Infocom 2023

mmFlexible: Flexible Directional Frequency Multiplexing for Multi-user mmWave Networks

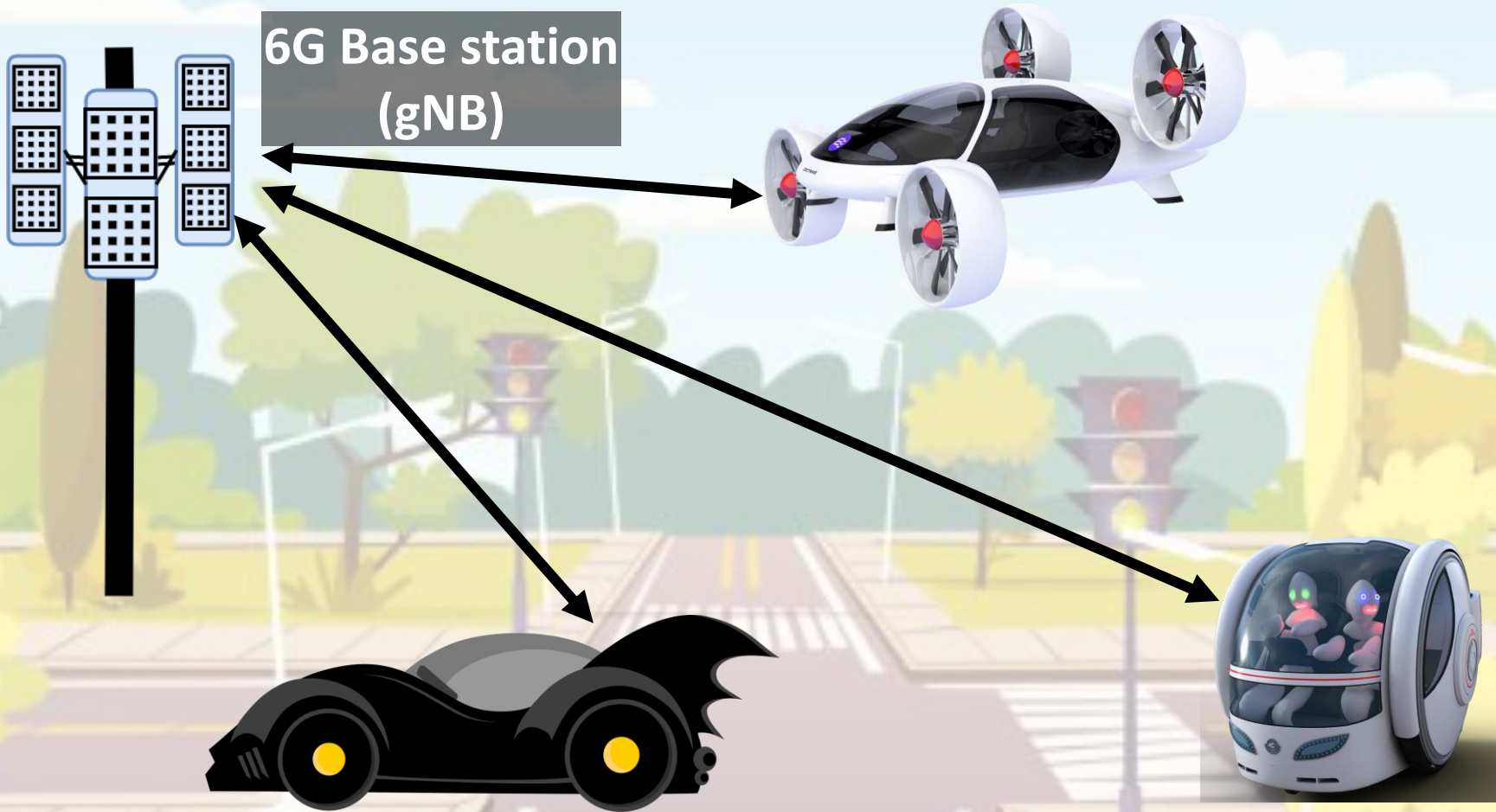**Ish Kumar Jain**   Rohith Reddy Vennam   Raghav Subbaraman   Dinesh Bharadia
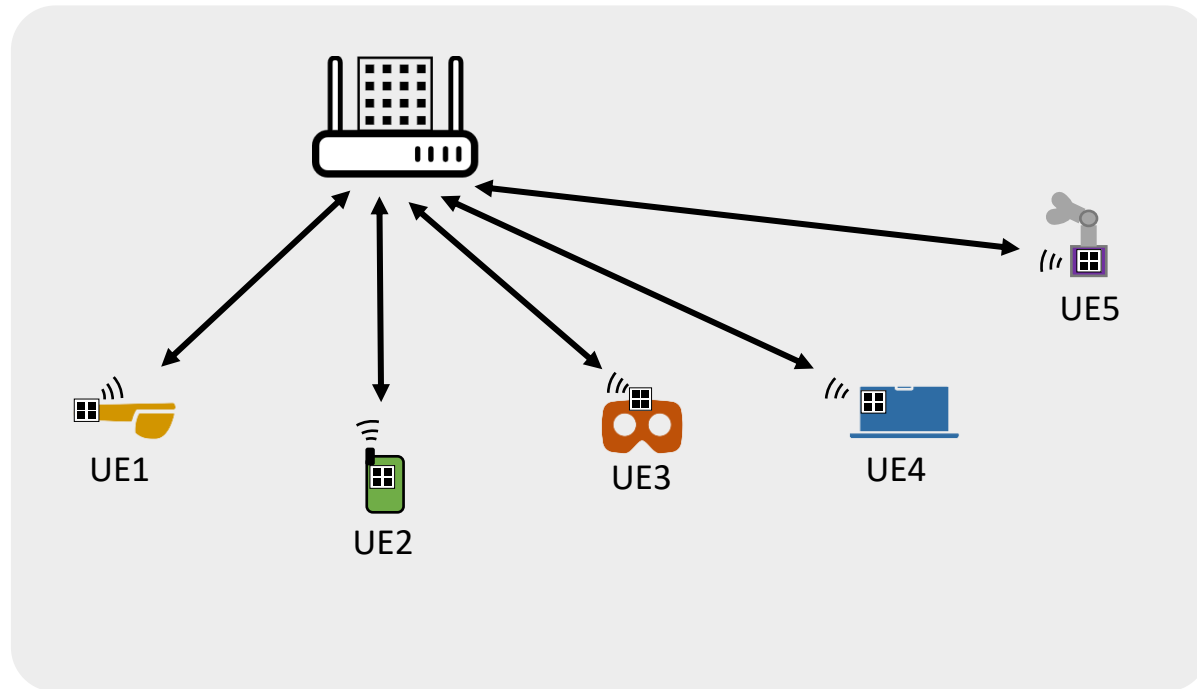
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Electrical and Computer Engineering

WCSNG

6G Base station (gNB)

Vehicle of the Future

6G Access Point (AP)

AR/VR for Health/Education

Images credit: pngegg.com
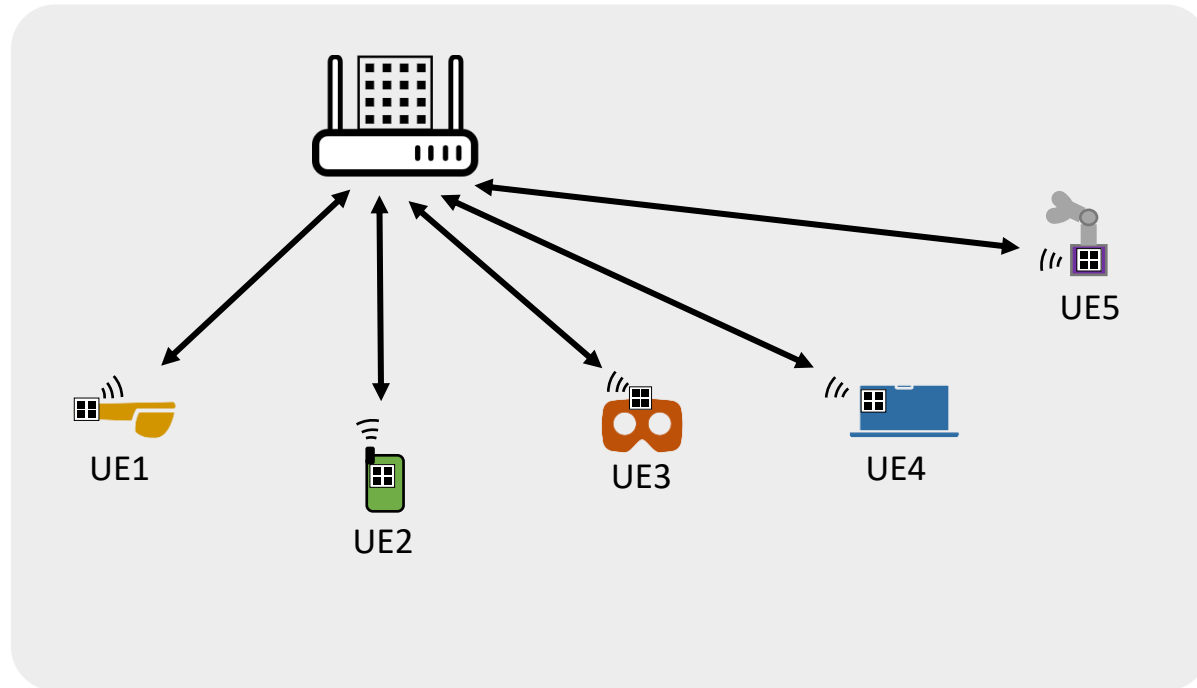
Requirements for NextG Applications

High-throughput

Low-latency

Scalable

mmWave systems today do not meet these requirements
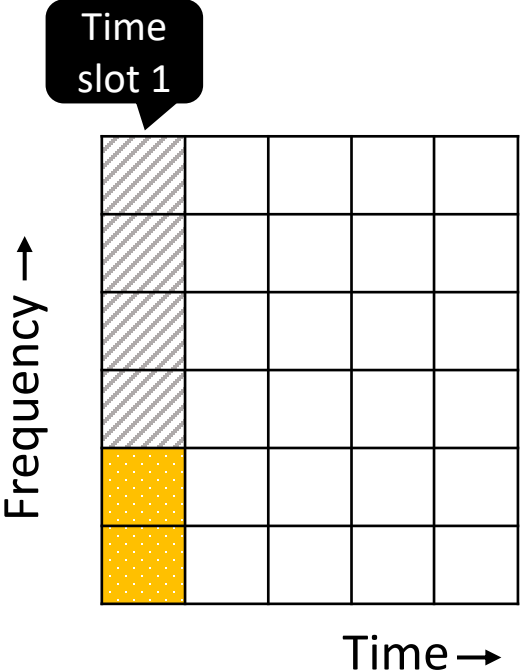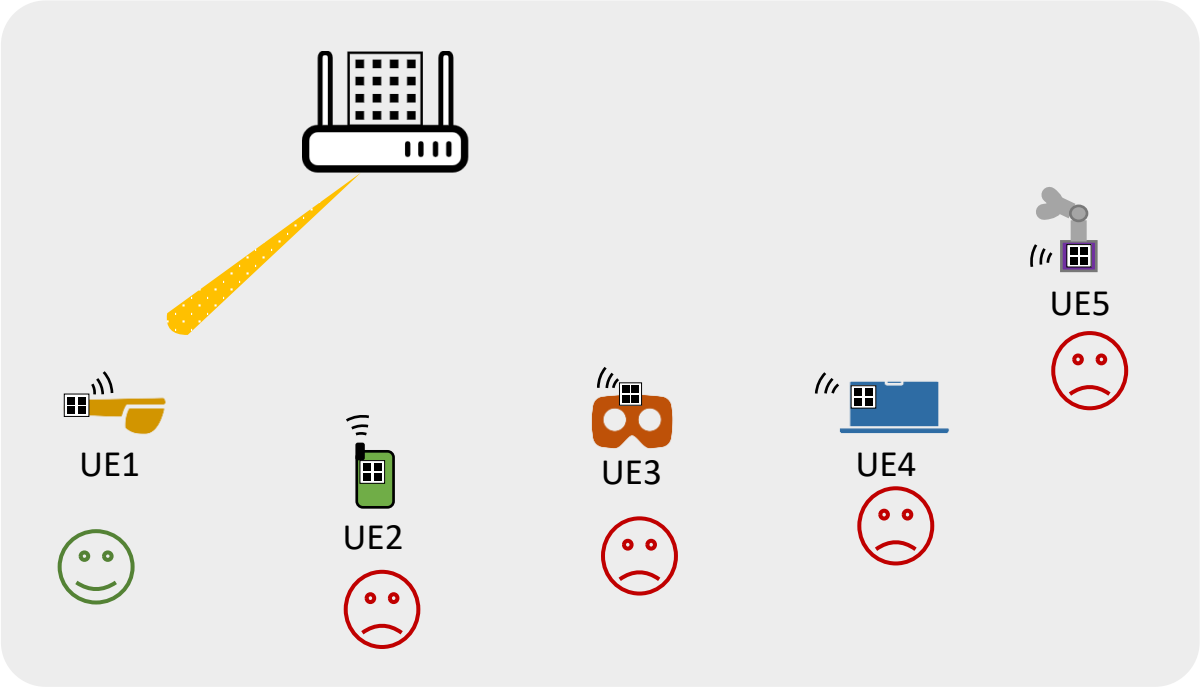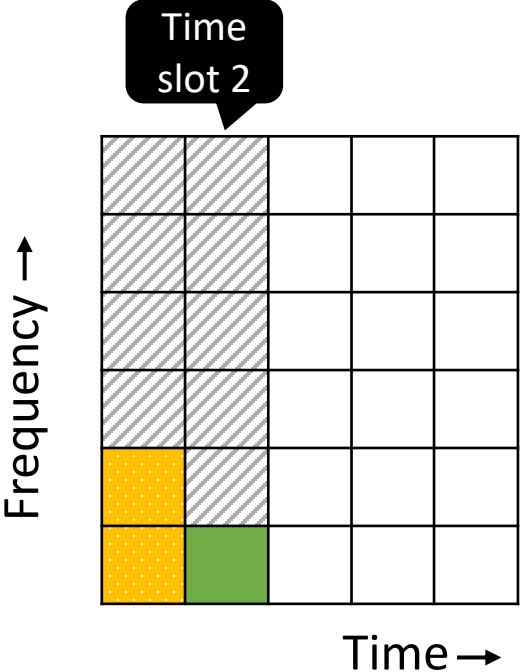

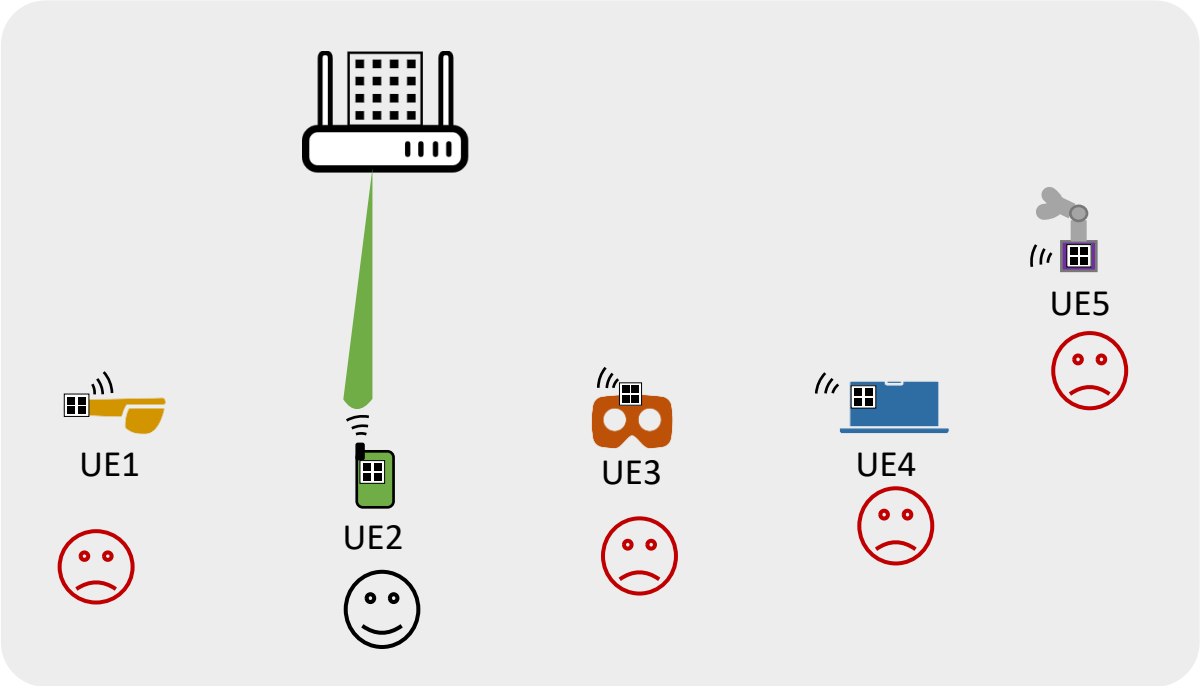High-throughput ✓

Low-latency ✗

Scalable ✗

Narrow beams impose restrictions on latency and scalability

Traditional mmWave is limited to Time-Division Multiple Access (TDMA)

Traditional mmWave is limited to Time-Division Multiple Access (TDMA)

Traditional mmWave is limited to Time-Division Multiple Access (TDMA)

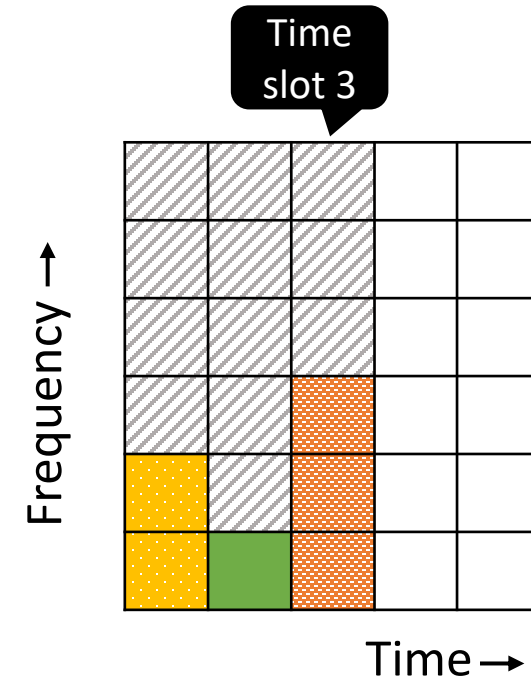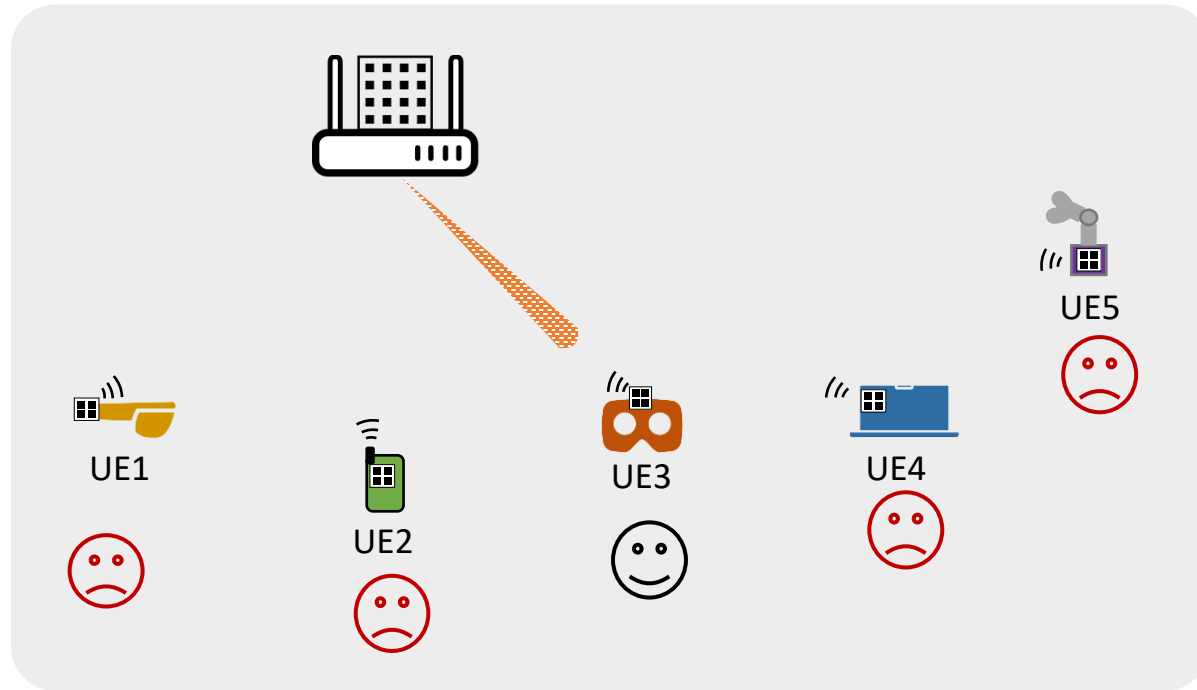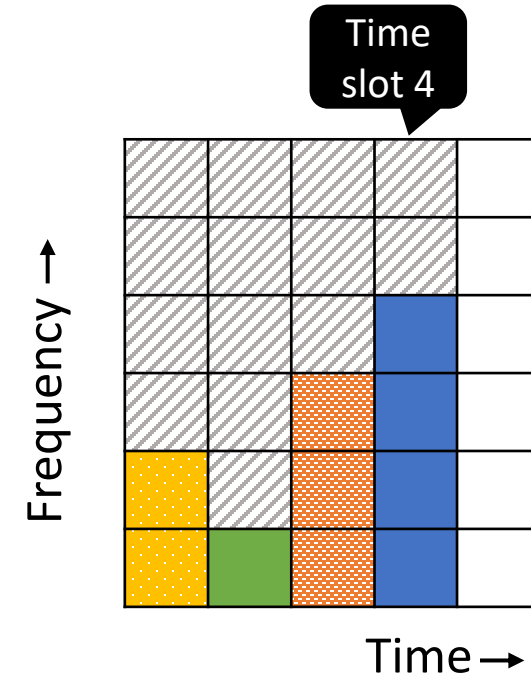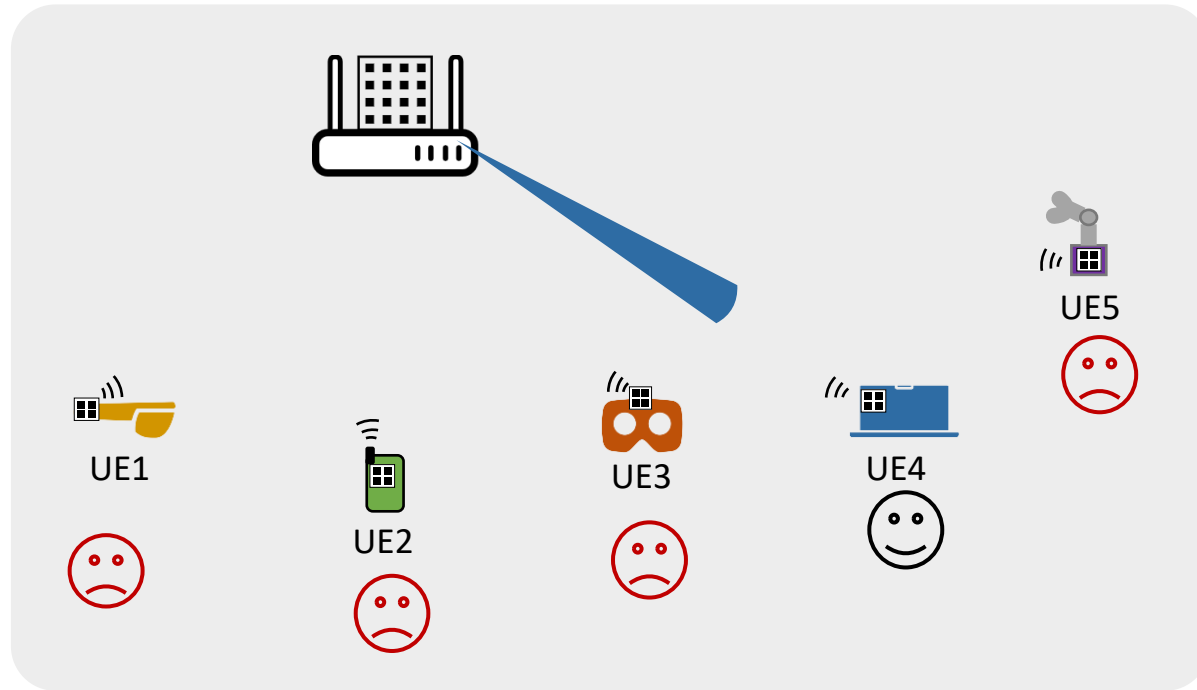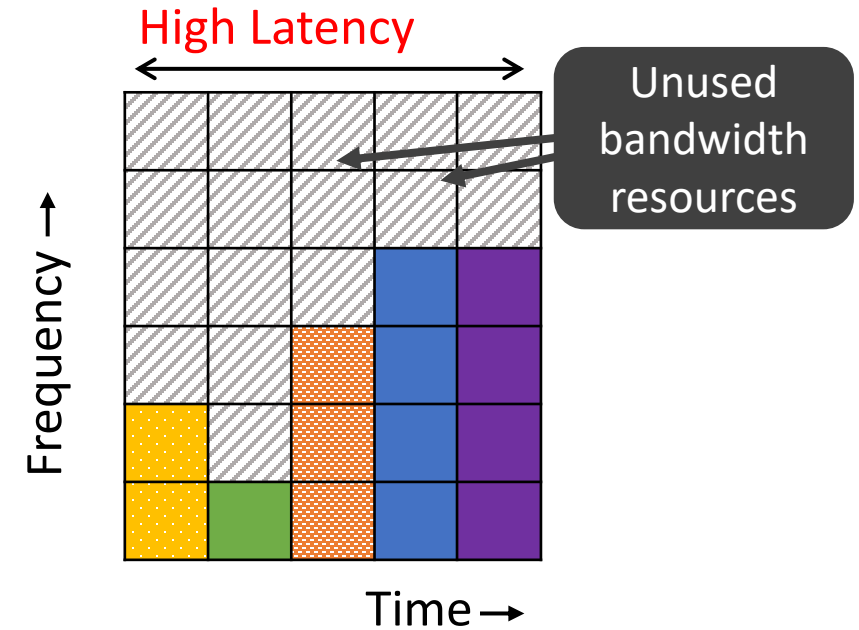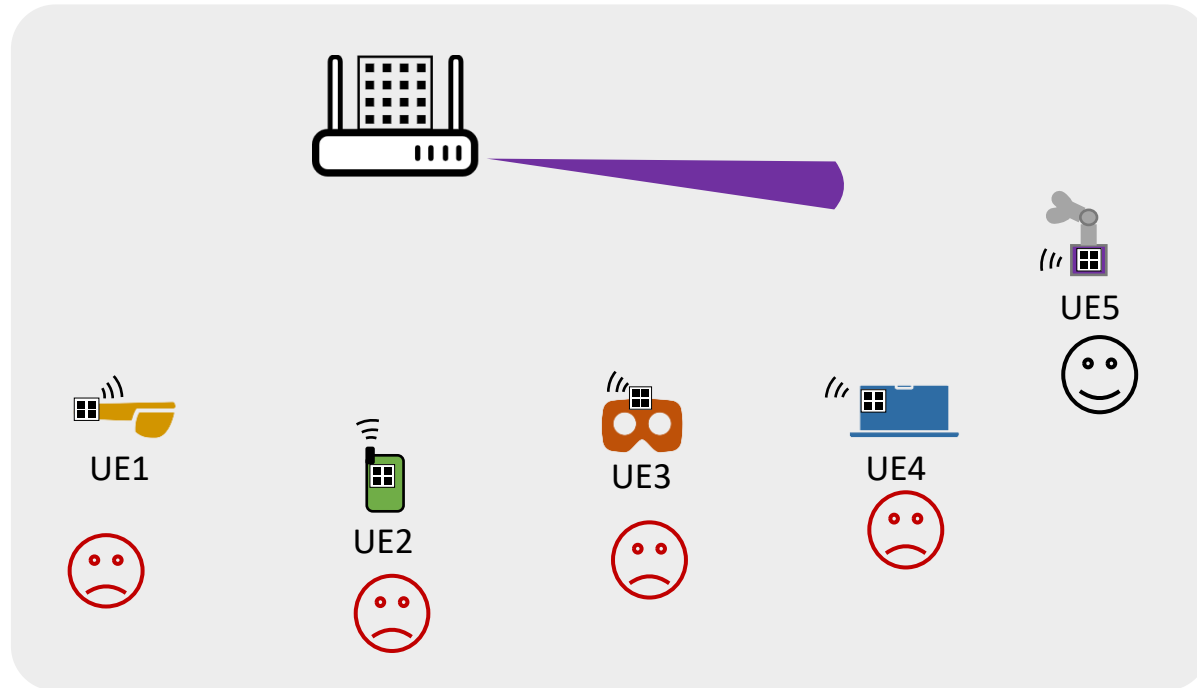# Traditional mmWave is limited to Time-Division Multiple Access (TDMA)

Traditional mmWave is limited to Time-Division Multiple Access (TDMA)

High Latency

Unused bandwidth resources

Frequency →

Time →

✓ High Throughput
✗ High Latency
✗ Not Scalable

UE1
UE2
UE3
UE4
UE5

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How to deliver low-latency and scalability with directional beams?
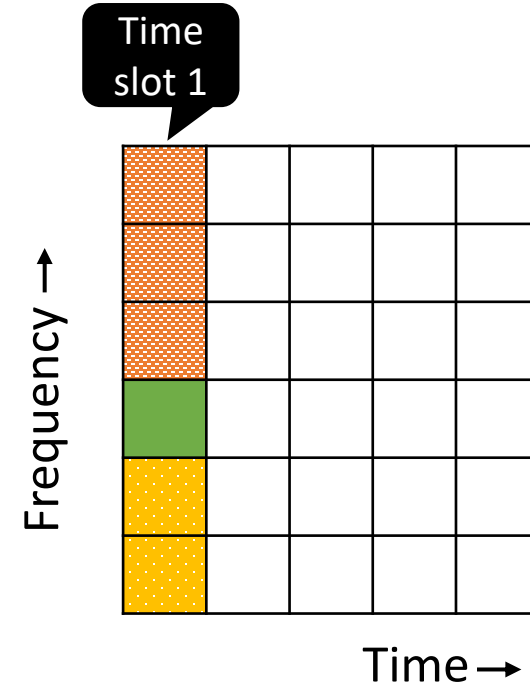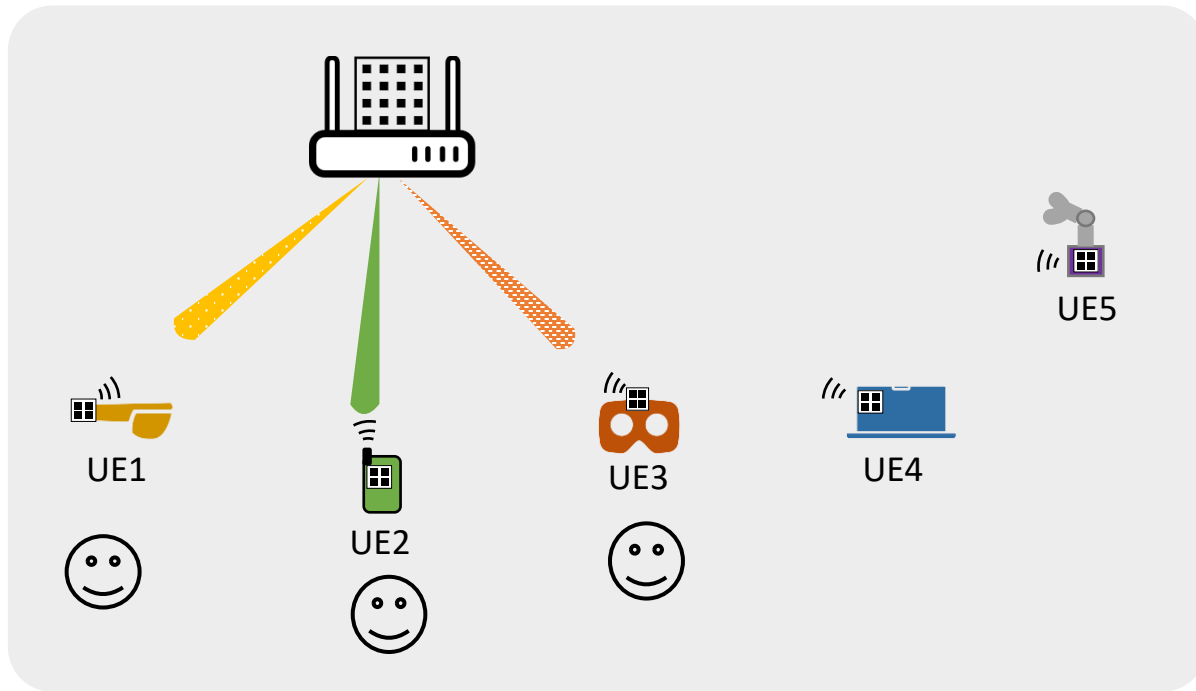
mmFlexible: Flexible time-frequency resource allocation

mmFlexible: Flexible time-frequency resource allocation
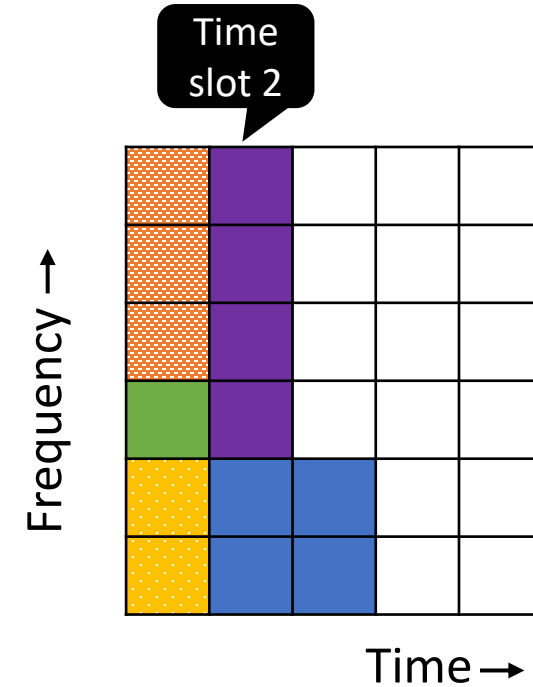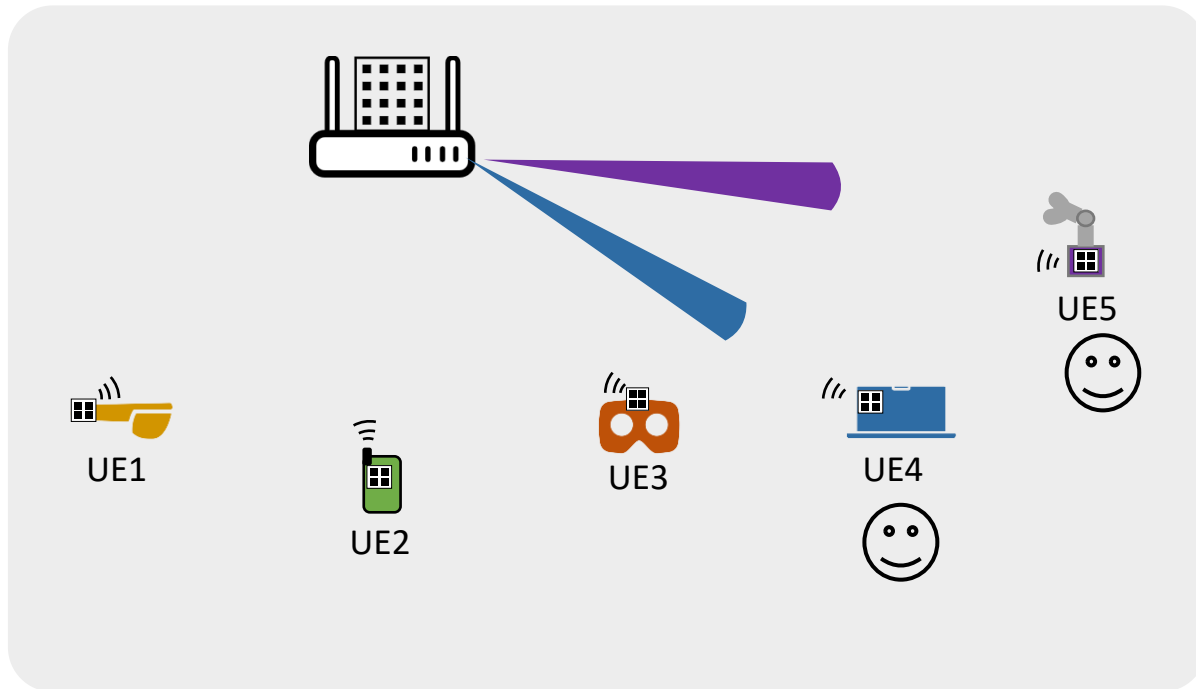
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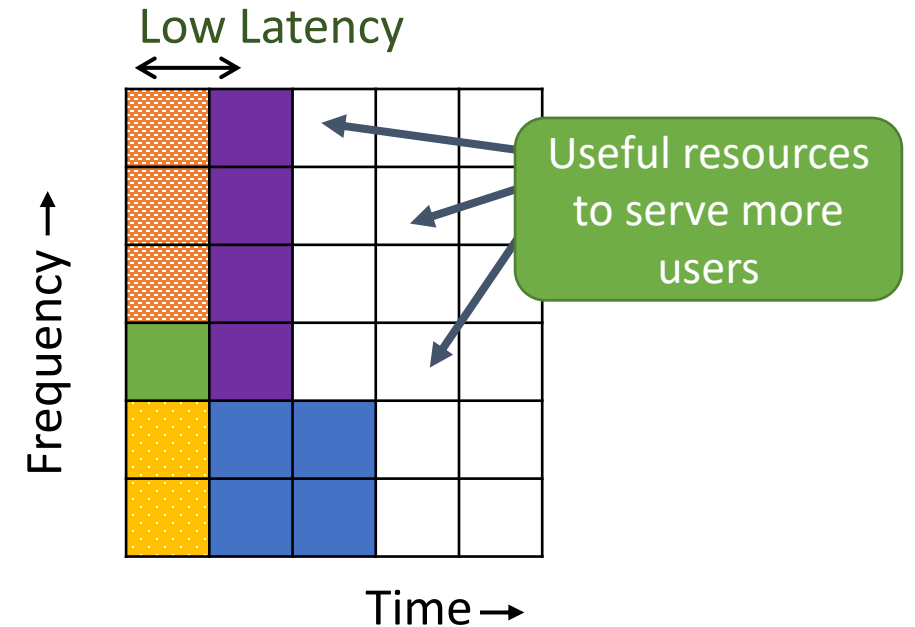Electrical and Computer Engineering

mmFlexible: Flexible time-frequency resource allocation

Low Latency

Frequency →

Time →

Useful resources to serve more users

UE1 UE2 UE3 UE4 UE5
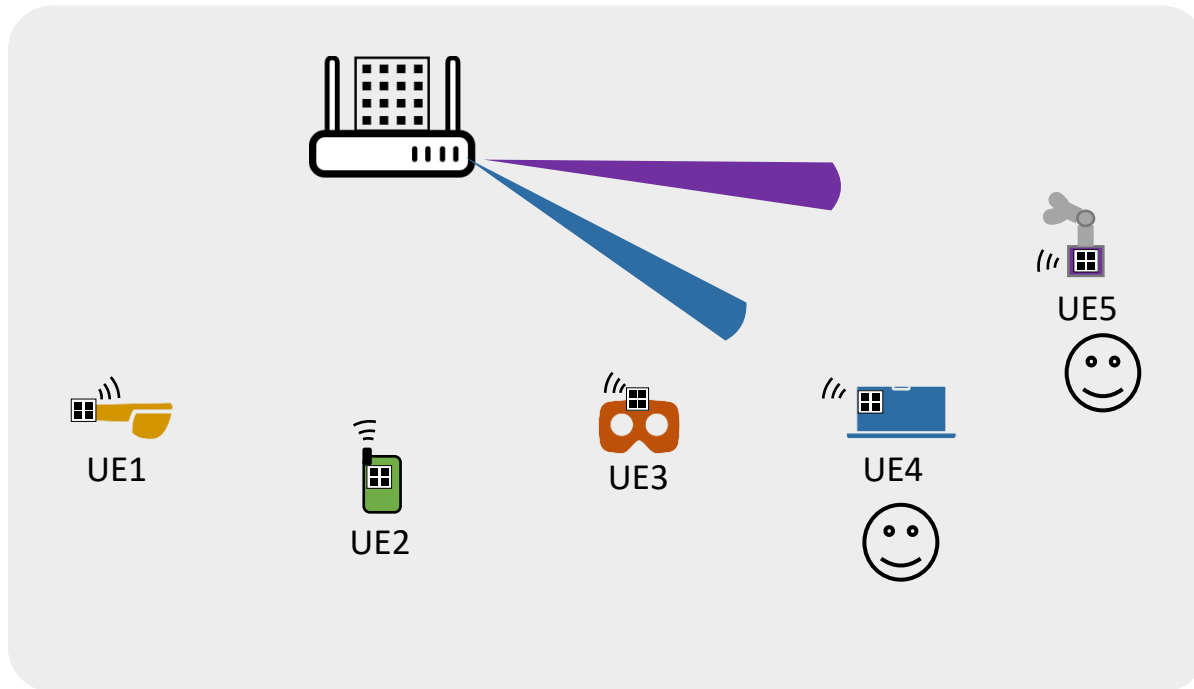
✓ High Throughput
✓ Low Latency
✓ Scalable

mmFlexible: Flexible time-frequency resource allocation
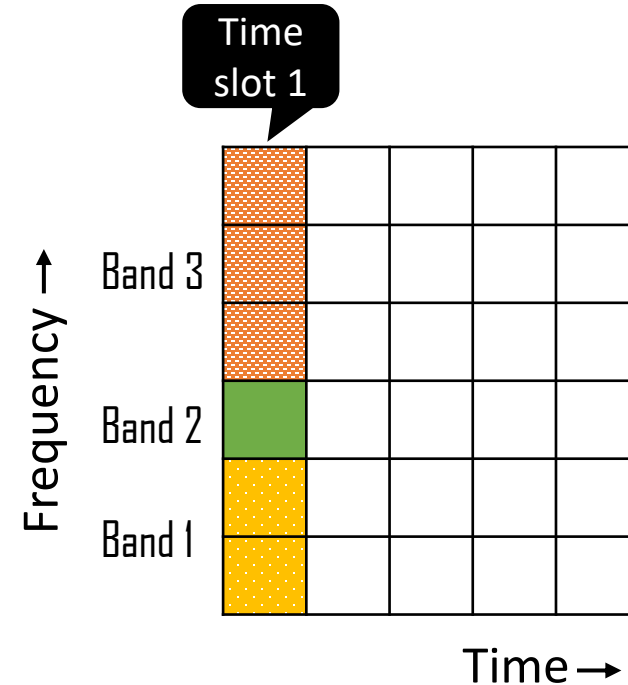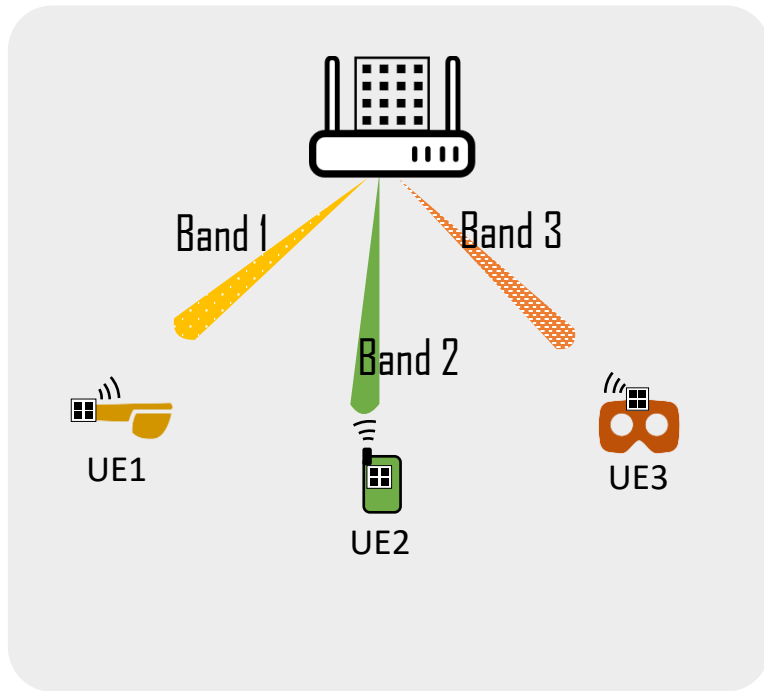
To serve concurrent users ➔ Need concurrent beams

Challenges in creating concurrent beams

Conventional single beam

Conventional split-antenna beams

mmFlexible delivers high-throughput beam for each user

Conventional single beam

Conventional split-antenna beams

mmFlexible concurrent beams

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mmFlexible delivers high-throughput beam for each user
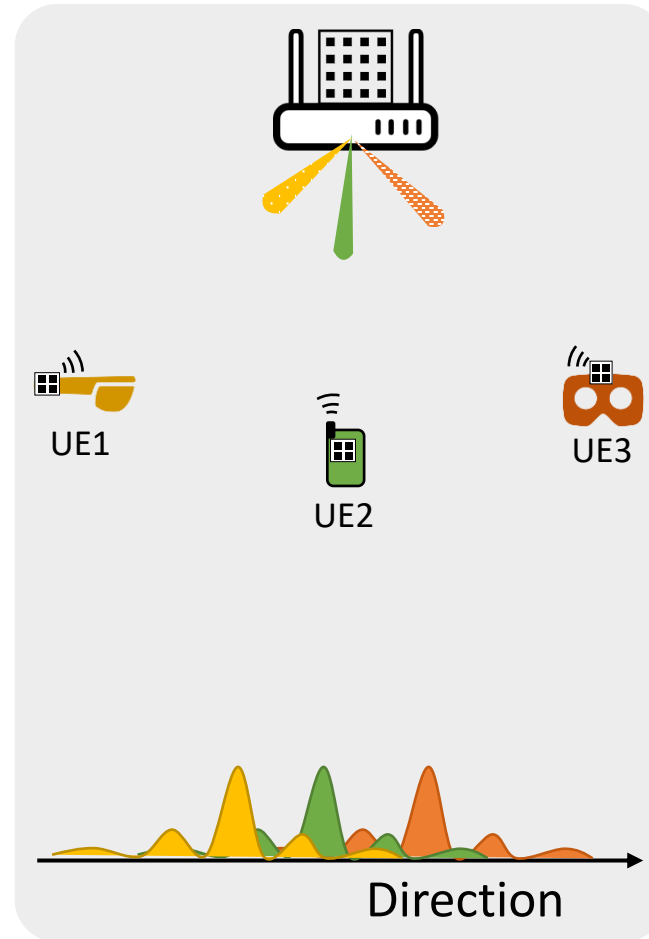

Conventional single beam

Conventional split-antenna beams

mmFlexible concurrent beams

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mmFlexible delivers high-throughput beam for each user

Conventional single beam

Conventional split-antenna beams

mmFlexible concurrent beams
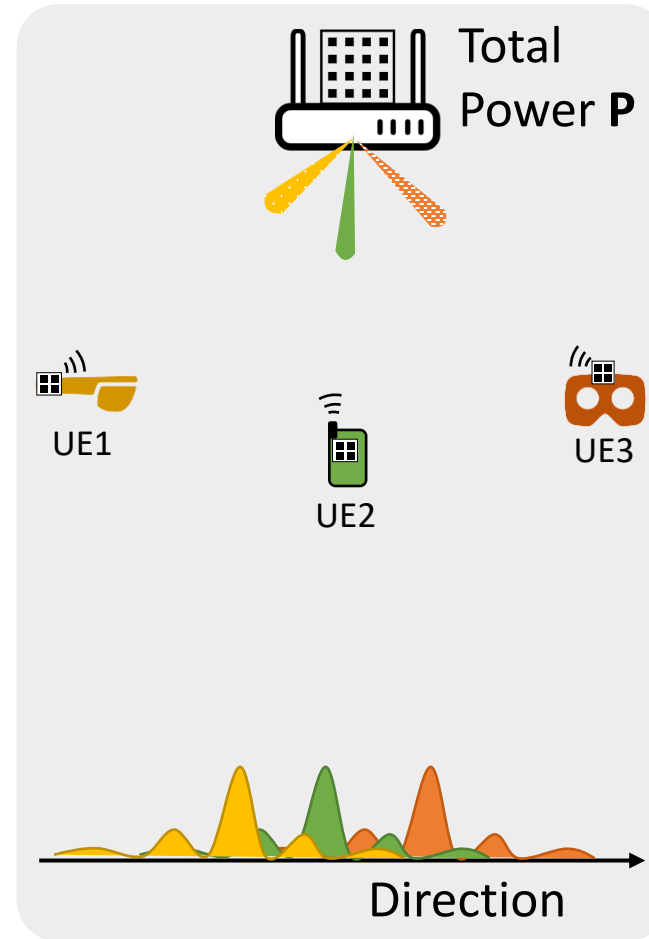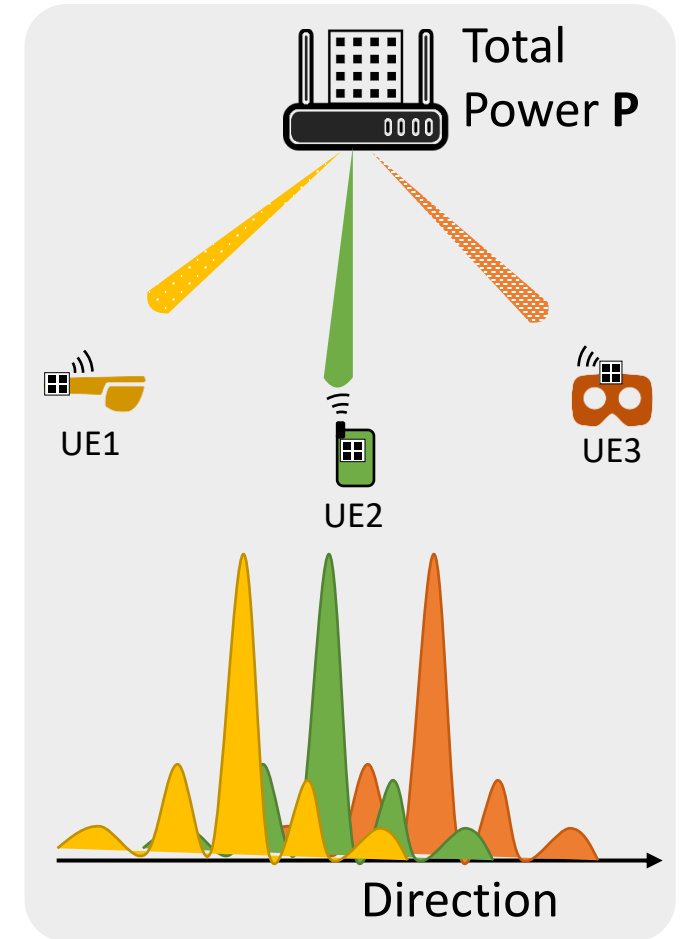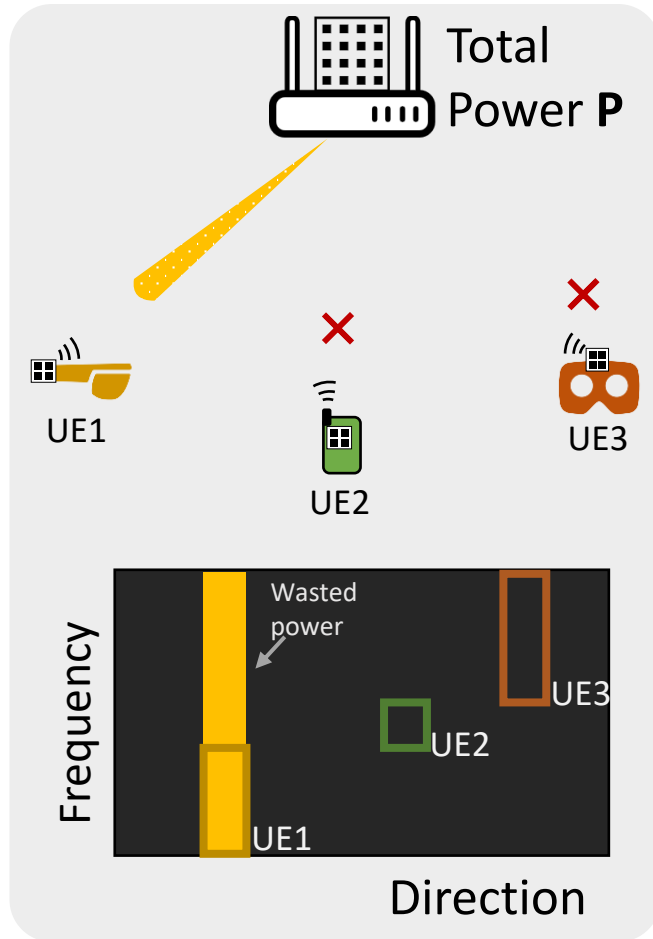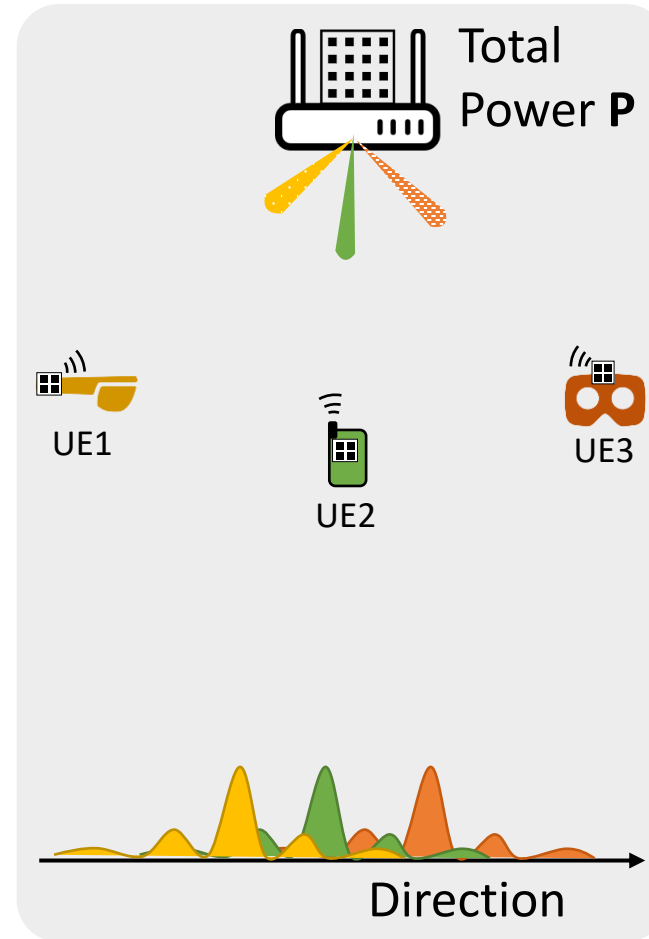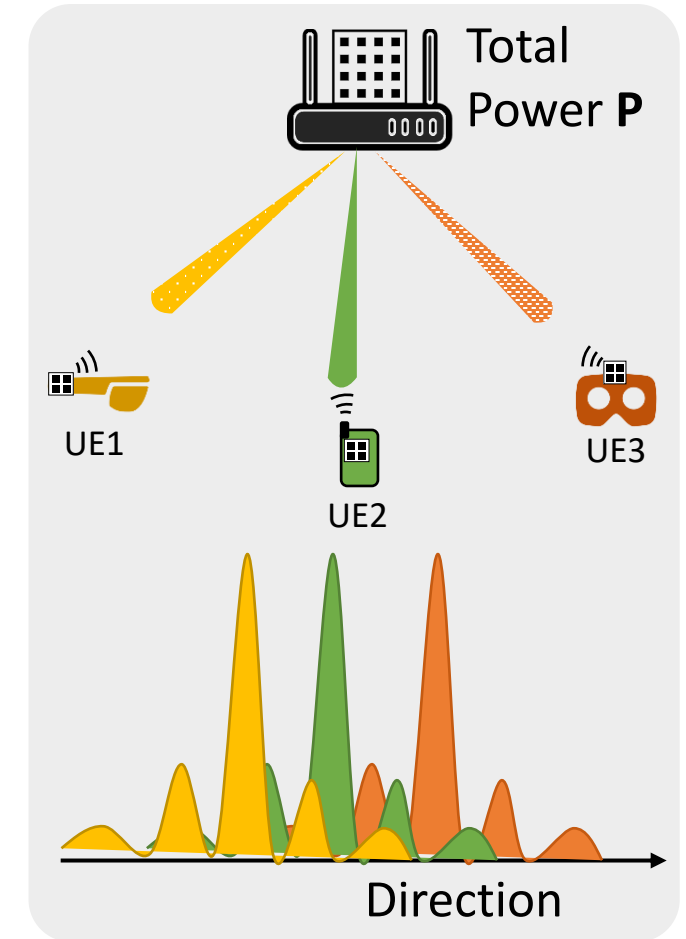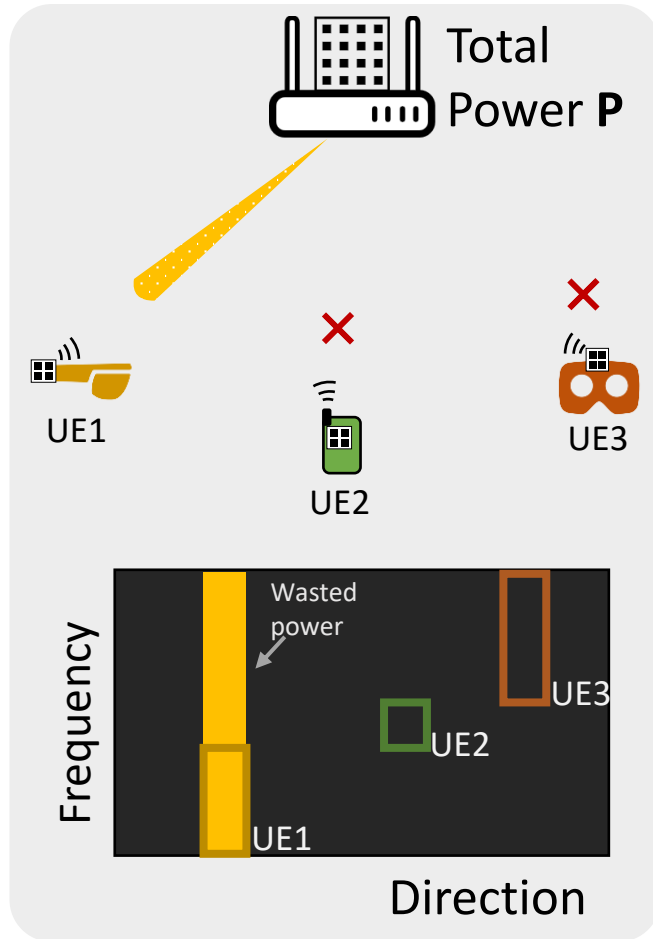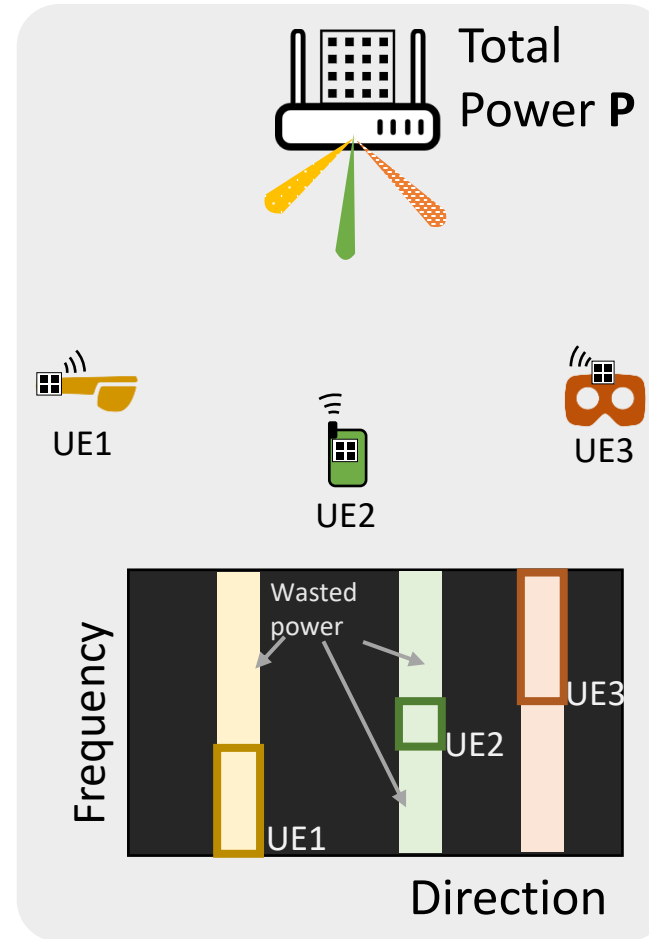
mmFlexible delivers high-throughput beam for each user

Conventional single beam
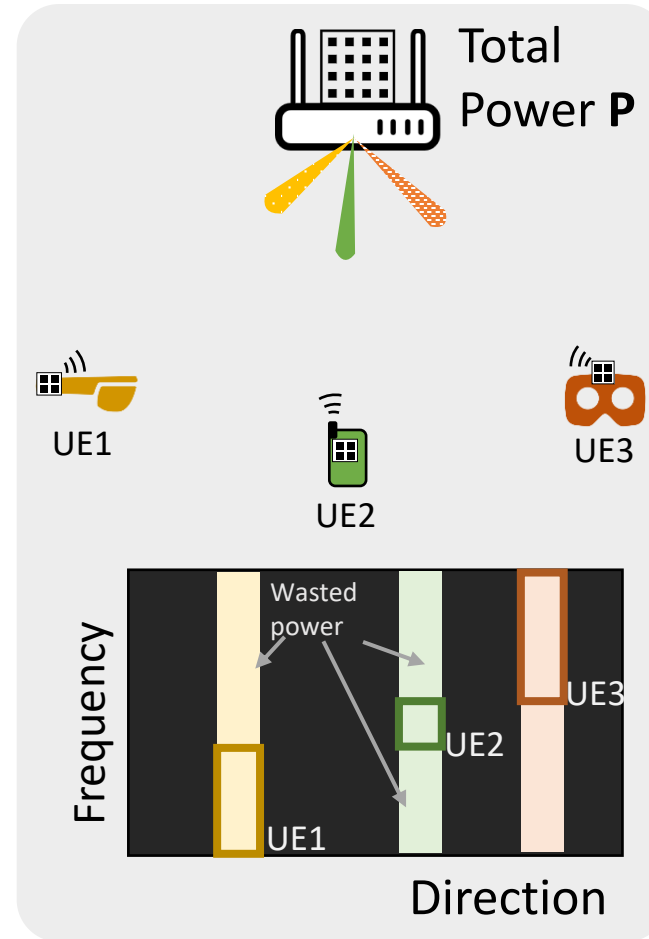
Conventional split-antenna beams
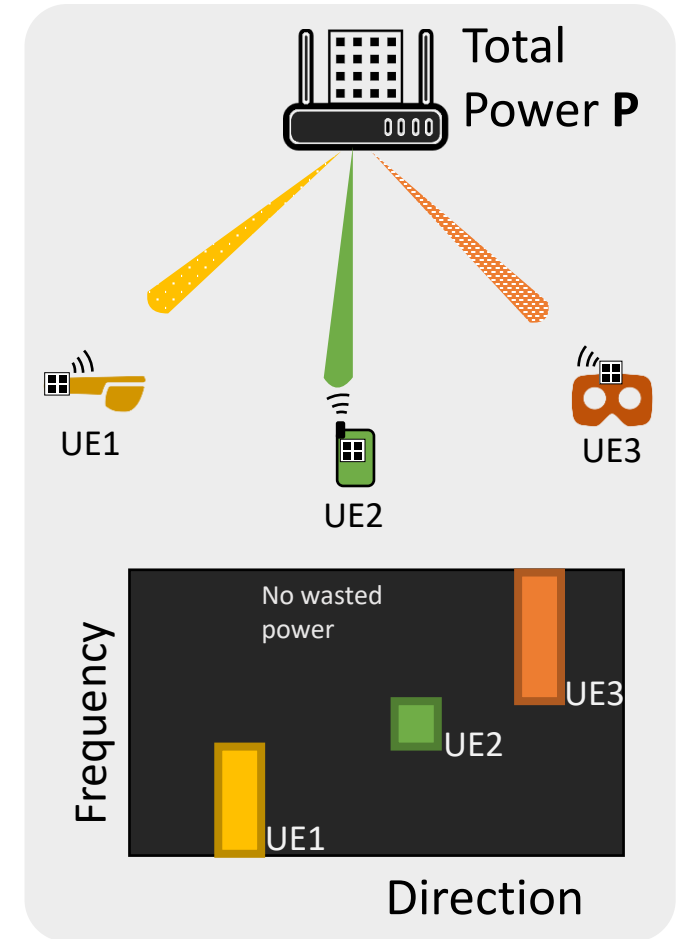
mmFlexible concurrent beams

mmFlexible: Contributions
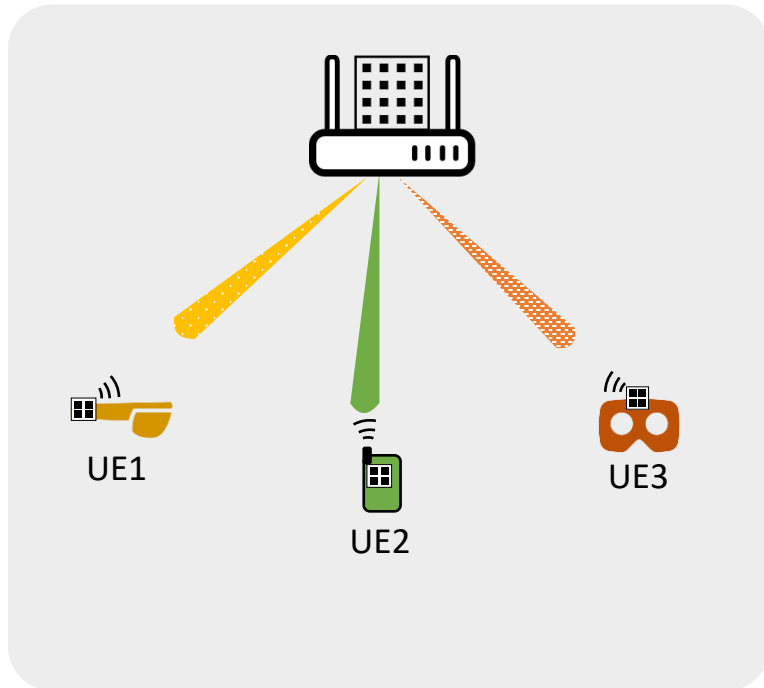
❖ Creating flexible concurrent beams for each user

❖ Developing hardware architecture for concurrent beams

❖ Configuring concurrent beams in real time

mmFlexible provides *flexible* concurrent beams

Any number of beams with narrow beamwidth

Arbitrary beam directions

Arbitrary **beam-bandwidth** (fraction of bandwidth per beam)

Frequency

Direction

Beamwidth

Beam-bandwidth

UE1

UE2

UE3
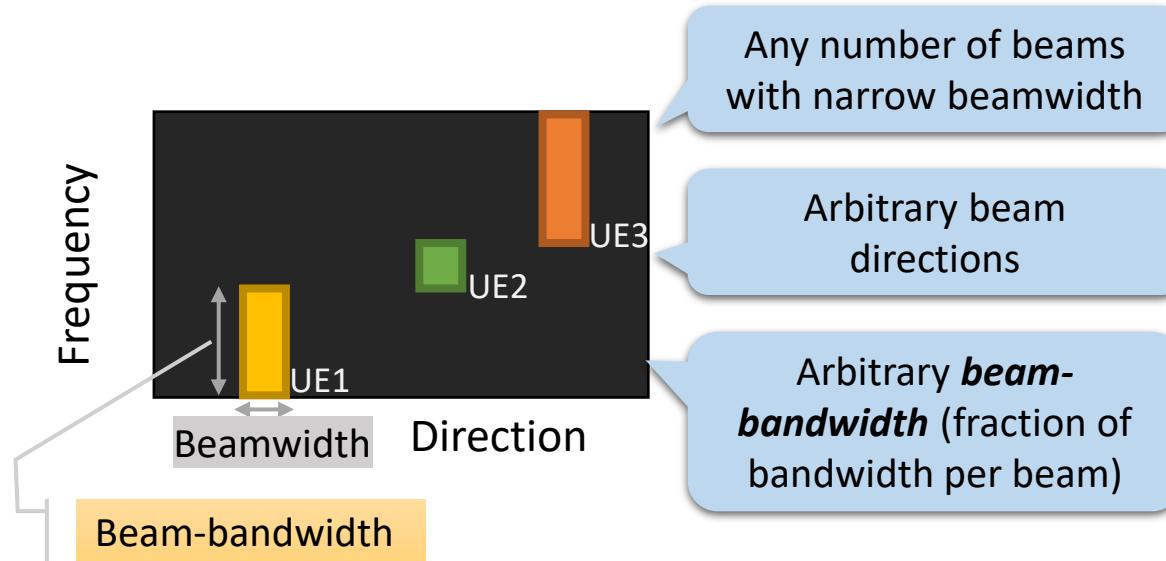
How to deliver flexible concurrent beams?

Designed a new *programmable* antenna array
Delay-Phased Array (DPA)
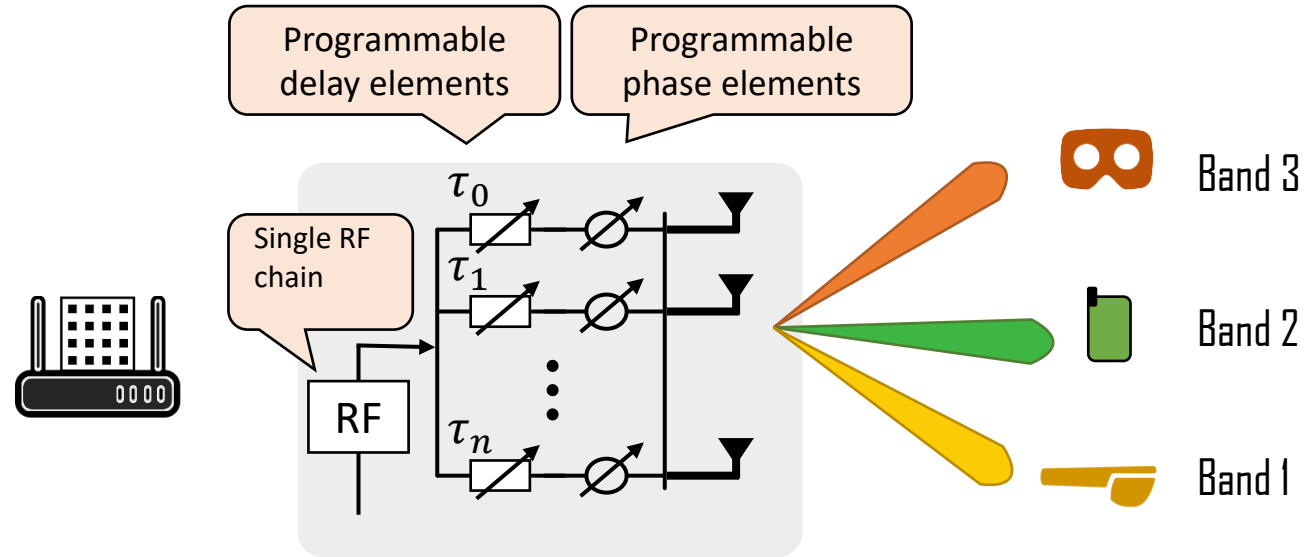
Proposed
Delay Phased Array (DPA)

Understanding **2** antennas DPA
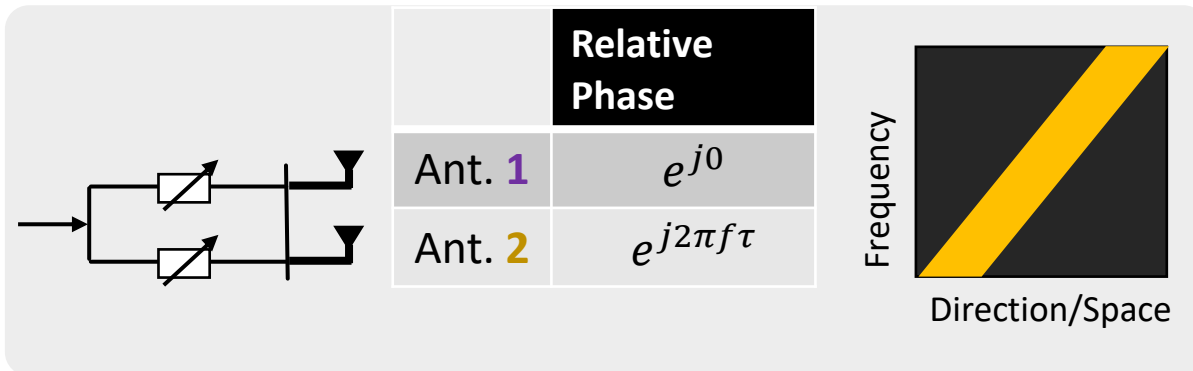
Phased array

	Relative Phase
Ant. **1**	e^{j0}
Ant. **2**	$e^{j\Phi}$

Frequency — Direction/Space
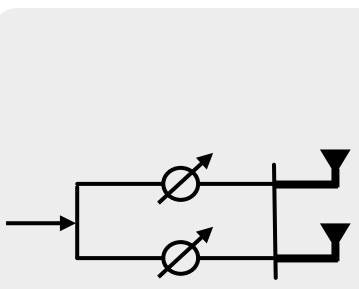
Phased array

True Time Delay array

	Relative Phase
Ant. **1**	e^{j0}
Ant. **2**	$e^{j2\pi f\tau}$

Frequency — Direction/Space

True Time Delay array

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Understanding **2** antennas DPA
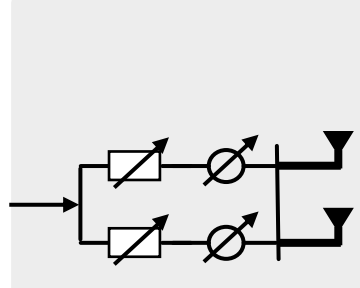
Phased array

	Relative Phase
Ant. **1**	e^{j0}
Ant. **2**	$e^{j\Phi}$

Frequency — Direction/Space

True Time Delay array

	Relative Phase
Ant. **1**	e^{j0}
Ant. **2**	$e^{j2\pi f\tau}$

Frequency — Direction/Space

Delay-phased array (DPA)

	Relative Phase
Ant. **1**	e^{j0}
Ant. **2**	$e^{j(2\pi f\tau+\Phi)}$

Frequency — Direction/Space

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Creating flexible beam response with DPA
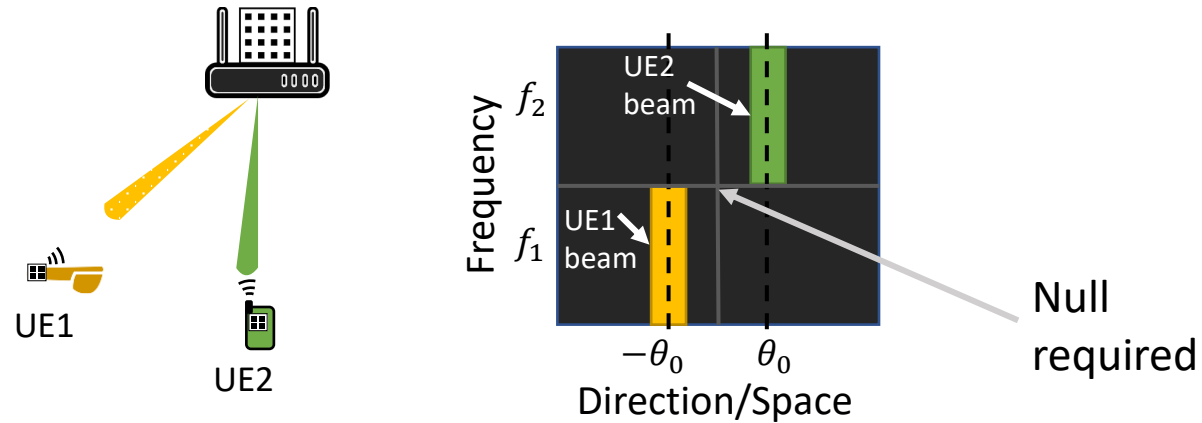
How to create this ***non-linear*** pattern with linear building blocks?

Creating flexible beam response with DPA

UE1

UE2

RF

Ant. **1**

Ant. **2**

Ant. **3**

Delay Phased Array (DPA)

Frequency

Direction/Space

F-S image for antennas **1**, **2**

Frequency

Direction/Space

F-S image for antennas **2**, **3**

Frequency

UE2 beam

UE1 beam

Direction/Space

Null achieved

F-S image for antennas **1**, **2**, **3**
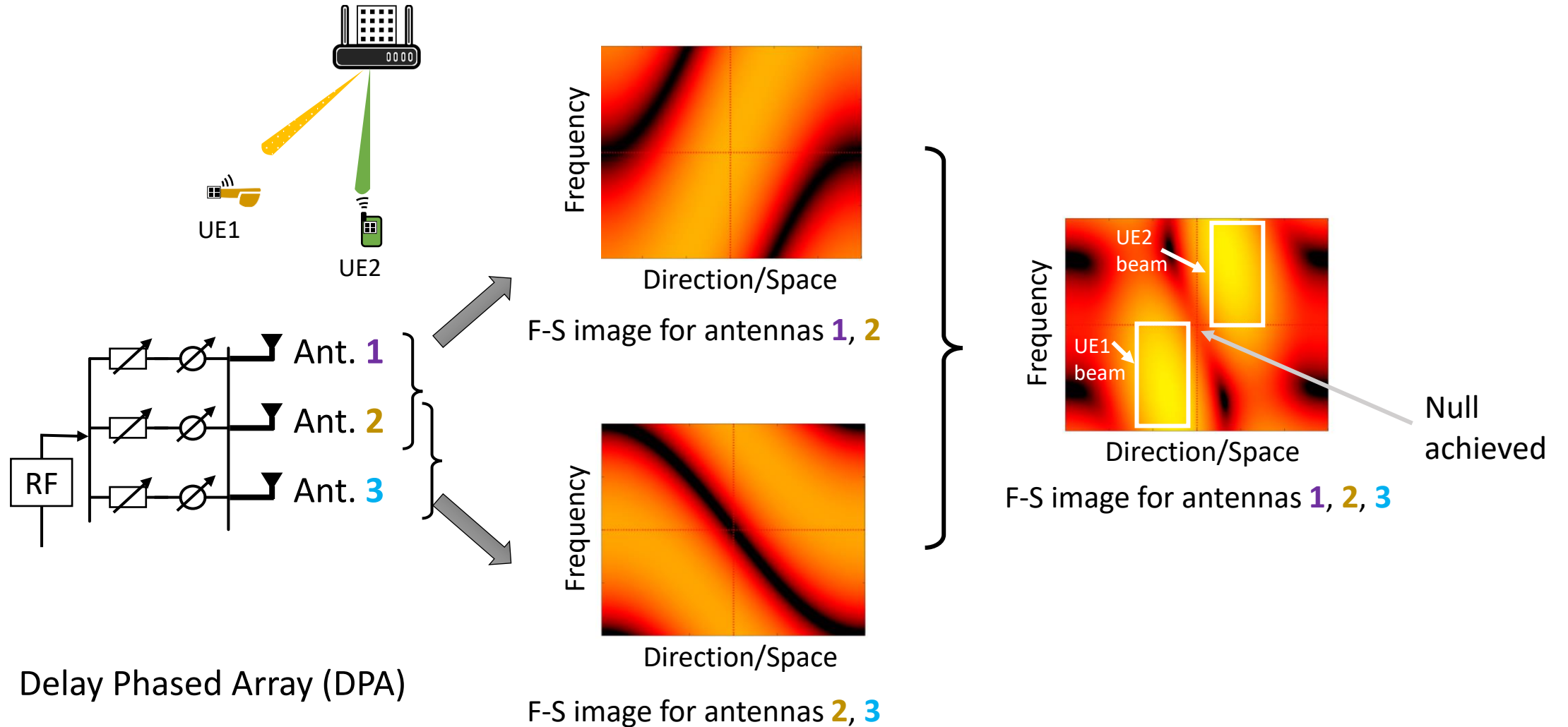
Creating narrow beam with **8** antennas

UE1

UE2

RF

Ant. **1**

Ant. **2**

Ant. **3**

⋮

Ant. **8**

Delay Phased Array (DPA)

UE2 beam

UE1 beam

Frequency

Direction/Space

F-S image for antennas **1** to **8**

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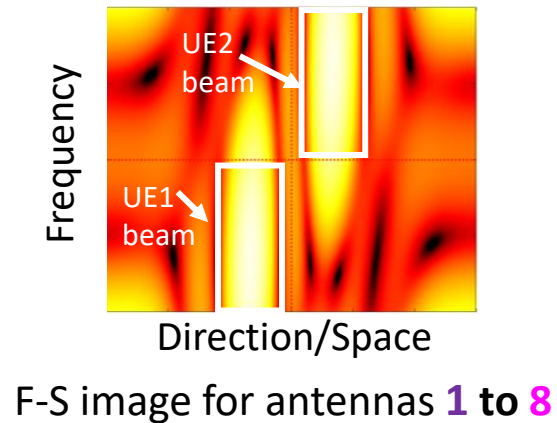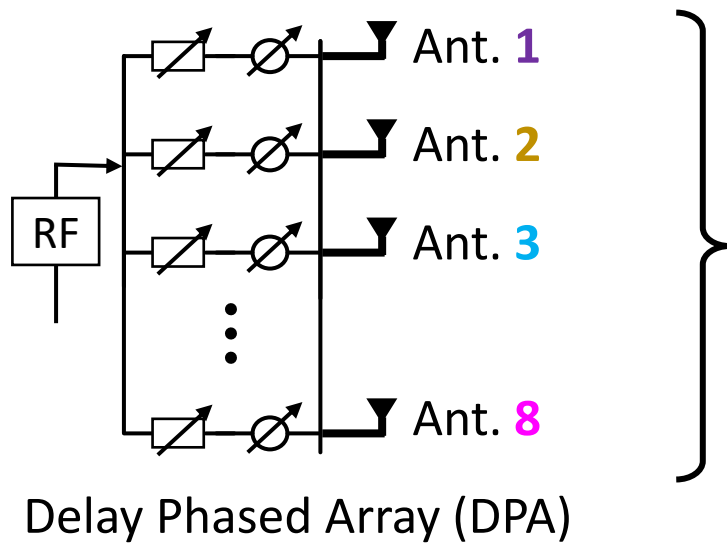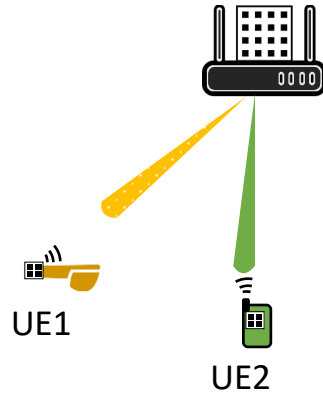
Configuring DPA in real time using closed-form formula
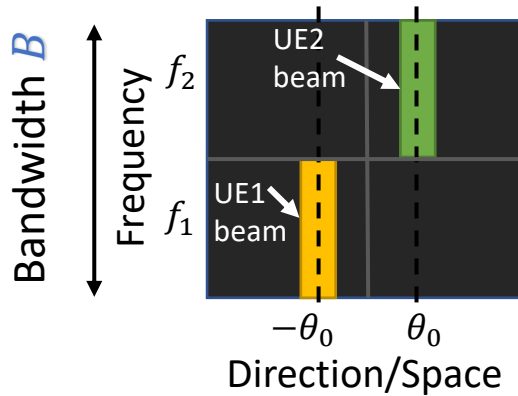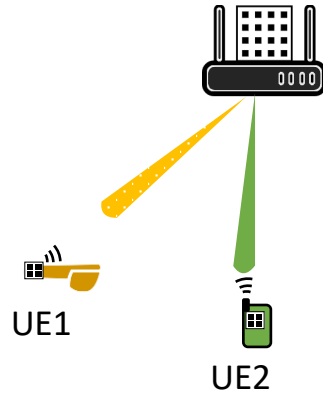
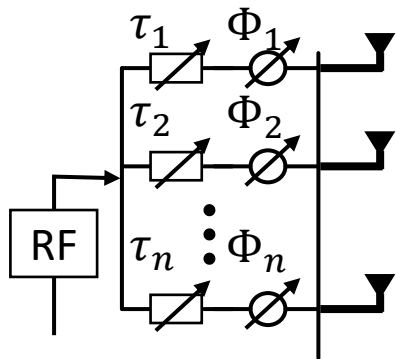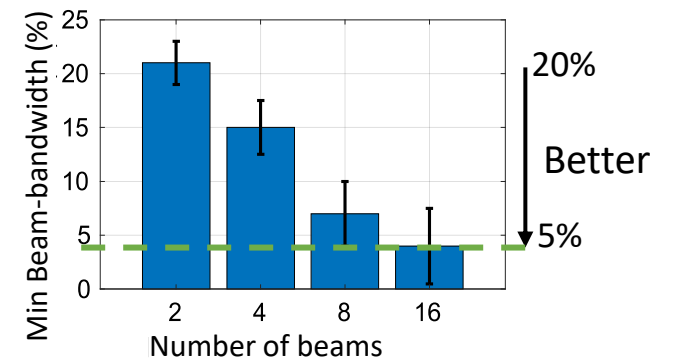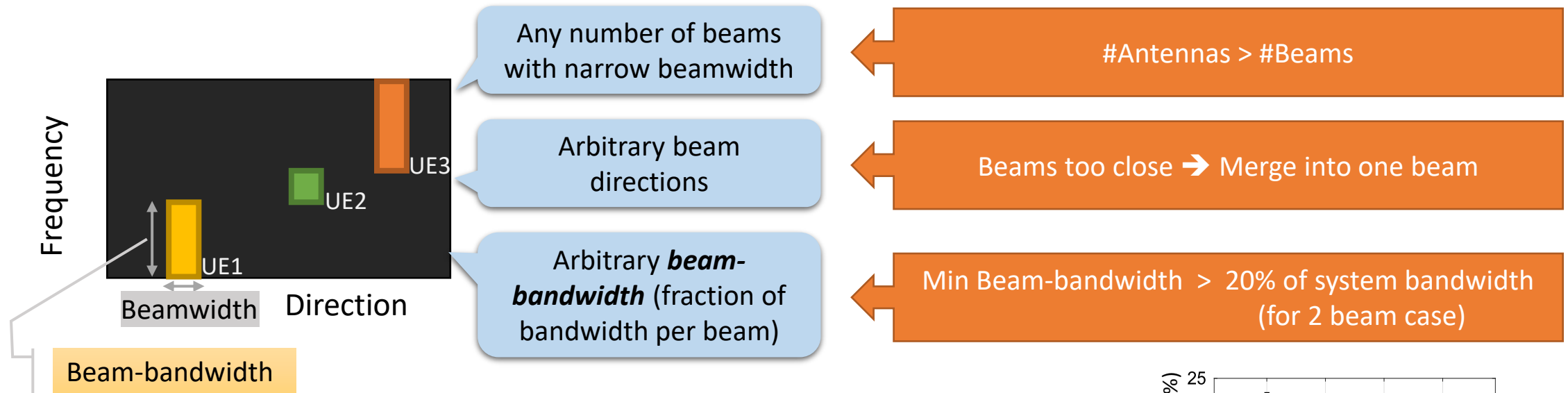We derive a **closed-form formula** for delay and phase configuration at each antenna

Bandwidth B / Frequency

f_2 — UE2 beam

f_1 — UE1 beam

$-\theta_0$ θ_0

Direction/Space

UE1

UE2

τ_1 Φ_1
τ_2 Φ_2
RF
τ_n Φ_n

2 beam case*

$$\tau_n = \left(\frac{3}{2B} n \sin(\theta_0)\right) \bmod \frac{3}{2B}$$

$$\Phi_n = \pi \, \mathrm{round}\big(n \sin(\theta_0)\big) \bmod 2\pi$$
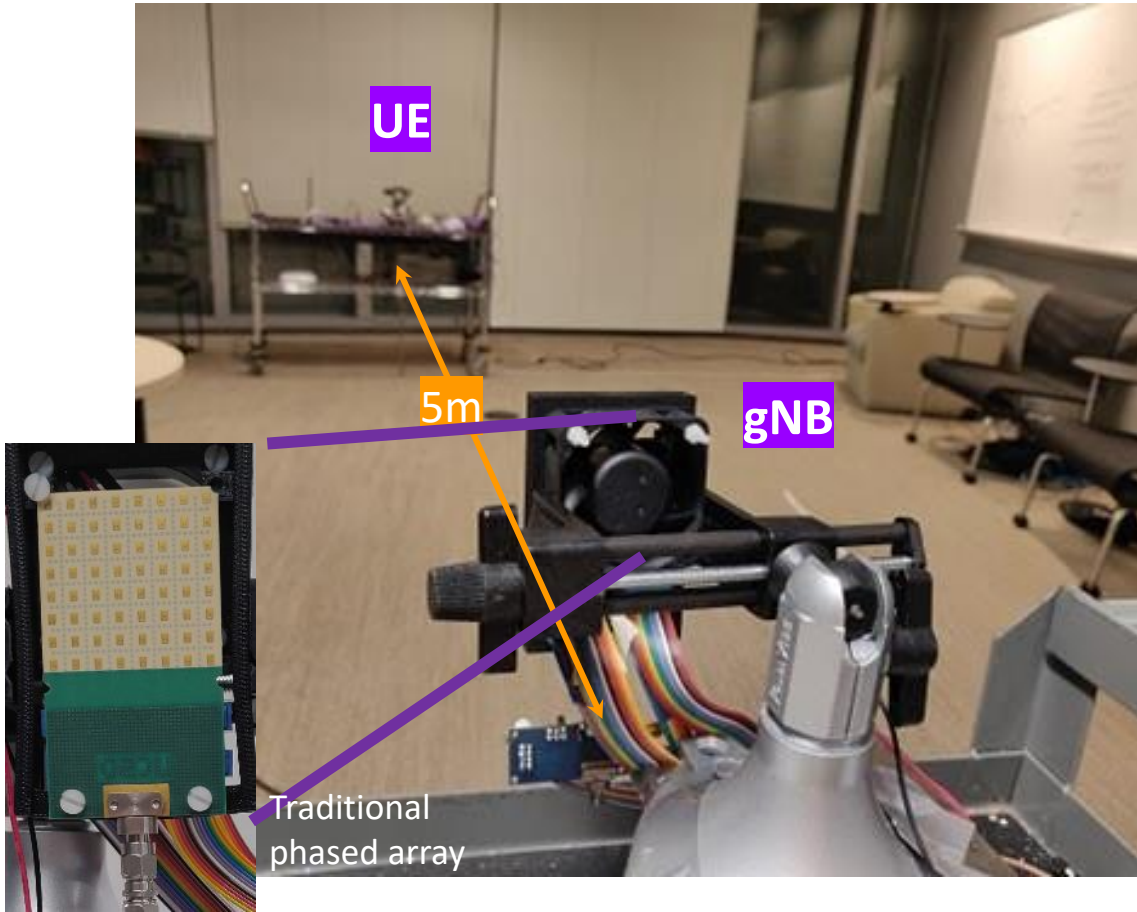
*Refer to Journal paper for a generalized formula for any number of beams, beam directions, and beam-bandwidths [Full paper: https://wcsng.ucsd.edu/dpa]

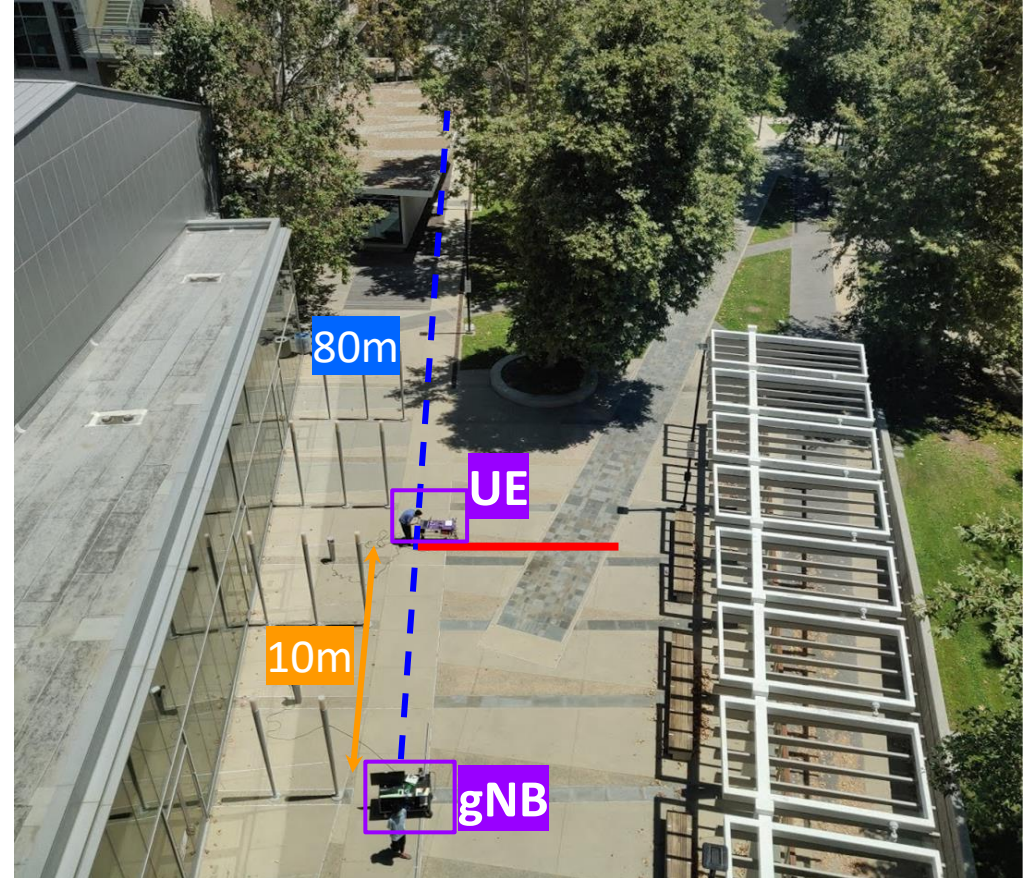Delay values are bounded (by $3/2B$) independent of number of antennas ➔ DPA is scalable to very large arrays

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How *flexible* is **Delay-Phased Array (DPA)?**

Frequency

Direction

Beamwidth

Beam-bandwidth

UE1

UE2

UE3

Any number of beams with narrow beamwidth

#Antennas > #Beams

Arbitrary beam directions

Beams too close ➔ Merge into one beam

Arbitrary ***beam-bandwidth*** (fraction of bandwidth per beam)

Min Beam-bandwidth > 20% of system bandwidth (for 2 beam case)

Min Beam-bandwidth (%)

Number of beams

20%

Better

5%

Implementation with mmWave channel dataset

Indoor Scenario

Outdoor Scenario

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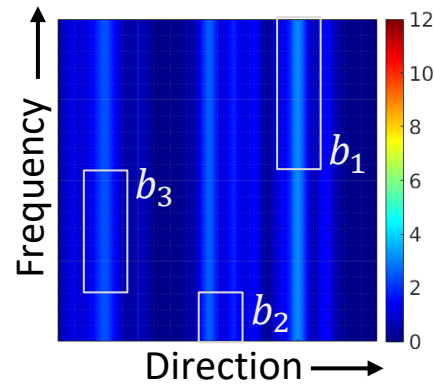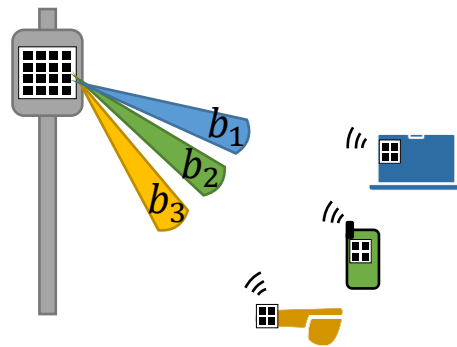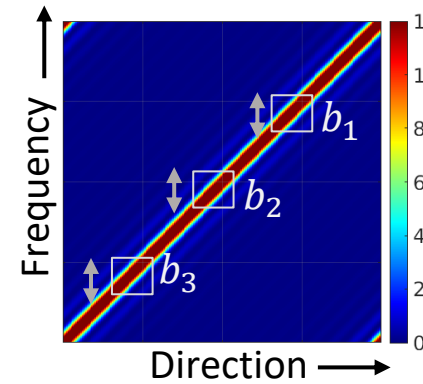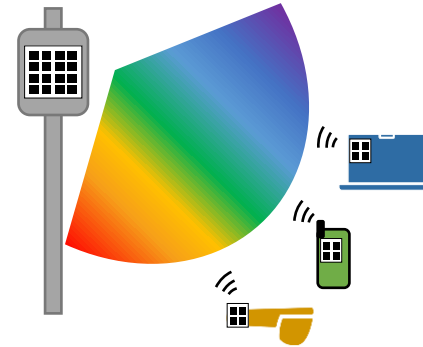
mmFlexible is more flexible than baselines
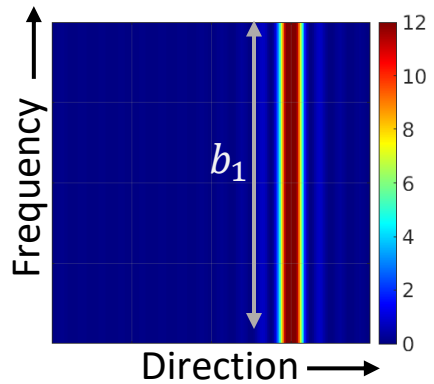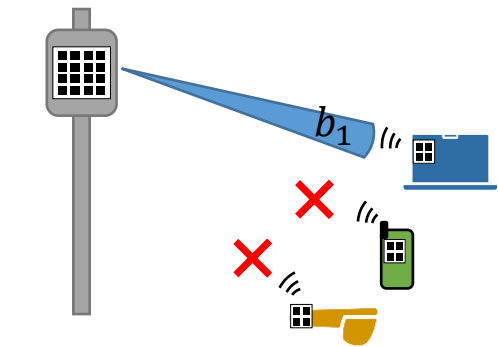
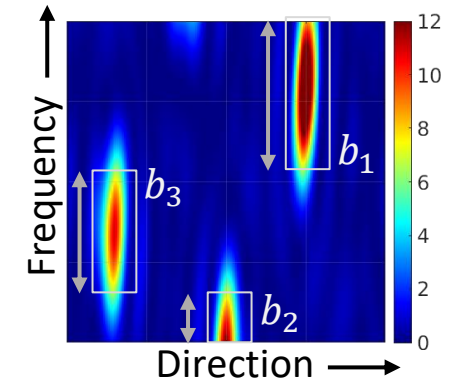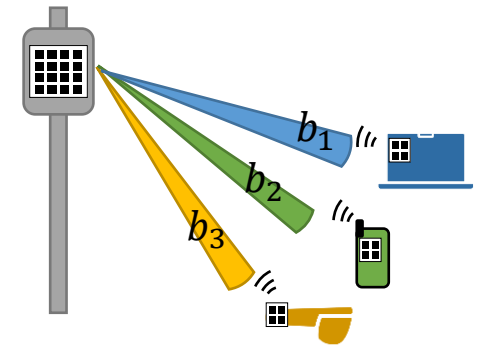TDMA Single beam
[cannot serve concurrent users]

Split Antenna beam
[low beamforming gain]

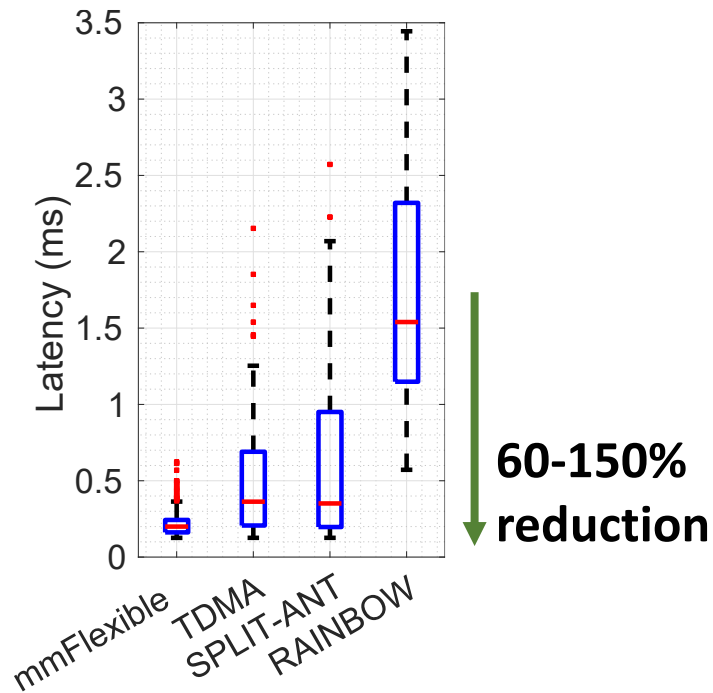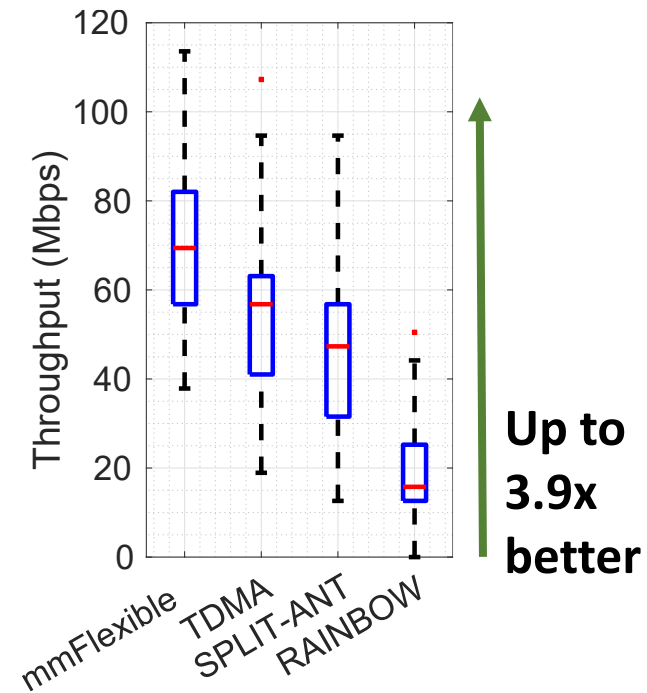Rainbow-link beam[1]
[low beam-bandwidth]

mmFlexible
[high gain and high beam-bandwidth per-beam]

[1] R. Li, H. Yan, and D. Cabric, "Rainbow-link: Beam-alignment-free and grant-free mmw multiple access using true-time-delay array," IEEE Journal on Selected Areas in Communications, 2022.

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Delivers low latency and high throughput

60-150% reduction

Latency Reduction

Up to 3.9x better

Throughput improvement

Improvement due to flexible allocation of time-frequency resources

mmFlexible: Flexible Directional Frequency Multiplexing for Multi-user mmWave Networks

Ish Kumar Jain
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Open-source code and dataset
https://wcsng.ucsd.edu/dpa