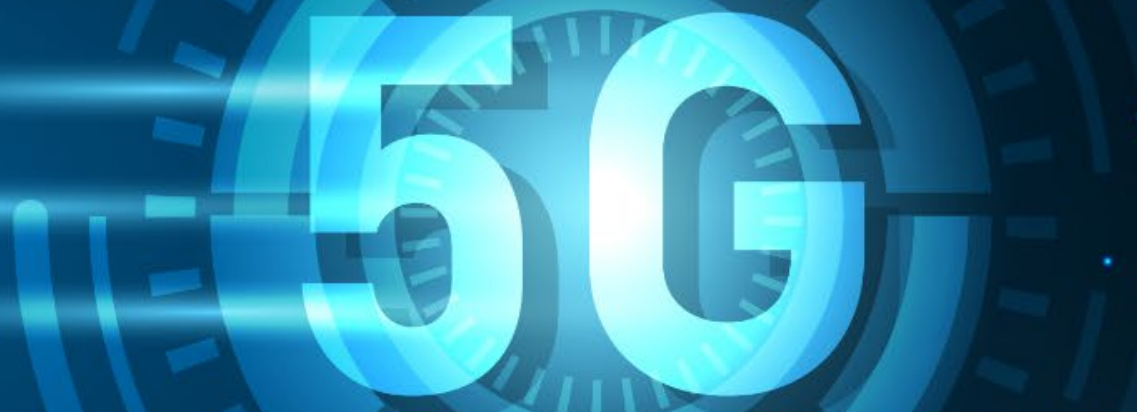
A Variegated Study of 5G Services: Challenges, Opportunities, and Application Innovations (on VR/MR)



Feng Qian

Associate Professor, Computer Science & Engineering
University of Minnesota

10/28/2022 @ ICNP NIB Workshop

About Myself

- I am an experimental networking & system researcher

- I discover real-world problems;
  I design, engineer, deploy, and evaluate real-world protocol & systems;
  I make my systems yield real-world impact

- Research focuses:
  mobile systems/networking, metaverse
  transport/application protocols (including NIB)

My network system research started

2009

2019

2019: Dawn of the 5G Era

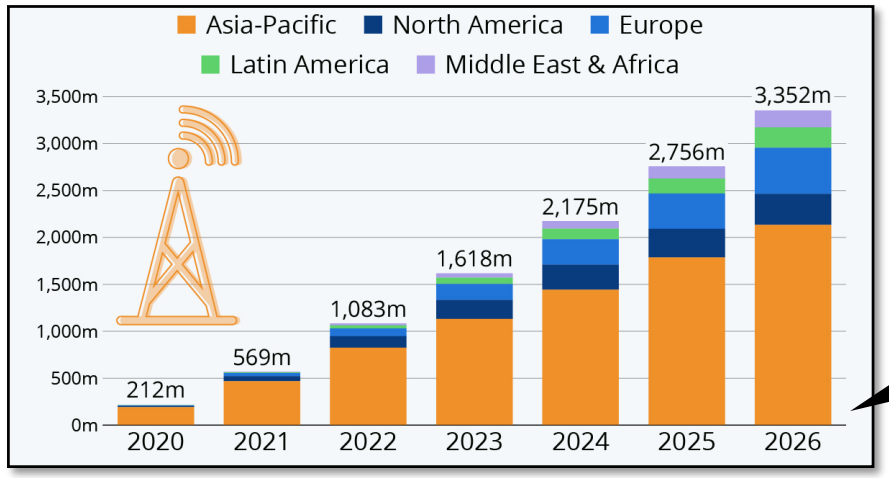
- World's **first commercial 5G** {**services** & **smartphones**} released in April 2019
  - USA | Chicago & Minneapolis | Verizon
  - South Korea | Nationwide | SK Telecom

- **Rapid surge** in 5G deployments globally

GLOBAL 5G STATISTICS

Total 5G City-Level Deployments	85223
Total 5G Operators	179

Dawn of the 5G Era



Global 5G adoption to hit 1 billion by 2022

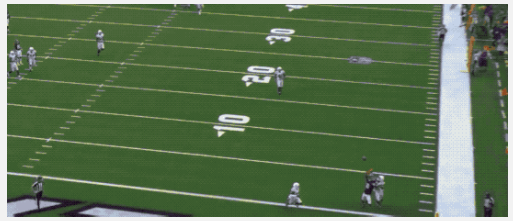
Source: Ericsson Mobility Report June 2021 / Statista

Despite 3 years of commercial 5G

There exists a vacuum in understanding 5G technology out in the wild

Promises

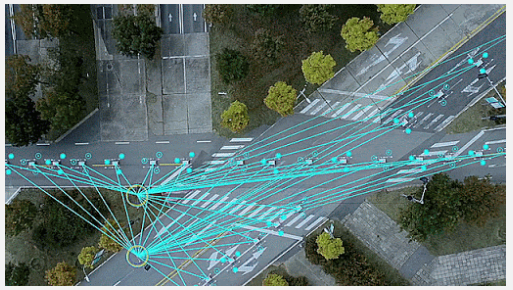
Source: Intel True View



Interactive Video Services

AR/VR Services

Source: Nebula Link



V2X

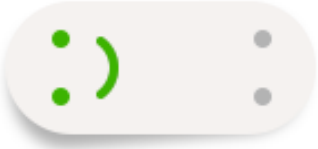
A Lack of Understanding of 5G in the Wild

What is the network performance footprint of 5G? Key issues?

Network Performance

Implications of 5G over Application QoE? How can Apps leverage 5G?

App. Perf & QoE



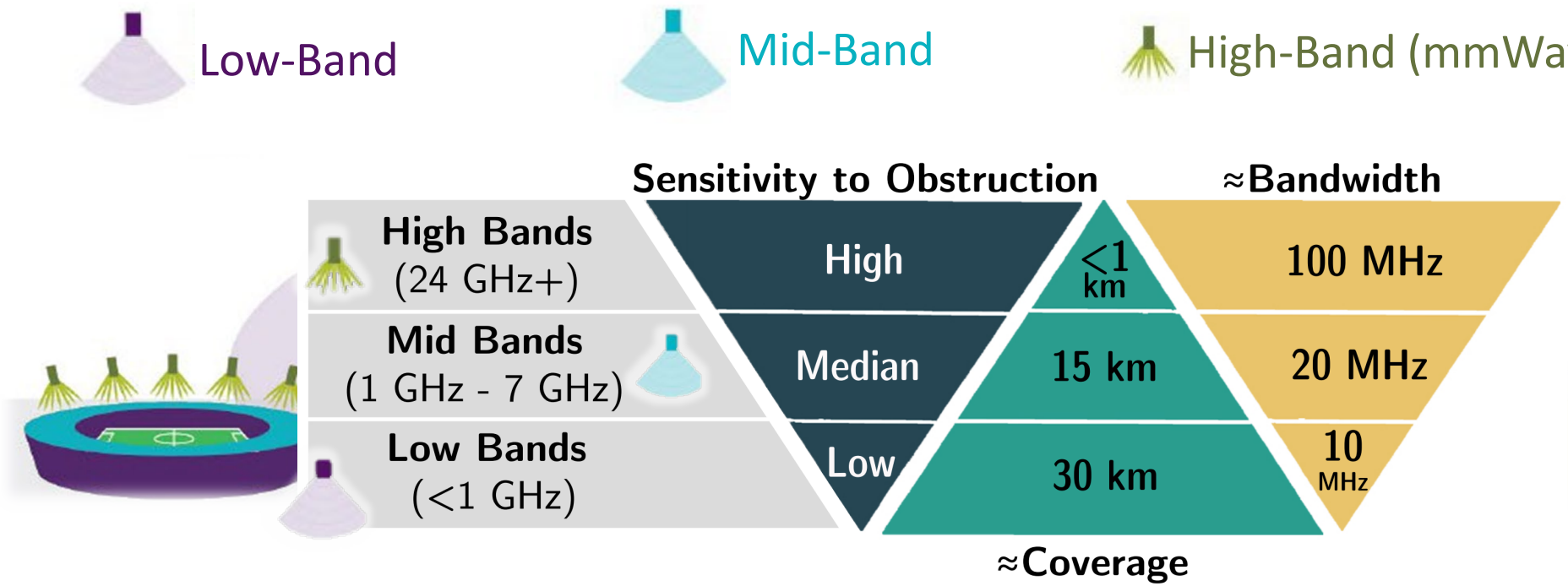
Is 5G more energy efficient than 4G/LTE? Trade-offs?

Power & Energy Efficiency

Challenges

- Complex ecosystem with heterogeneous bands and architectures
- No visibility into carrier's infrastructure
- A lack of tools and datasets
- Diverse applications

Diverse 5G Bands

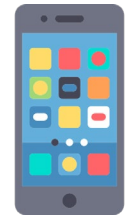


Talk Outline

- What is 5G performance in the wild?
  - 3-year extensive measurement study
- How to accurately predict 5G performance?
  - Making 5G systems intelligent

5G Network 

- How to innovate emerging applications for 5G?
  - Using virtual/mixed reality (VR/MR) as a case study

5G Application 

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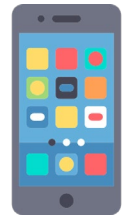
5G Application 

Major 5G Measurement Campaigns (2019 – 2021)

5G-Tracker
Our developed 5
Measurement To
[SIGCOMM20-Den

The first research paper on commercial 5G

April 2019 | Aug. 2019 | Nov. 2019 | May 2020 | Oct. 2020 | Jan. 2021 | June | Sep

[www20] [imc20] [sigcomm21] submission

5G Launch in US

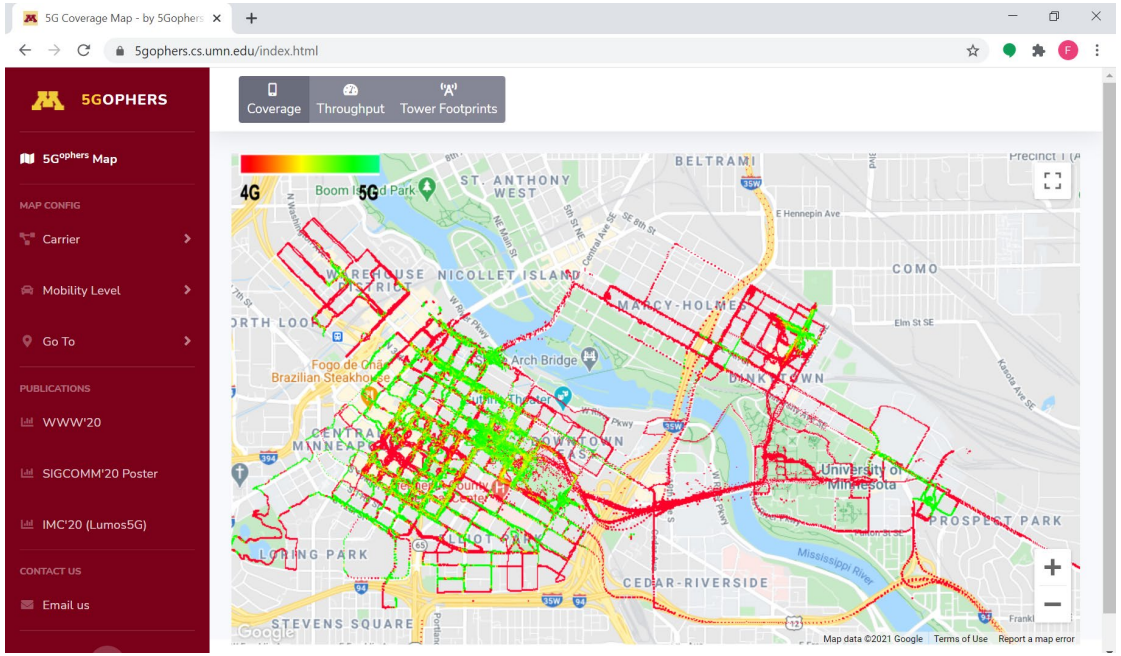
4 months | 3 U.S. cities
Baseline Study
3 carriers
Campaign #1

6 months | 331km walking
Throughput Prediction
132km driving
Campaign #2

4 months | 2 carriers
3 smartphone models | 2 U.S. cities
Performance & Power
Power Characterization
RRC state inference
Campaign #3

3 carriers | 6,500km + drive tests
Mapping, Cross-Layer, Latency
7 smartphones | 5 U.S. cities
Campaign #4

Total Data Usage: 100 TB+
Total Driving Distance: 8,000km+


5G Coverage Map - by 5Gophers
5gophers.cs.umn.edu/index.html
5GOPHERS
5Gophers Map
MAP CONFIG
Carrier
Mobility Level
Go To
PUBLICATIONS
WWW'20
SIGCOMM'20 Poster
IMC'20 (Lumos5G)
CONTACT US
Email us
Coverage
Throughput
Tower Footprints
4G
5G
BELTRAMI
ST. ANTHONY WEST
COMO
MARCY-HOLMES
DINKYTOWN
PROSPECT PARK
CEDAR-RIVERSIDE
STEVENS SQUARE
LORING PARK
University of Minnesota
Map data ©2021 Google
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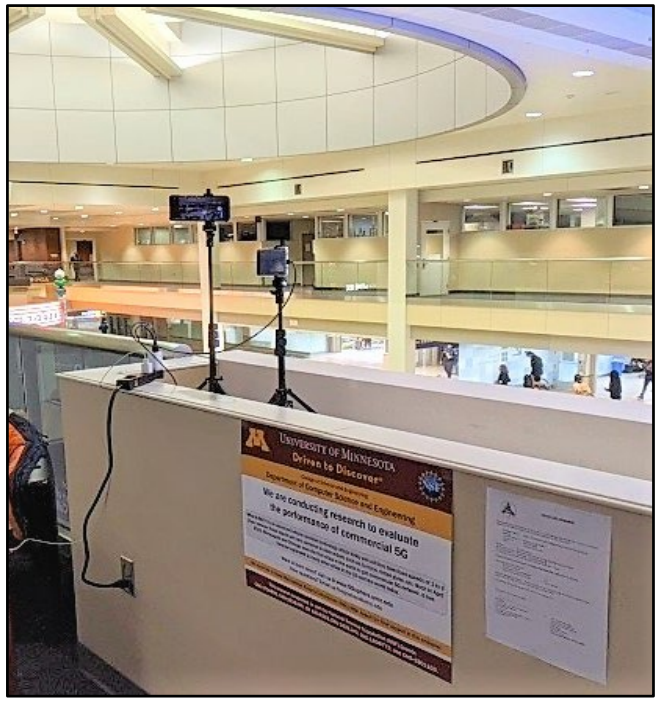
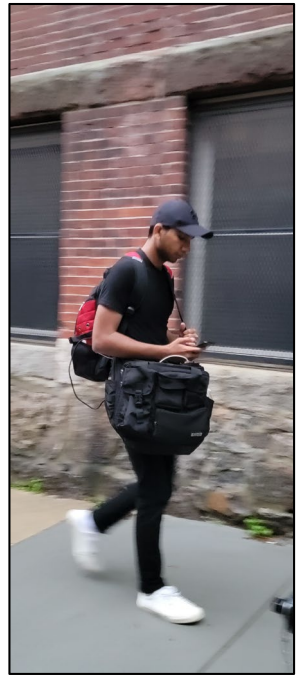
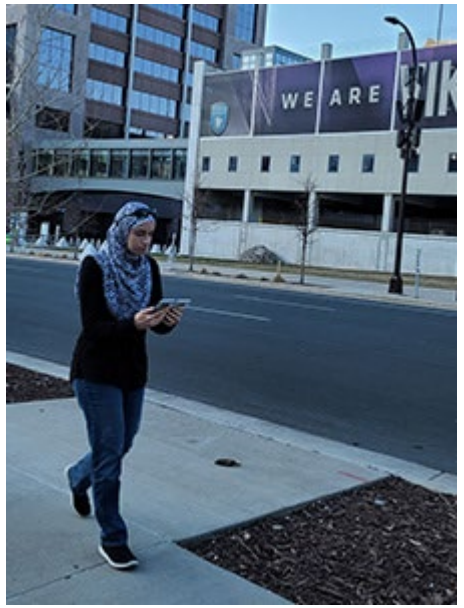
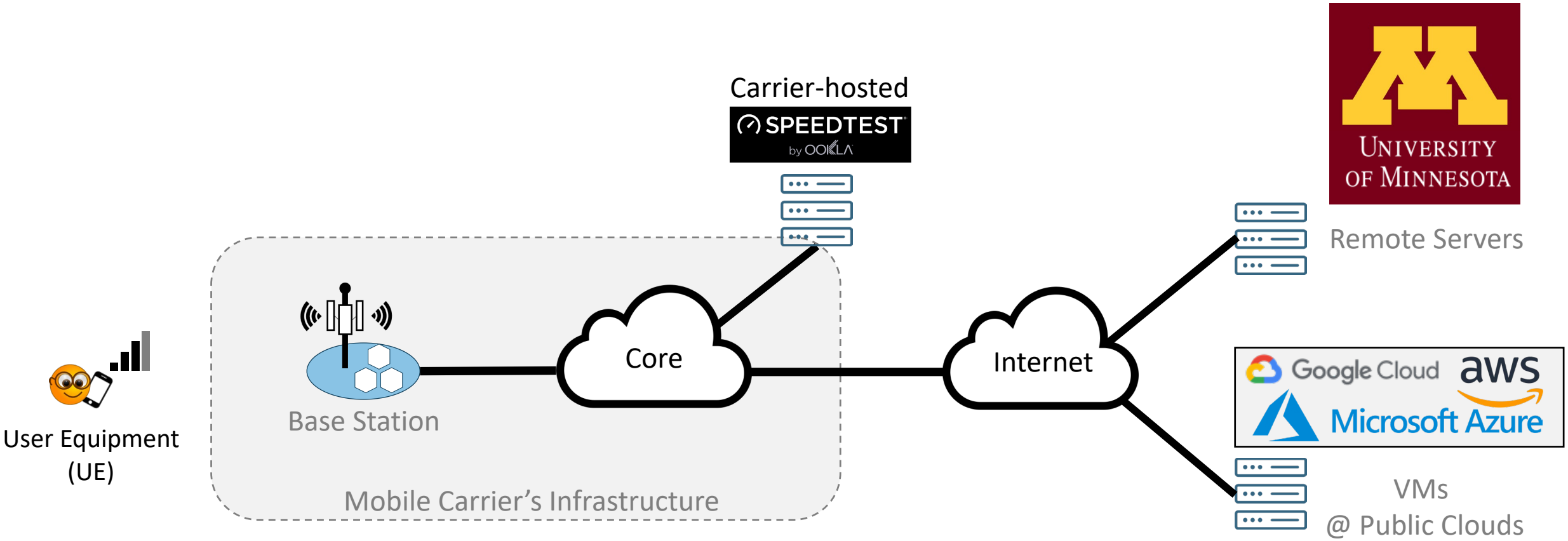
Report a map error


UNIVERSITY OF MINNESOTA
Driven to Discover




WE ARE

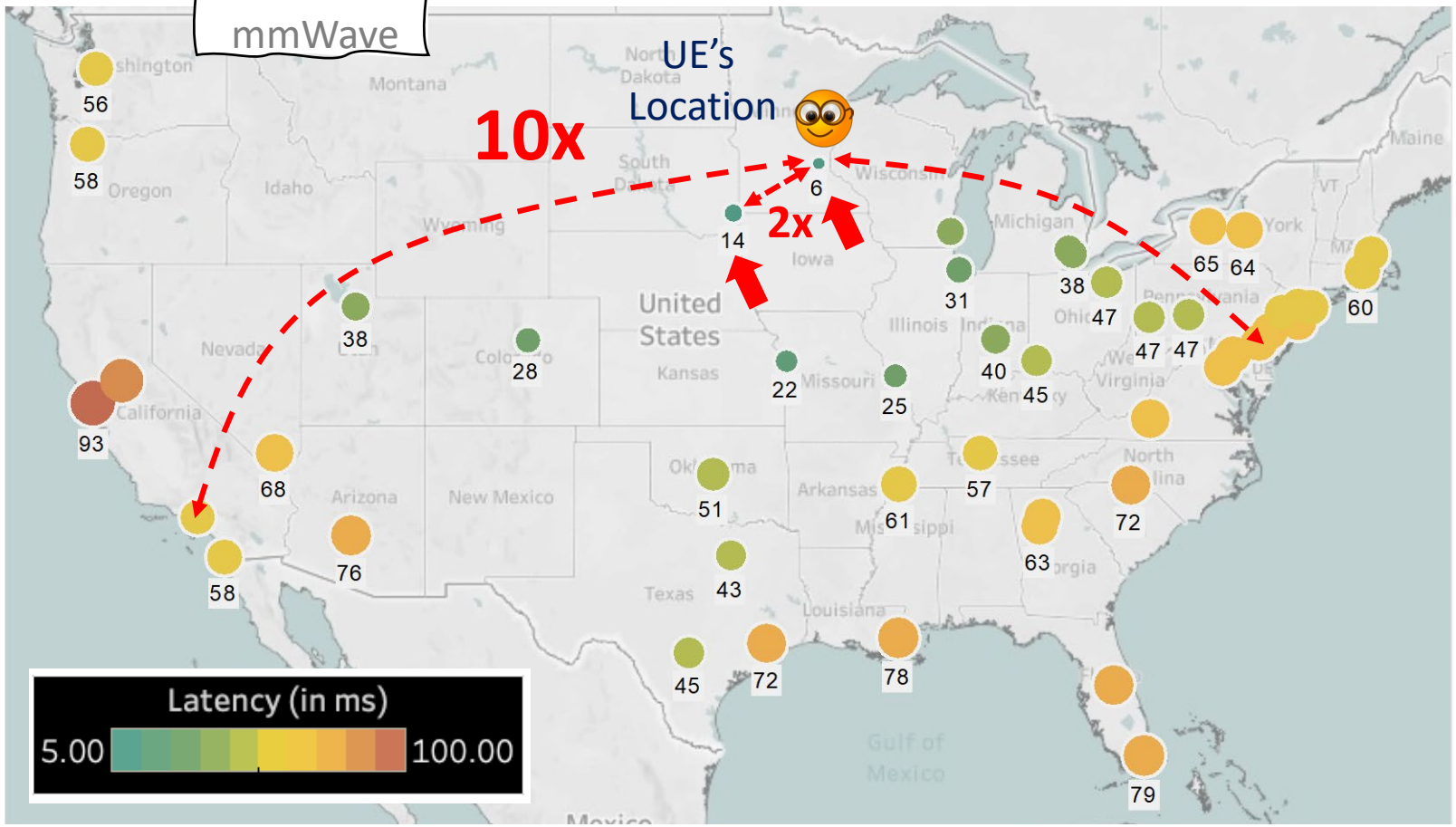
Measurement Setup



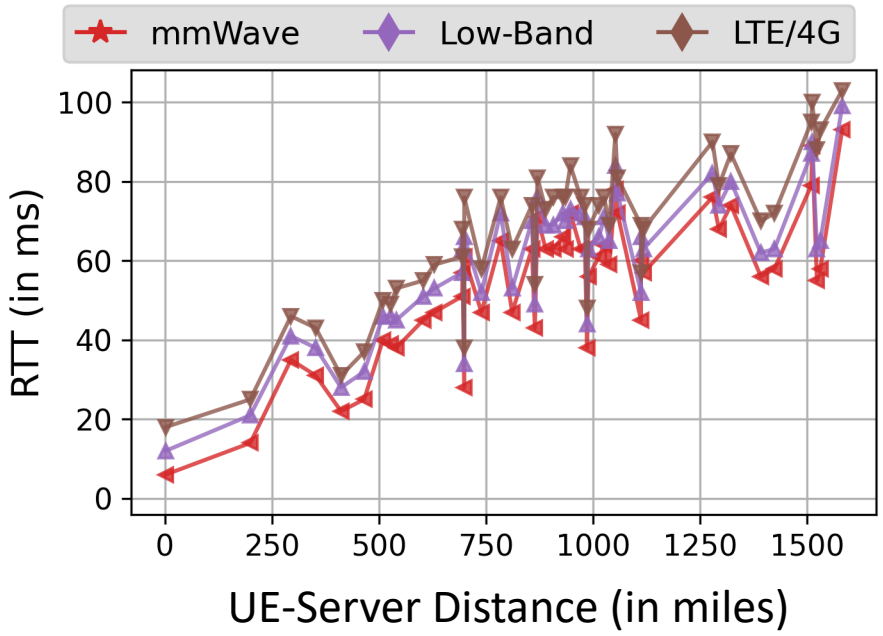
Impact of UE-Server Distance on E2E Latency

verizon mmWave

Setup: UE @ Minneapolis **All Verizon Servers in US**



Latency v/s Distance Relationship

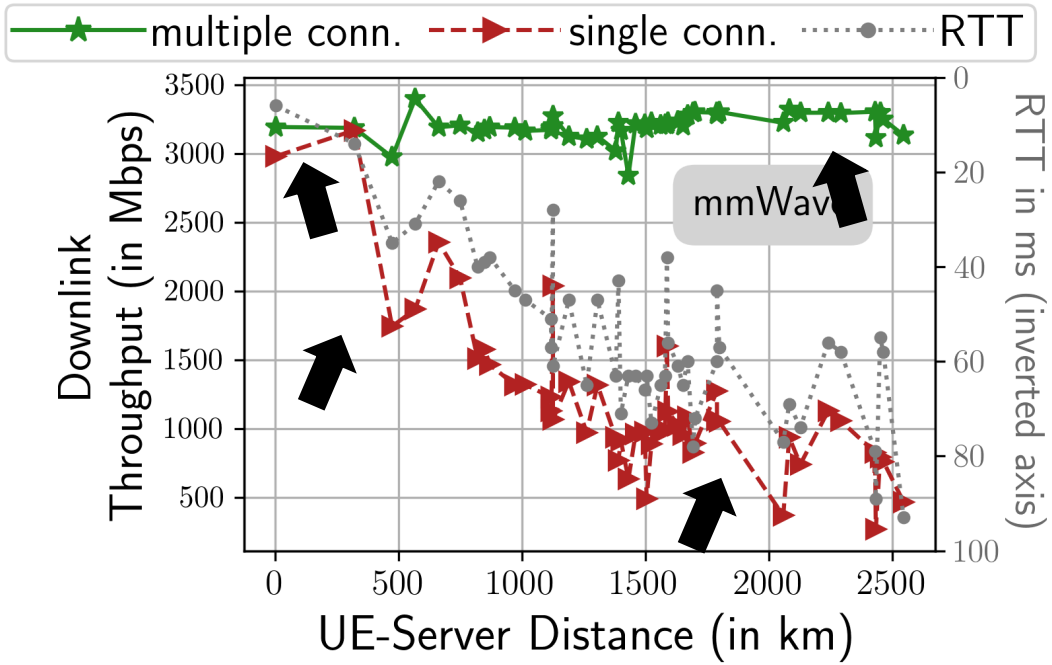


Edge computing is critical for 5G

Impact of Distance on Throughput

Setup: UE @ Minneapolis  **All Verizon Servers in US**

verizon mmWave



Reasons

- TCP parameters
- TCP congestion control
- Interplay between TCP and base station's resource allocation mechanism

Complex interaction between upper-layer and 5G

Bottlenecks in Achieving Ultra-High Throughput

Transport Protocols

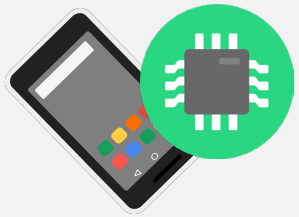
(Single Connection TCP-tuning)

Tuned-TCP: up to 80% performance improvement

Server-Side

(Bandwidth Capacity)

Bound by port capacity, infrastructure limitations and/or costs.



Smartphone-Side

(mmWave Radio Capabilities)

Level of carrier aggregation (CA) supported.

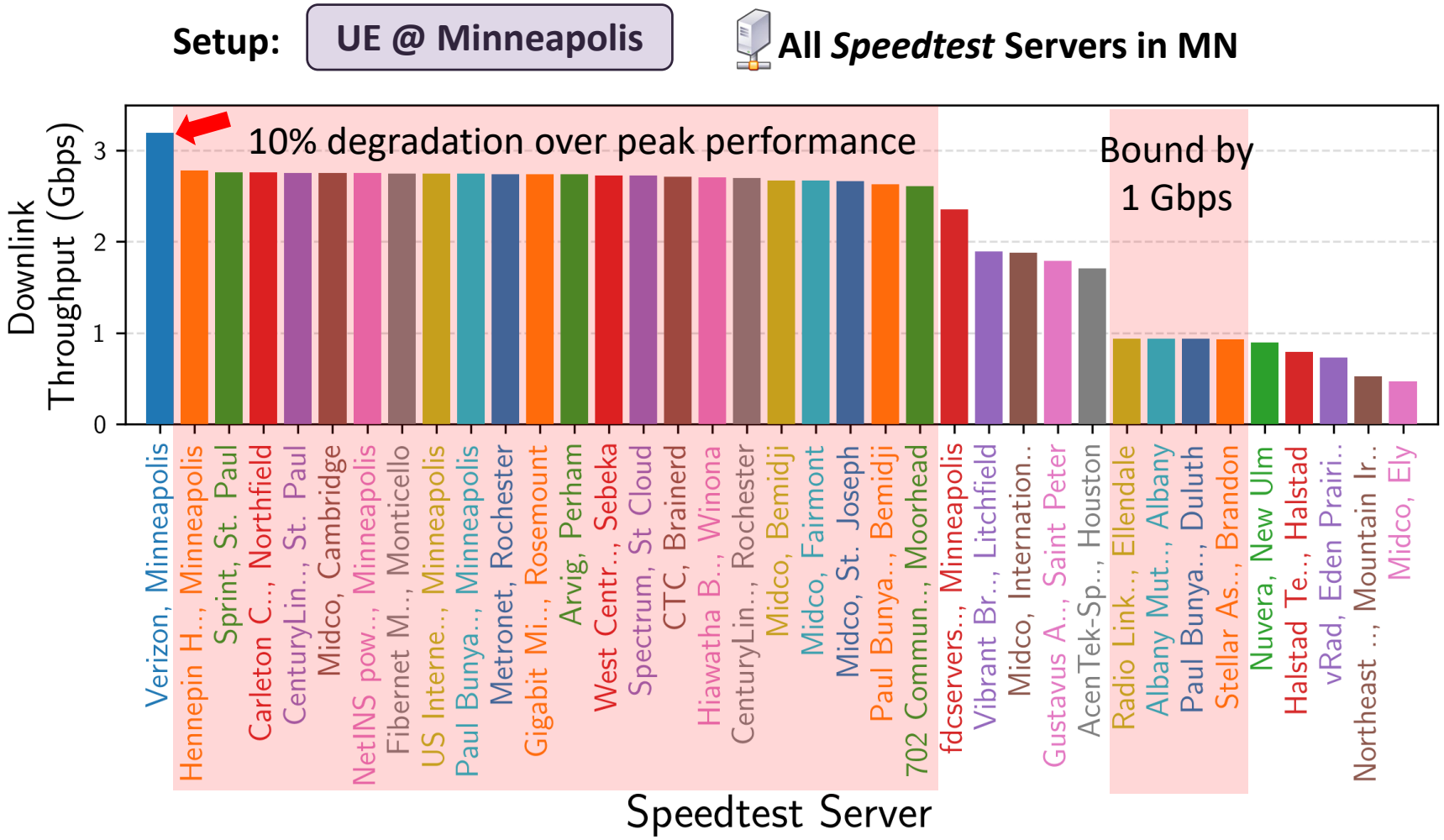
App-Layer Ops.

(HTTPS vs HTTP)

Due to the TLS encryption/decryption overhead, **HTTPS takes** on an average 23% more time to download 1GiB file versus **HTTP.**

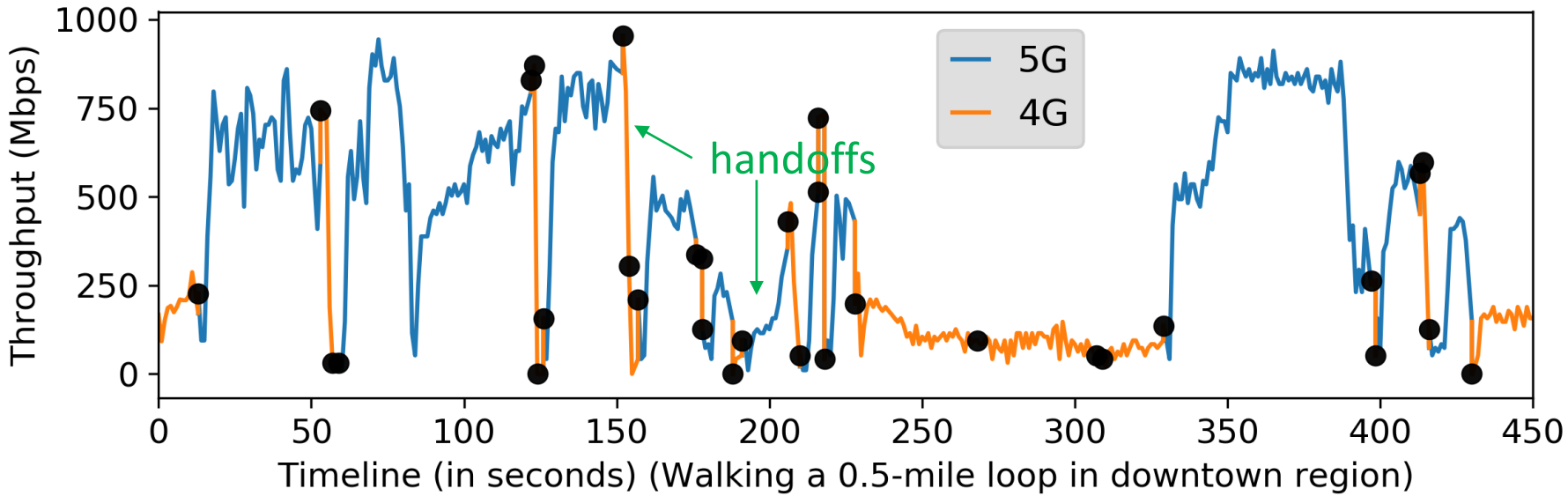
See our papers for details **[WWW20][SIGCOMM21]**

Server-side Bottleneck



Impact of Mobility (w/ mmWave Coverage)

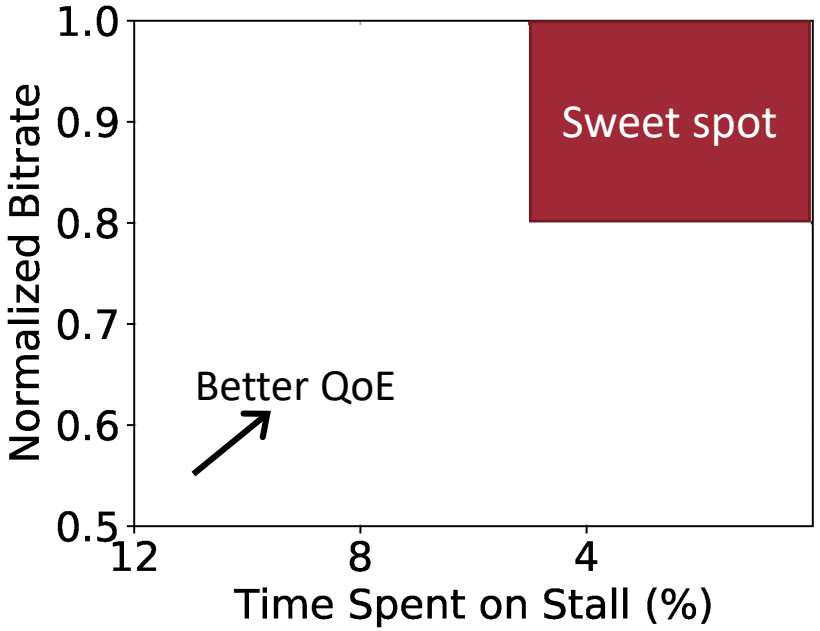
Setup: mmWave | Walking a 0.5 mile loop @ MPLS | US East

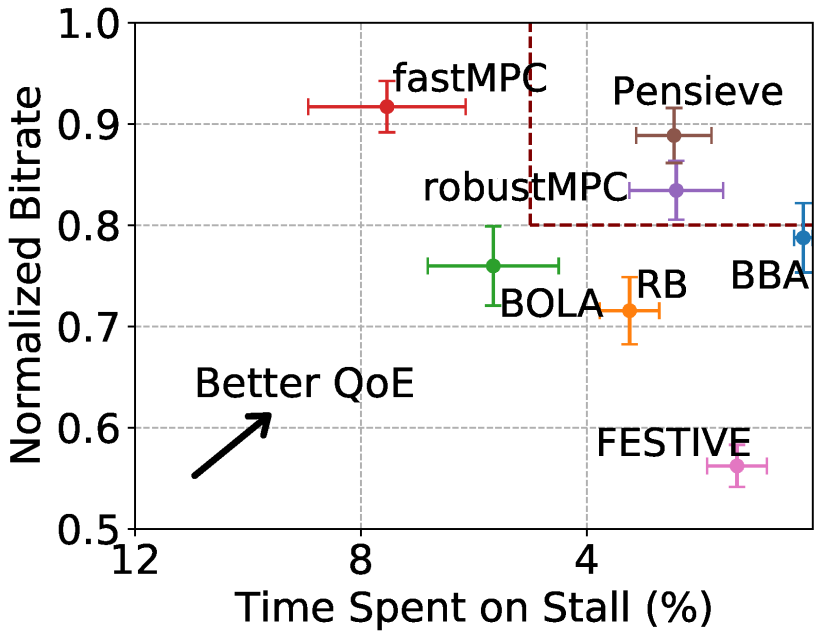


- UE experiences a total of **31 handovers** within 8 minutes!

Frequent handoffs cause frequent throughput fluctuations

ABR Algorithms (Video Streaming)





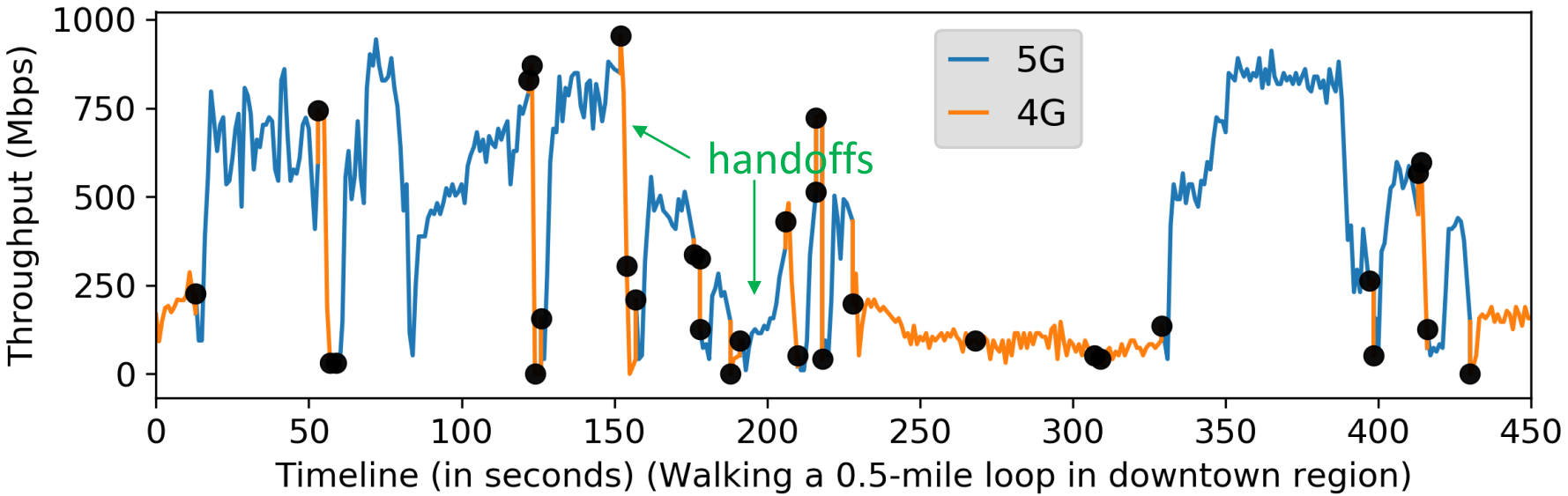
5G

(mmWave + other bands)

On average, compared to 4G/LTE, video streaming over 5G leads to approx. 35% increase in video stalls!

Impact of Mobility (w/ mmWave Coverage)

Setup: mmWave | Walking a 0.5 mile loop @ MPLS | US East



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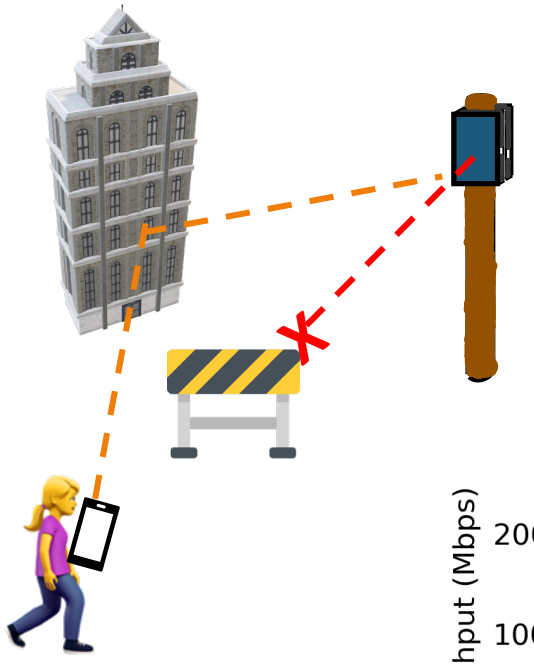
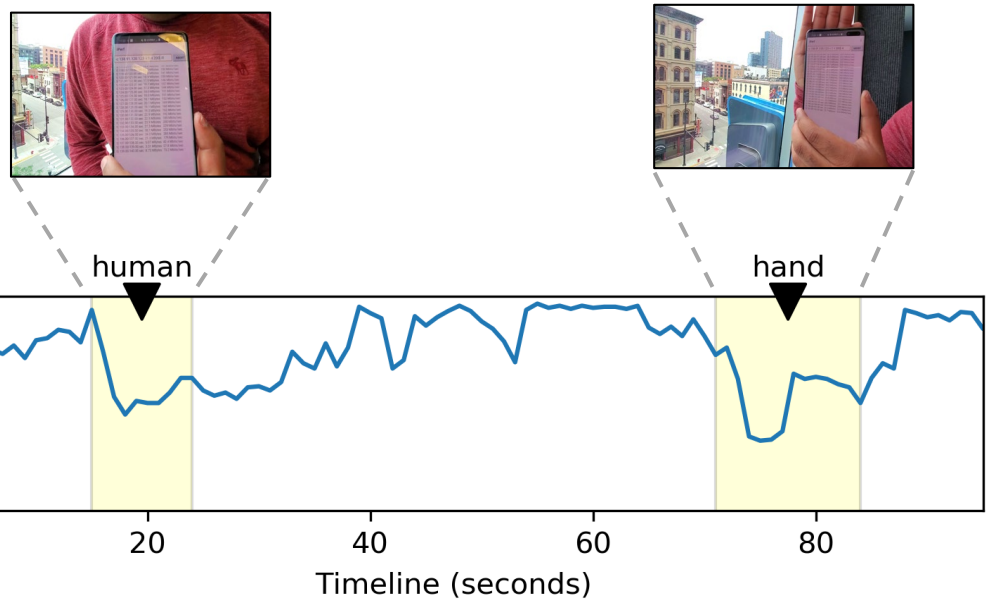
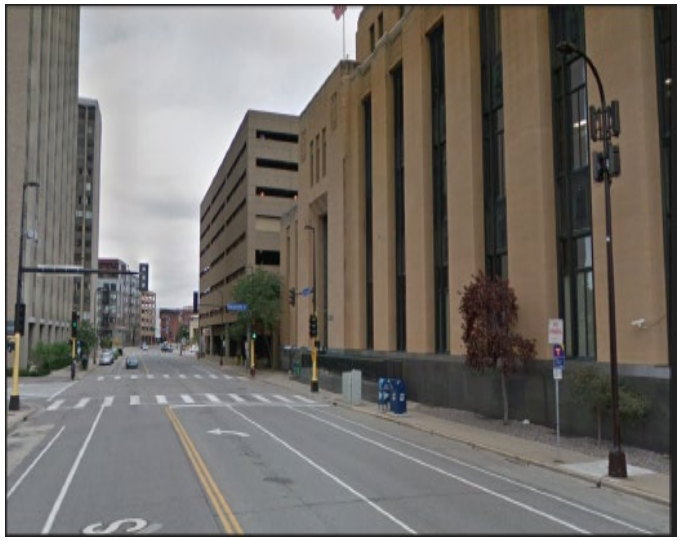
Frequent handoffs cause frequent throughput fluctuations

Non-Line of Sight (NLoS) Performance



Setup: mmWave UE-Stationary US East





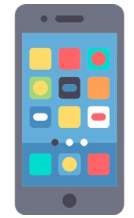
NLoS performance in outdoor settings often driven by reflection characteristics of the surrounding environment.

Talk Outline

- What is 5G performance in the wild?
  - 3-year extensive measurement study
  - **Contributions: measurement tools, experiment design, datasets, and measurement findings**
- **How to accurately predict 5G performance?**
  - **Making 5G systems intelligent**

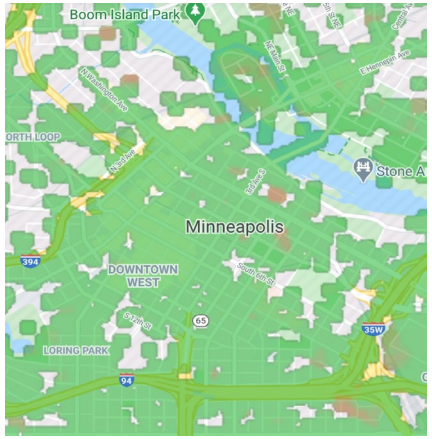
5G Network 

- How to innovate emerging applications for 5G?
  - Using virtual/mixed reality (VR/MR) as a case study

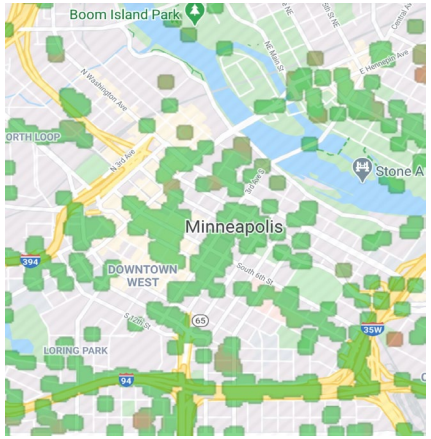
5G Application 

Mapping Coverage & Throughput

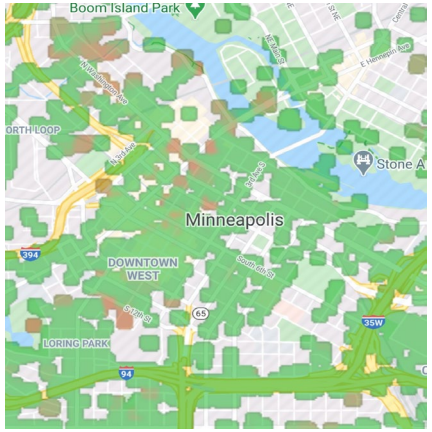
Bad Coverage  Good Coverage



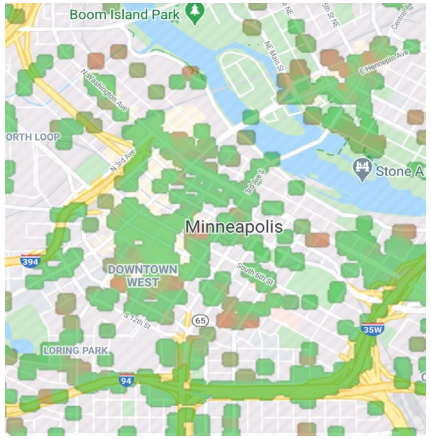
T-Mobile



AT&T



Verizon



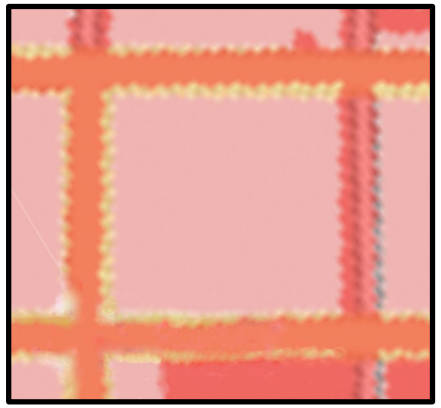
Sprint

Geographic location was able to **largely characterize** 4G performance

Source of coverage maps: Opensignal

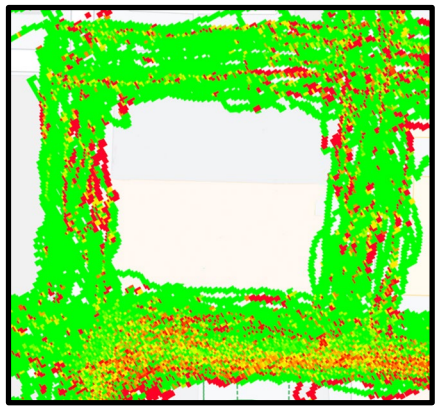
Mapping mmWave 5G Performance of a City Block

5G service area



5G coverage provided by carrier

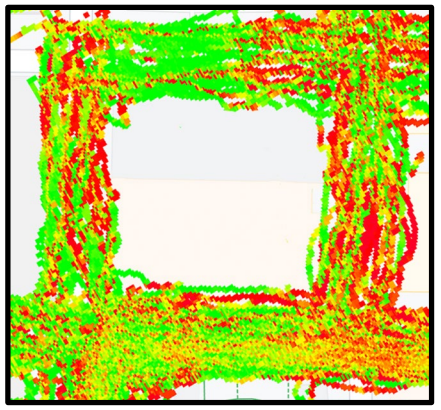
0 % 100 %



# of samples with active 5G connectivity over total samples

Data Driven

<60Mbps 1000+Mbps



Average throughput

Data Driven

Location alone is **inadequate** for mapping mmWave 5G performance

what are the different UE-side factors impacting mmWave 5G throughput?

can such impact be characterized to help predict 5G throughput?

Dataset Statistics

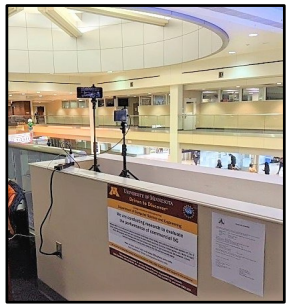
500K+ data points

300+ km walking

130+ km driving

35+ TB downloaded

MSP International Airport (Indoor)

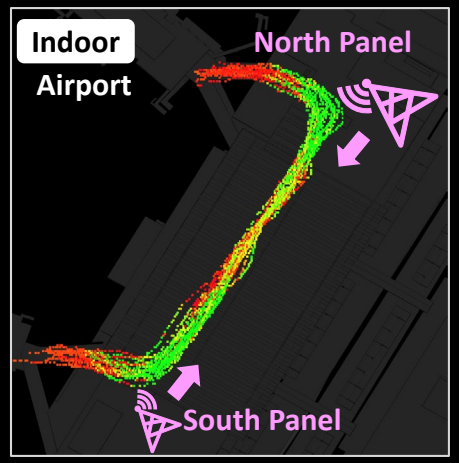


4-way Traffic Intersection (Outdoor)

Loop near US Bank Stadium

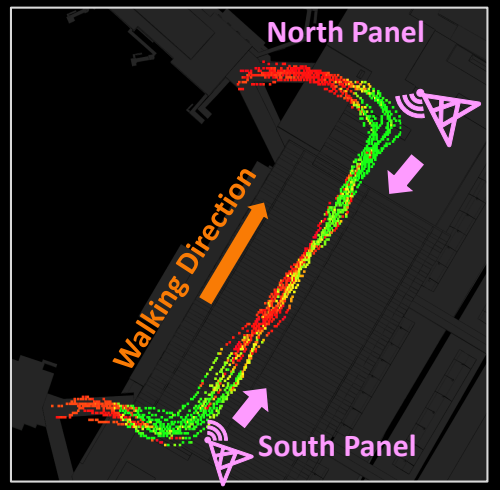
Impact of Geolocation on 5G Throughput

{North + South} Bound

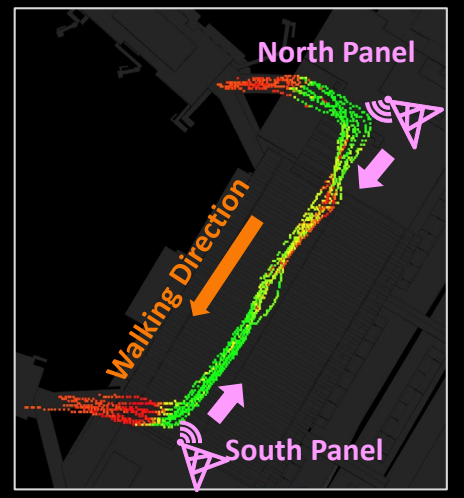


~52% of geolocations have normal distributions

Walking North Bound



Walking South Bound

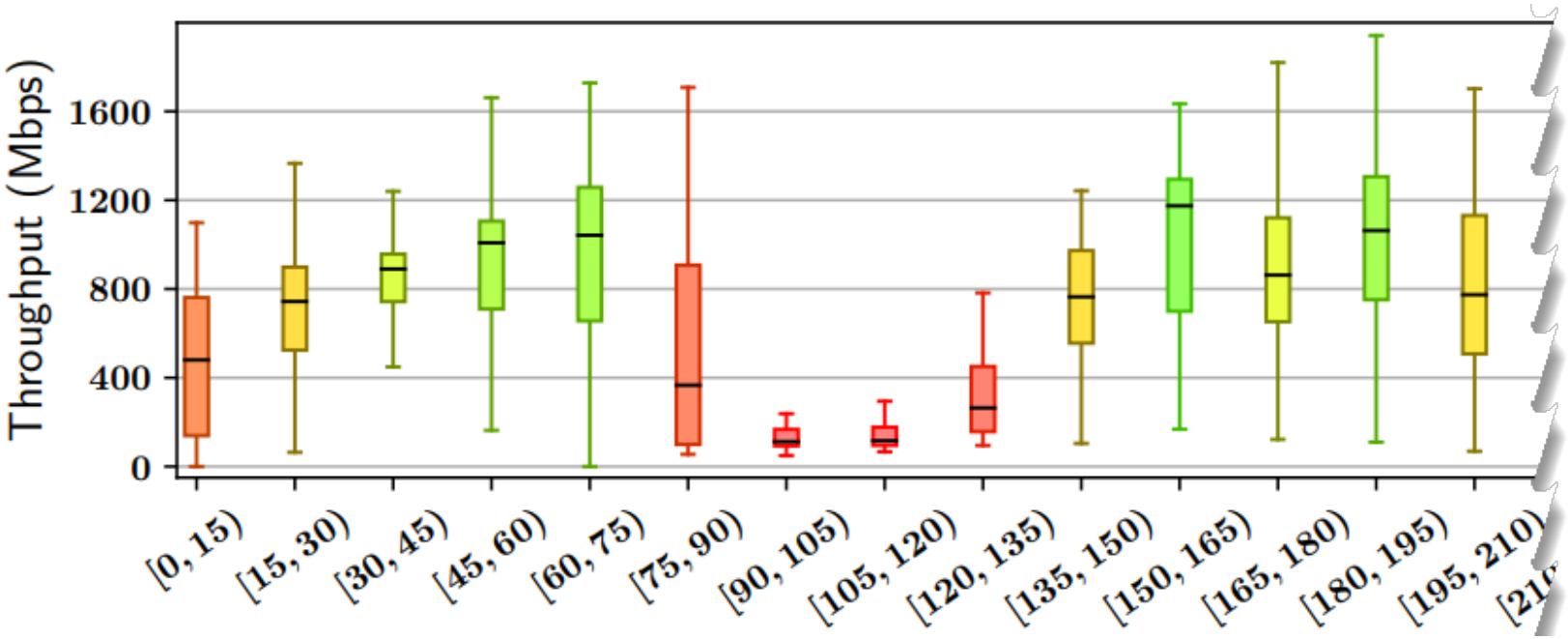


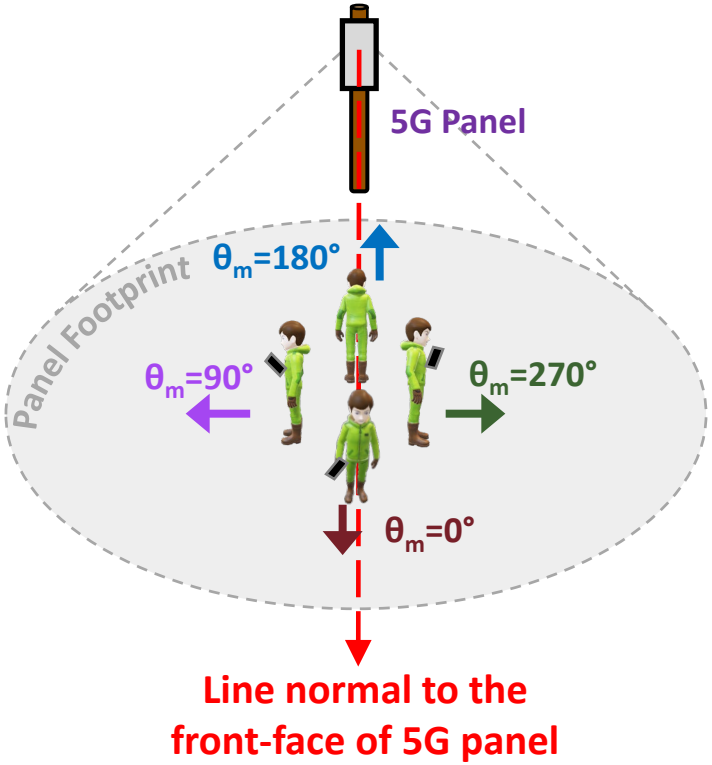
~78% of geolocations have normal distributions

In addition to geolocation, considering movement direction leads to better 5G throughput characterization.

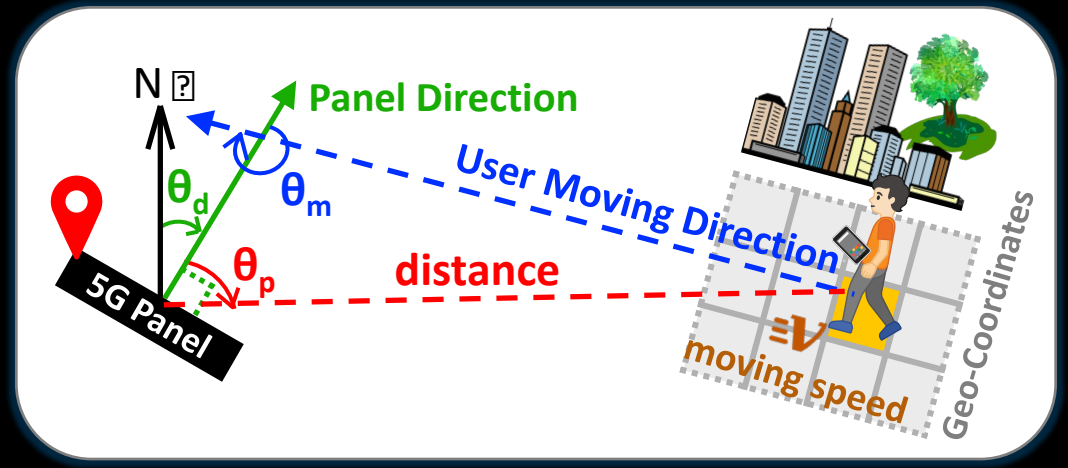
UE-Panel Mobility Angle (θ_m)

θ_m: the angle between the line normal to the front-face of the 5G panel and the UE's trajectory.





Key Takeaways of Impact Factor Analysis



UE-Side Contextual Factors

- Besides geolocation, **numerous UE-side factors impact 5G throughput**.
  - UE's compass orientation
  - UE-Panel positional angle
  - UE-Panel mobility angle
  - Season of year
  - UE-Panel distance
  - UE's moving speed
  - UE's mode of transport
  - Weather
- **Complex interplay** of factors, very **difficult** to model analytically.

what are the different UE-side factors impacting mmWave 5G throughput?

can such impact be characterized to help predict 5G throughput?

can we build “good” machine learning models for 5G throughput prediction?

Lumos5G – Composable Feature Groups

Composable Feature Groups

Location Based (L)
- Longitude
- Latitude

Mobility-Based (M)
- UE Moving Speed
- UE Compass Direction

Tower-Based (T)
- UE-Panel Distance
- UE-Panel Positional Angle
- UE-Panel Mobility Angle

Connection-Based (C)
- Past throughput
- Radio Type
- Signal Strength Info.
- Handoffs

Combinations of Feature Groups (Examples)

L + M

L + M + C

T + M

T + M + C

Potentially transferrable

Lumos5G – Composable Feature Groups

Composable Feature Groups

Location Based (L)
- Longitude
- Latitude

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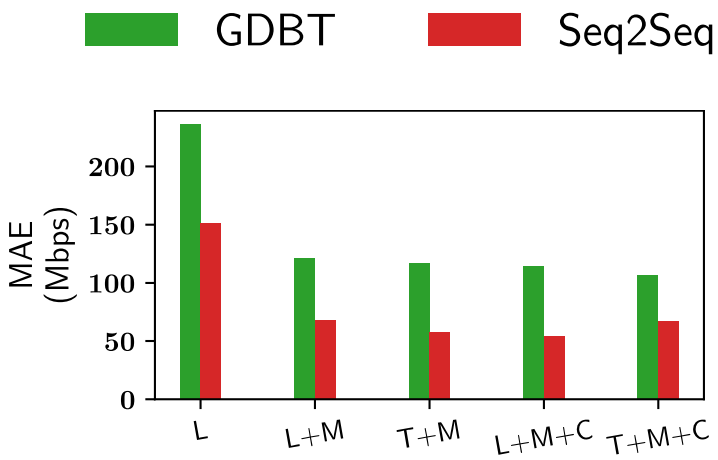


Key Observations

- L group alone is not adequate, need M and/or C groups.
- T-based feature groups show comparable performance to that of L
- **Seq2Seq** produces **better** prediction results than **GDBT**.

Lumos5G – Composable Feature Groups

Location

- Longitude
- Latitude

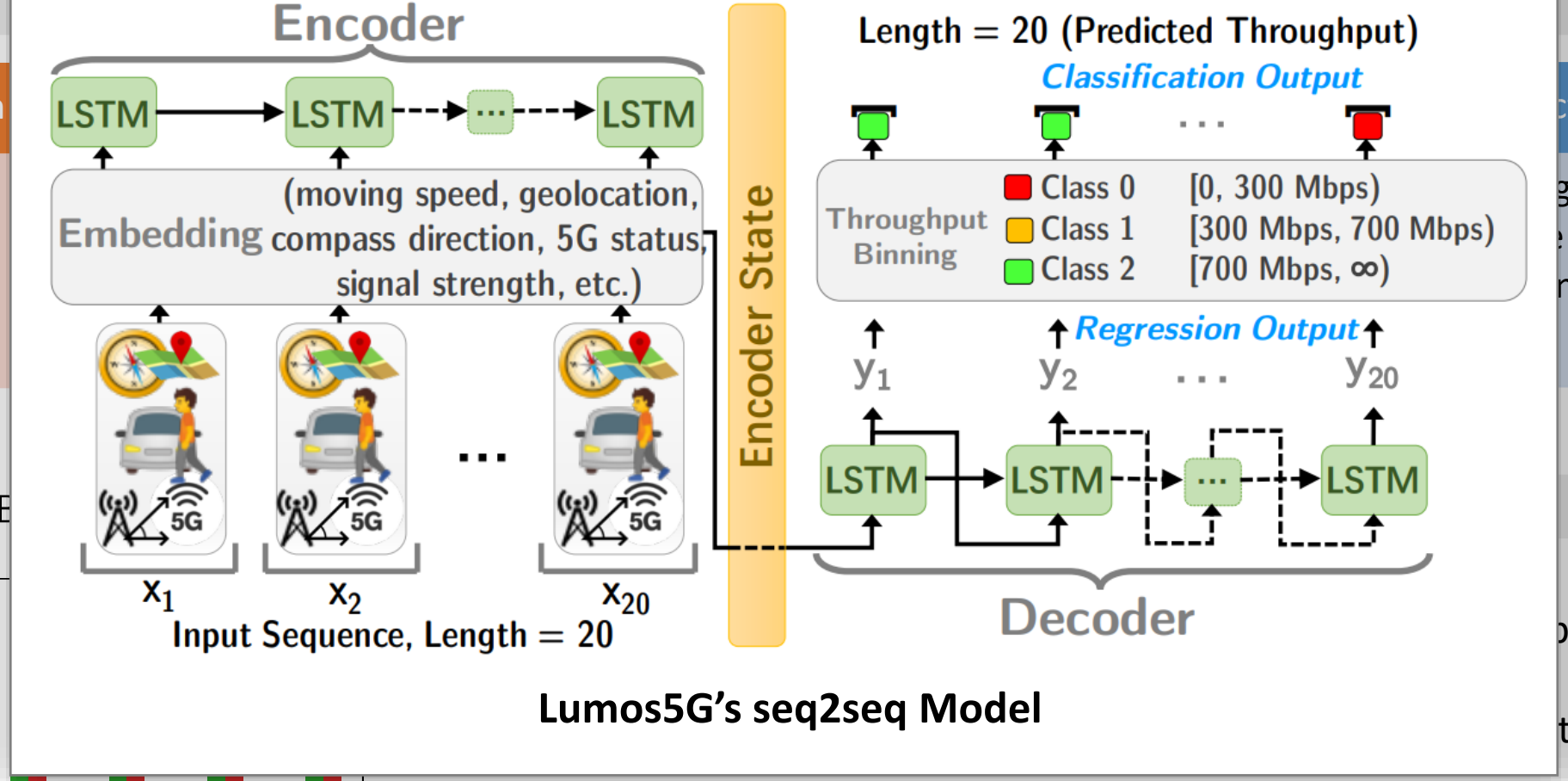
ction-Based C

ghput

ngth Info.

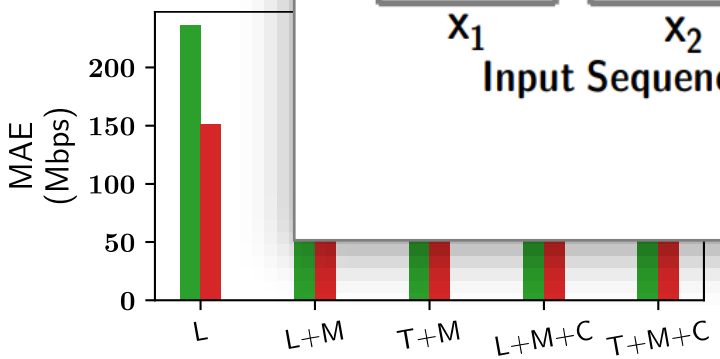
os.

to that of L



Lumos5G's seq2seq Model

GDBT



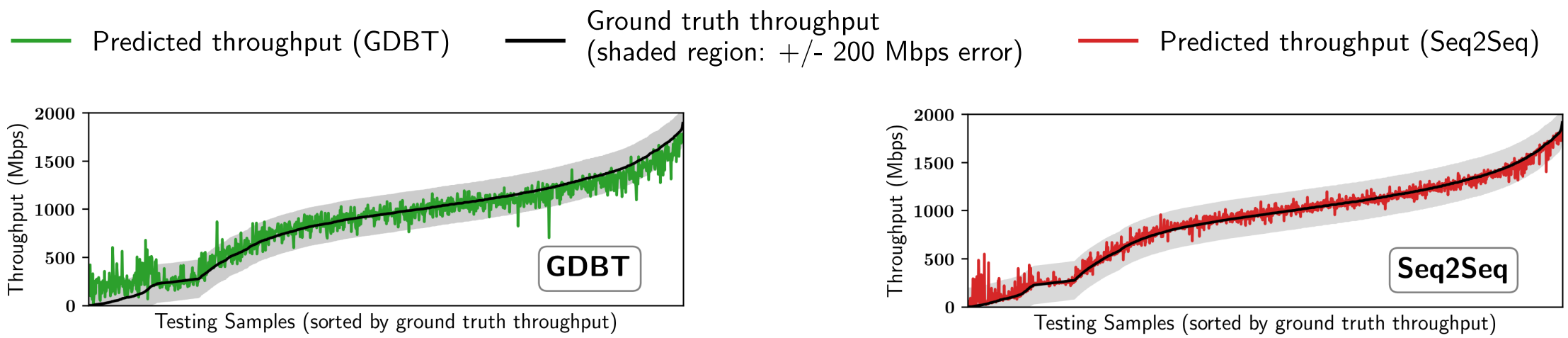
- **Seq2Seq** produces **better** prediction results than **GDBT**.

Lumos5G – Composable Feature Groups

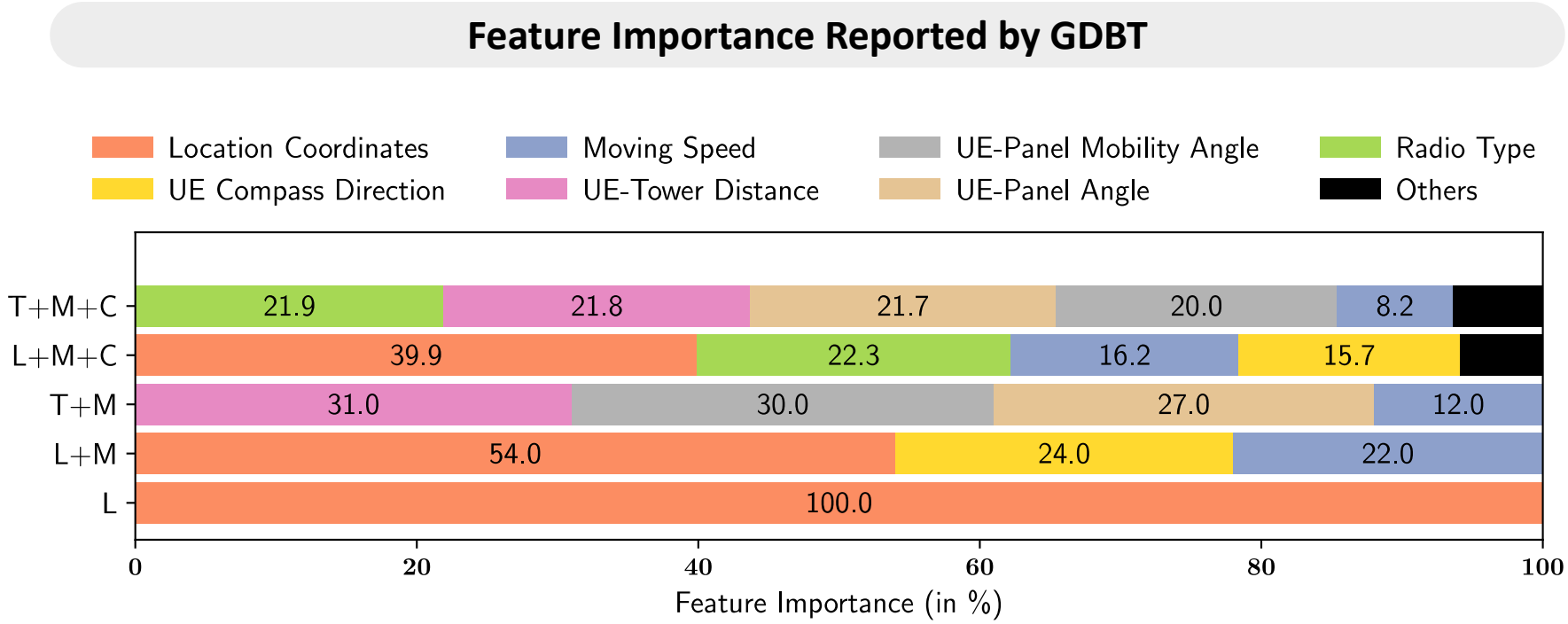
Composable Feature Groups

Location Based (L)	Mobility-Based (M)	Tower-Based (T)	Connection-Based (C)
• Longitude • Latitude	• UE Moving Speed • UE Compass Direction	• UE-Panel Distance • UE-Panel Positional Angle • UE-Panel Mobility Angle	• Past throughput • Radio Type • Signal Strength Info. • Handoffs

1.4x to 4.8x reduction of prediction error compared to existing approaches (3G/4G throughput prediction).



Lumos5G – Evaluating GDBT & Seq2Seq



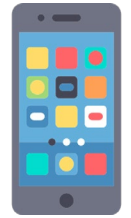
No single feature dominates in predicting 5G throughput

Talk Outline

- What is 5G performance in the wild?
  - 3-year extensive measurement study
- How to accurately predict 5G performance?
  - **Contributions: systematic feature discovery; data-driven prediction framework design; evaluation using real-world 5G data**

5G Network 

- **How to innovate emerging applications for 5G?**
  - **Using virtual/mixed reality (VR/MR) as a case study**

5G Application 

Take-aways From our 5G Study

- 5G enables numerous emerging applications
  - Networked VR/AR, telepresence/metaverse, connected vehicles …
- High peak bandwidth ≠ stable/consistent data rate
- It is crucial to…
  - reduce bandwidth usage
  - handle bandwidth fluctuation

What are new design spaces for emerging 5G/nextG applications?

Intelligent 5G/NextG Application Design

Network Adaptation

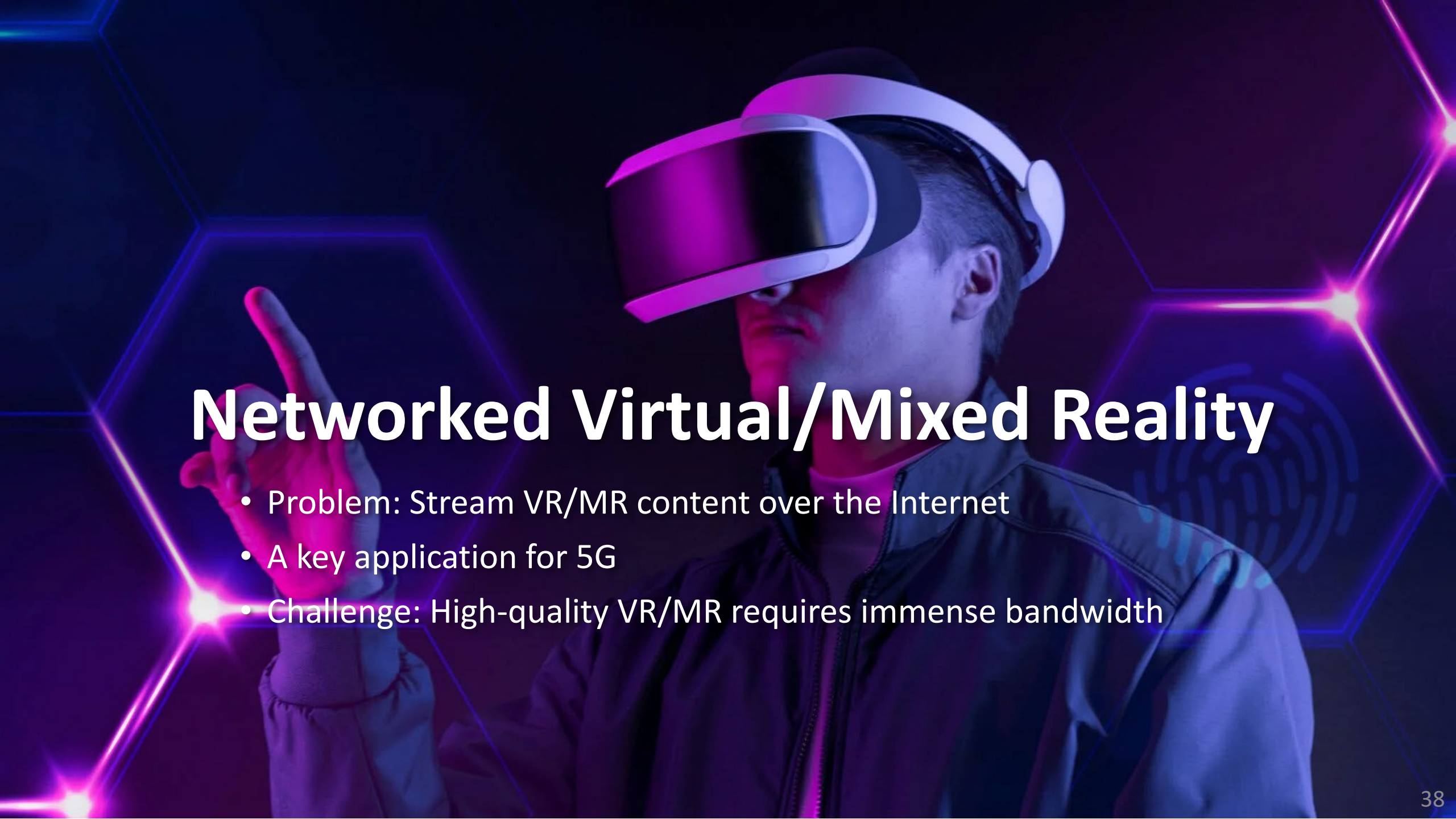
[MobiCom21]
[SIGCOMM21]
[SIGCOMM22]
[NSDI21][IMC20]
[WWW20]
[MobiSys20]
[MobiCom19]

AI-powered **Content** Processing

[WWW21][NSDI22]
[MobiCom22a] [MobiCom22b]

User Behavior Adaptation

[MobiCom18]
[CoNEXT19]
[MobiCom20]
[ATC20][CHI22]



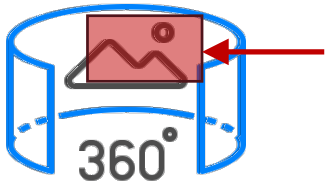
Networked Virtual/Mixed Reality

- Problem: Stream VR/MR content over the Internet
- A key application for 5G
- Challenge: High-quality VR/MR requires immense bandwidth

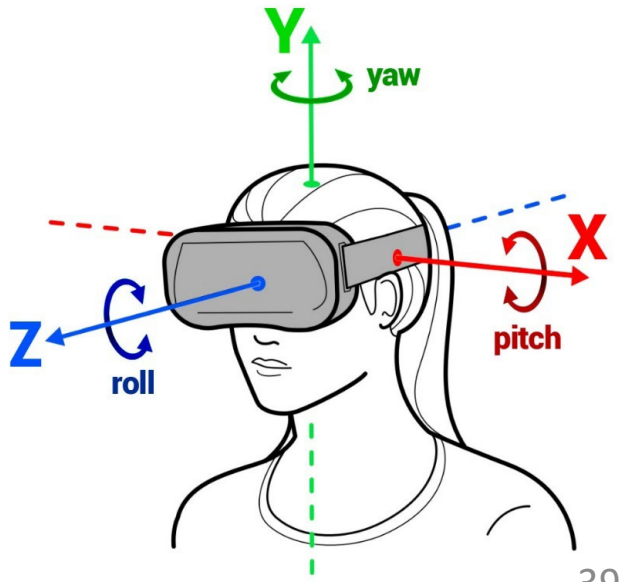
Viewport-adaptive Streaming

- Key observation: Human head motion is (to some extent) predictable
  - Validated based on our extensive user study: 275 users, 150-hour VR streaming [CoNEXT19]
- Resulting idea: Viewport-adaptive Streaming
  - Proposed in 2016
  - Adopted by 100+ networked VR papers as the content delivery protocol

Predict Next…	Median Error (Yaw)	Median Error (Pitch)
0.1 second	0.3°	0.2°
1 second	7.5°	2.5°
2 seconds	19°	4.0°



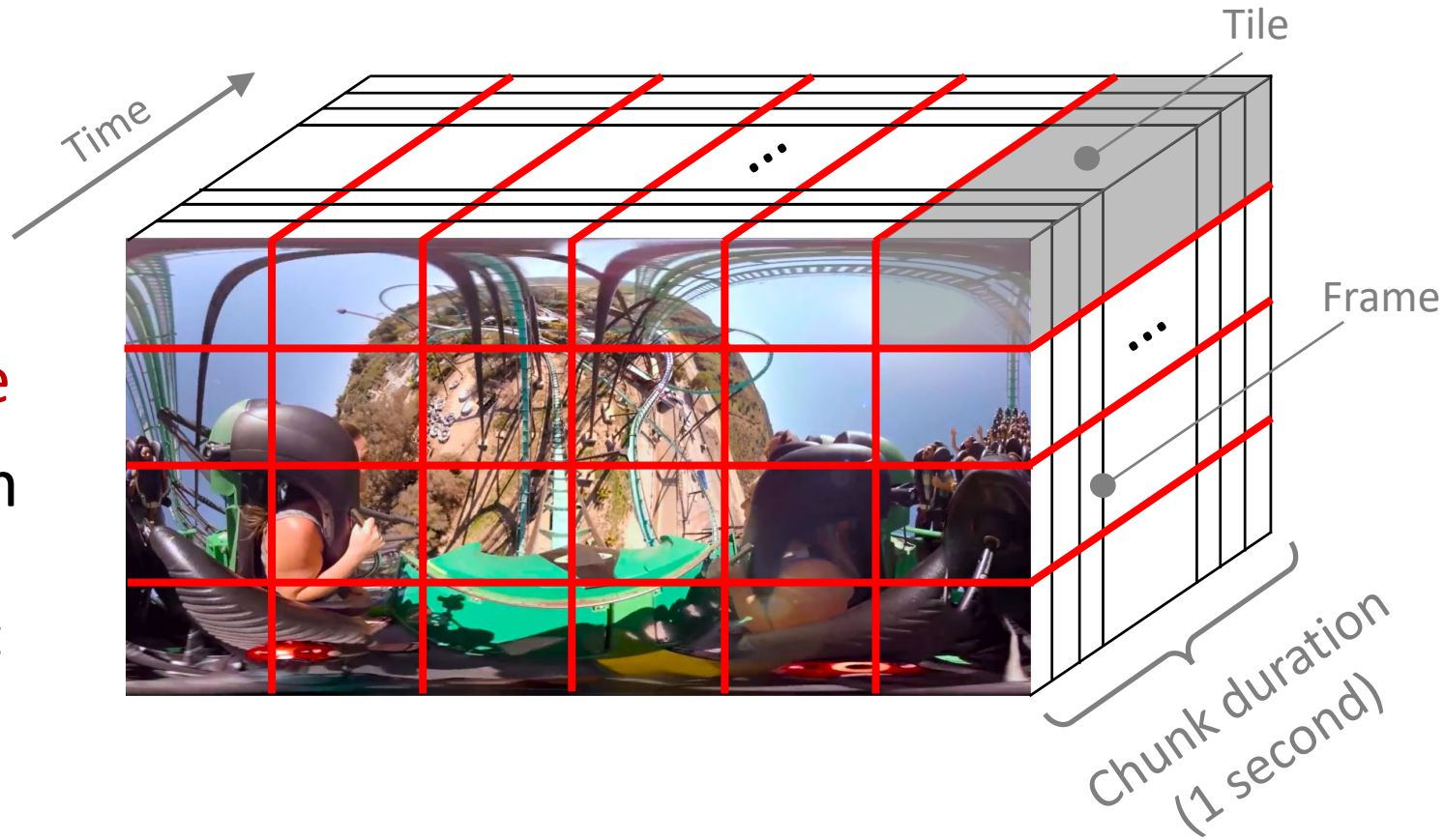
Drastic Bandwidth Reduction



Flare: a Full-fledged Viewport-adaptive System

[MobiCom18]

- Segment a panoramic VR chunk into tiles
- Each tile is independently decodable and downloadable
- An online scheduling problem
  - Input: predicted motion and predicted network throughput
  - Output: which tiles to fetch, at which quality levels?
  - Objective: maximize the viewer's quality-of-experience
  - Challenge: large solution space, real-time scheduling



Flare Evaluation

- A holistic system for off-the-shelf smartphones
- 400-hour playback on WiFi and 100-hour on cellular
- Up to 18x quality level improvement compared to the state-of-the-art

Petrangeli etal., An HTTP/2-based adaptive streaming framework for 360° virtual reality videos. ACM Multimedia 2017

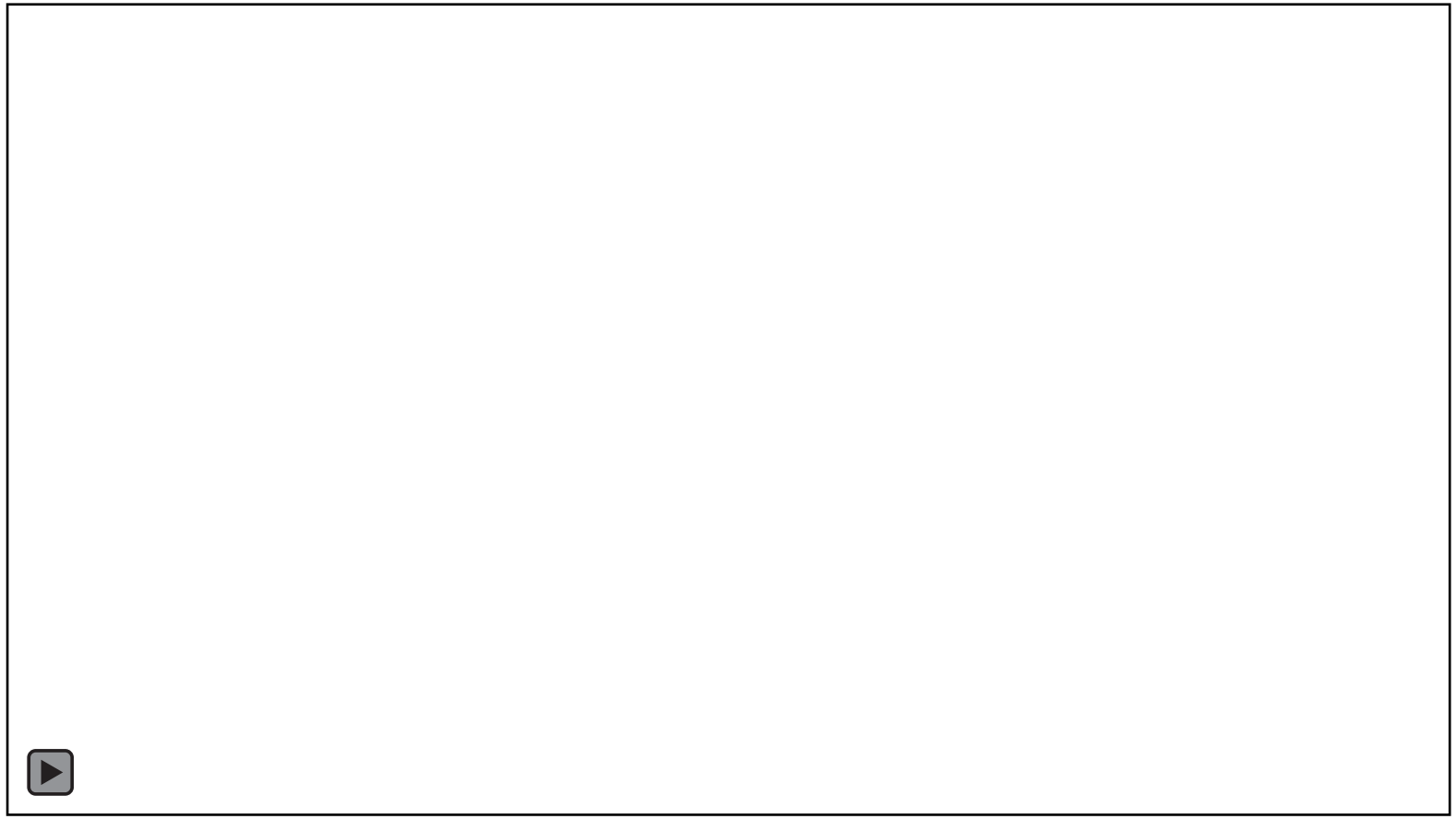
Flare

Video source: "*Visit Hamilton Island*" https://www.youtube.com/watch?v=lJype_TafRk

3D Volumetric Content

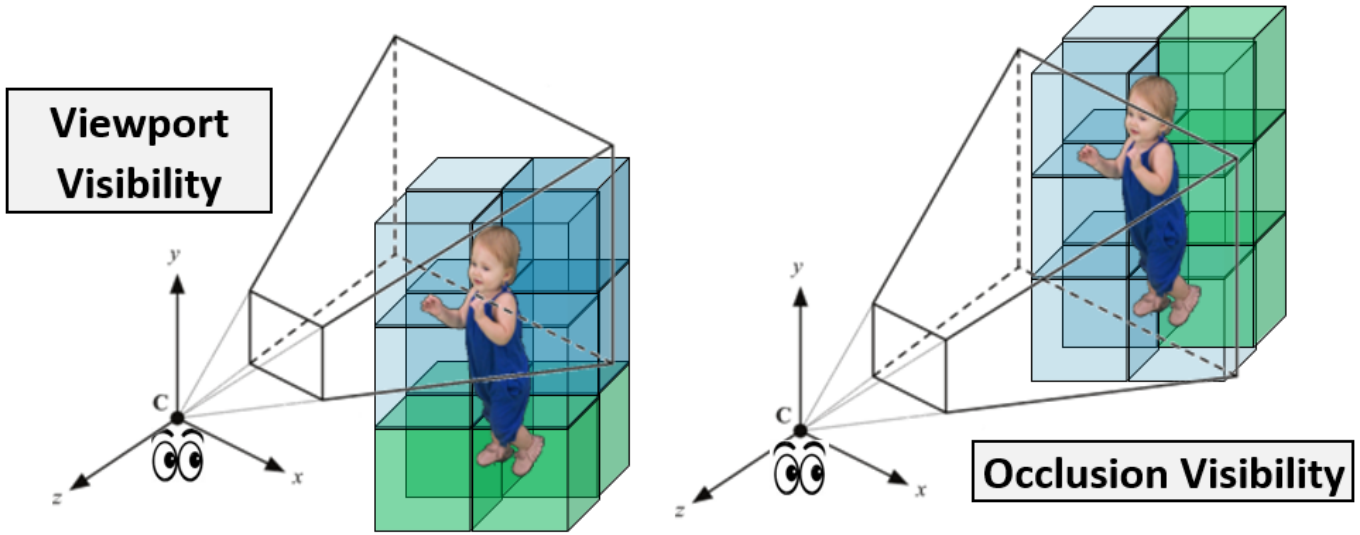
- A key building block of telepresence
- Each frame is a 3D model (e.g., point cloud)
- An emerging app for 5G
- Requires Gbps+ bandwidth

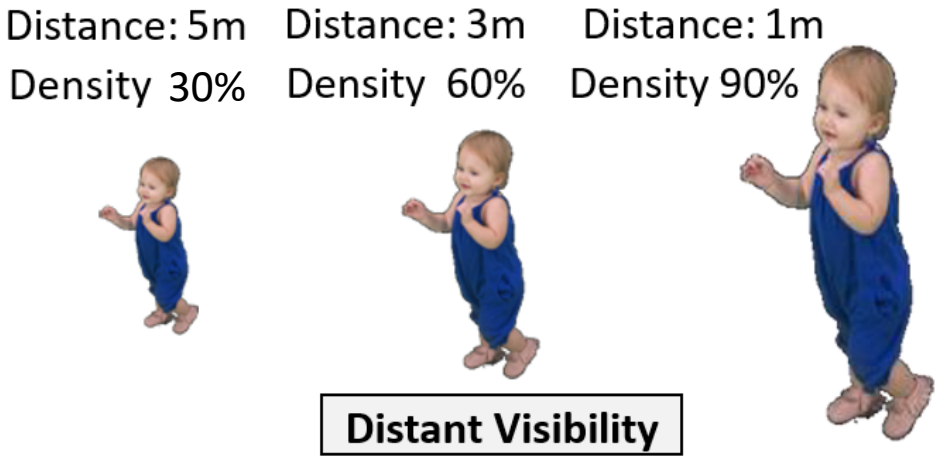
Real volumetric content



3D Volumetric Content

- Viewport Adaptation is still applicable!
- 2D Tile → 3D Tile
- New optimization opportunities: 3D occlusion and viewing distance
- Up to 80% of bandwidth reduction with virtually no drop in visual quality [ViVo, MobiCom 20]





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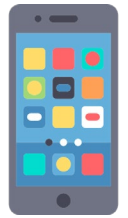
Talk Outline

- What is 5G performance in the wild?
  - 3-year extensive measurement study
- How to accurately predict 5G performance?
  - Making 5G systems intelligent

5G Network 

- How to innovate emerging applications for 5G?
  - Using virtual reality (VR) as a case study
  - **Contributions: discovering new tradeoffs and optimization dimensions; system design, implementation, and evaluation**
  - **Implications on L3/L4 protocol design for Metaverse**
    - **Need mechanisms adapting to low latency, bursty traffic, and multiple streams.**

5G Application 

Thank You

- fengqian@umn.edu
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