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Abstract: While THz band suffers from huge propagation losses, large arrays of sub-millimeter wavelength antennas can be realized in ultra-massive multiple-input multiple-output (UM-MIMO) systems to enhance the received power and overcome the distance limitation. In this talk, challenges, architectures, and open problems of the THz hybrid beamforming design are presented.

Purpose: Information of IEEE 802.15 SC THz

Hybrid Beamforming for Terahertz Wireless Communications: Challenges, Architectures, and Open Problems

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THz Communications Challenges

I. F. Akyildiz, C. Han* and S. Nie, "Combating the Distance Problem in the Millimeter Wave and Terahertz Frequency Bands," *IEEE Communications Magazine, 2018.*

- **Distance limitation: a major challenge at THz frequencies caused by the very high propagation loss**

- **Reasons:**
  - Spreading loss: increases quadratically with the frequency, as defined by Friis' law
  - Molecular absorption loss: part of the wave energy is converted into internal kinetic energy of the medium molecules (e.g., water-vapor)
  - Reflection and scattering loss: rough surface scattering arises with tens of dB losses

THz Ultra-Massive MIMO

Taking MIMO Up to THz

- **As we move to higher frequencies**
  - Antennas become smaller:
    - More elements per array
    - Potentially, more parallel transmissions/streams
    - Certainly, more challenges related to the control of the arrays

From MIMO, Massive MIMO to Ultra-Massive MIMO

State-of-the-art

512 antennas at 60 GHz

Z. Gao, L. Dai, D. Mi, Z. Wang, M. A. Imran and M. Z. Shakir, "MmWave massive-MIMO-based wireless backhaul for the 5G ultra-dense network," IEEE Wireless Communications, 2015.

1024 graphene nano-antennas at 1 THz

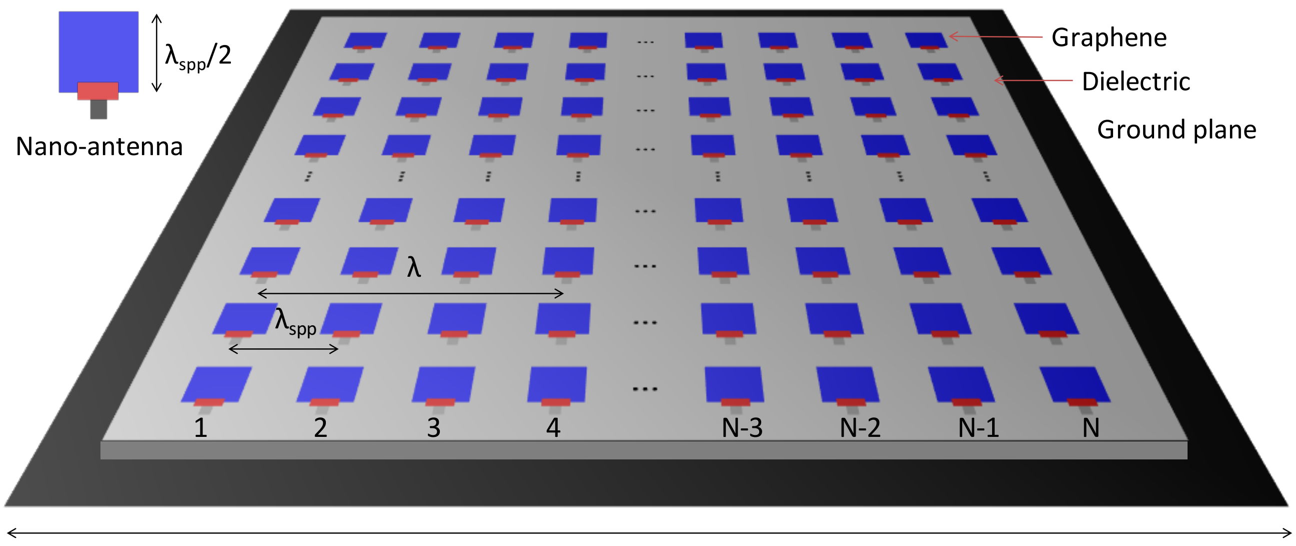
C. Han, J. M. Jornet, and I. F. Akyildiz, "Ultra-Massive MIMO Channel Modeling for Graphene-Enabled Terahertz-Band Communications", in Proc. of IEEE VTC, 2018

Graphene-based Plasmonic Nano-antenna Arrays

- **At THz frequencies, antennas are even smaller:**
  - true for omnidirectional dipoles
  - also true for directional antennas

- **By using plasmonic materials, antennas can be further miniaturized:**
  - Metamaterial-based plasmonic antennas for 0.1-1 THz
  - Graphene-based plasmonic nano-antennas for 1-10 THz

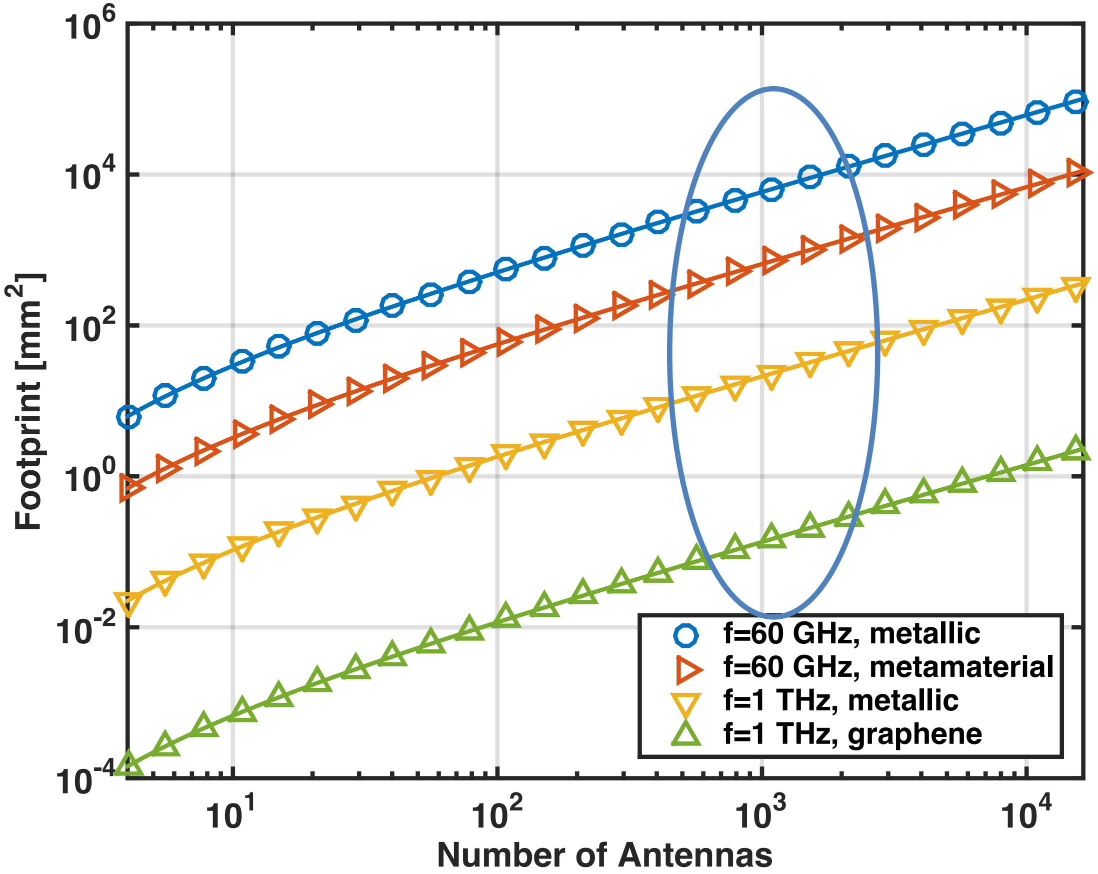
Plasmonic antennas can be placed much closer to each other than traditional metallic antennas without suffering from mutual coupling



I. F. Akyildiz and J. M. Jornet, "Realizing Ultra-Massive MIMO communication in the (0.06-10) Terahertz band," Nano Communication Networks (Elsevier) Journal, 2016. U.S. Patent 9,825,712 Nov. 21, 2017.

Footprint

- **We can build very large antenna arrays with thousands of elements (1024) in a very small footprint (a few millimeters)**



Challenges and Guidance

C. Han, and Y. Chen, "Propagation Modeling for Wireless Communications in the Terahertz Band", *IEEE Communications Magazine, 2018.*

- **Very high path loss**
  - Distance limitation → beamforming is critical
- **Channel sparsity**
  - Limited number of multi-paths → limited spatial multiplexing gains
- **Large multipath K factor**
  - Line-of-sight dominance → inter-intra-spatial multiplexing, blockage
- **Very large antenna array**
  - Many antennas, phase shifters, RF chains → hardware and energy efficiency
  - Phase front fluctuation → spherical- or planar-wave propagation
  - Beam squint of large bandwidth → codebook design, true-time-delay (TTD)

THz Dynamic Hybrid Beamforming

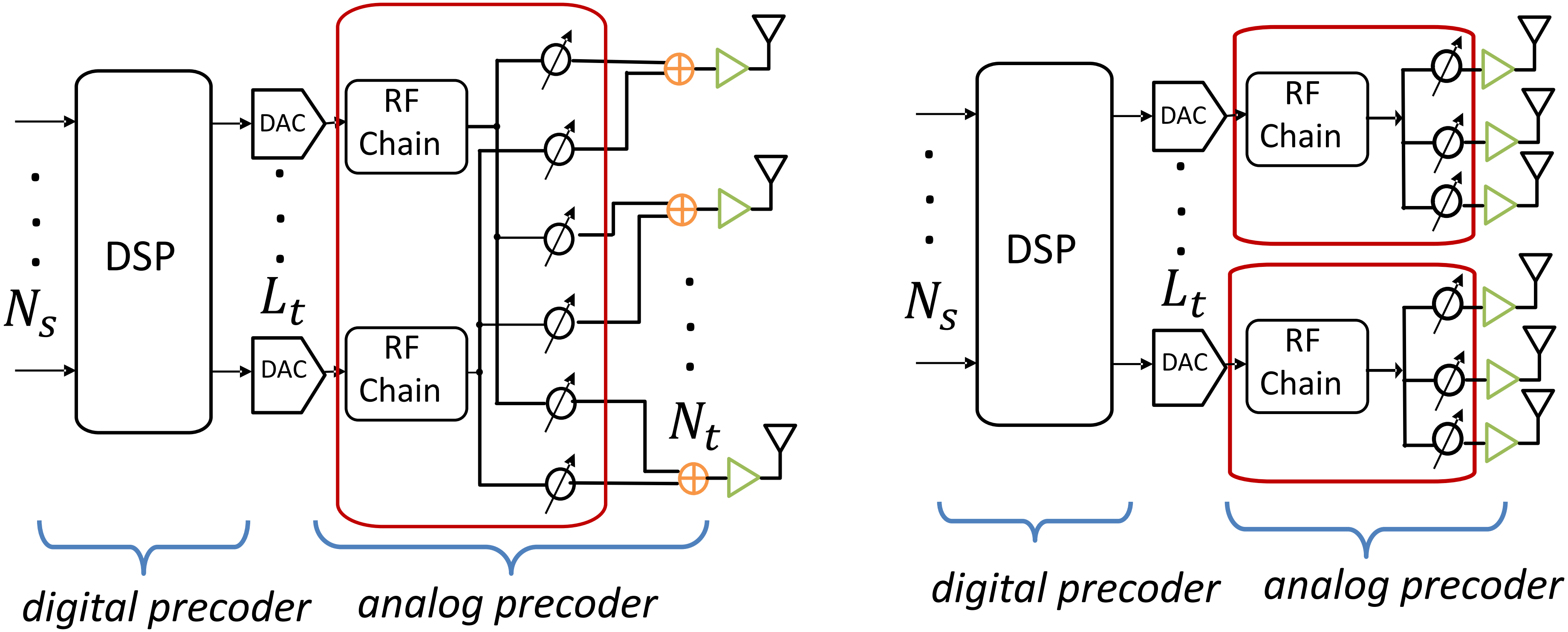
Digital, Analog, or Hybrid ??

- **Digital beamforming: each RF chain connects to each antenna**
  - Optimal performance but very high hardware costs and energy consumption
  - Support multiple data streams

- **Analog beamforming: one RF chain connects to all antennas**
  - Low cost, low complexity and compromised performance
  - Only support one data stream

- **Hybrid beamforming: balance among performance, complexity and cost**
  - Adaptively support one or multiple data streams
  - Similar performance with digital beamforming
  - Lower cost and complexity than digital beamforming

Hybrid Beamforming Architectures



Fully-connected architecture: each RF chain connects to all antennas

Array-of-subarrays architecture: each RF chain connects to a subset of antennas

C. Lin and G. Y. L. Li, "Terahertz Communications: An Array-of-Subarrays Solution," *IEEE Communications Magazine, 2016.*

Fully-connected vs Array-of-subarrays

	Hardware complexity	Quantity of devices	Spectral efficiency
Fully-connected	Higher	Larger	Higher
Array-of-subarray	Lower	Smaller	poorer

Total power = quantity of devices × individual power

High operation frequency of THz → large individual device power → power consumption of fully-connected architecture is too high

Data rate = spectral efficiency × bandwidth

Huge bandwidth of THz → large data rate loss of array-of-subarrays architecture

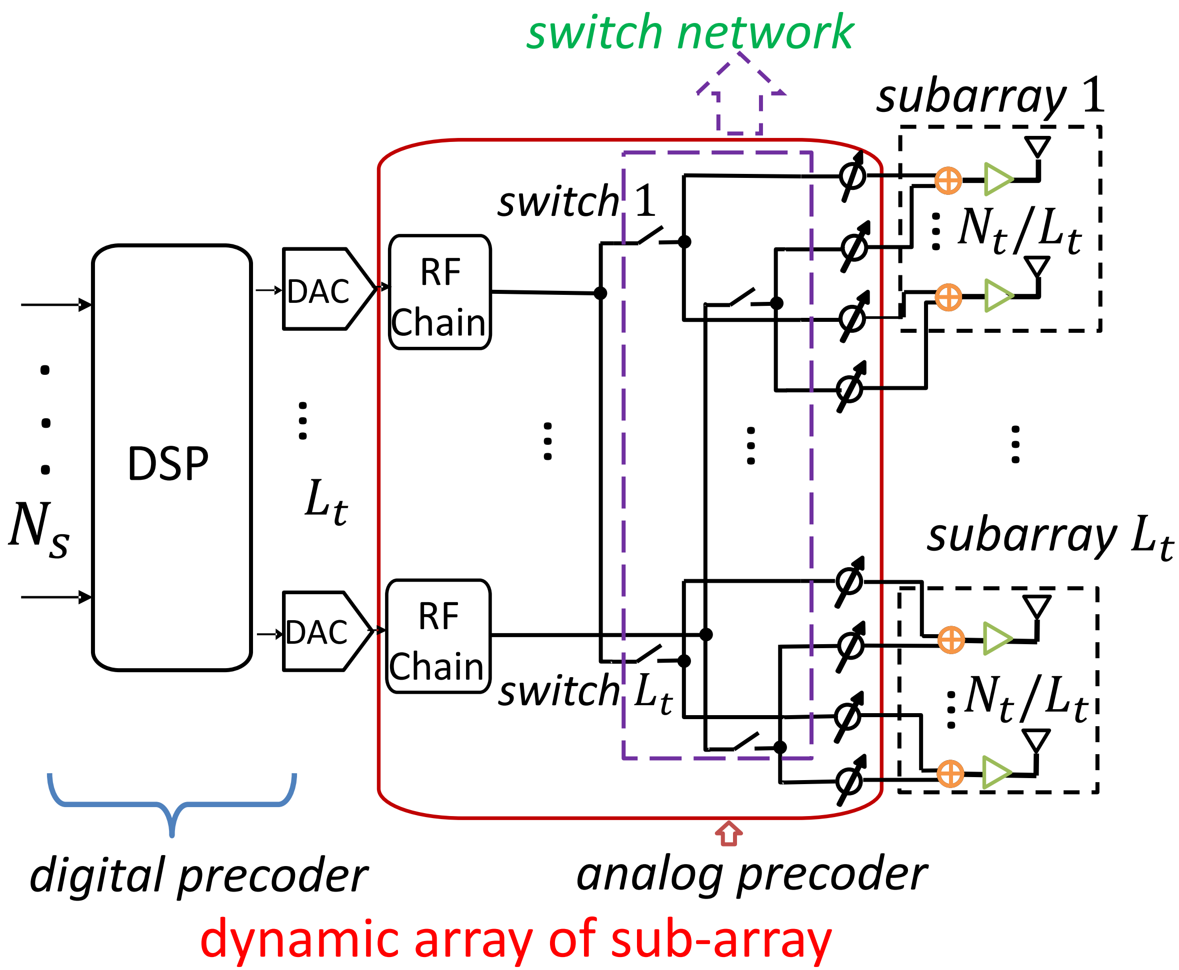
What about Dynamic

- **Can we have a balanced trade-off between fully-connected and array-of-subarrays?**

- **Yes! Dynamic array-of-subarrays for THz wireless communications**

L. Yan, C. Han, and J. Yuan, "A Dynamic Array-of-Subarrays Architecture and Hybrid Precoding Algorithms for Terahertz Wireless Communications", *IEEE Journal on Selected Areas in Communications (JSAC), 2020*

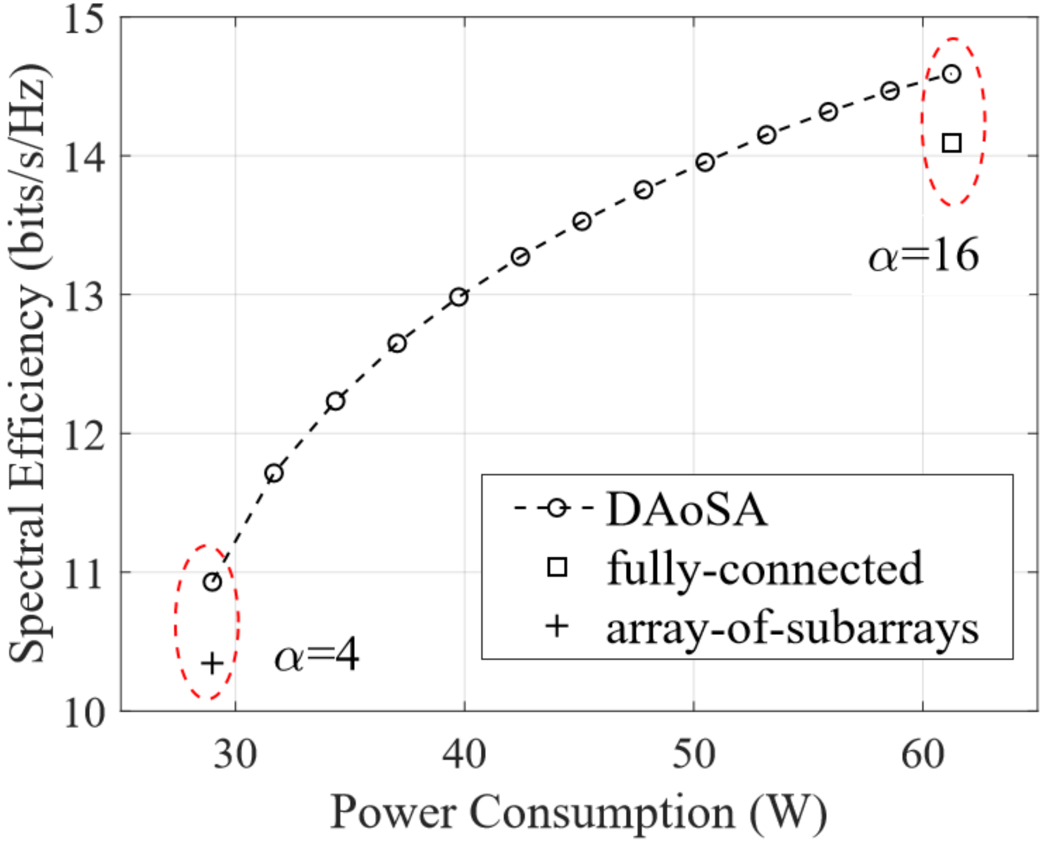
Dynamic Array of Sub-Array



- Antennas are divided into L_t subarrays
- Each RF chain connects to each subarray through a switch
- Denote α as the number of closed switches. The *fully-connected* is the special case with α $=L_t^2$.
- The *array-of-subarrays* architecture is one special case when α = L_t.

L. Yan, C. Han, and J. Yuan, "A Dynamic Array of Sub-Array Architecture for Hybrid Precoding in the Millimeter Wave and Terahertz Bands", in Proc. of IEEE ICC Workshop, 2019

Benefits of DAoSA



256 antennas at transmitter and receiver, transmitted power is 20 dBm, $L_t = 4$.

Both the fully-connected and array-of-subarrays architectures are special cases when α=16 and 4.

Through intelligently controlling the switches, the DAoSA architecture can achieve different levels of spectral efficiency and power consumption.

Design Target

- Design considerations
  - At THz band, communication distance should be ensured.
  - In THz UM-MIMO system, power consumption is urgently needed to be reduced.
  - High data rate should be guaranteed.

→ Design target of THz DAoSA:

At a required distance, minimize the power consumption while achieving a required data rate.

Hybrid Precoding Algorithms

Hybrid precoding problem:

$$\begin{aligned} \min_{\widetilde{\mathbf{P}}_{\mathrm{A}},\mathbf{P}_{\mathrm{D}}} \quad & \|\mathbf{P}^{\mathrm{opt}} - \widetilde{\mathbf{P}}_{\mathrm{A}}\mathbf{P}_{\mathrm{D}}\|_F^2 \\ \text{s.t.} \quad & \widetilde{\mathbf{p}}_{il} \in \{\mathbf{0}_{n_t\times 1} \cup \mathcal{F}\}, \\ & \|\widetilde{\mathbf{P}}_{\mathrm{A}}\mathbf{P}_{\mathrm{D}}\|_F^2 = N_s, \end{aligned}$$

Solution 1: element-by-element (EBE) algorithm, general solution for $L_t \geq N_s$

Solution 2: vectorization-based (VEC) algorithm, special solution for $L_t = N_s$, better performance

Switch Network Connection Algorithms

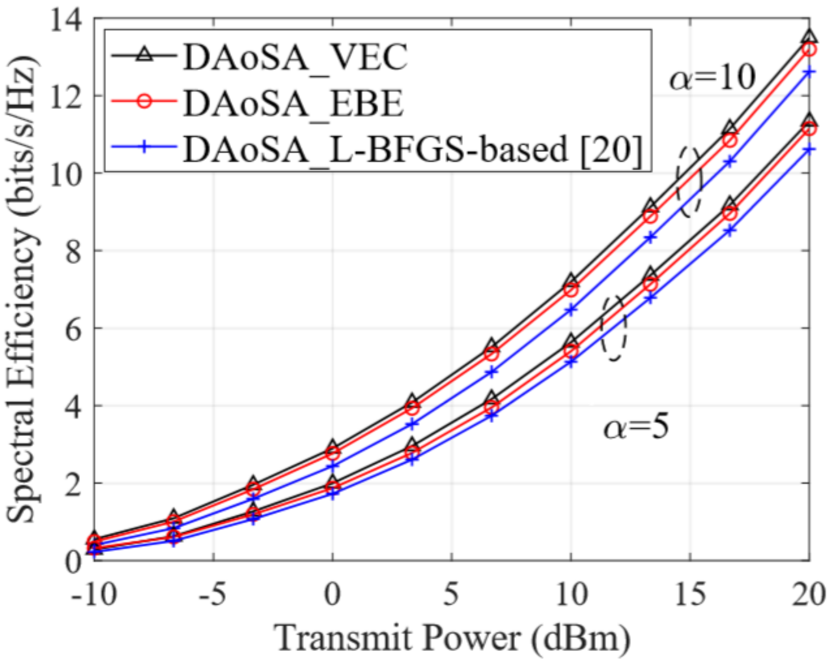
Switch network connection problem: design W to minimize power consumption with the data rate constraint

- **Solution 1: progressive stage-by-stage (PSBS) algorithm, near-optimal performance but high complexity**
- **Solution 2: alternating-selection (AS) algorithm, medium performance and low complexity**
- **Solution 3: block-diagonal-search (BDS) algorithm, poor performance and extremely-low complexity**

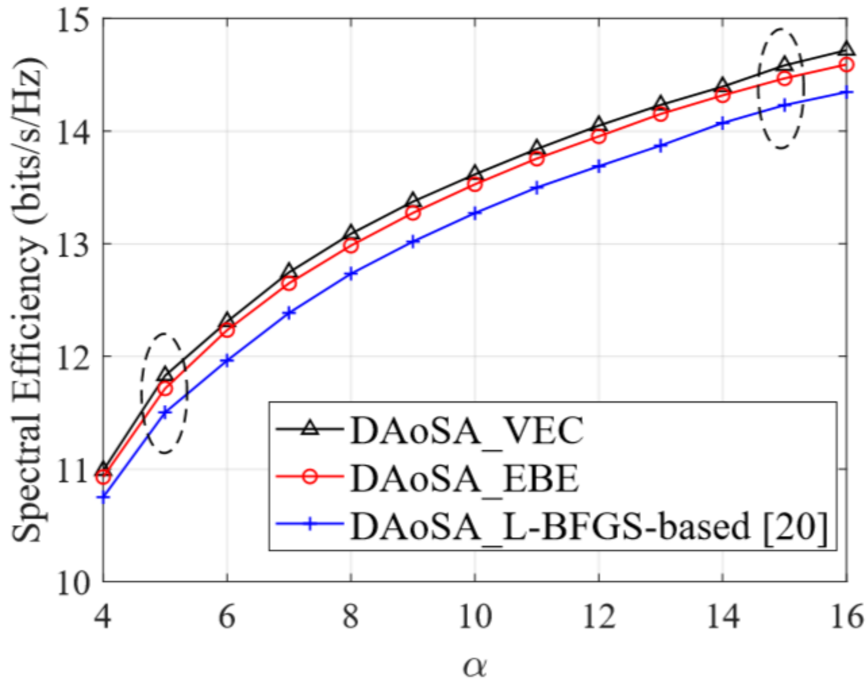
L. Yan, C. Han, and J. Yuan, "A Dynamic Array-of-Subarrays Architecture and Hybrid Precoding Algorithms for Terahertz Wireless Communications", IEEE Journal on Selected Areas in Communications (JSAC), 2020

Spectral Efficiency Performance

The proposed hybrid precoding algorithms (VEC, EBE) achieve better spectral efficiency than the one from the literature.

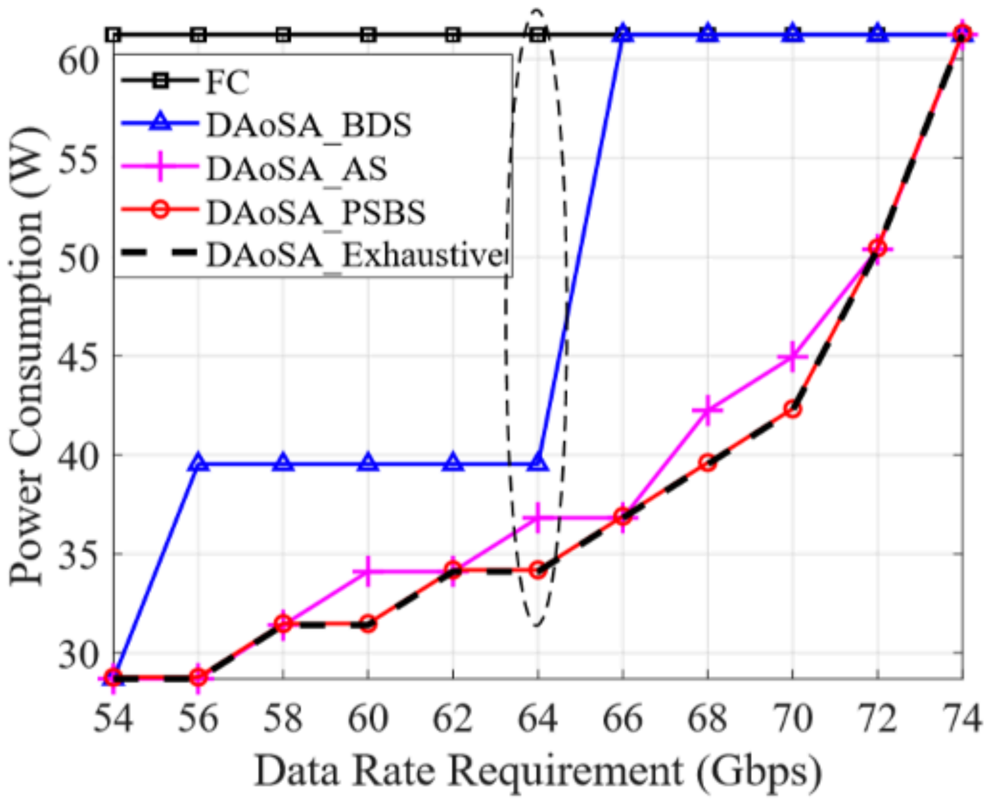


Spectral efficiency versus transmit power



Spectral efficiency versus number of closed switches

Power Consumption Performance

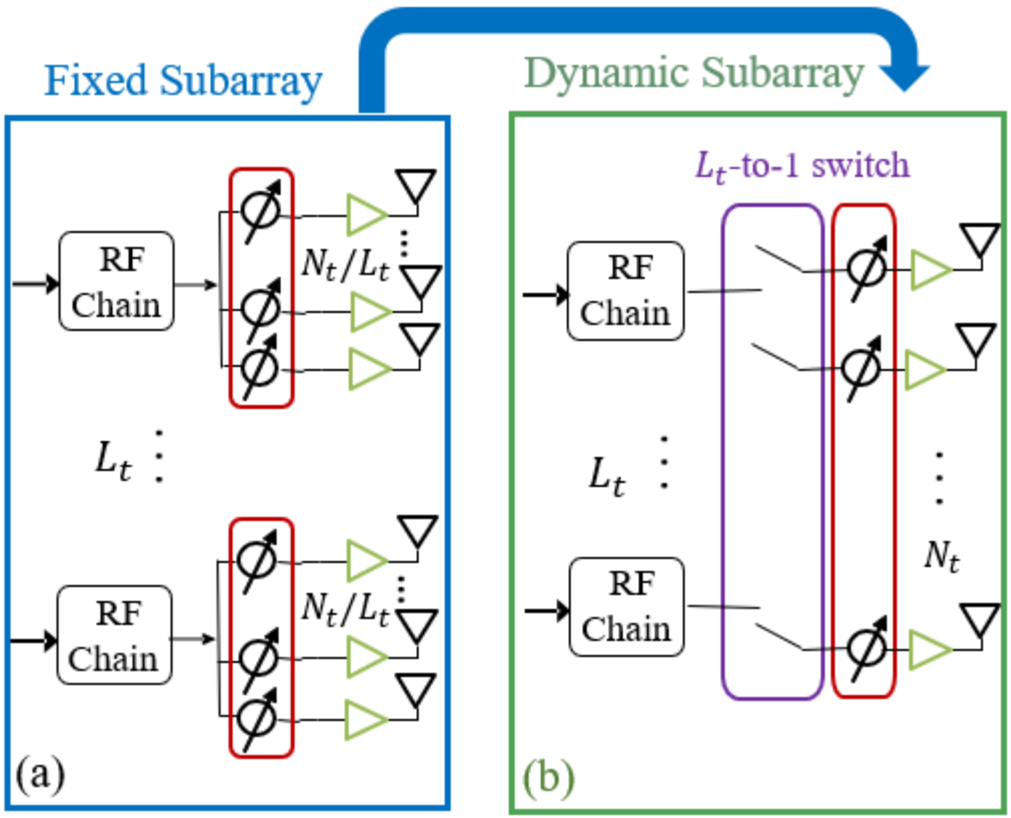


At 0.3 THz and a communication distance d= 40m, with different required data rate, the DAoSA architecture can intelligently minimize the power consumption to different level.

Can we further decrease hardware complexity?

Yes, with quantized- and fixed-phase shifters.

Dynamic-subarray (DS) architecture



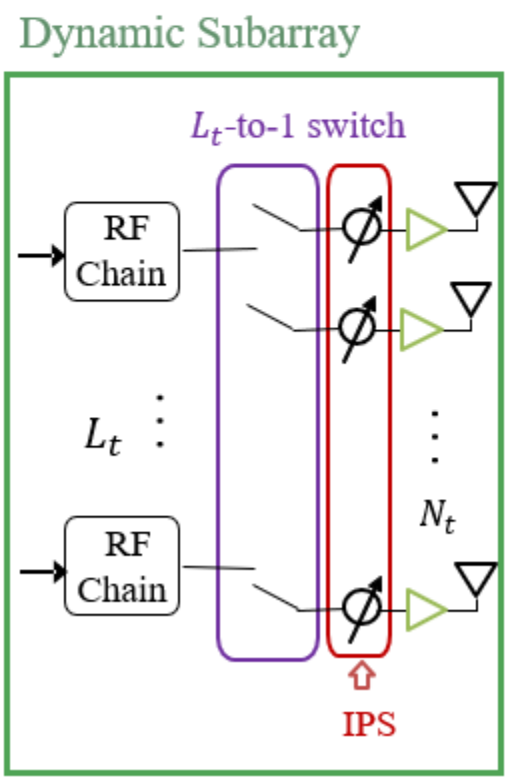
(a) AoSA architecture (b) DS architecture

- Each antenna has an L_t-*to-1* switch to intelligently select one RF chain from *Lt* RF chains.
- Through the dynamic connection of the switch network, the spectral efficiency and energy efficiency are improved.

S. Park, A. Alkhateeb and R. W. Heath, "Dynamic Subarrays for Hybrid Precoding in Wideband mmWave MIMO Systems," *IEEE Trans. Wireless Commun.*, 2017.

Dynamic Hybrid BF with Quantized- and Fixed-phase Shifters

L. Yan, C. Han, N. Yang and J. Yuan, "Dynamic-subarray with Quantized- and Fixed-phase Shifters for Terahertz Hybrid Beamforming", in Proc. of IEEE GLOBECOM, 2020

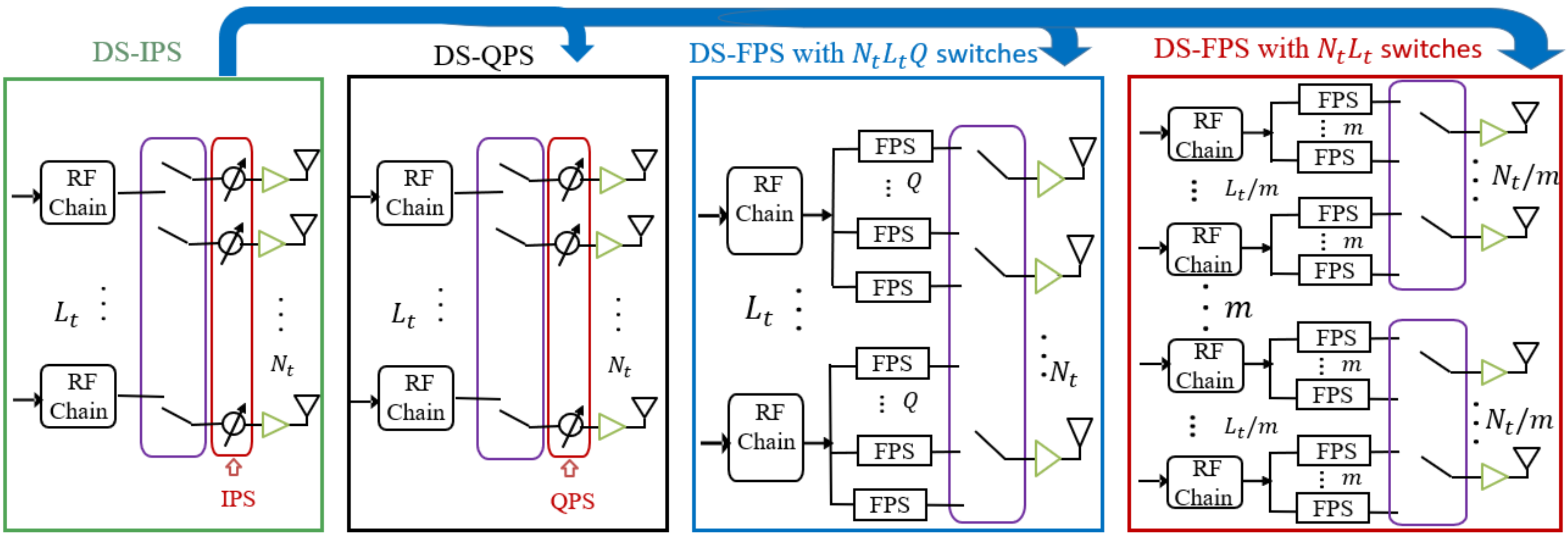


The DS architecture usually assumes the use of ideal infinite-resolution phase shifters (IPS), which are hard to realize.

To reduce the hardware complexity and power consumption, we propose to

- Use quantized-phase shifters (QPS), i.e., with a selection of discrete phases.
- More interestingly, use fixed-phase shifters (FPS), i.e., with pre-determined phases without tuning

Quantized- and Fixed-phase Shifters

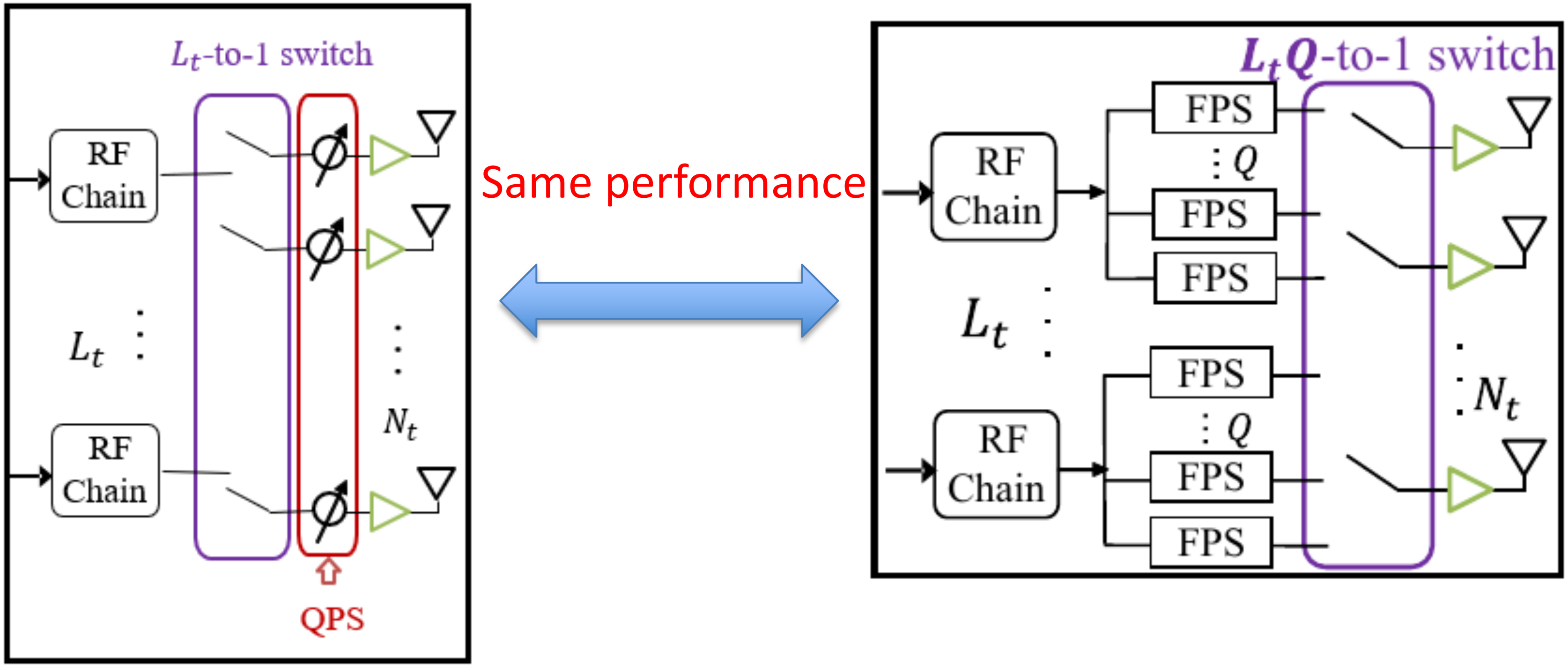


SE: DS-IPS ≈ DS-QPS = DS-FPS with $N_t L_t Q$ switches > DS-FPS with $N_t L_t$ switches

EE: DS-IPS ≪ DS-QPS ≈ DS-FPS with $N_t L_t Q$ switches < DS-FPS with $N_t L_t$ switches

FPS-realization of DS-QPS

Dynamic Subarray & QPS



- The alternative phases of each QPS are set as $0, 2\pi/Q, \ldots, (Q-1)2\pi/Q$.
- Each RF chain connects to Q FPS, whose phases are set as $0, 2\pi/Q, \ldots, (Q-1)2\pi/Q$, respectively.

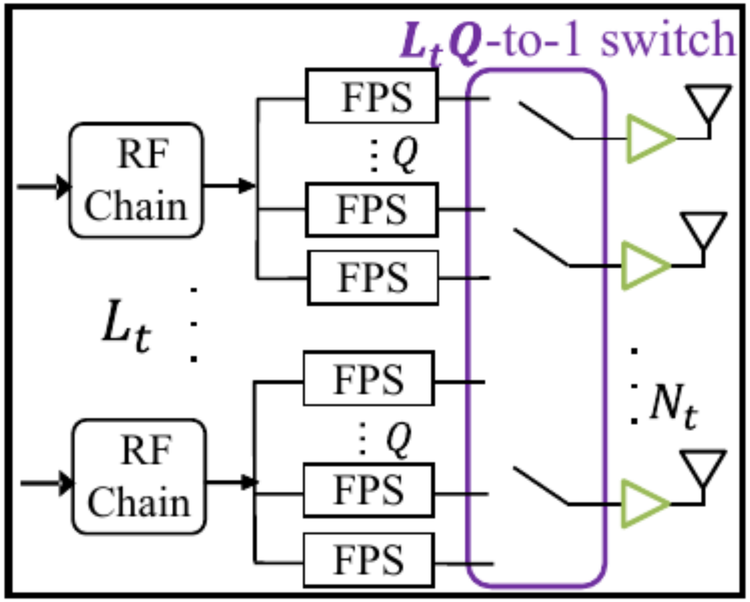
The FPS-realization of DS-QPS can reduce the number of phase shifters substantially.

DS-QPS and DS-FPS Architectures

FPS-realization of DS-QPS:

- Pros: The hardware complexity of FPS is lower than QPS.
- Cons: L_tQ-to-1 switch is more complex than L_t-to-1 switch.

Hence, based on the FPS-realization, we propose the DS-FPS architecture to further reduce the hardware complexity.

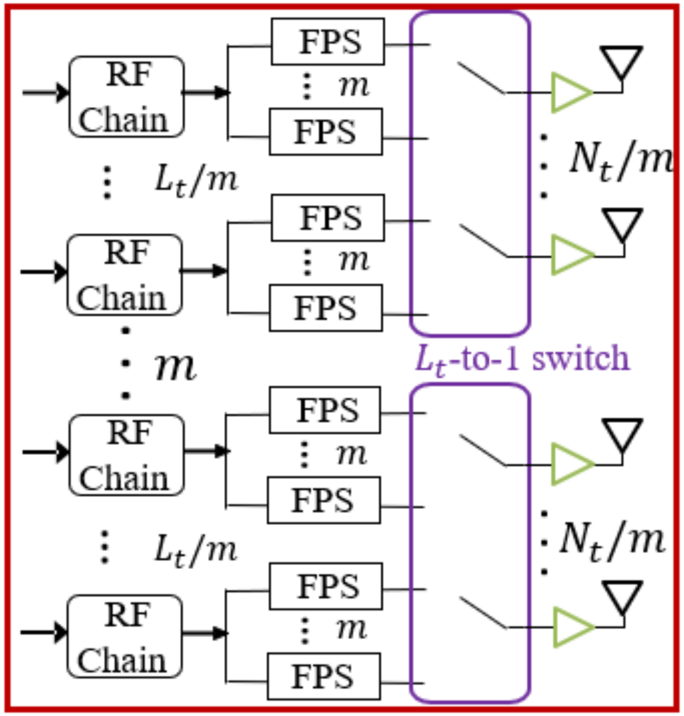


FPS-realization of DS-QPS

Divide the RF chains and antennas into m groups

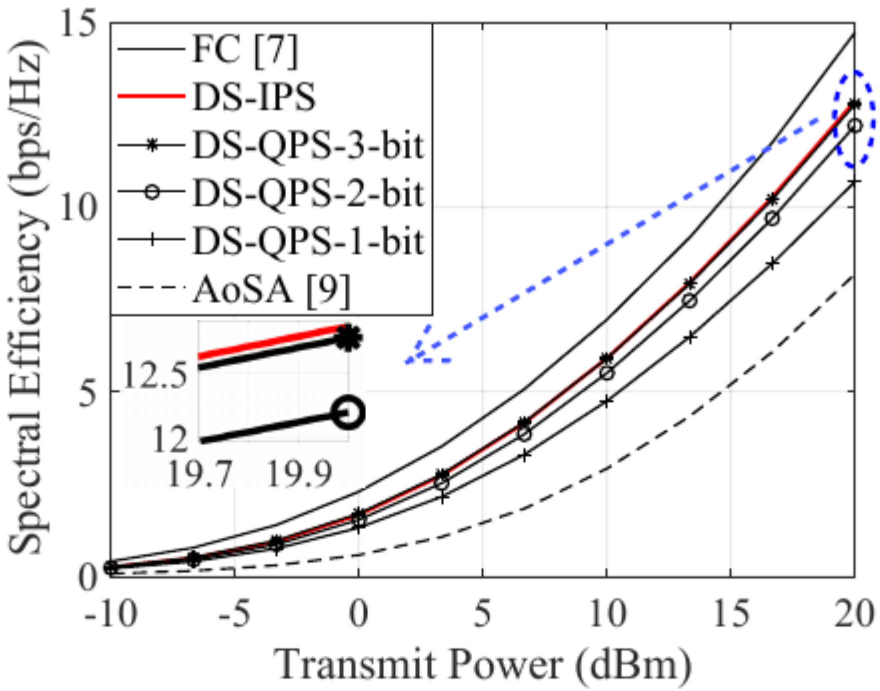
Use L_t-to-1 switch rather than L_tQ-to-1 switch

Dynamic Subarray & FPS

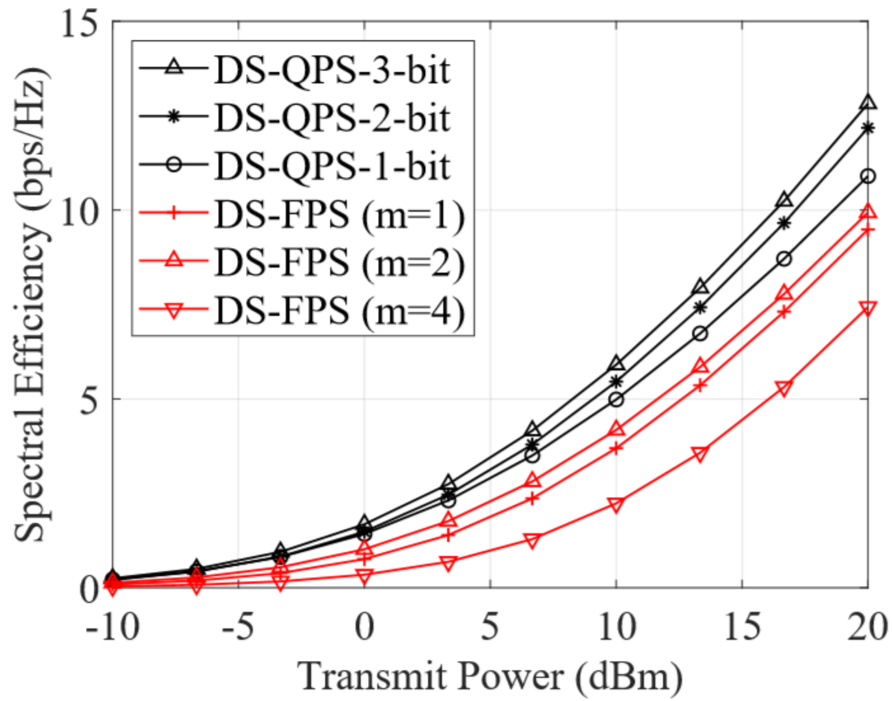


DS-FPS architecture

Spectral Efficiency



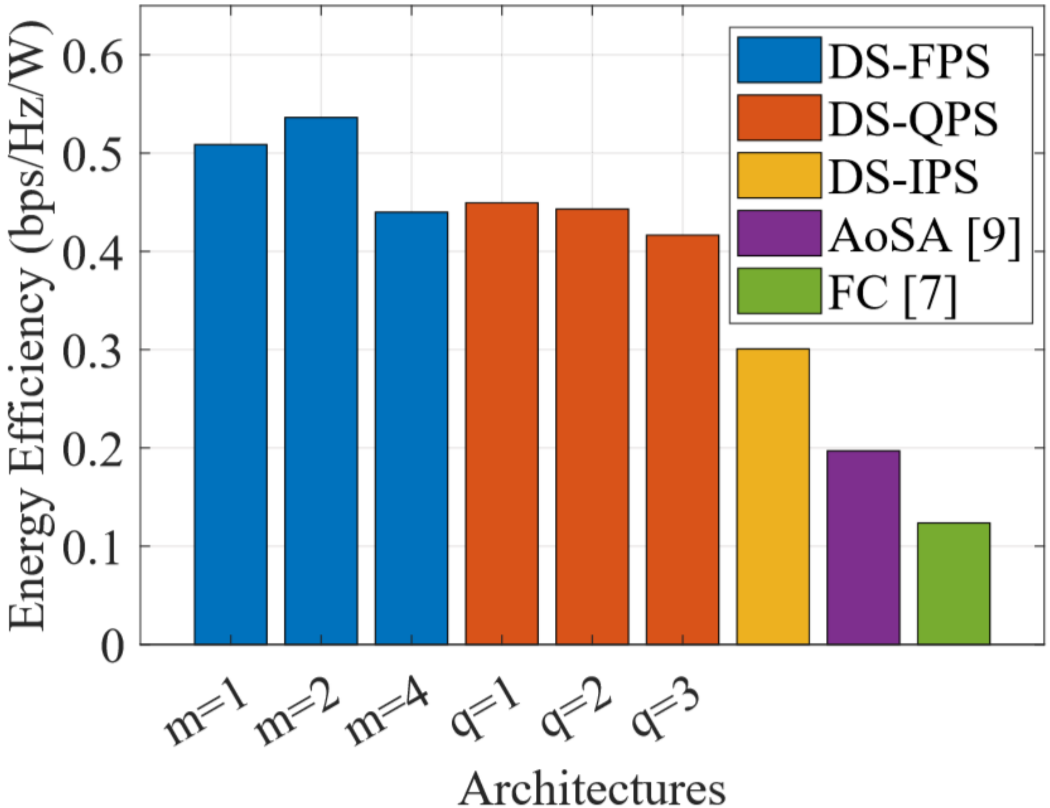
Spectral efficiency of the DS-QPS



Spectral efficiency of the DS-FPS

- The spectral efficiency of DS-QPS-3-bit approaches that of the DS-IPS.
- The spectral efficiency of DS-FPS (m=2) is 21% lower than the DS-QPS-3-bit.

Energy Efficiency



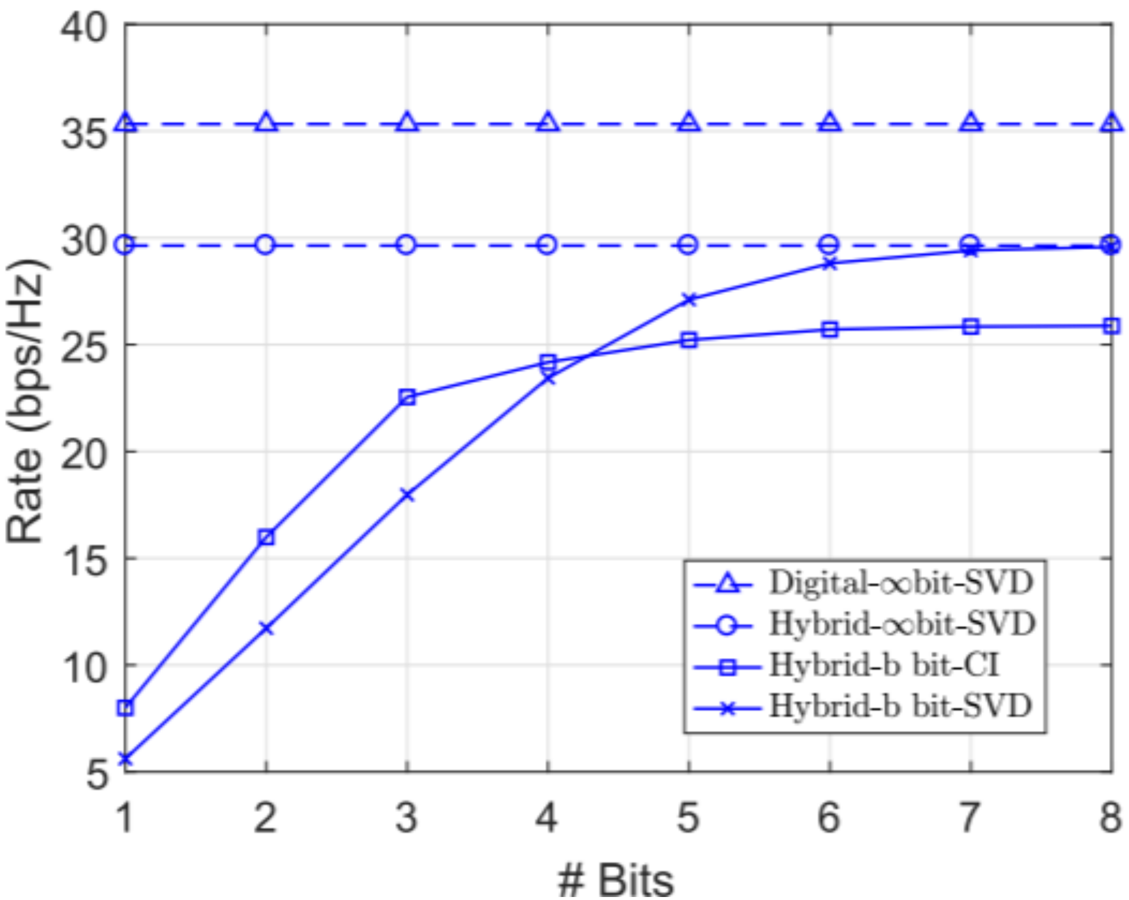
1. The energy efficiency of the DS-FPS (m=2) is 1.3, 1.76, 2.6, and 4.4 times of the DS-QPS (3-bit), DS-IPS, AoSA, and FC architectures.

2. The energy efficiency of the DS-QPS-3-bit is 1.36, 2, and 3.4 times of the DS-IPS, AoSA, and FC architectures,

DS-FPS > DS-QPS > DS-IPS > AoSA > FC

Open Problems and Future Work

Open Problem (1): Hardware-efficient Design



At THz band, the high-resolution ADC/DAC is impractical to implement.

The use of low bit ADC/DAC can reduce the hardware complexity.

The trade-off between data rate and hardware complexity need to be analyzed.

J. Mo, A. Alkhateeb, S. Abu-Surra and R. W. Heath, "Hybrid Architectures With Few-Bit ADC Receivers: Achievable Rates and Energy-Rate Tradeoffs," *IEEE Transactions on Wireless Communications, 2017.*

Open Problem (2): Hybrid Beamforming with Imperfect CSI

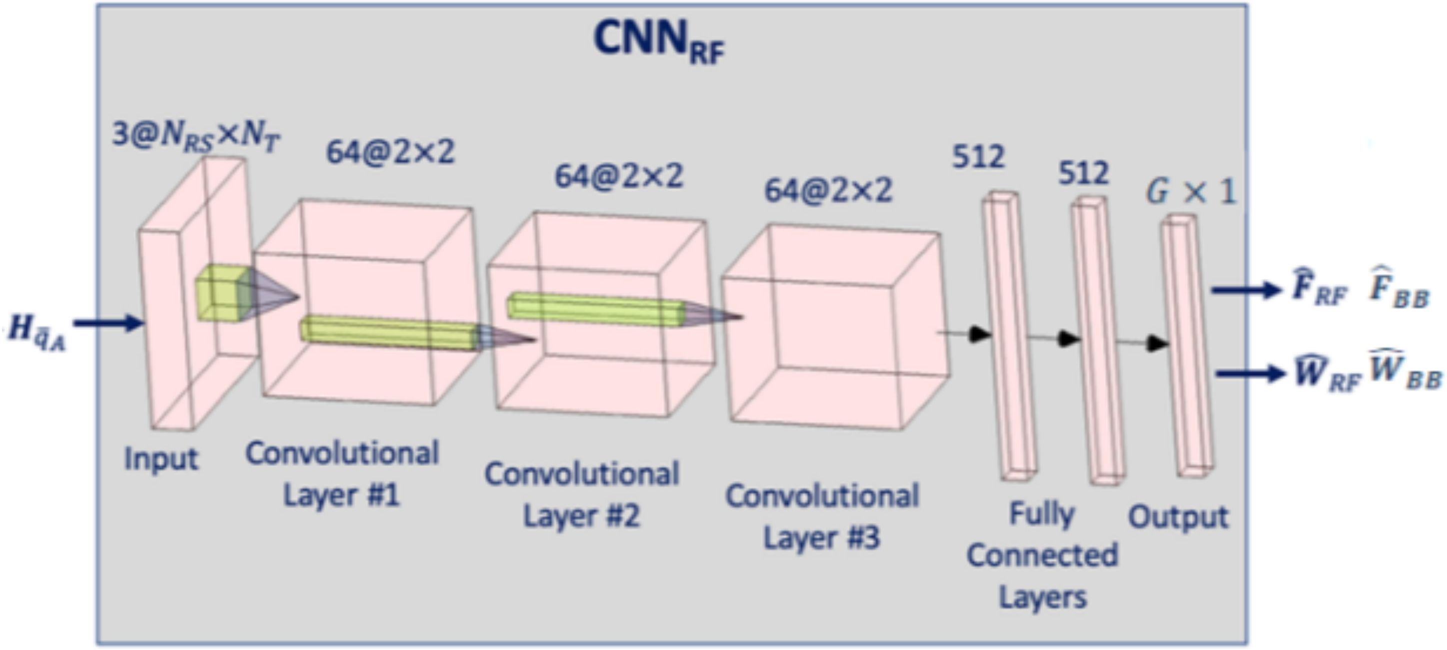
In THz hybrid beamforming architecture, due to the high frequency and the large-scale channel matrix, the channel state information (CSI) is hard to acquire. Therefore, the analysis of imperfect CSI is needed.

- **CSI-tolerant THz hybrid beamforming architecture**
- **Hybrid beamforming algorithm design under imperfect CSI**
- **Performance loss of THz hybrid beamforming system brought by imperfect CSI**

Open Problem (3): Deep-learning-based Algorithms

Using deep-learning method to further reduce the computational complexity of the hybrid beamforming algorithms.

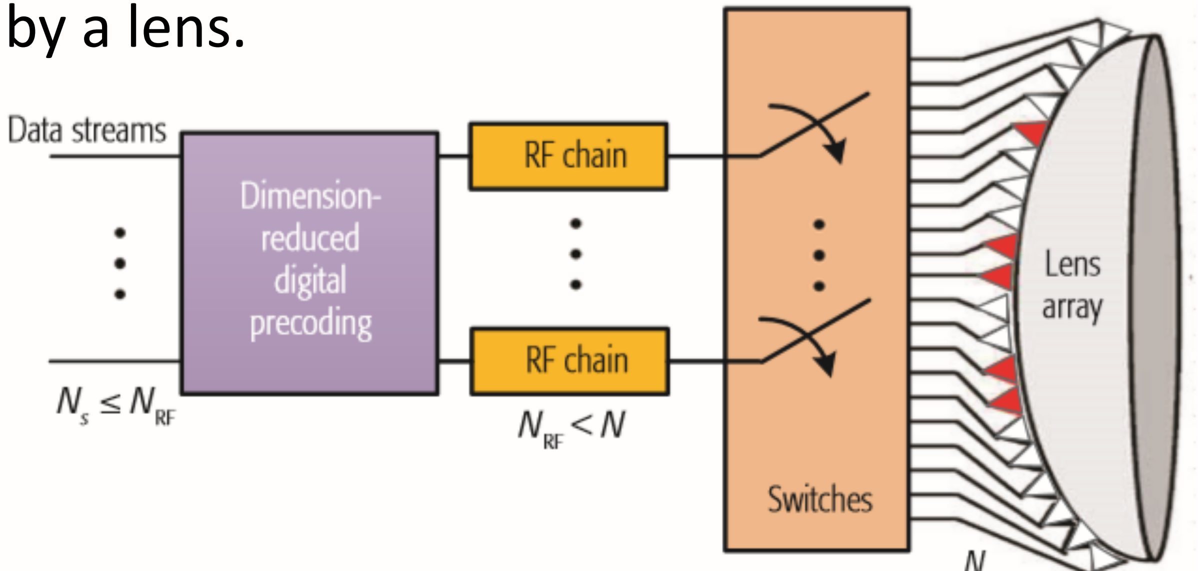
- Input of the deep network is channel information, and the output is the analog and digital beamformers.



A. M. Elbir and K. V. Mishra, "Joint Antenna Selection and Hybrid Beamformer Design using Unquantized and Quantized Deep Learning Networks," *IEEE Transactions on Wireless Communications, 2019*

Open Problem (4): Lens-based Hybrid Beamforming

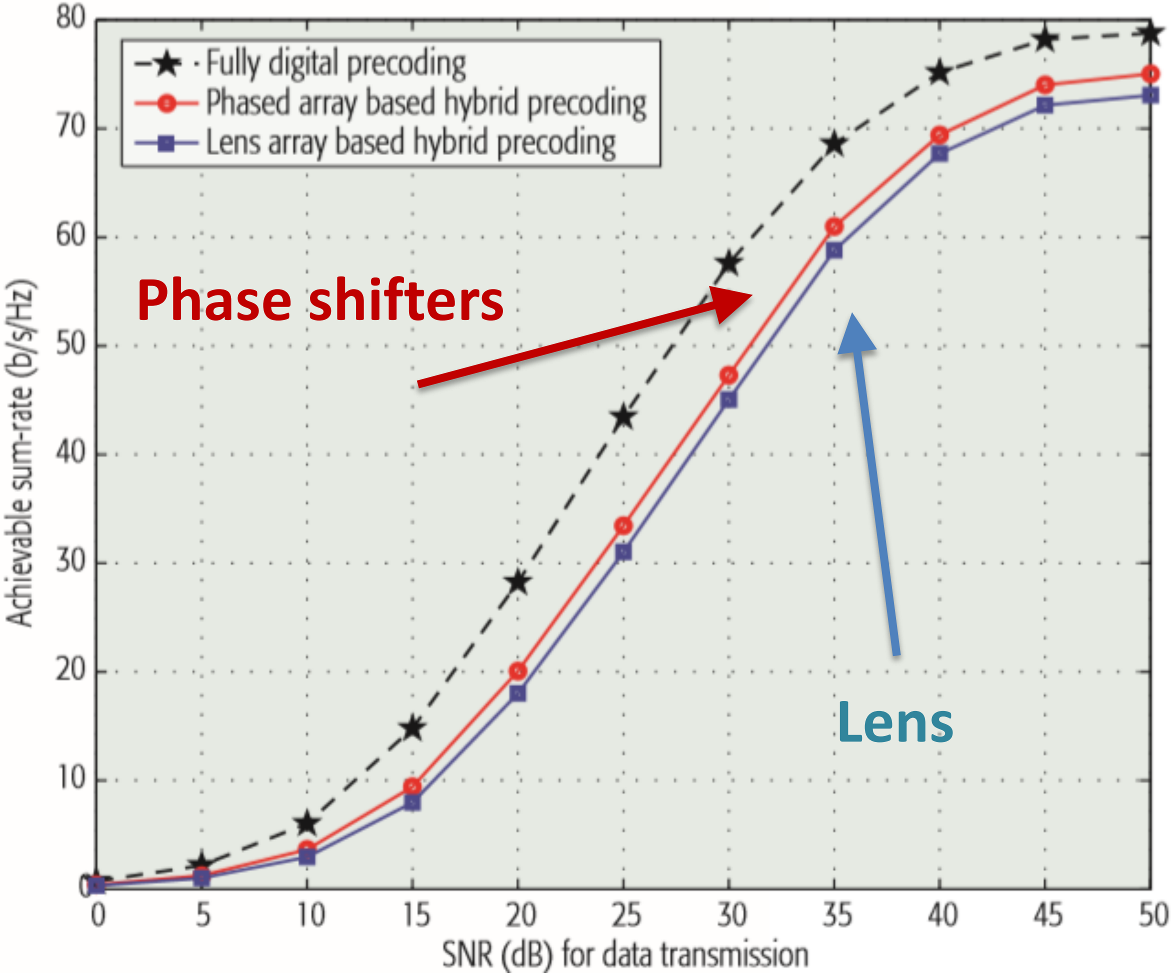
- By employing a lens, the signals from different directions (beams) can be concentrated on different antennas, and the spatial channel can be transformed to the beamspace channel.
- The hardware complexity is reduced since massive phase shifters are replaced by a lens.



(a)

X. Gao, L. Dai and A. M. Sayeed, "Low RF-Complexity Technologies to Enable Millimeter-Wave MIMO with Large Antenna Array for 5G Wireless Communications," *IEEE Communications Magazine, 2018.*

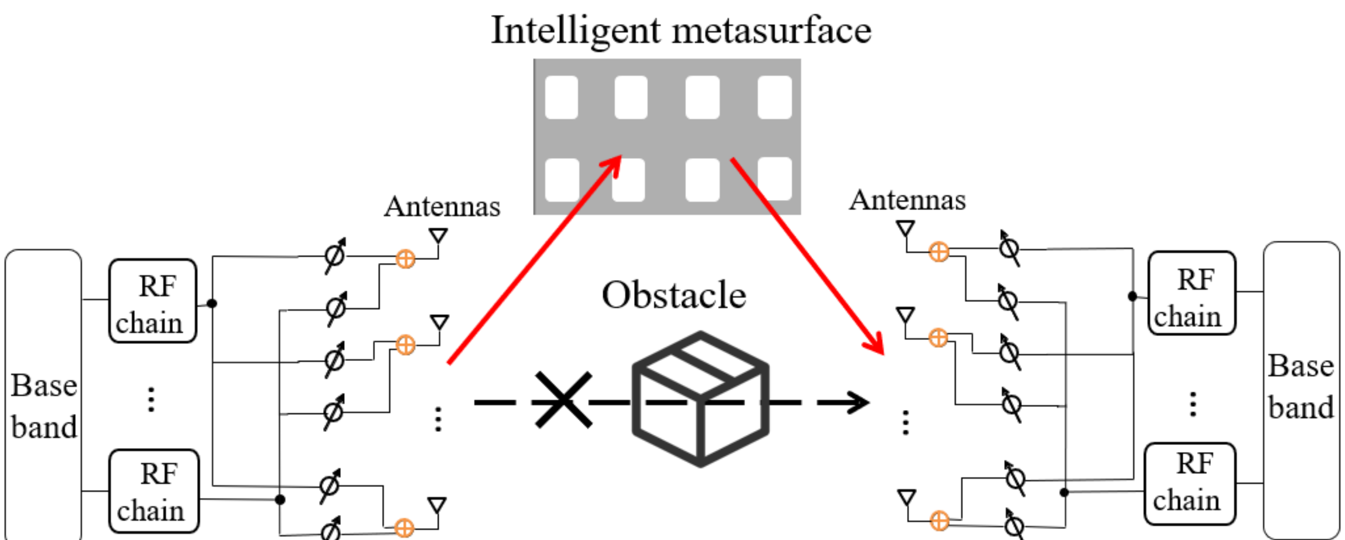
Lens-based Hybrid Beamforming



- Using lens, the spectral efficiency of hybrid beamforming architecture is similar to the fully-connected architecture using phase shifters.

Open Problem (5): UM-MIMO + Intelligent Metasurfaces

- **UM-MIMO** provides abundant beamforming, multiplexing diversity gains.
- **Intelligent metasurfaces** support smartly control of beams (direction, phase, polarization, etc.)
- **Combining these two technologies to address the coverage limitation, blockage problem, security and privacy.**



I. F. Akyildiz, C. Han* and S. Nie, "Combating the Distance Problem in the Millimeter Wave and Terahertz Frequency Bands," *IEEE Communications Magazine, 2018.*

Conclusions

- **Hybrid beamforming technology is critical to the THz UM-MIMO systems, to overcome the distance limitation**

- **Device and channel features in the THz band need to be kept in deep mind to design and implement THz UM-MIMO systems**

- **Many open problems need to be addressed!**