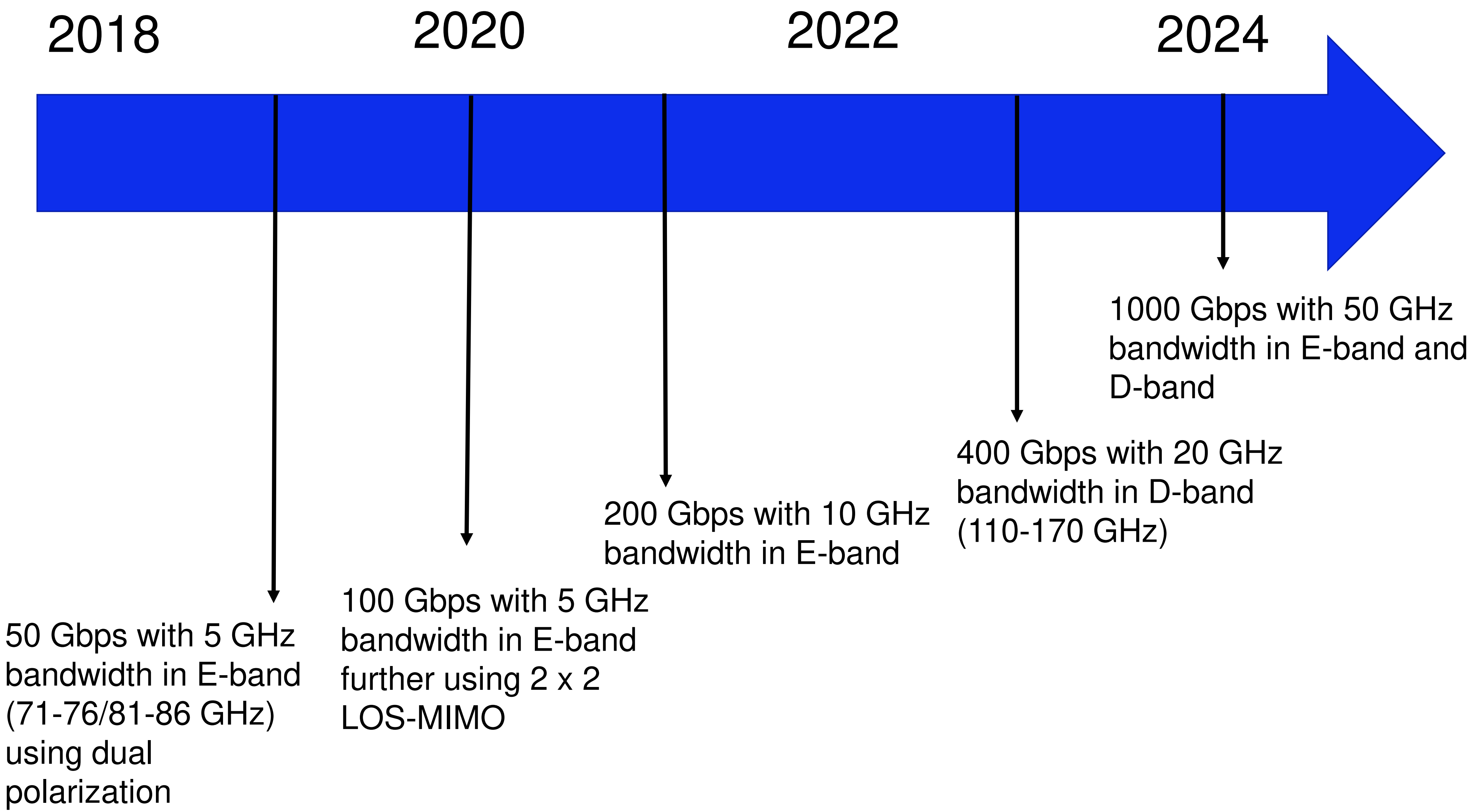
- Digital Modem + RF Front-end



Current 50 Gbps E-band Project: Challenges

- Higher bandwidth
  - From 2.5 GHz to 5 GHz
- Higher sampling rate
  - From 2.5 Gsps to 5 Gsps
- Higher modulation level
  - From 16QAM to 64OQAM
- Direct conversion RF front-end
  - No IF stage
- Dual-polarization
  - Cross-polarization Interference Cancellation (XPIC) is necessary
- Practical impairments
  - I/Q imbalance compensation
- Current progress:
  - Feasibility study completed
  - Digital and RF system design underway

UTS Tbps Wireless Roadmap



Outline

- Wireless Communication Evolution
- Integrated Space and Terrestrial Networks
- Millimetre Wave RF Backbone
- Other Enabling Techniques
- UTS Terabit Roadmap
- Conclusions

Conclusions

- Future wireless communications should achieve global coverage while further increasing its capacity
- The integrated space and terrestrial network is a ultimate goal of global communications technology research and development, where high-speed aerial backbone is of significant importance.
- Mm-wave communications combined with other enabling technologies can achieve the Tbps data rate required for the aerial backbone links.
- There are still a lot of technical challenges to be solved, which requires research collaborations.

Thank
you

UTS