Increasing Cellular Capacity Using ISM Band Side-channels: A First Study

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Before Smartphone Revolution

WiFi- Laptop

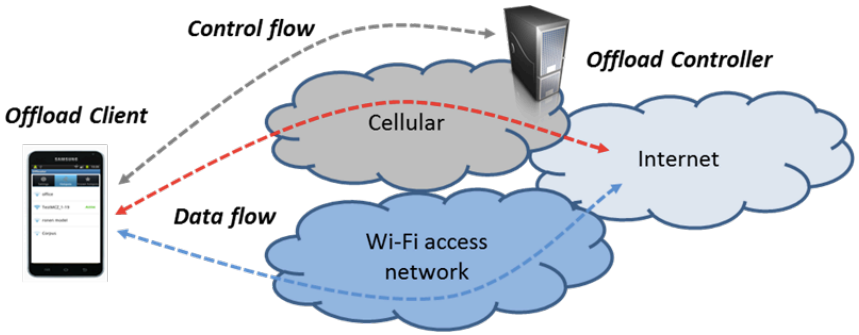
Cellular- phone

Today's Smartphones

- Cellular band:
  - UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz); LTE (Bands 1, 2, 3, 4, 5, 8, 13, 17, 19, 20, 25) …
- ISM band:
  - 802.11a/b/g/n Wi-Fi (802.11n 2.4GHz and 5GHz)
  - Bluetooth 4.0 ...

Use of ISM Band on Smartphones

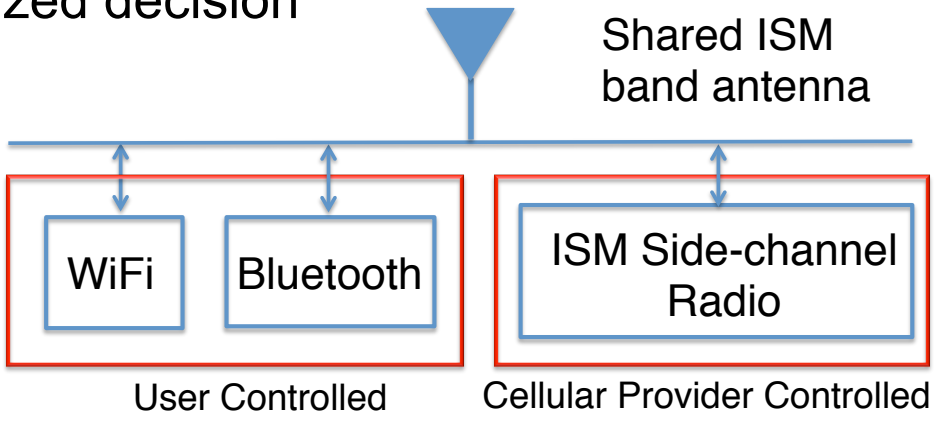
- Simultaneous use of ISM- and Cellular band
  - Assisted GPS
    - Location accuracy
  - Data Offloading
    - Cellular network congestion
  - Data Forwarding
    - Wireless tethering



New Use of ISM Band: ISM Side-channel

- Create **side-channels** for interference management to increase the overall cellular network capacity
  - Side-channels are established between mobile clients

- Serve as an additional radio to access ISM bands when available and **controlled by cellular providers**
  - ISM bands are usually controlled by end-users
    - Local knowledge
    - Inefficient and unstructured
  - Make centralized decision

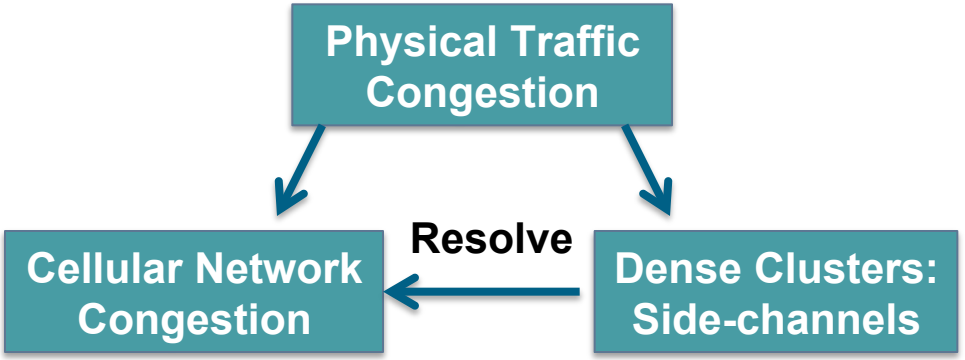


- How often can we establish ISM side-channels between smartphones?
- PART I: Availability of ISM side-channels in highways

- How can we benefit from ISM side-channels?
- PART II: Impact on cellular capacity of future wireless architecture (MU-MIMO and full-duplex network)

Highway – WiFi Free Locations

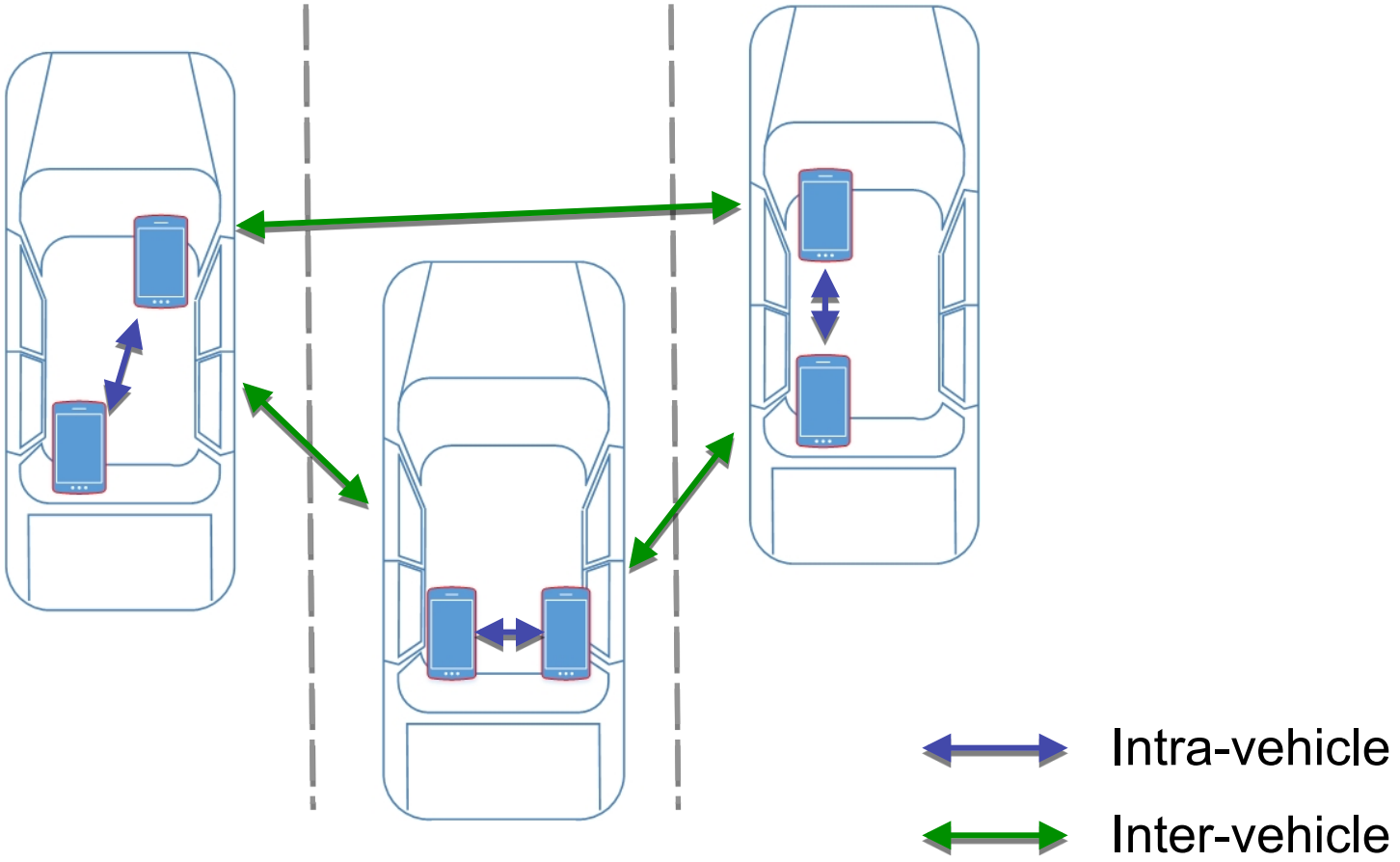
- No WiFi infrastructure
  - Opportunity of using ISM band among users
- Rush hour: traffic congestion
  - Need to invoke complicated techniques to increase cellular capacity



PART I: Availability of ISM Side-channels in Highways

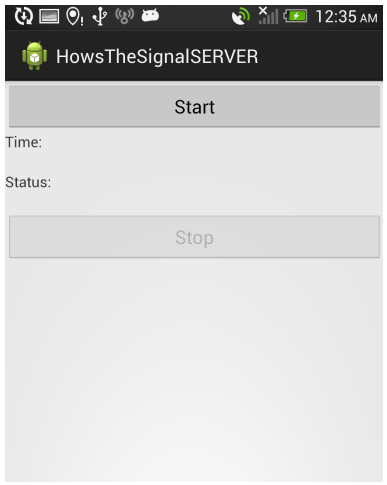
- Highway: Practically no WiFi coverage
- Methodology
  - Measure WiFi channel strength between smartphones
    - Our designed Android Application
- Range Test + Highway Traffic data = Estimate
  - Use WiFi frequency band as an example in ISM band

Intra-vehicle and Inter-vehicle ISM Side-channels in Highway



Methodology

- Set up WiFi connection using WiFi Hotspot
  - Measure the WiFi channel strength using our designed Android apps

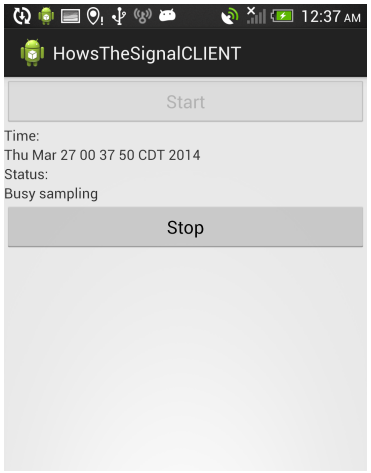


Server

Request to join

Setup the connection

Client



Server-side App

Client-side App

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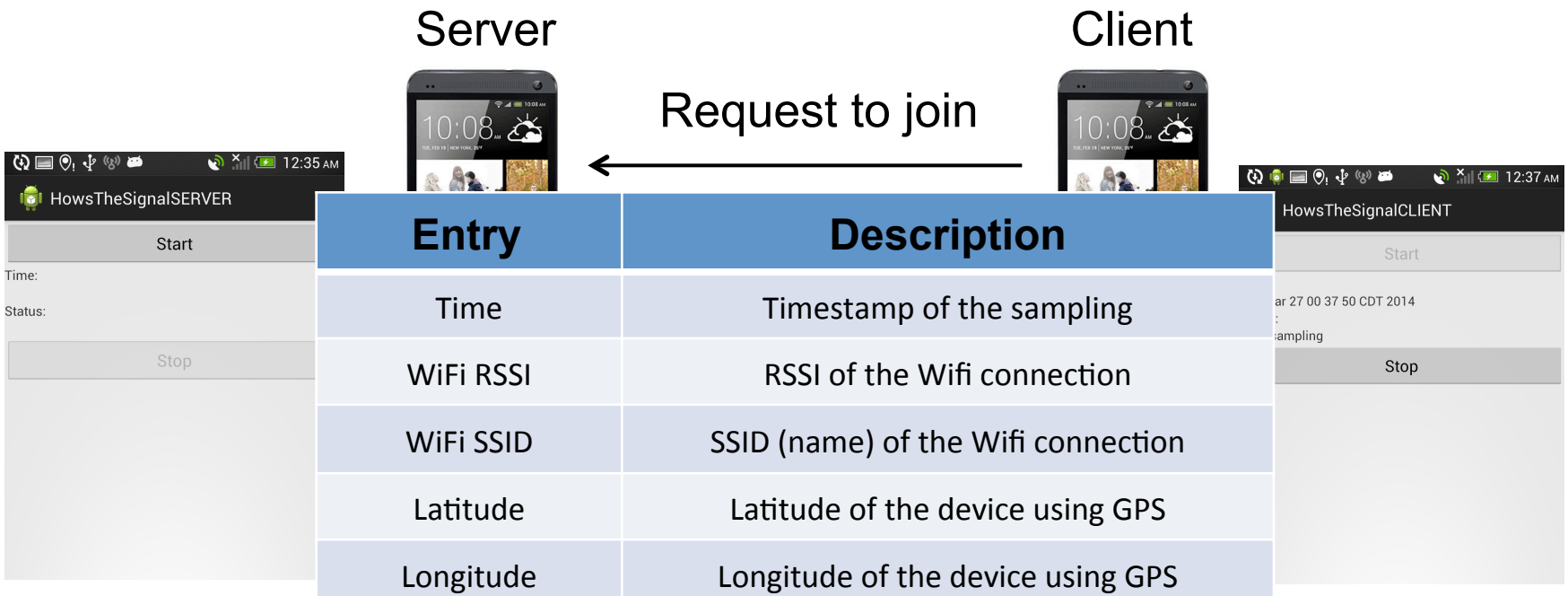


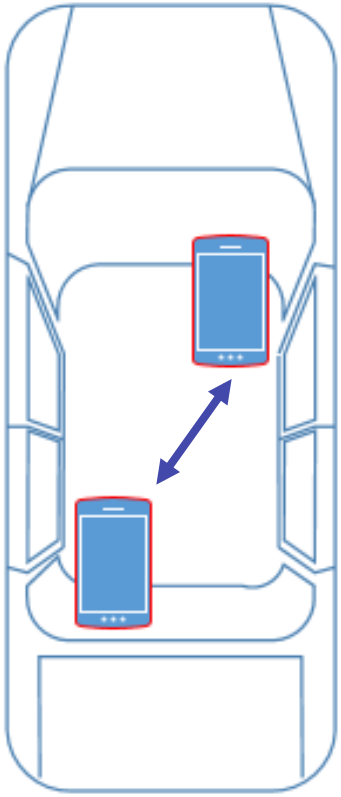
Server-side Ap

lient-side App

Entry	Description
Time	Timestamp of the sampling
WiFi RSSI	RSSI of the Wifi connection
WiFi SSID	SSID (name) of the Wifi connection
Latitude	Latitude of the device using GPS
Longitude	Longitude of the device using GPS
Neighboring CellInfo	Info about the neighboring cellular network such as RSSI and Cell ID

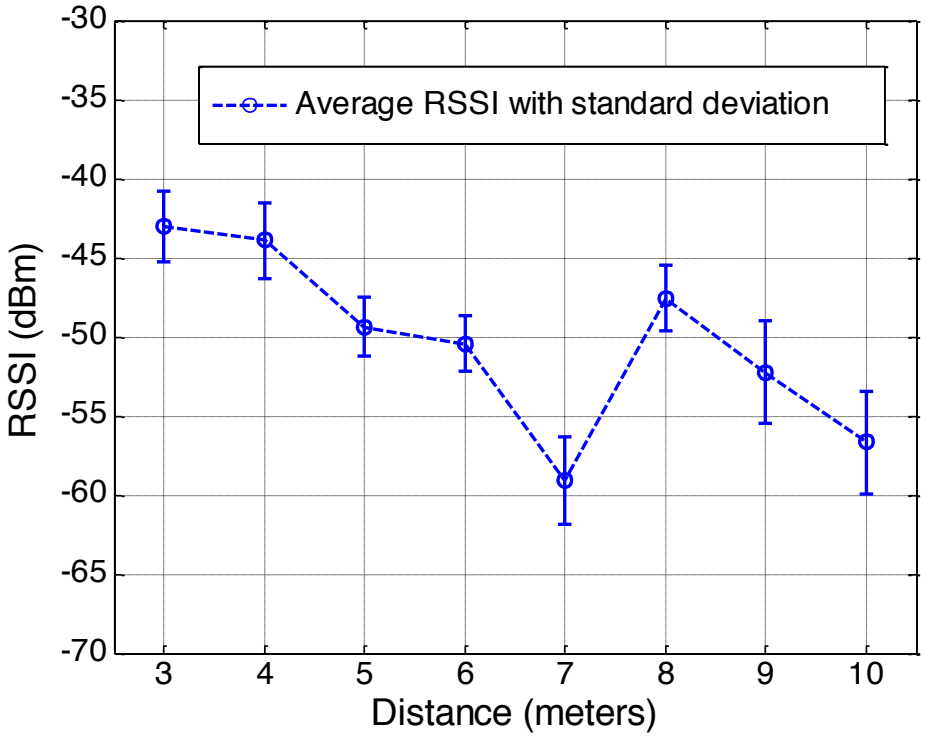
Server-side and Client-side Logs

Intra-vehicle Environment



- For a compact car:
  - Average RSSI is -34.5 dBm, with a standard deviation of 5.5 dBm.

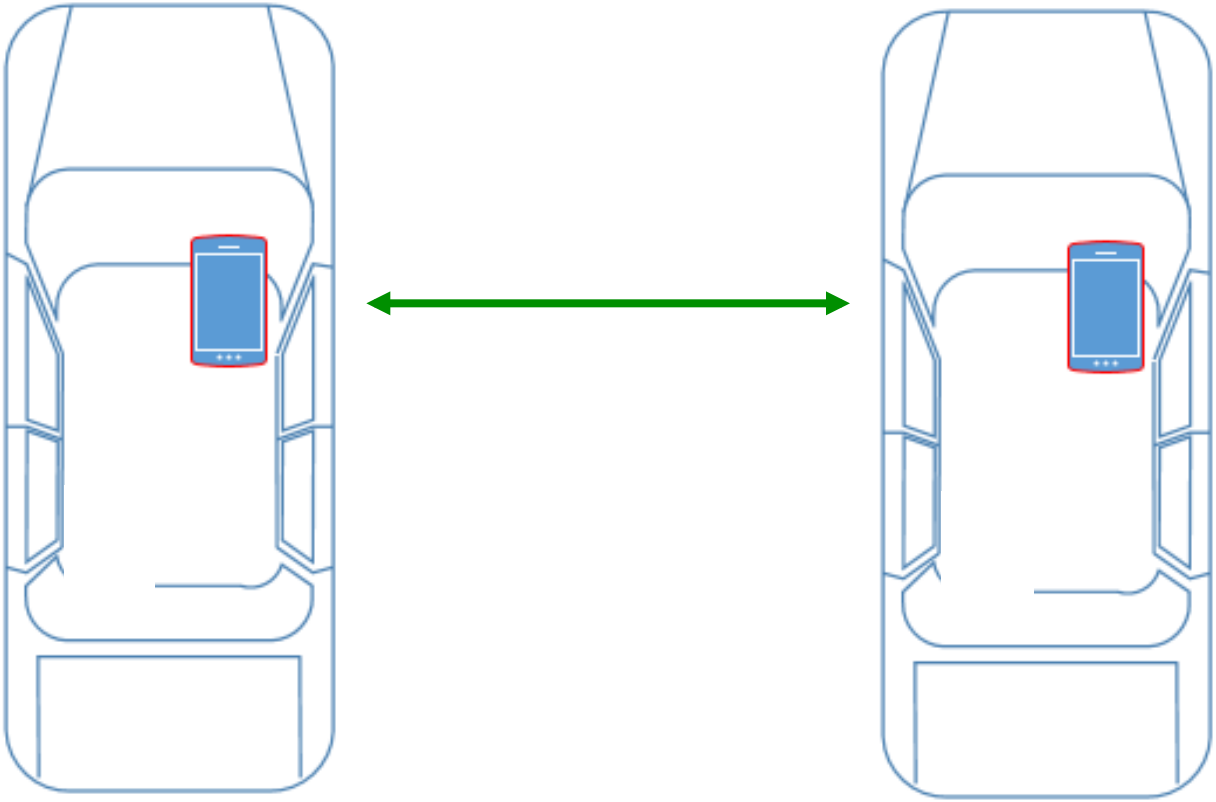
Mimic Intra-vehicle Environment



- High-scattering indoor
  - Mimic vehicles of large size
  - SNR of 32 to 54 dB (assuming the WiFi noise floor is -95 dBm)

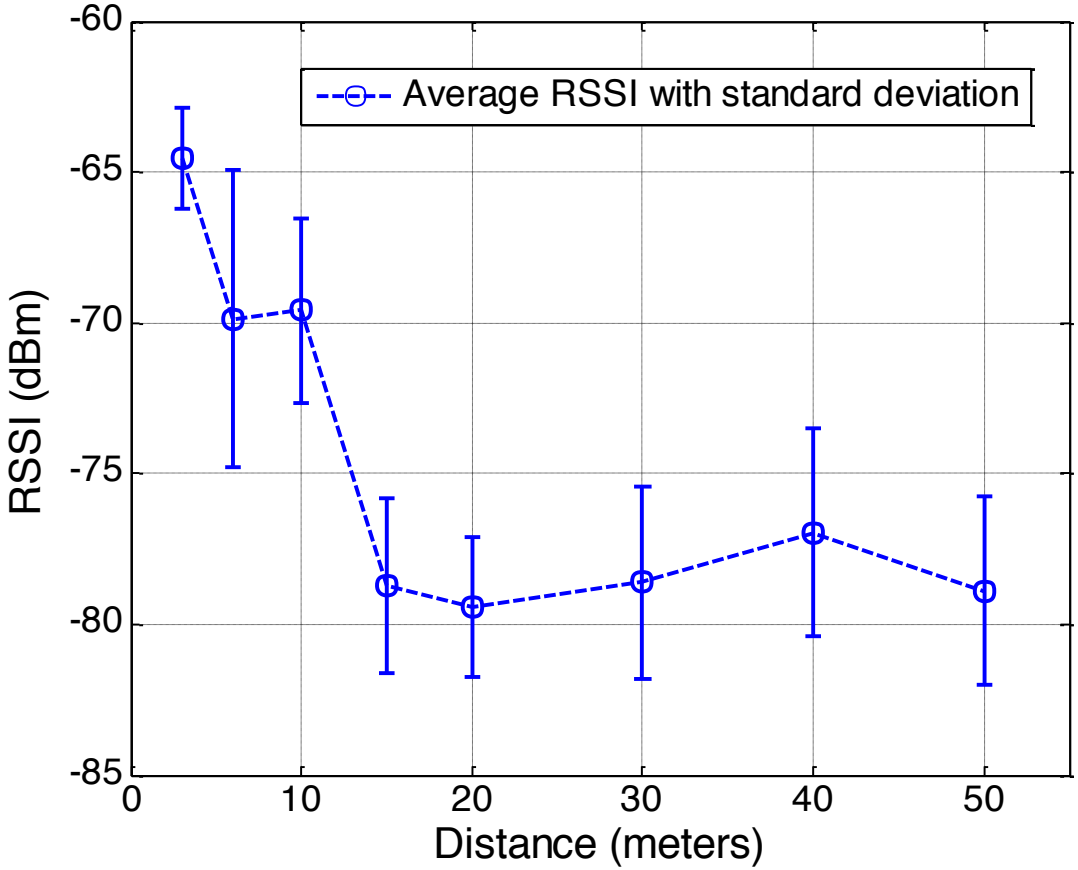
High-Scattering Indoor Environment

Inter-vehicle Environment



- Place two vehicles at different distance separation
  - Measure inter-vehicle ISM side-channel

Inter-vehicle Environment



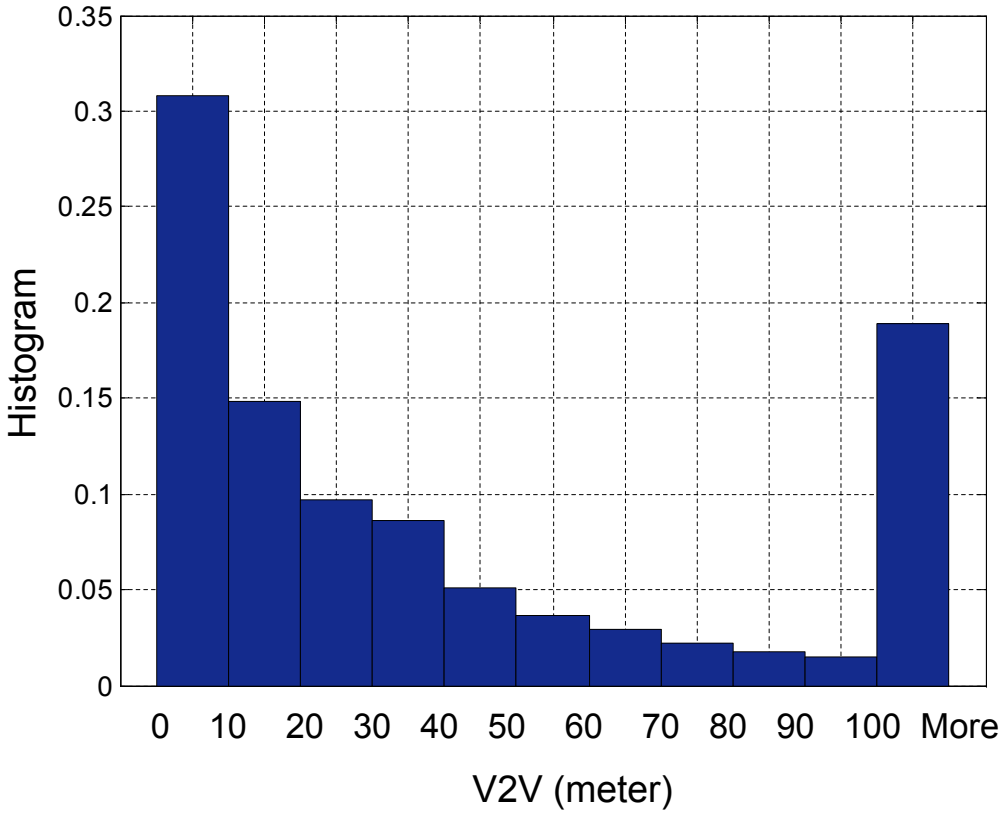
Average SNR ≥ 15 dB

Rush Hour Highway Traffic Data

- Rush hour traffic counts on California State
  - 900 California State Highways: interstate, CA Route, US Route
  - Calculate vehicle-to-vehicle range
  - Estimate of the smartphone-to-smartphone WiFi communication range

$$\text{V2V Range(meter)} = \frac{\text{Avg Rush Hour Speed(meters/hour)}}{\text{Rush Hour Traffic Counts(vehicles/hour)}}.$$

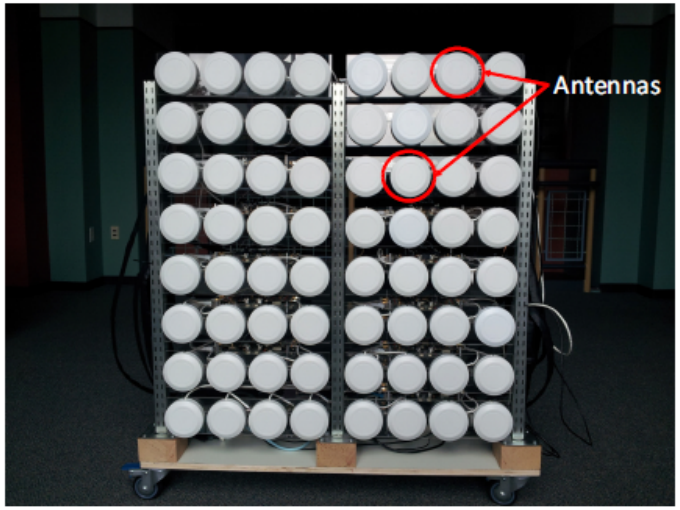
V2V Range Histogram



- 69% of time, there is at least one ISM side-channel within 50m
  - Given at least one smartphone per vehicle

PART II: Impact on Cellular Capacity of Future Wireless Architecture

- Trend of Base Station
  - RF resources
  - Processing capability



Rice Argos Platform

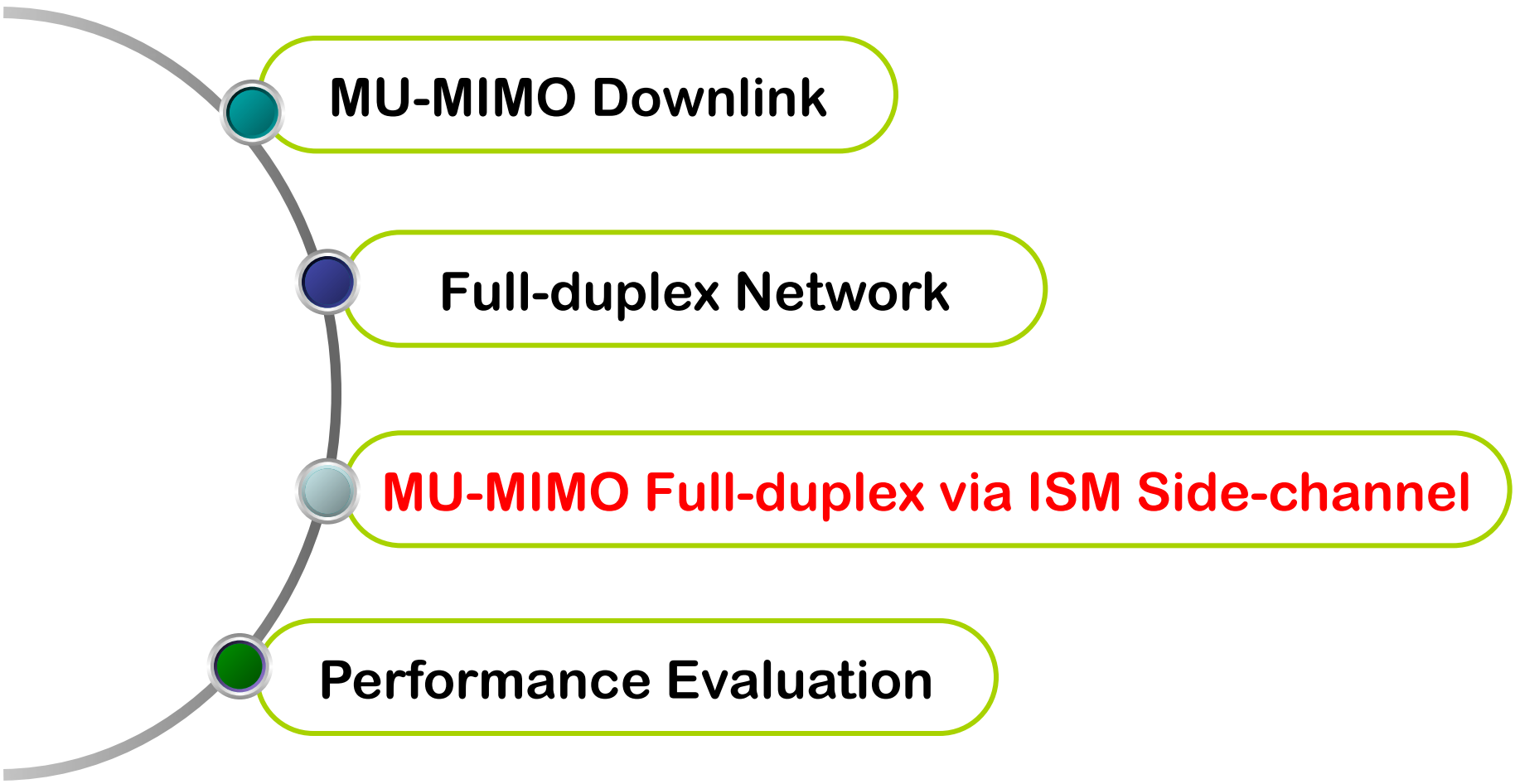
Massive MIMO BS → Symmetric Traffic: MU-MIMO

Massive MIMO BS → Asymmetric Traffic: Full-duplex Network

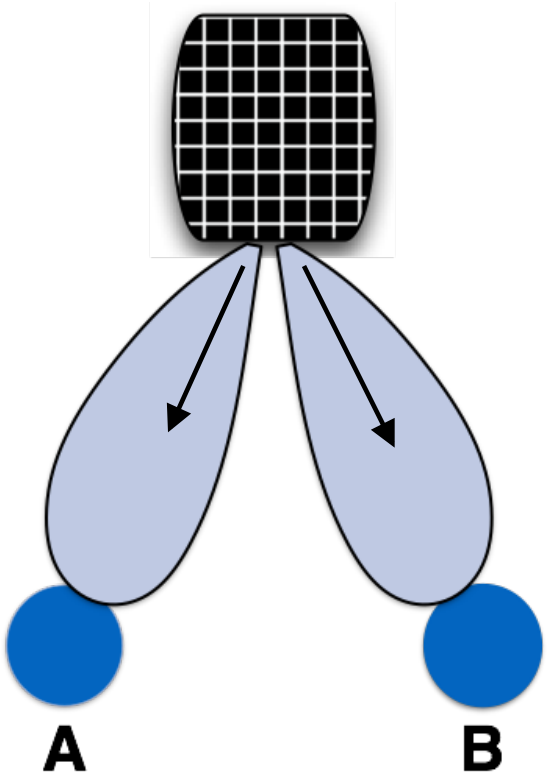
Massive MIMO BS ↓

Support multiple flows in the same cell simultaneously

PART II: Impact on Cellular Capacity of Future Wireless Architecture



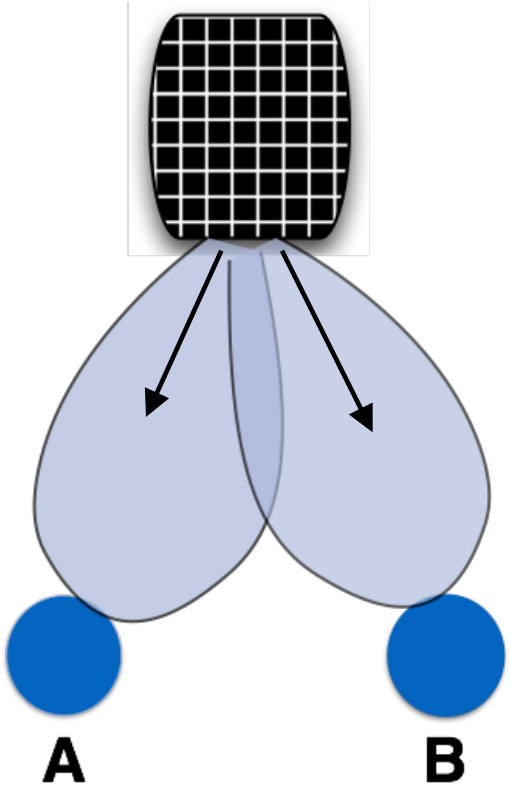
MU-MIMO Downlink



- Massive MIMO BS
  - Zero-forcing beamforming (ZFBF)
    - Create orthogonal beam for each user
  - With perfect Channel State Info at the Transmitter (CSIT), ZFBF can completely null out interference

MU-MIMO ZFBF System with Perfect CSIT

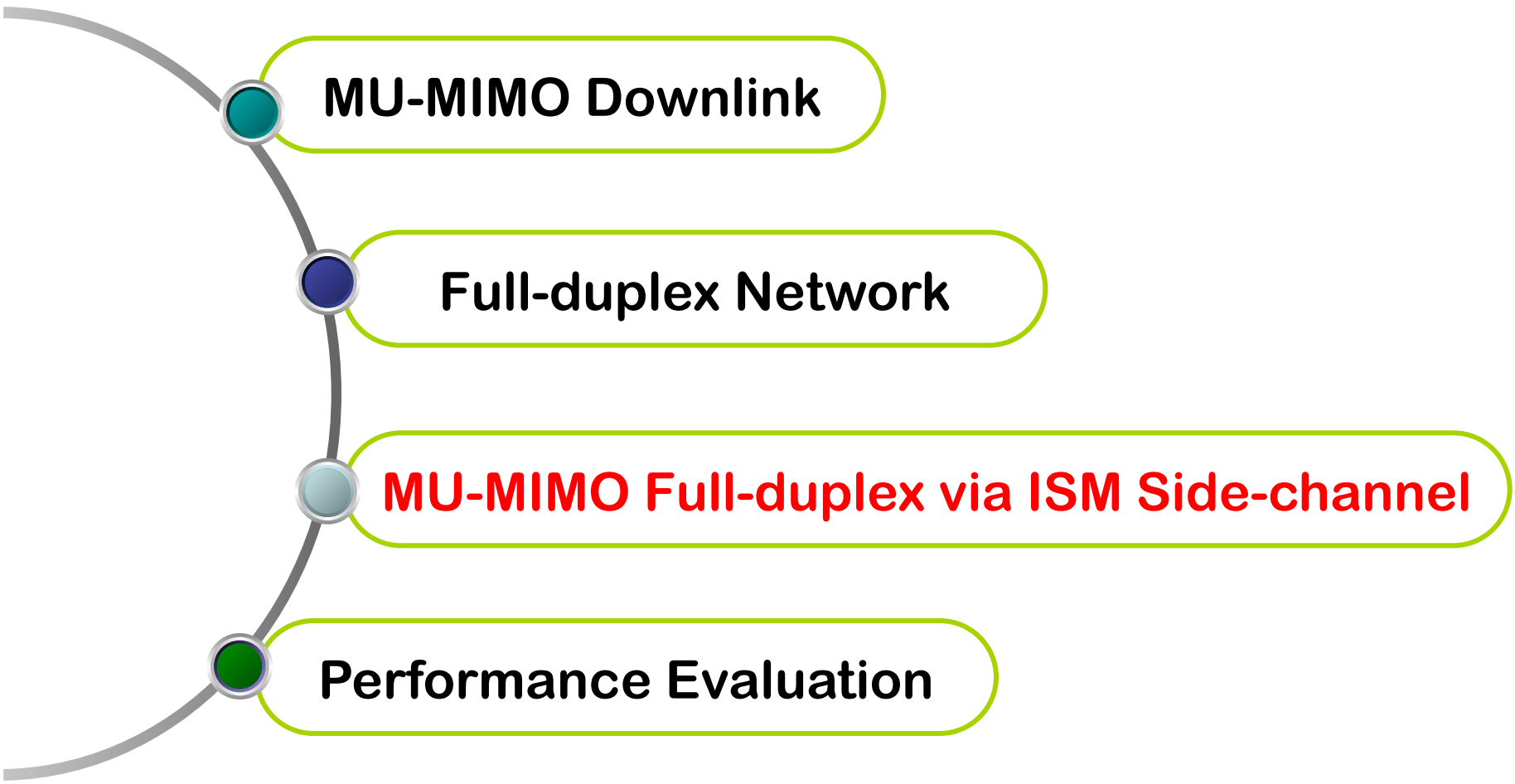
MU-MIMO Downlink



- In practice: CSIT is not perfect
  - Finite feedback bit → quantize channel instantiation
- Imperfect CSIT → **Inter-beam Interference**

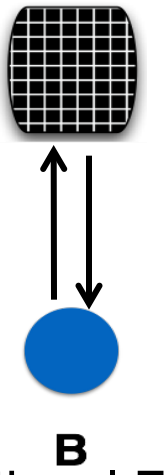
MU-MIMO ZFBF System with Imperfect CSIT

PART II: Impact on Cellular Capacity of Future Wireless Architecture

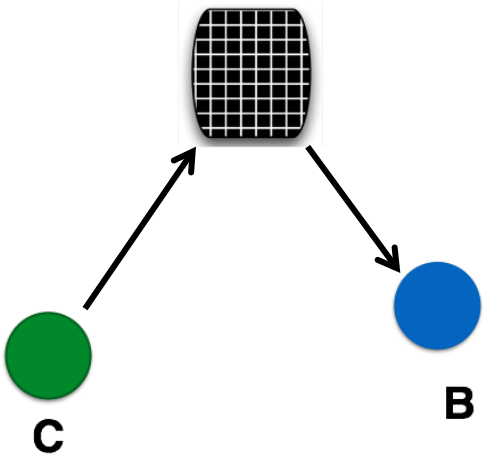


Full-duplex Network

- Asymmetric traffic: full-duplex doubles spectral efficiency



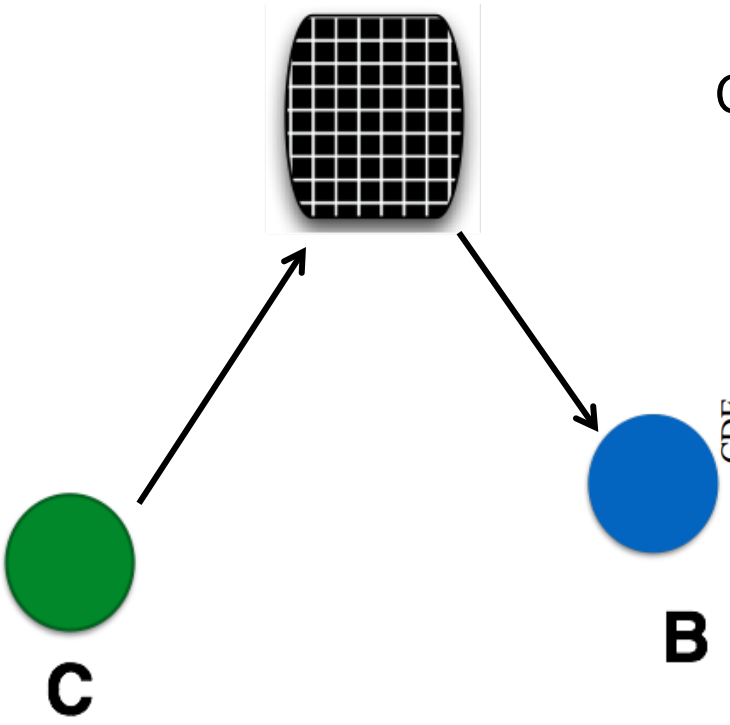
Bi-directional Full-duplex



Full-duplex Network

- Massive MIMO BS
  - Use some of the antennas for transmission and others for reception to enable **full-duplex** operation.
  - Passive self-interference suppression
    - Polarization, directionality, absorption
  - Active self-interference cancellation

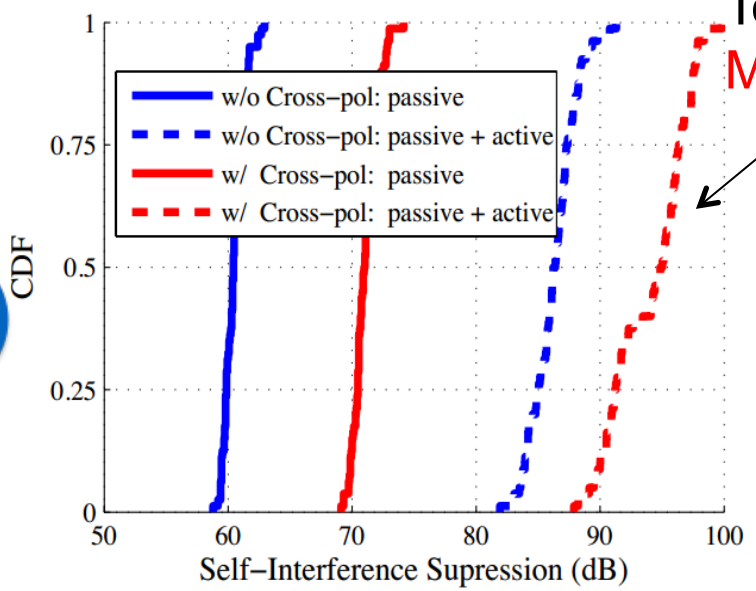
Full-duplex Network



- Mobile handsets remain half-duplex

Cancel Self-Interference Close to Noise Floor

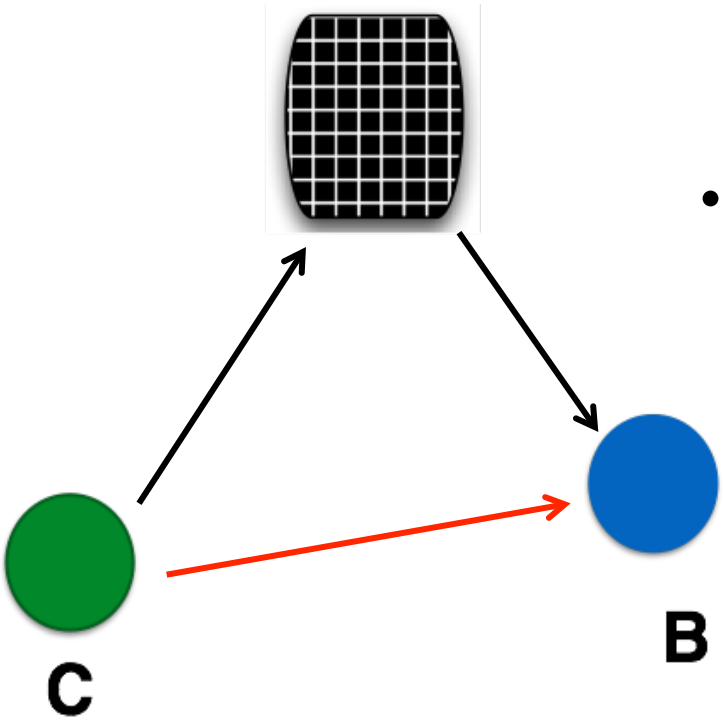
Total cancellation
Mean 95dB+



Everett, Sahai, Sabharwal, Rice, 2013

Full-duplex Network with Half-duplex Clients

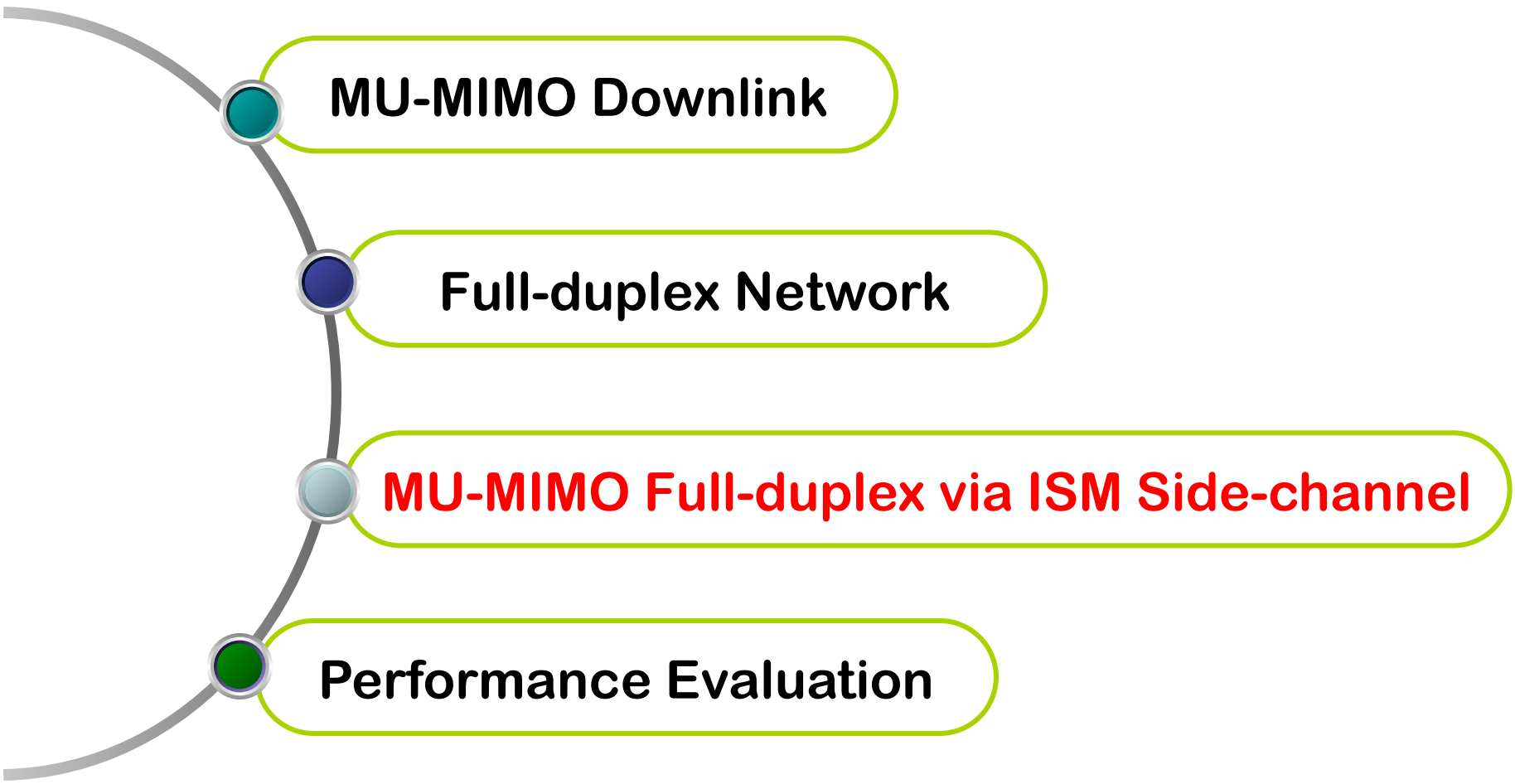
Full-duplex Network



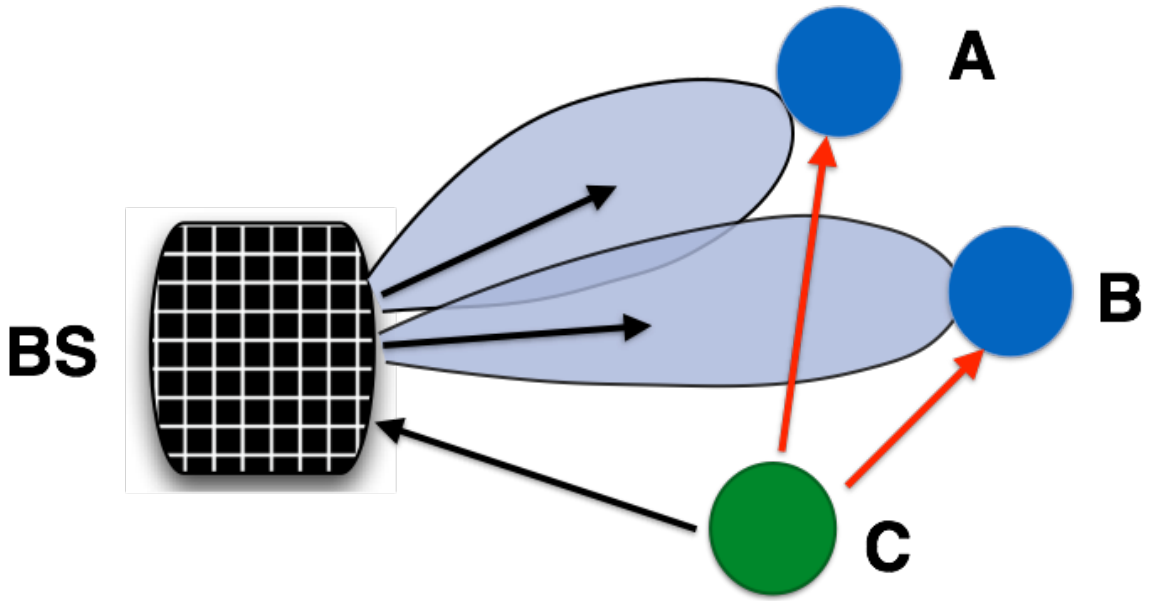
- Close distance between UL and DL users → **Uplink-downlink Interference**

Full-duplex Network with Half-duplex Clients

PART II: Impact on Cellular Capacity of Future Wireless Architecture



Massive MIMO: MU-MIMO Full-duplex



Crisis

MU-MIMO Downlink -- Inter-beam interference
Full-duplex -- Uplink-downlink interference

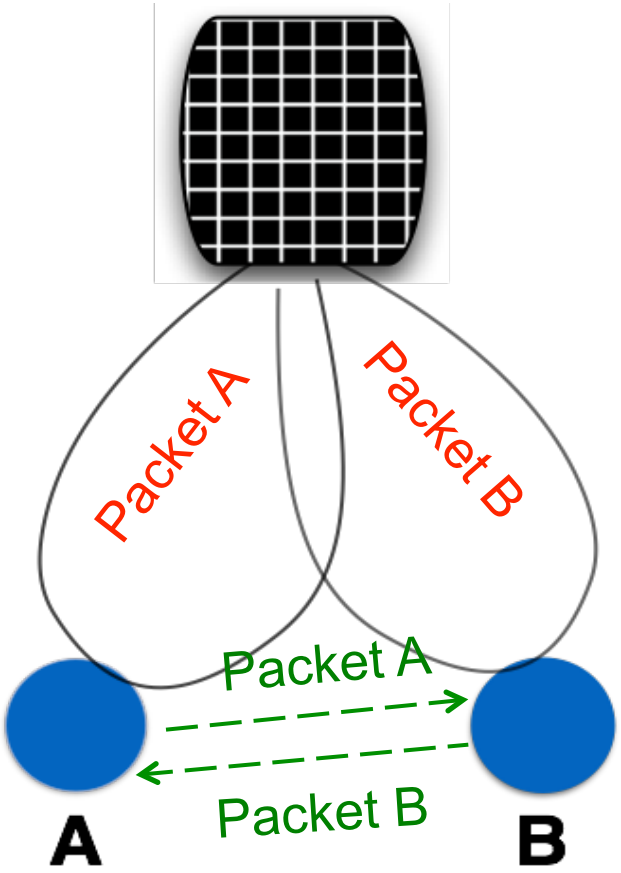
MU-MIMO Full-duplex: Intra-cell Interference

Improved Interference Management

- Leverage ISM side-channels in dense environments

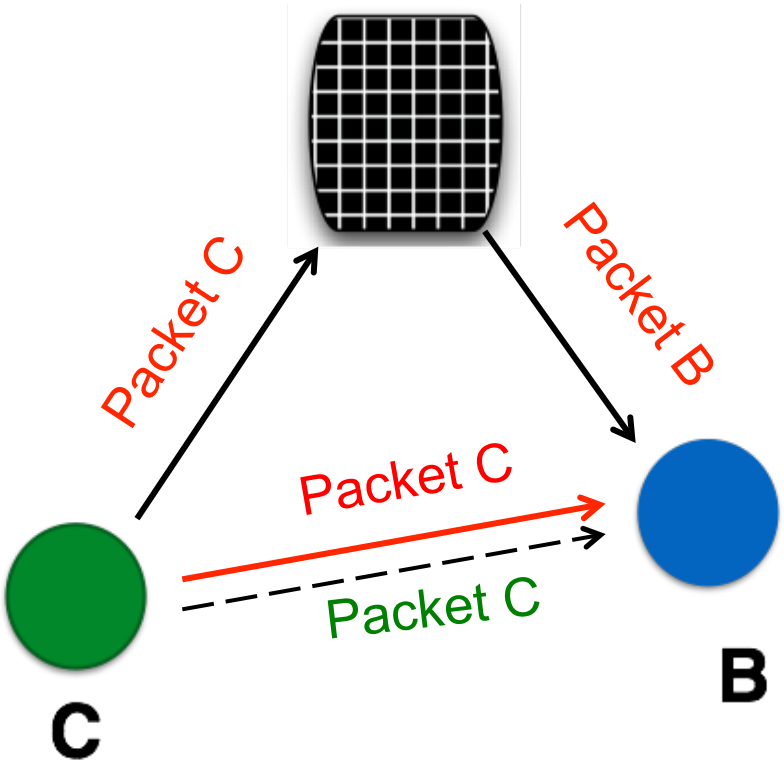
- Our Solution
  - **Amplify-and-forward**: Inter-beam interference for MU-MIMO downlink
  - **Decode-and-cancel**: Uplink-downlink interference for full-duplex network

MU-MIMO Downlink: Amplify-and-Forward



- A (B) amplifies the received signal and forwards it to B (A) on the side-channel
- A and B perform receive-beamforming to decode its own packet based on all received signal and channel knowledge.

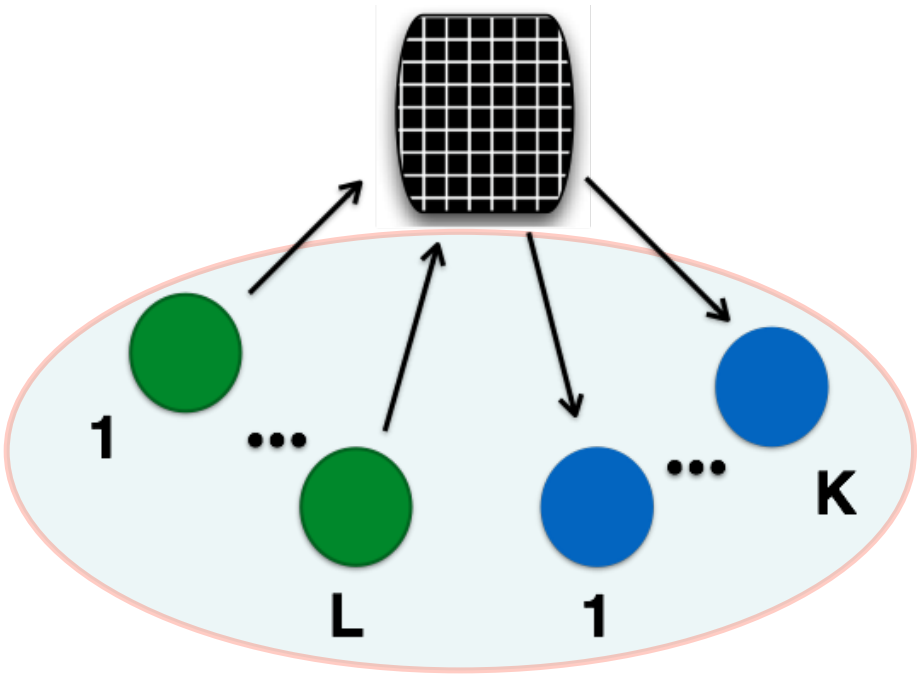
Full-duplex: Decode-and-Cancel



- C sends the packet encoded for the side-channel
- B decodes Packet C, re-encodes, then cancels from main-channel
- After canceling out Packet C, B can decode Packet B

MU-MIMO Full-duplex via ISM Side-channels

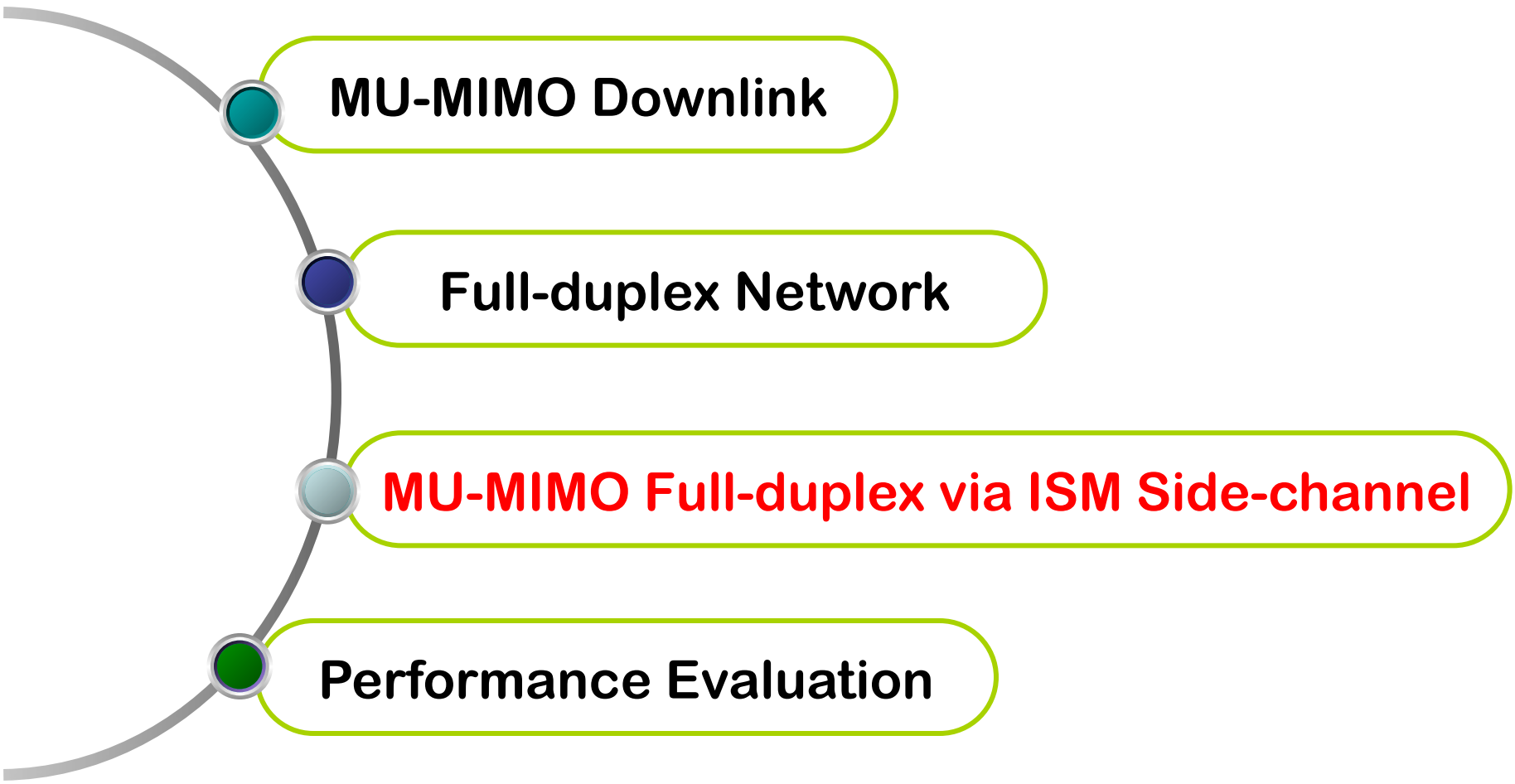
Base Station: M antennas



- BS: **No CSIT is required**
  - Blindly serve DL with only K antennas
  - ZFBF to serve UL with the remaining antennas
- DL users:
  - amplify-and-forward
- UL users:
  - decode-and-cancel

BS can schedule the use of ISM side-channels for intra-cell interference management

PART II: Impact on Cellular Capacity of Future Wireless Architecture



Performance Evaluation

- Goal: show the benefits of leveraging ISM side-channels

Area	50×50 square meters
Base station antennas	M = 20
Maximum number of users	K + L = 20
Uplink and Downlink SNR	35 dB
ISM Side-channel RSSI	Refer to our measurement
Main-channel	Rayleigh fading

Results I: MU-MIMO Downlink

- Compare three systems with only downlink users:
  - ZFBF with perfect CSIT
    - Use all M antennas
  - ZFBF with finite-bit feedback
    - Use all M antennas
    - Finite-bit feedback:10 bits per user
  - User cooperation via ISM side-channels
    - Amplify-and-forward
    - Use only K antennas without acquiring CSIT

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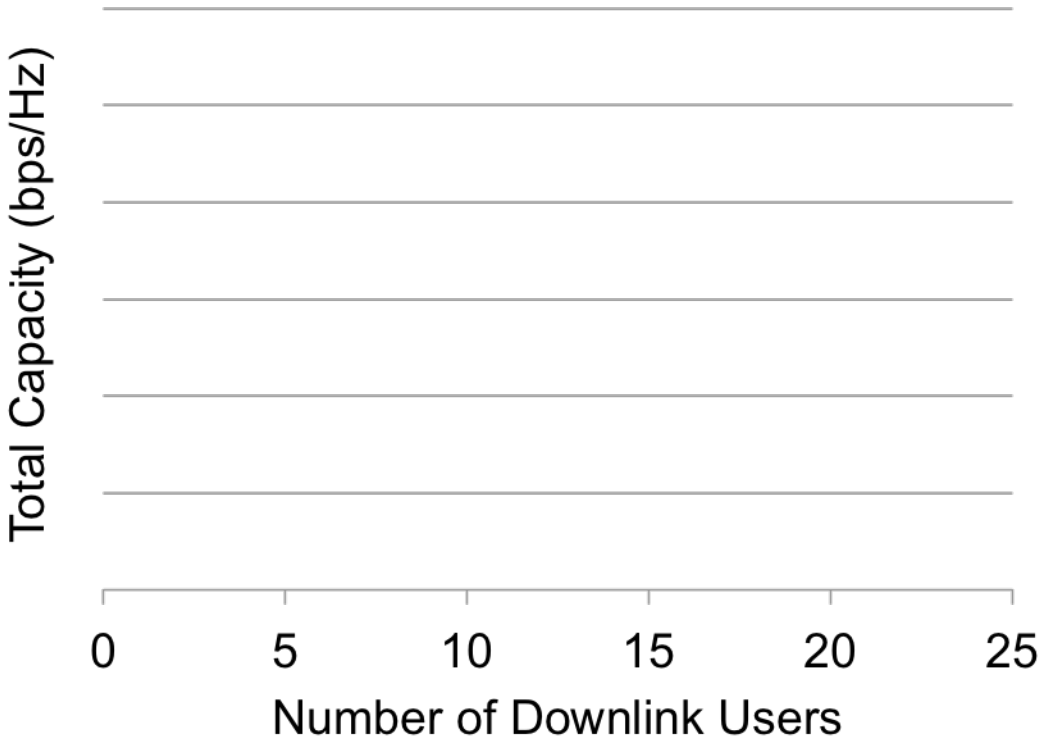
MU-MIMO Downlink with Increasing User Density



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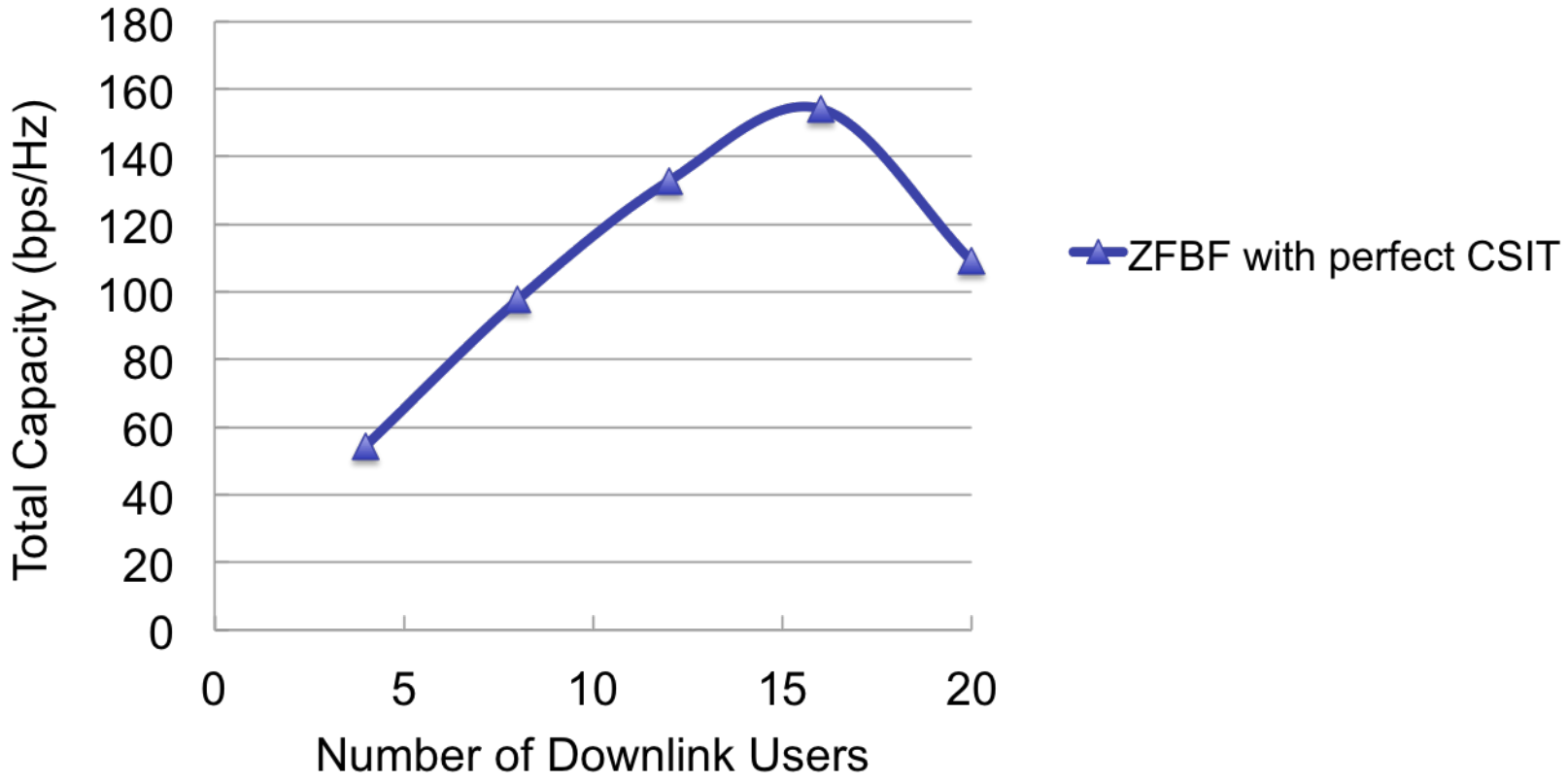

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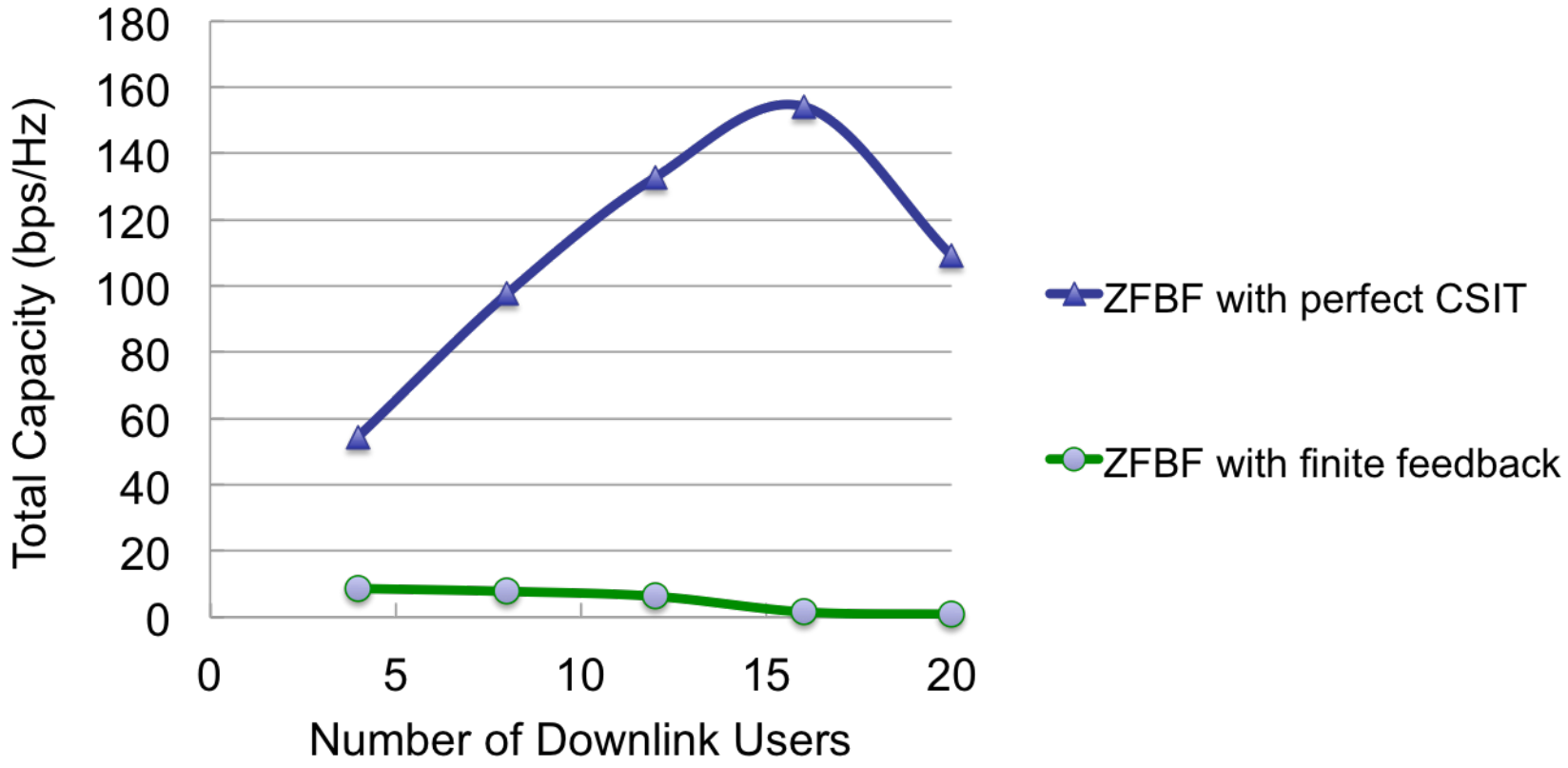

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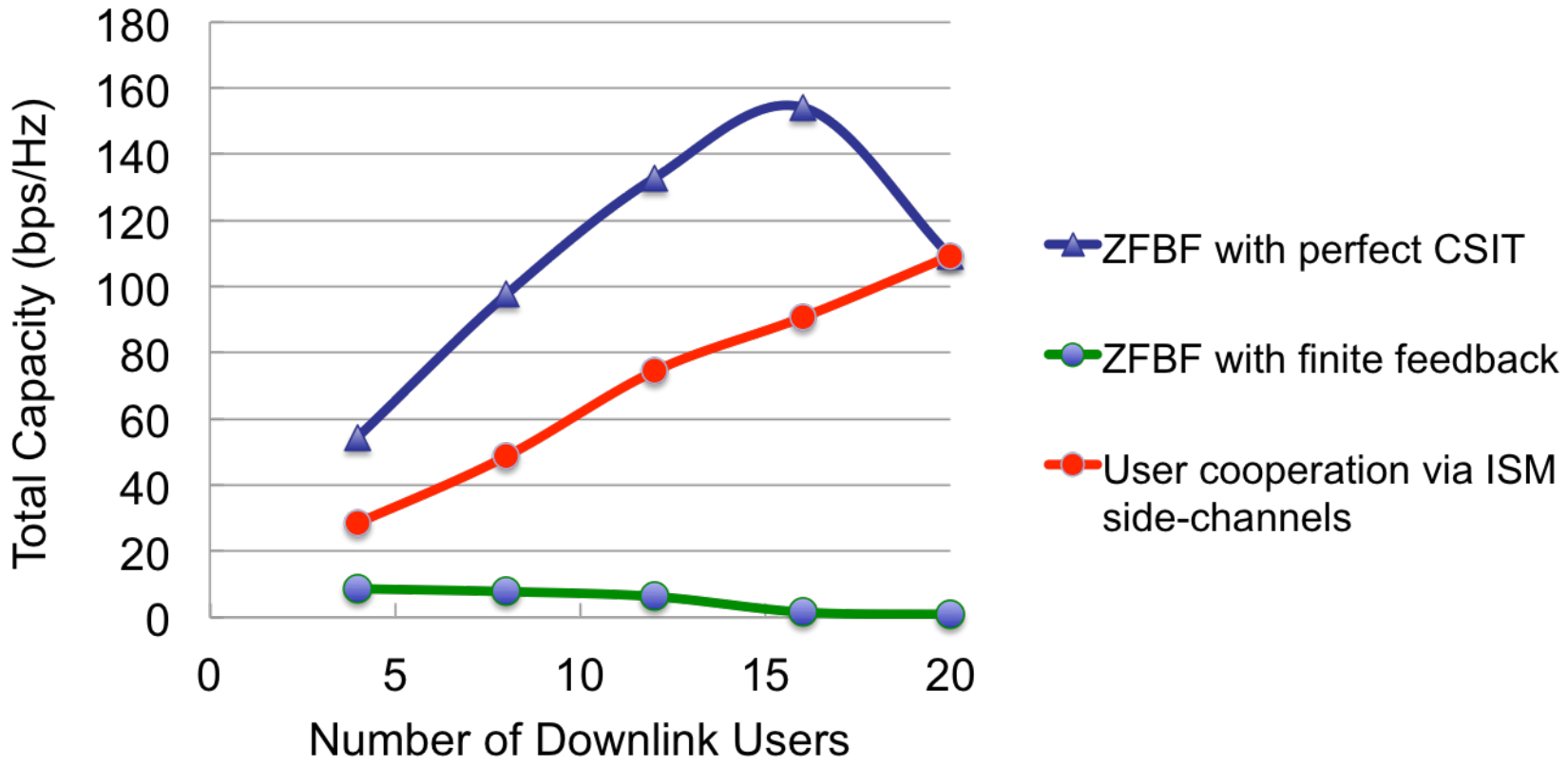

Results II: MU-MIMO Full-duplex

- Compare four systems with both up- & downlink users:
  - TDMA
    - Serve one user at a time; Use all M antennas
  - ZFBF downlink with perfect CSIT
    - Use all M antennas
  - Full-duplex ZFBF with perfect CSIT
    - Use a subset of antennas for DL
    - Remaining antennas for UL
  - MU-MIMO full-duplex via ISM side-channels
    - Use a subset of antennas to blindly serve DL without CSIT
    - Remaining antennas for UL

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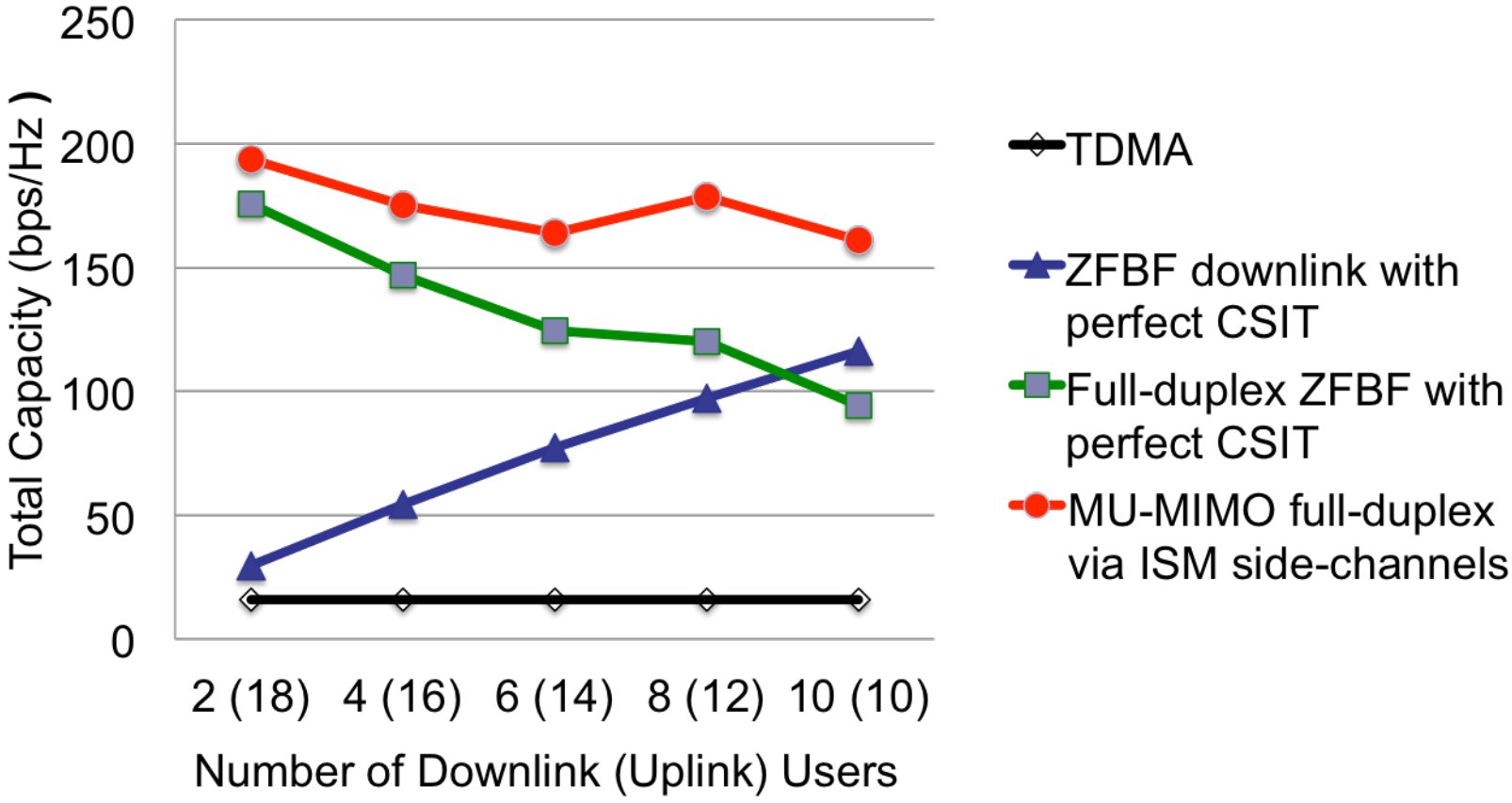
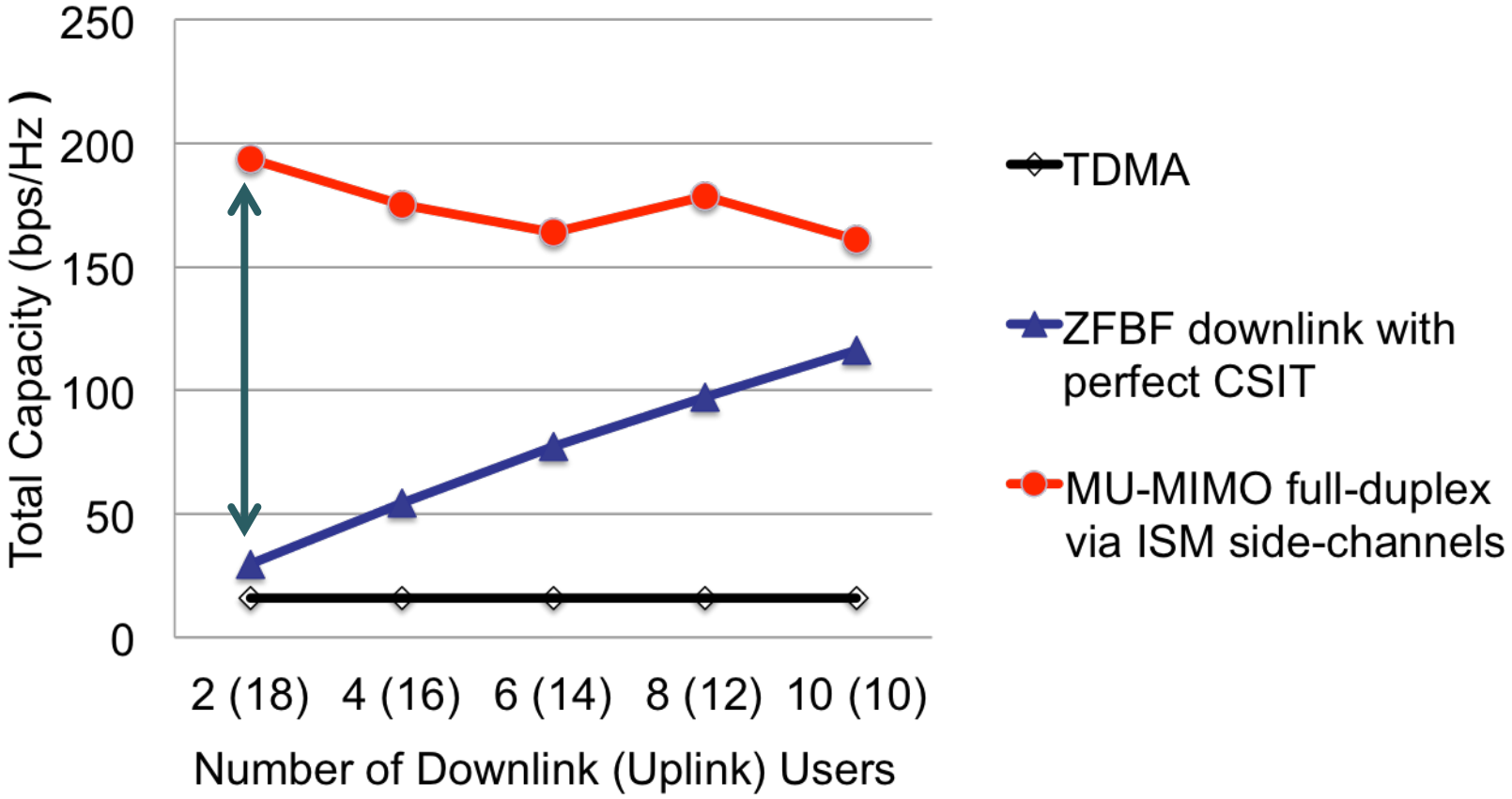
MU-MIMO Full-duplex with Fixed User Density

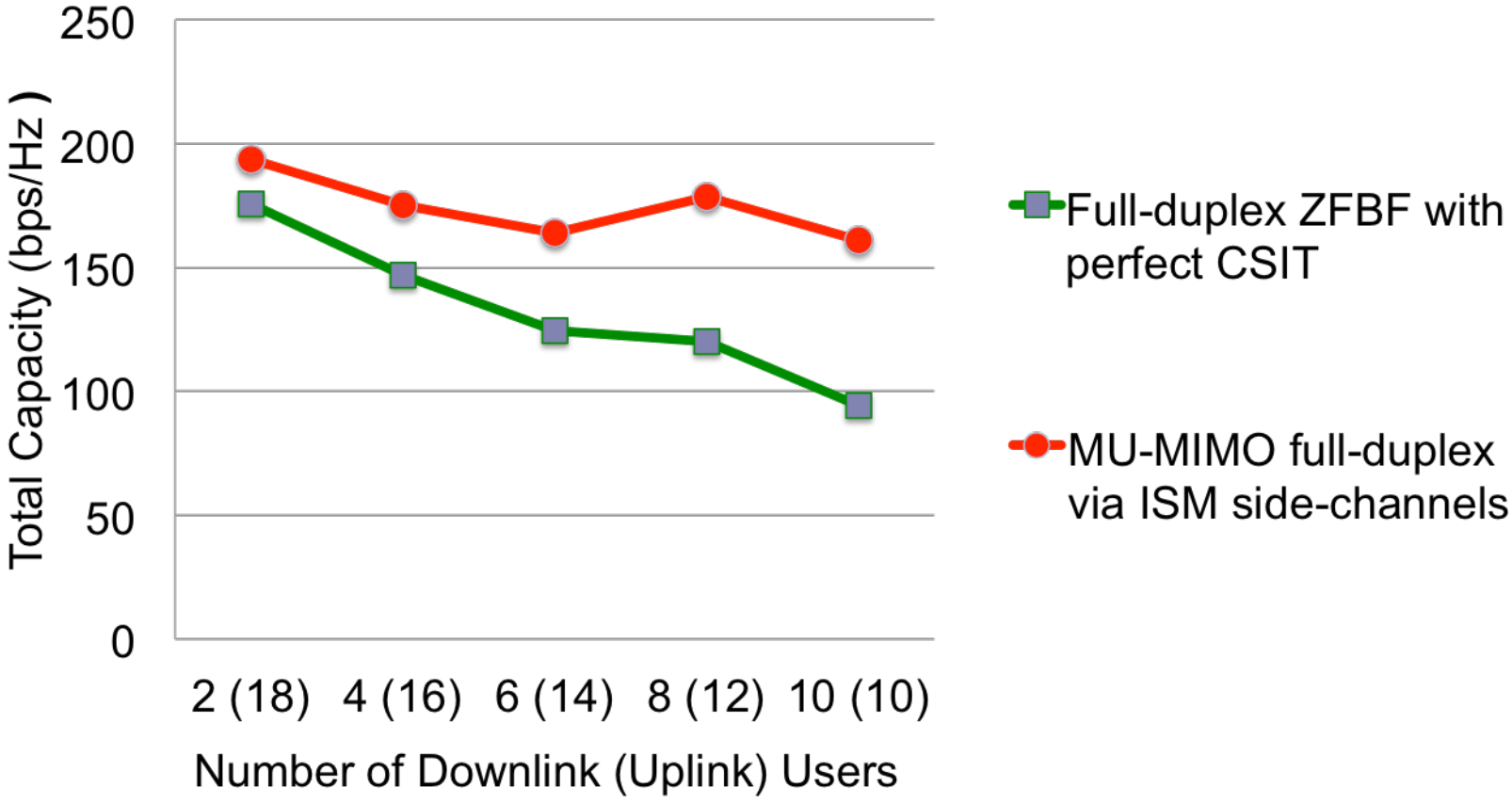


MU-MIMO Full-duplex with Fixed User Density



6.5X over ZFBF Downlink
12X over TDMA

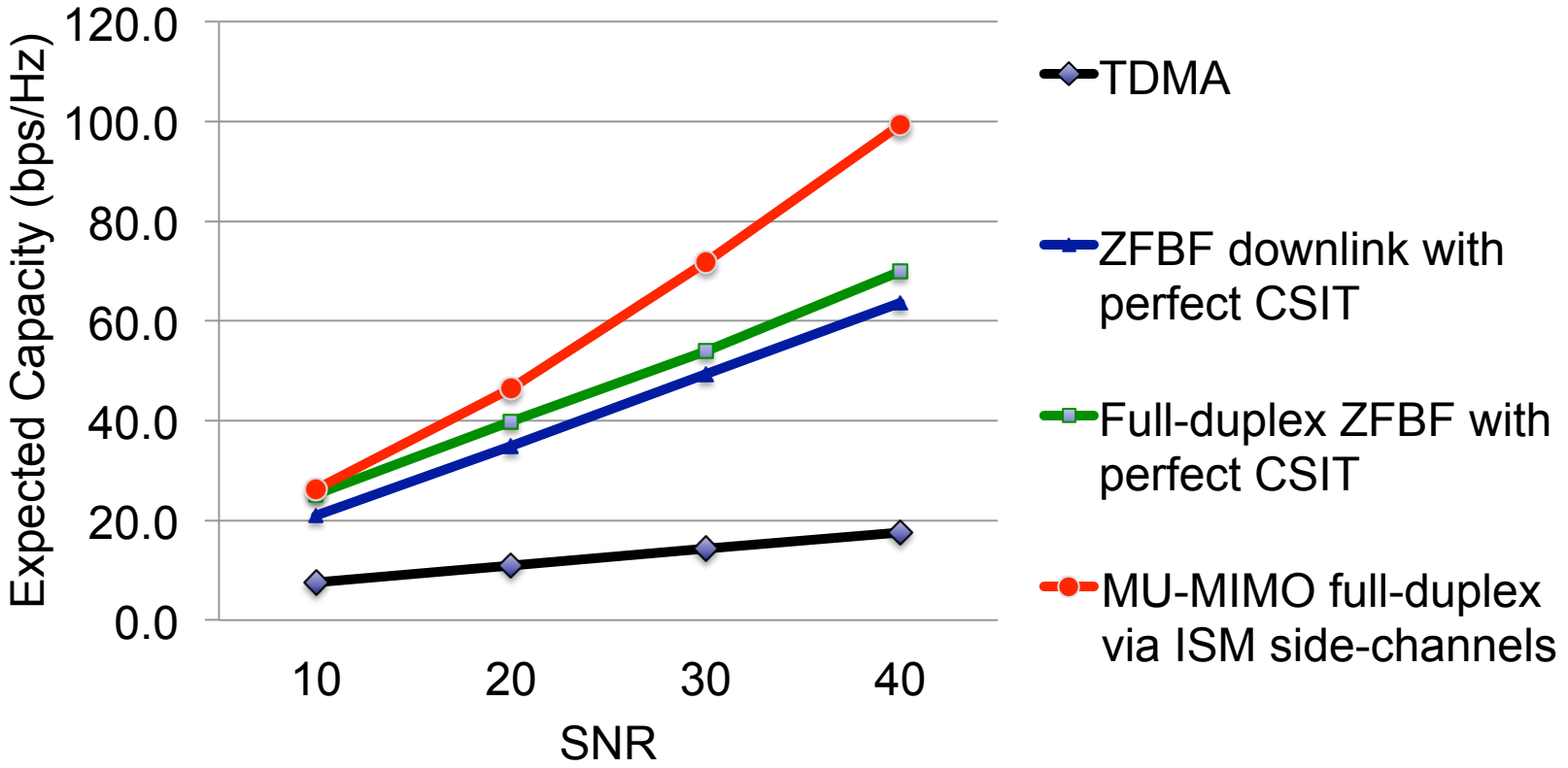
MU-MIMO Full-duplex with Fixed User Density



Recovering 2X full-duplex gain

MU-MIMO Full-duplex with SNR

- Expected capacity $\mathbb{E}_d\left[\mathrm{Capacity}(d)\right]$
  - The expectation is taken over the estimate of the ISM side-channel range distribution we found in PART I



Expected Capacity Scales with SNR

Conclusion

- Availability of ISM side-channels
  - 69% of time, we can establish ISM side-channels within 50m range on highway during rush hour with reliable link quality
- ISM band for improved interference management
  - Enable a flexible wireless architecture design of MU-MIMO full-duplex
  - Promise to improve the cellular network capacity many-fold