A Case for Temperature-Aware Scheduler for Millimeter-Wave Devices and Networks

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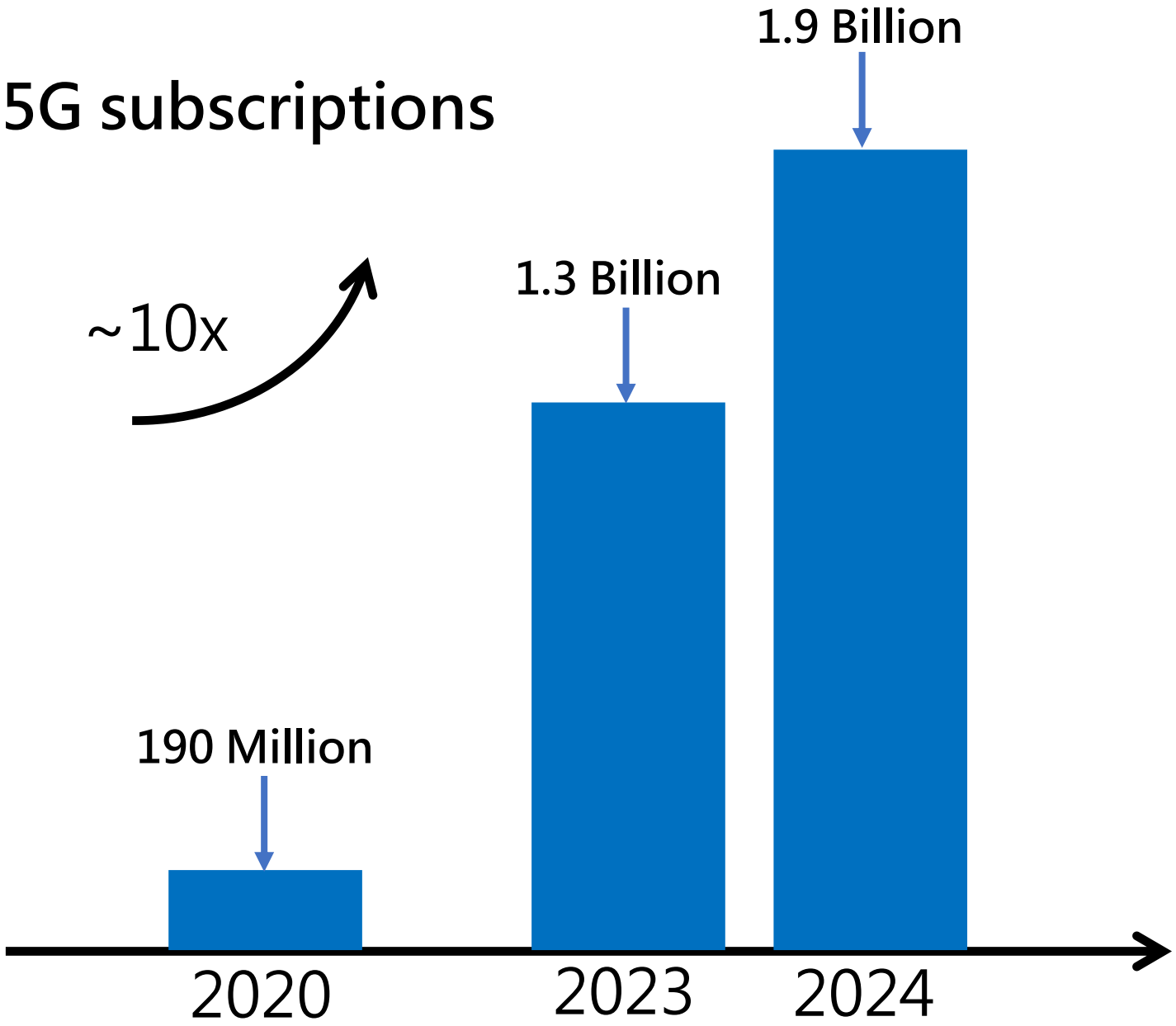
Outline

- Why Millimeter-Wave for 5G?
- Device overheating under Millimeter-Wave
- Thermal characterization
- *Aquilo* : A multi-antenna scheduler
- Summary and Conclusions

Why Millimeter-Wave for 5G?

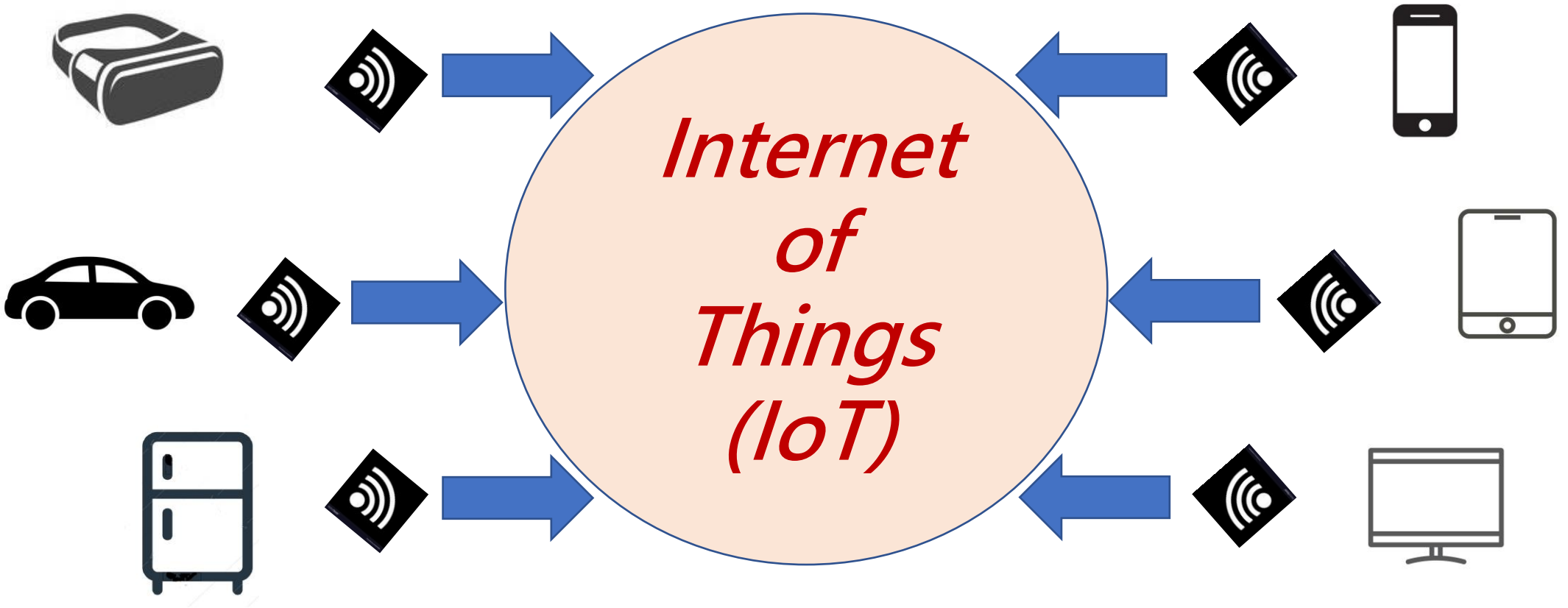
5G: Growth in wireless data demand

Number of 5G subscriptions



Source: Statista, 2020-2024

New technology for 5G: The IoT reality



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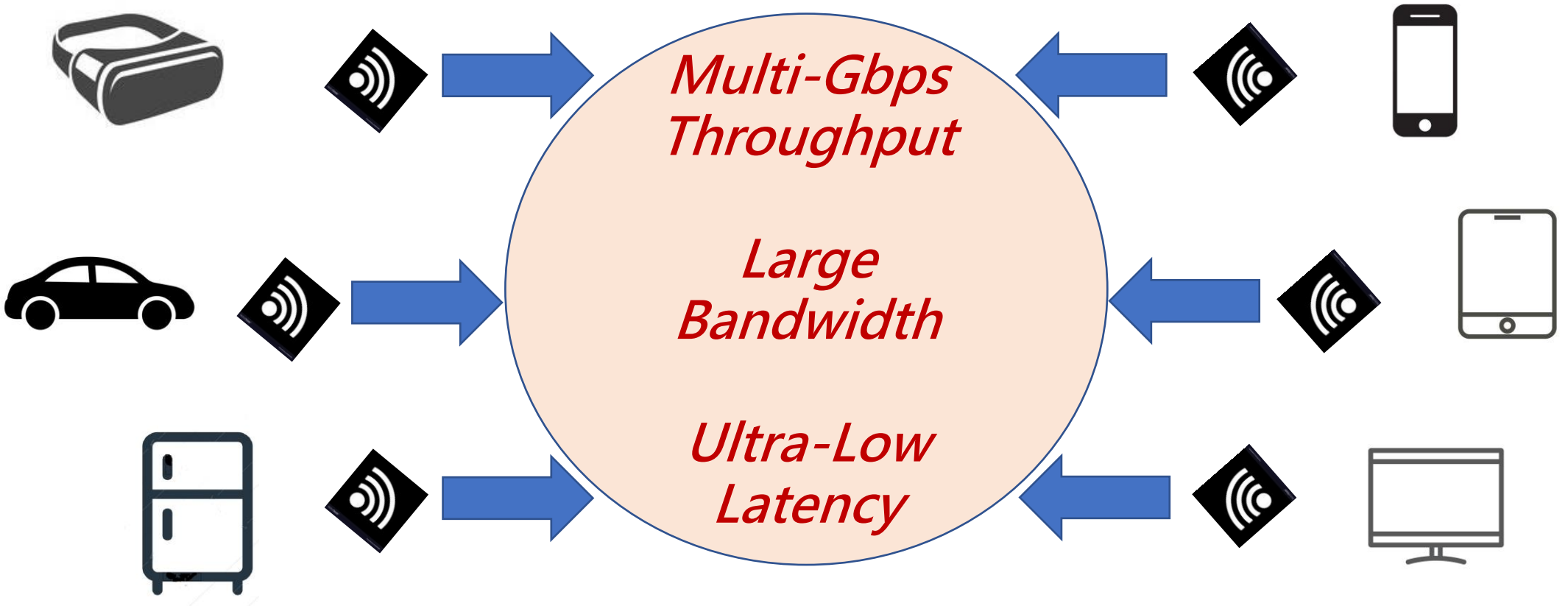


New technology for 5G: high requirements

Immersive VR/AR

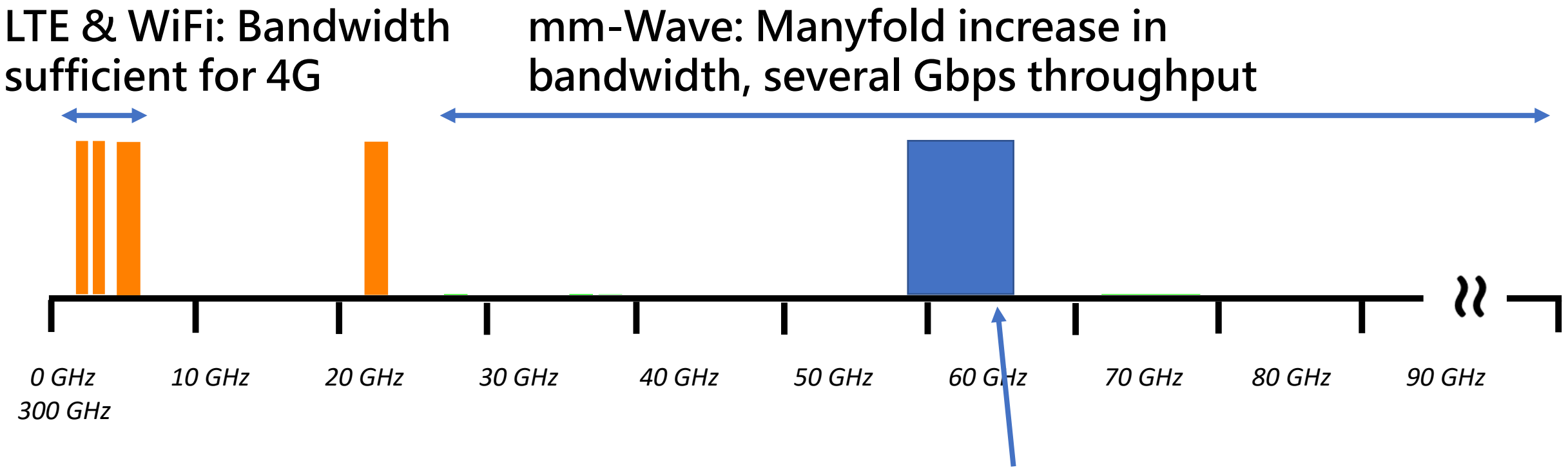
5 ~ 6 Gb/s wireless speed with sub-10 millisecond latency

Autonomous car

Locally generates more than 10 Gb/s *

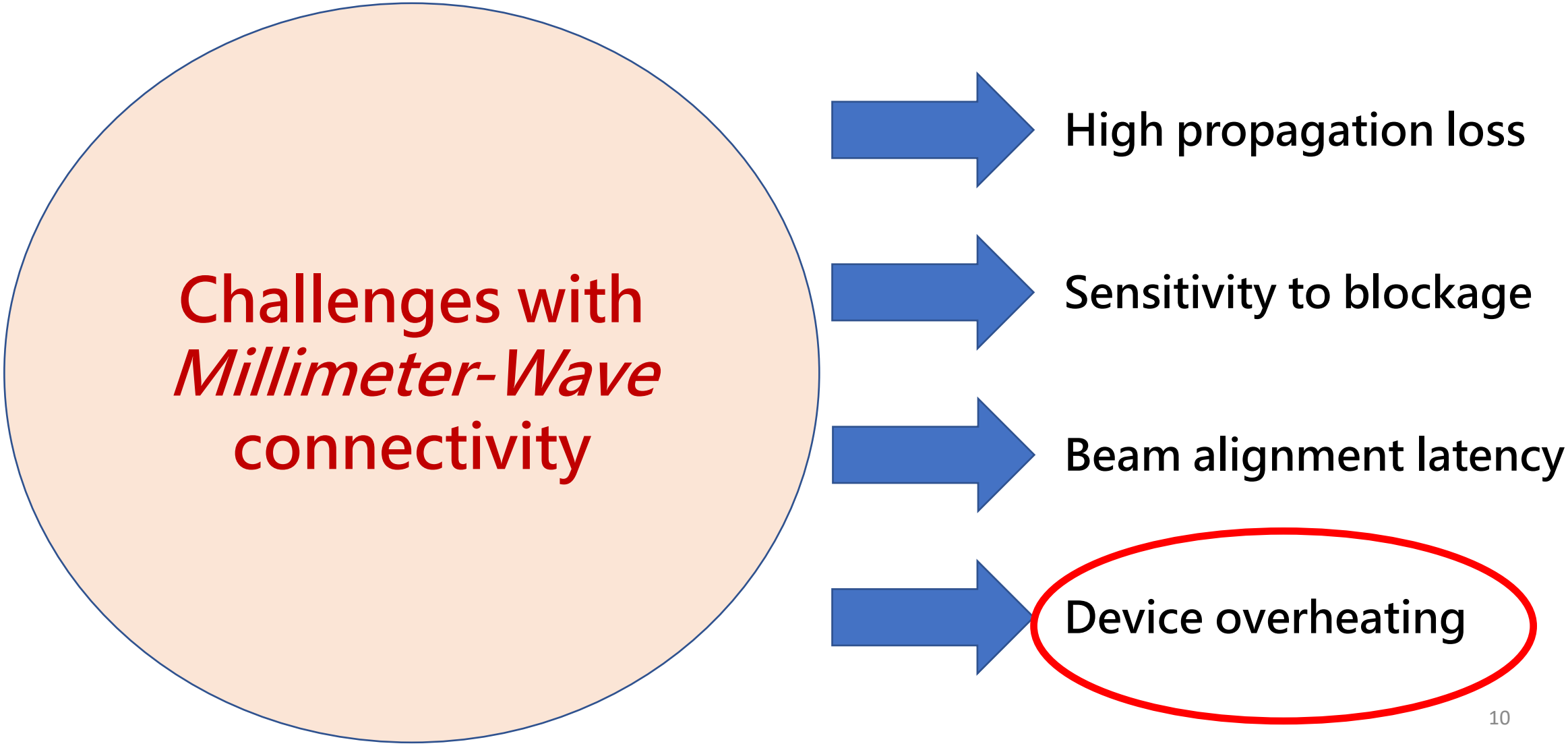
* https://datacenterfrontier.com/autonomous-cars-could-drive-a-deluge-of-data-center-demand/

New technology for 5G: Millimeter-Wave



Device overheating in Millimeter-Wave networks

Millimeter-Wave challenges



Overheating in Millimeter-Wave devices

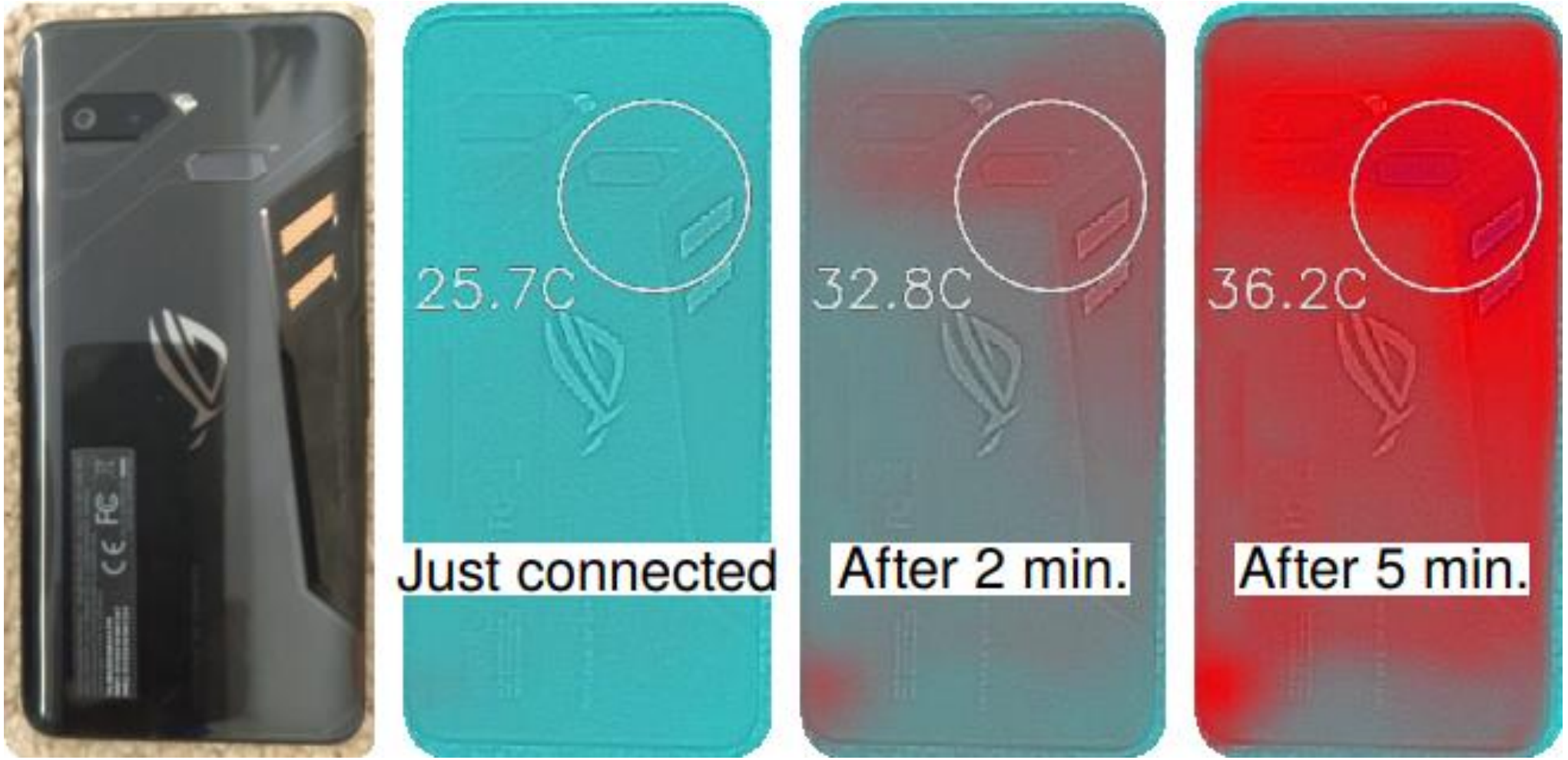
60 GHz Antenna

Reel from a thermal camera

Sped up by 30X,
Total duration ~ 300 s

60 GHz ROG
Smartphone

60 GHz ROG smartphone overheating



Reports of mmWave device overheating

Device overheating: *discomfort* and *network degradation*

Devices used near face & brain,
e.g. Smartphone, VR

- Potential health hazards
- User discomfort

High temperature → high noise and leakage current

- Fluctuation in throughput
- Degraded network

Thermal characterization of Millimeter-Wave devices

60GHz measurement testbed

- Nighthawk X10 60 GHz AP
- ASUS ROG 60 GHz Smartphone

Device Features:

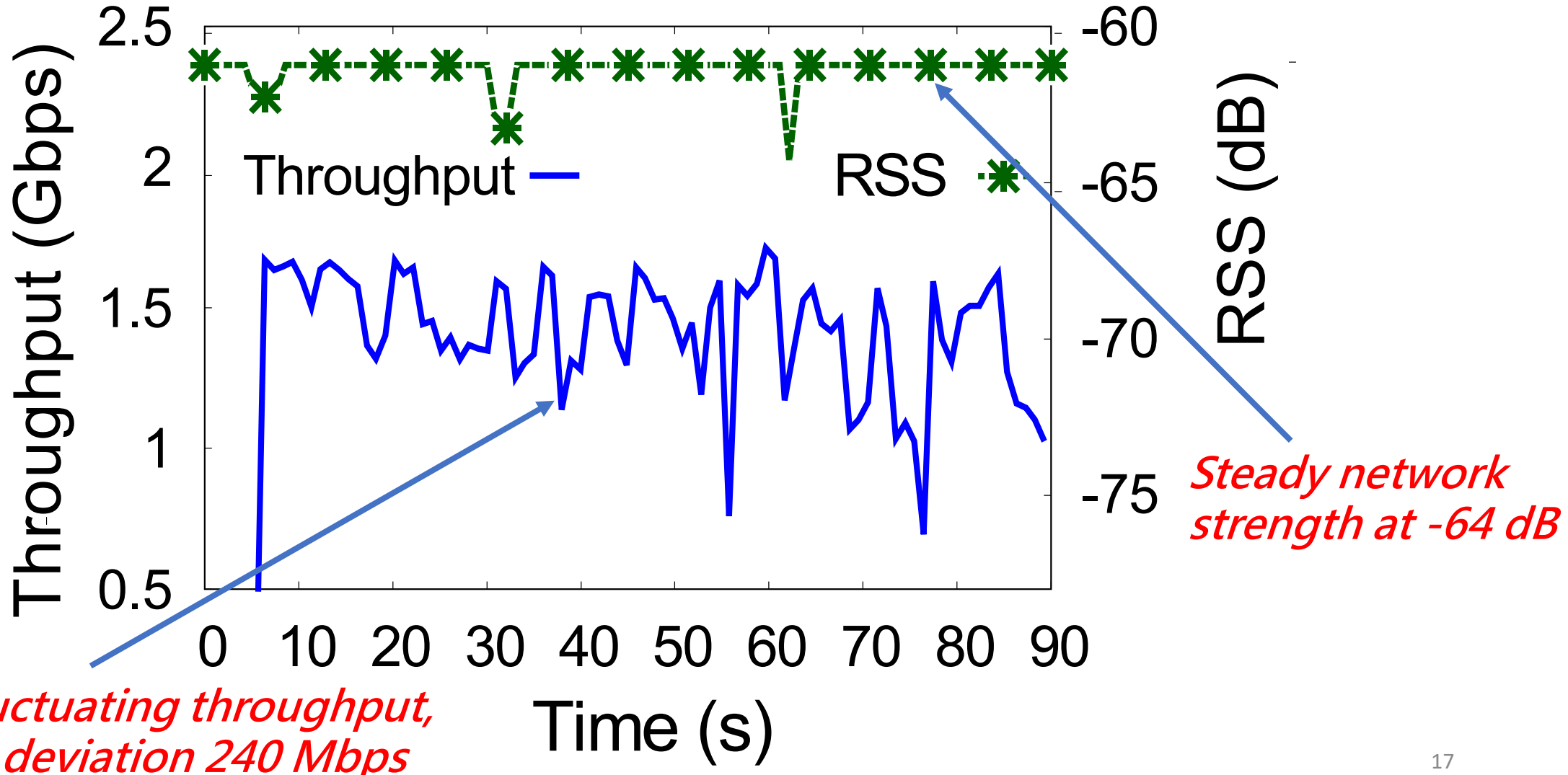
✓ IEEE 802.11ad compliant

✓ 32-element phased array antenna

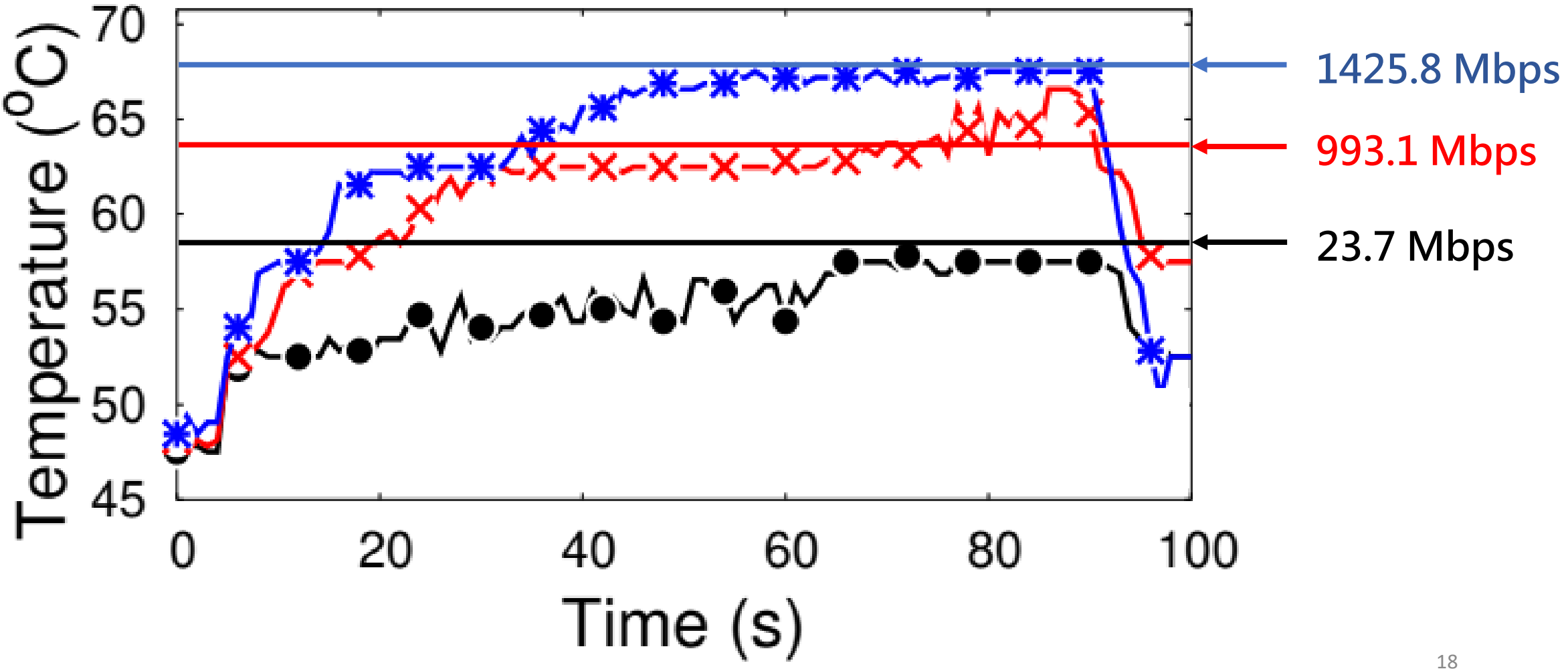
✓ 2.16 GHz bandwidth

✓ 4.62 Gbps peak bit-rate

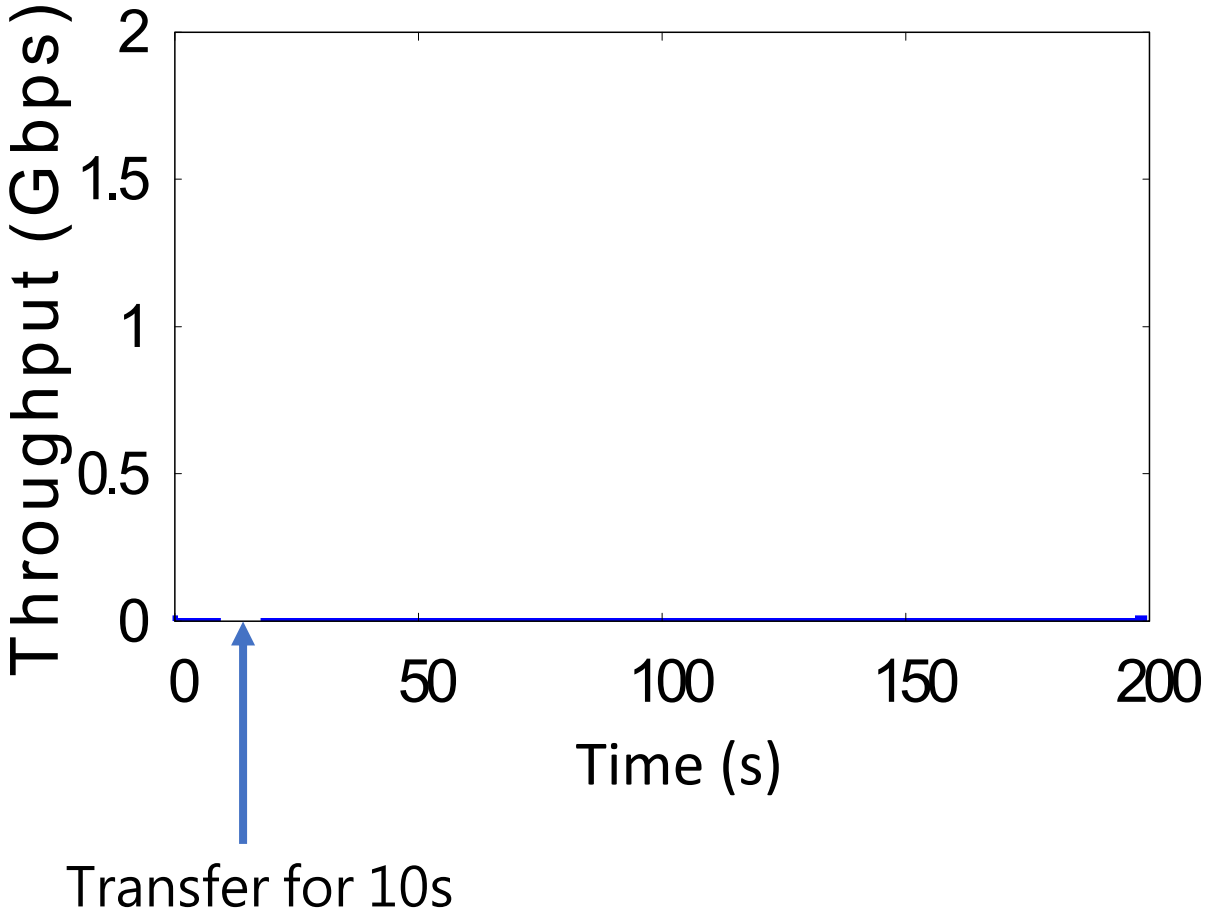
Performance degradation under temperature

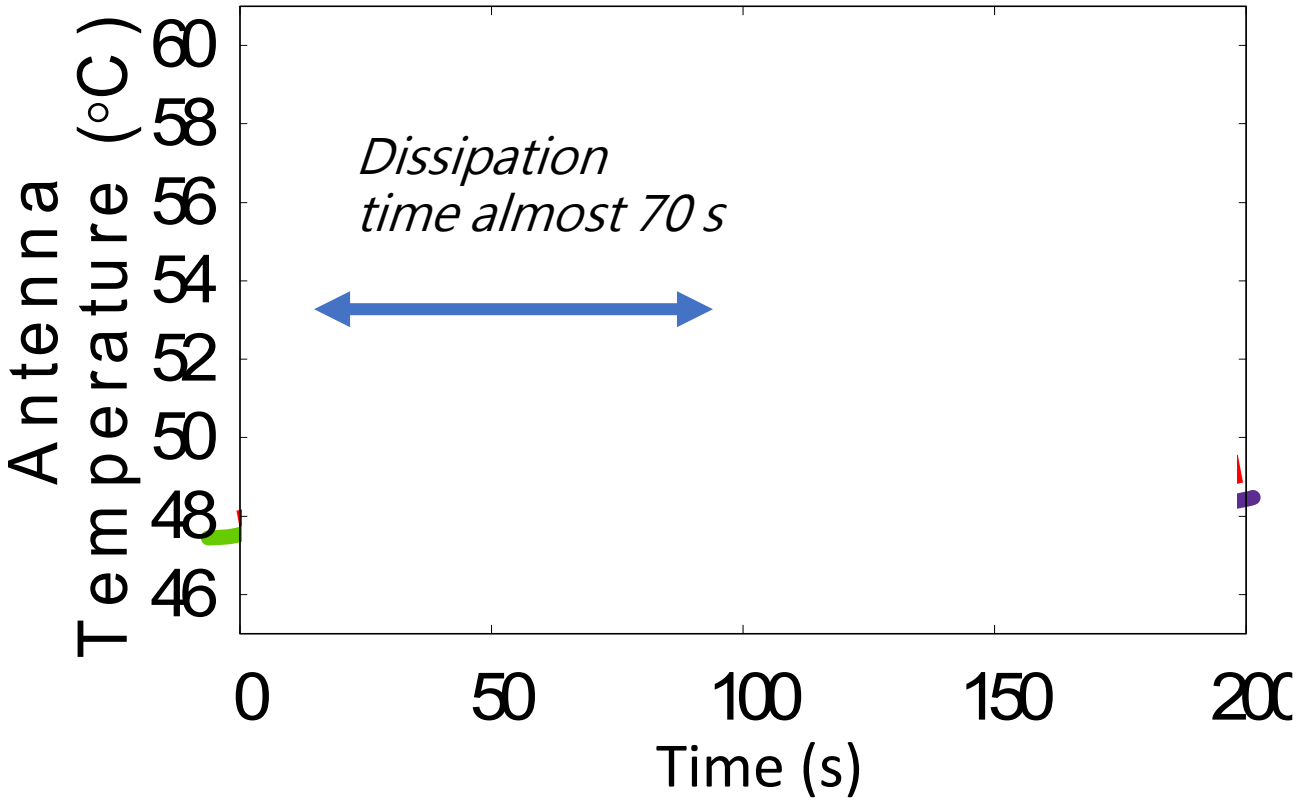


Temperature increase in active state



Study of heat dissipation



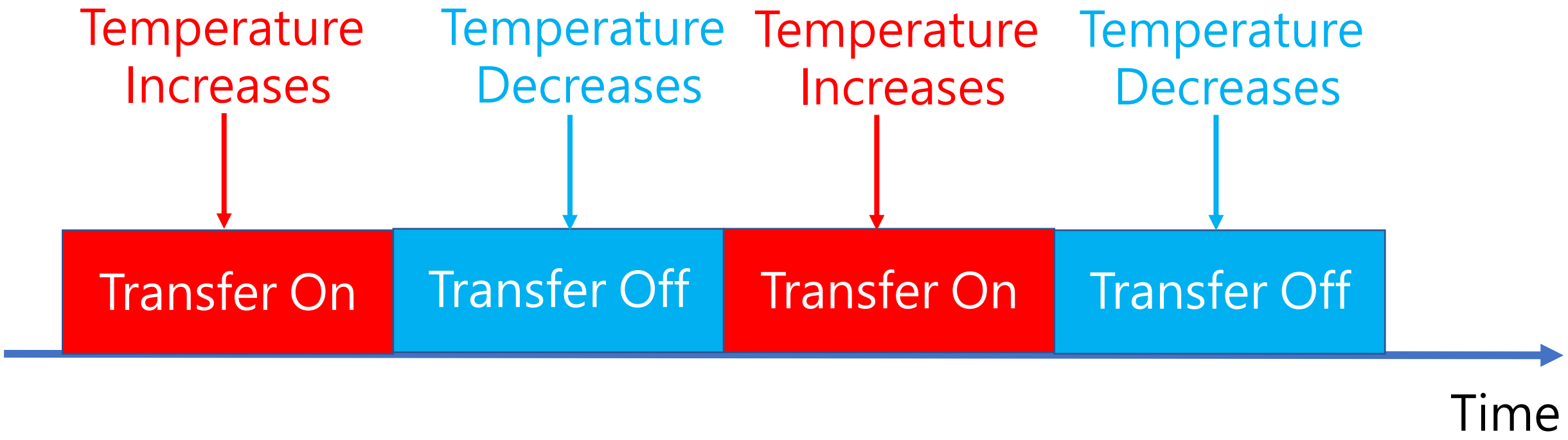


10 s of Data Transfer

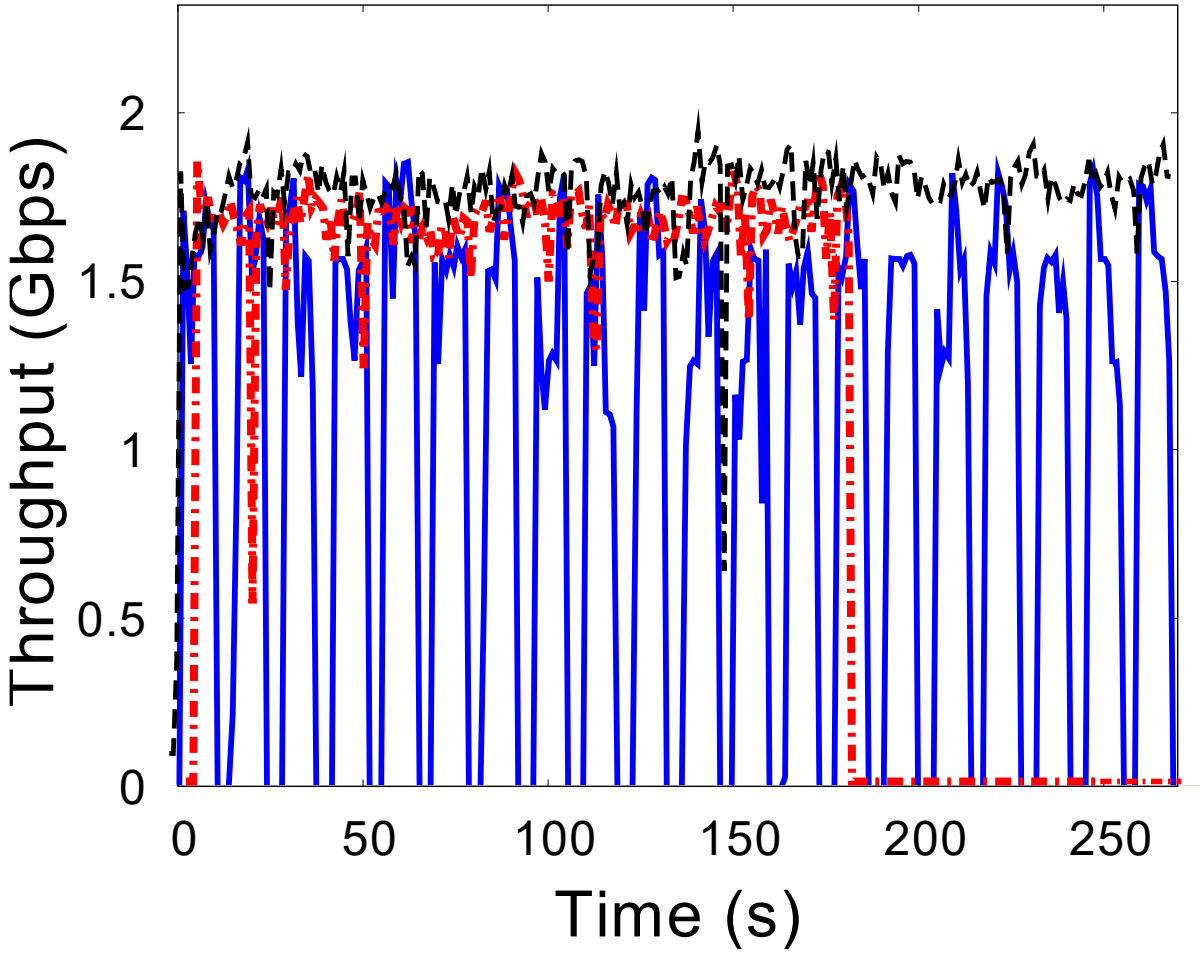
70 s Heat Dissipation

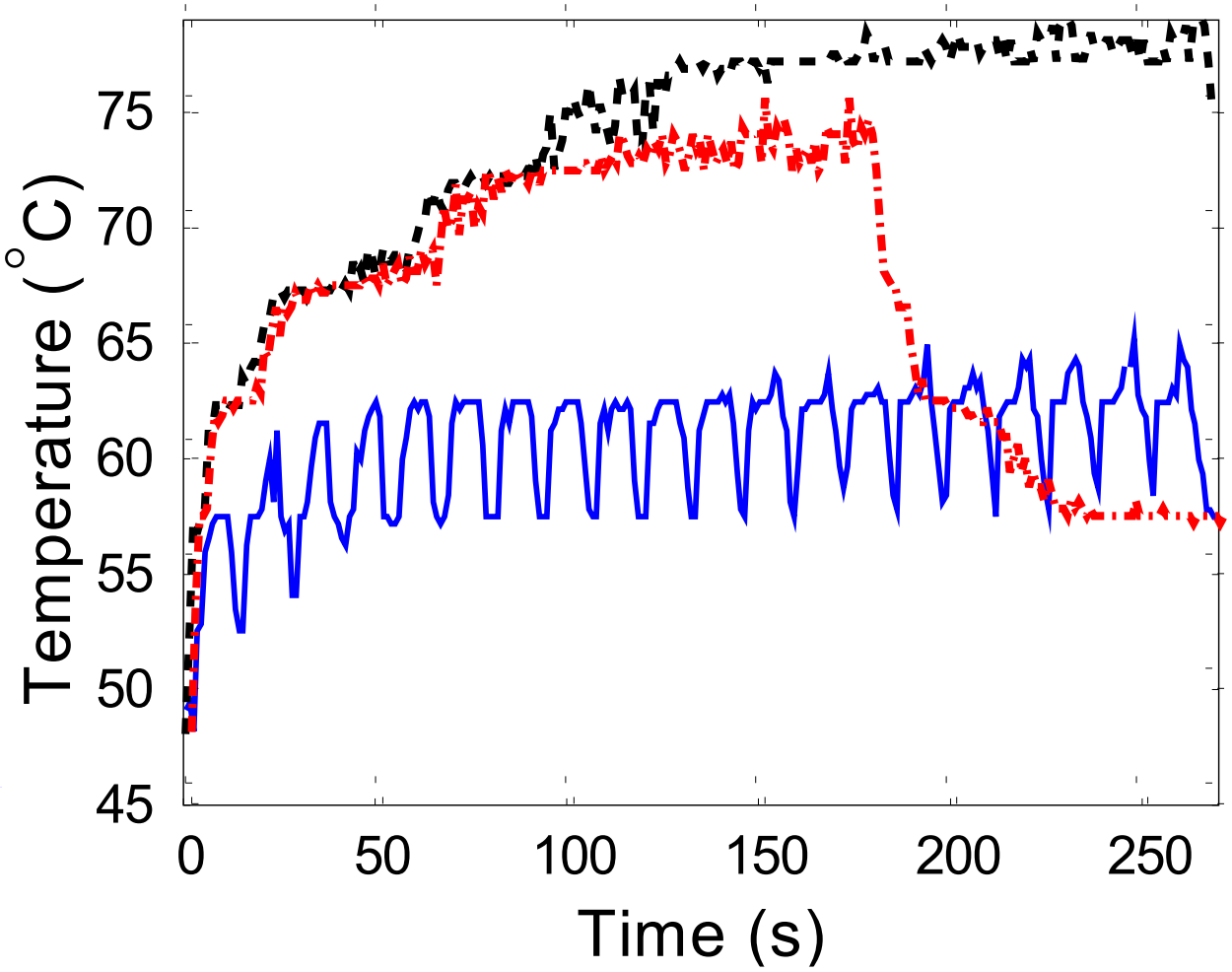
Aquilo: Scheduler for multi-antenna devices

Inducing periodic idleness



Inducing periodic idleness





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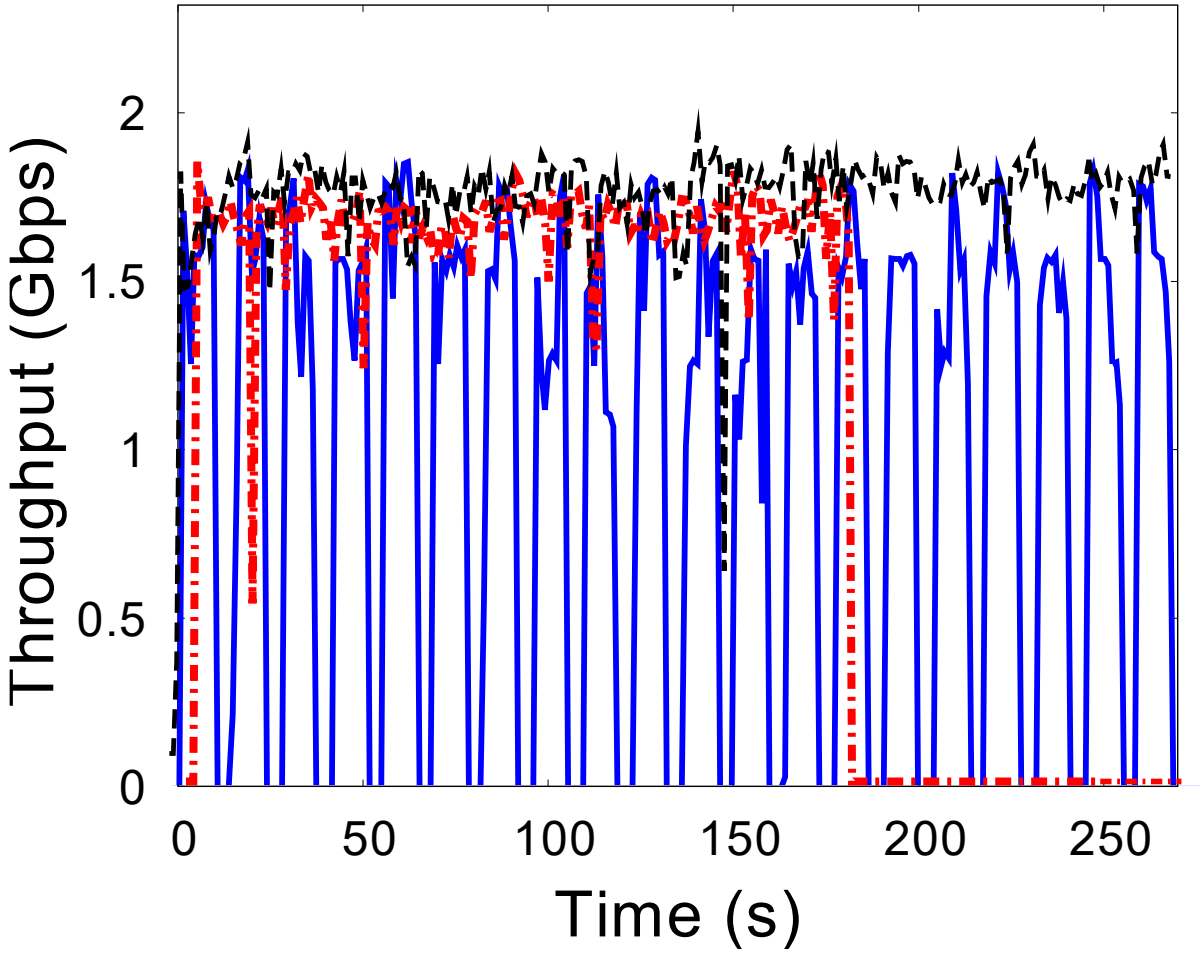
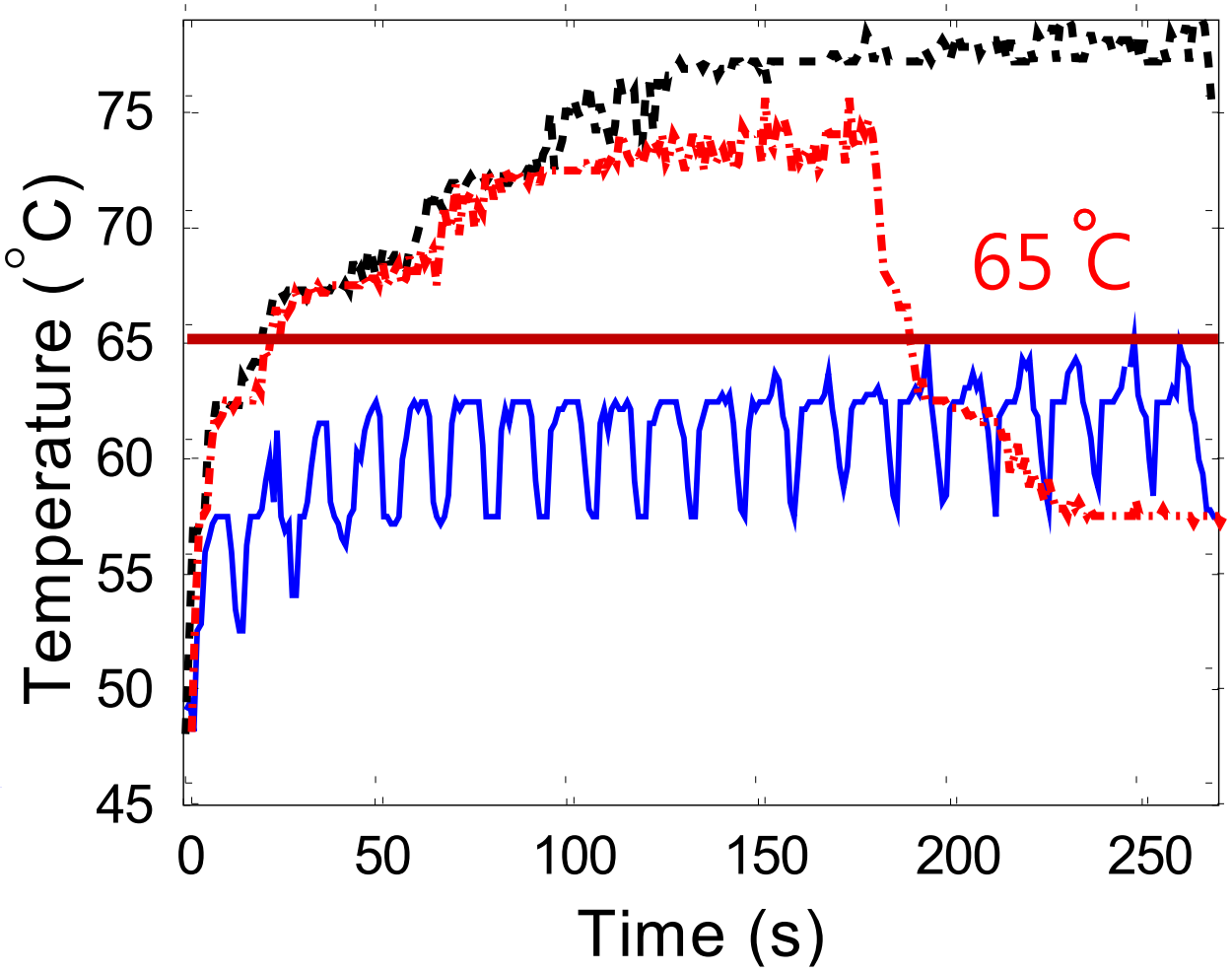


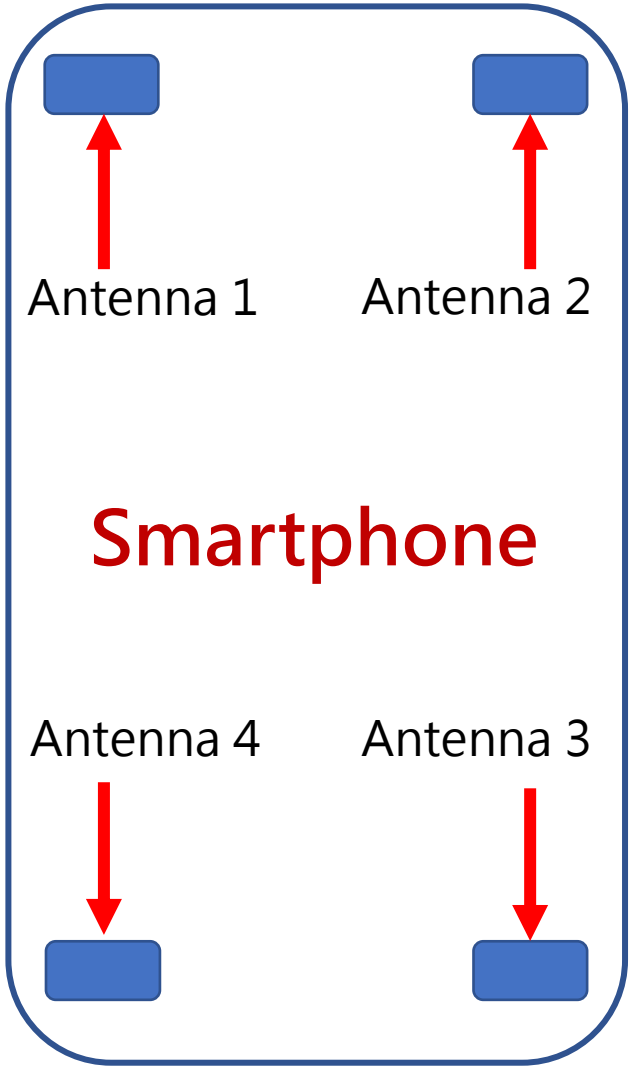


Latency and throughput requirements

Applications	Max. Latency (ms)	Min. Throughput (Mbps)
Virtual Reality	1 - 3	900 - 1100
Augmented Reality	~1	700-800
Real Time Gaming	10	10
Tactile Internet	~1	>1000

Source: L. Xu, "Context Aware Traffic Identification Kit (TriCK) for Network Selection in Future HetNets/5G Networks", *2017 International Symposium of Networks, Computers and Communications (ISNCC)*

Multi-Antenna design



Millimeter-Wave Network

↓

Vulnerable to Rampant Signal Outage

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Multi-Antenna Design improves network reliability

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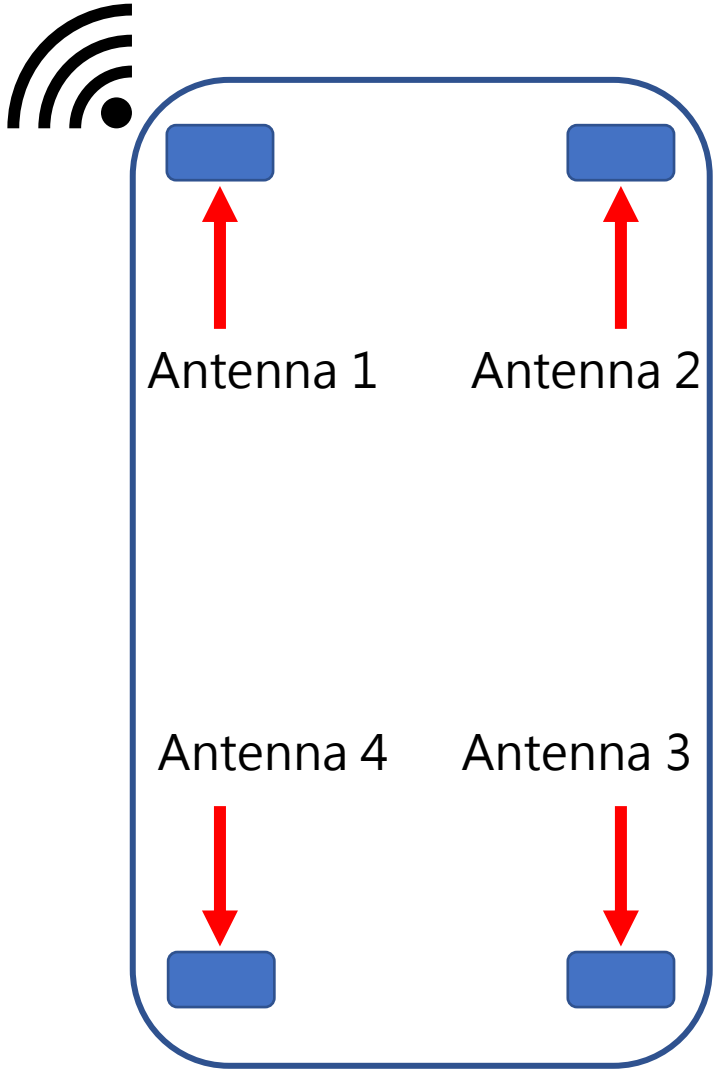
Switch antenna based on *temperature-awareness*

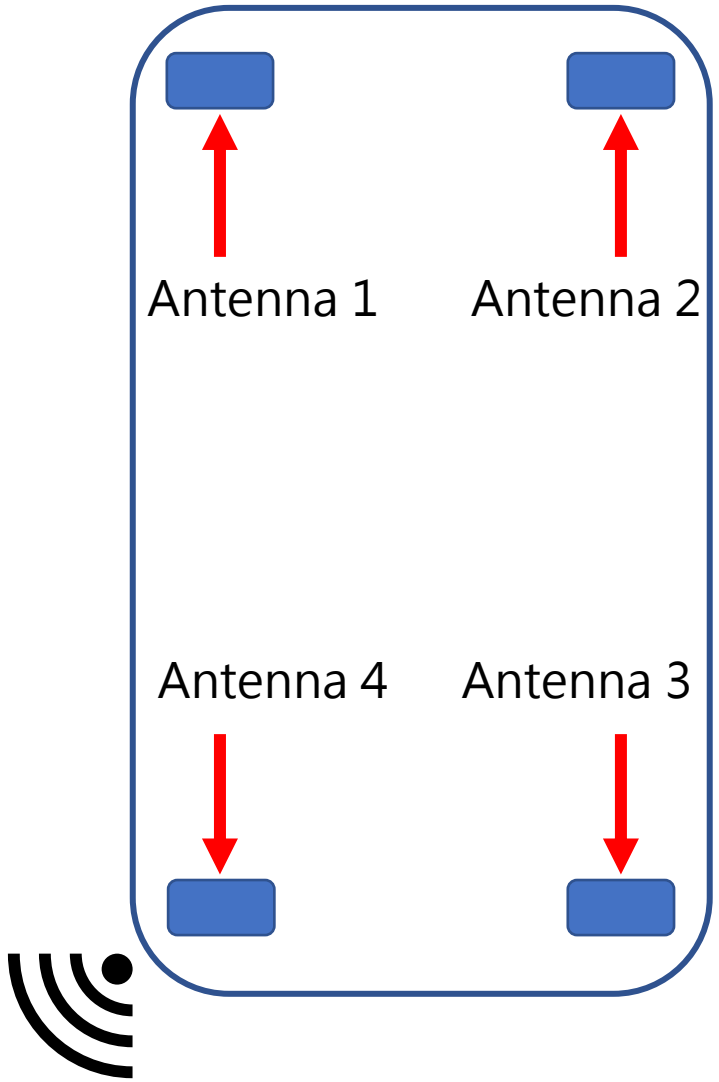
Antenna switching over time



Time Slot: 1

Antenna: 1

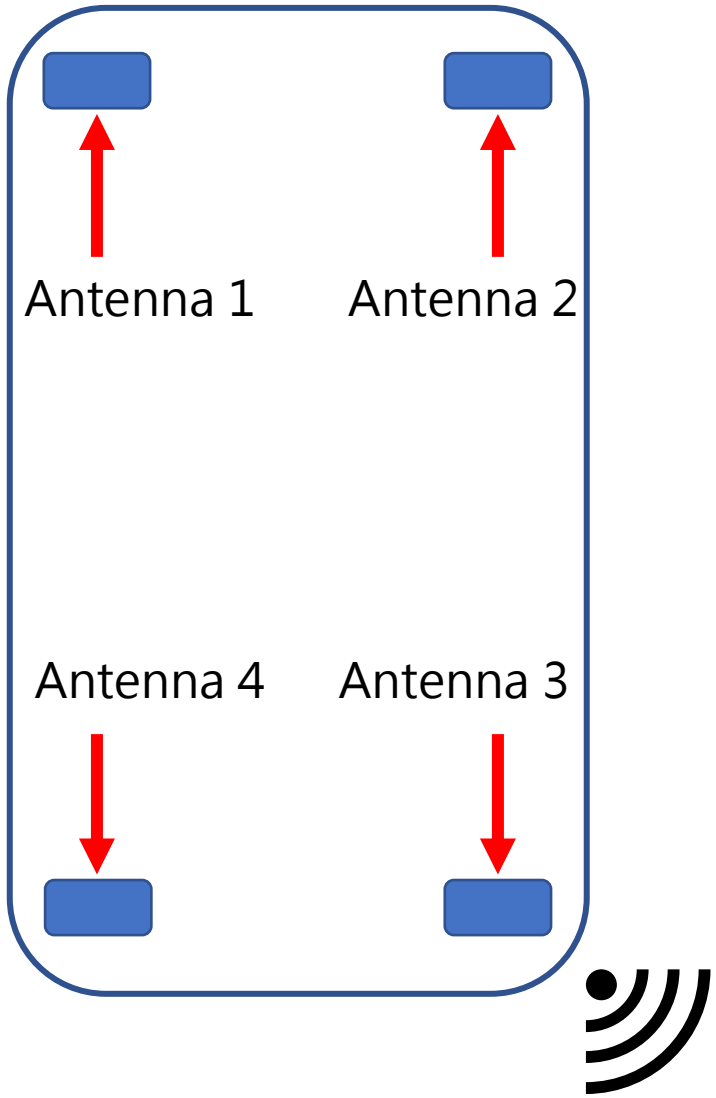
Antenna switching over time



Time Slot: 2

Antenna: 4

Antenna switching over time



Time Slot: 3

Antenna: 3

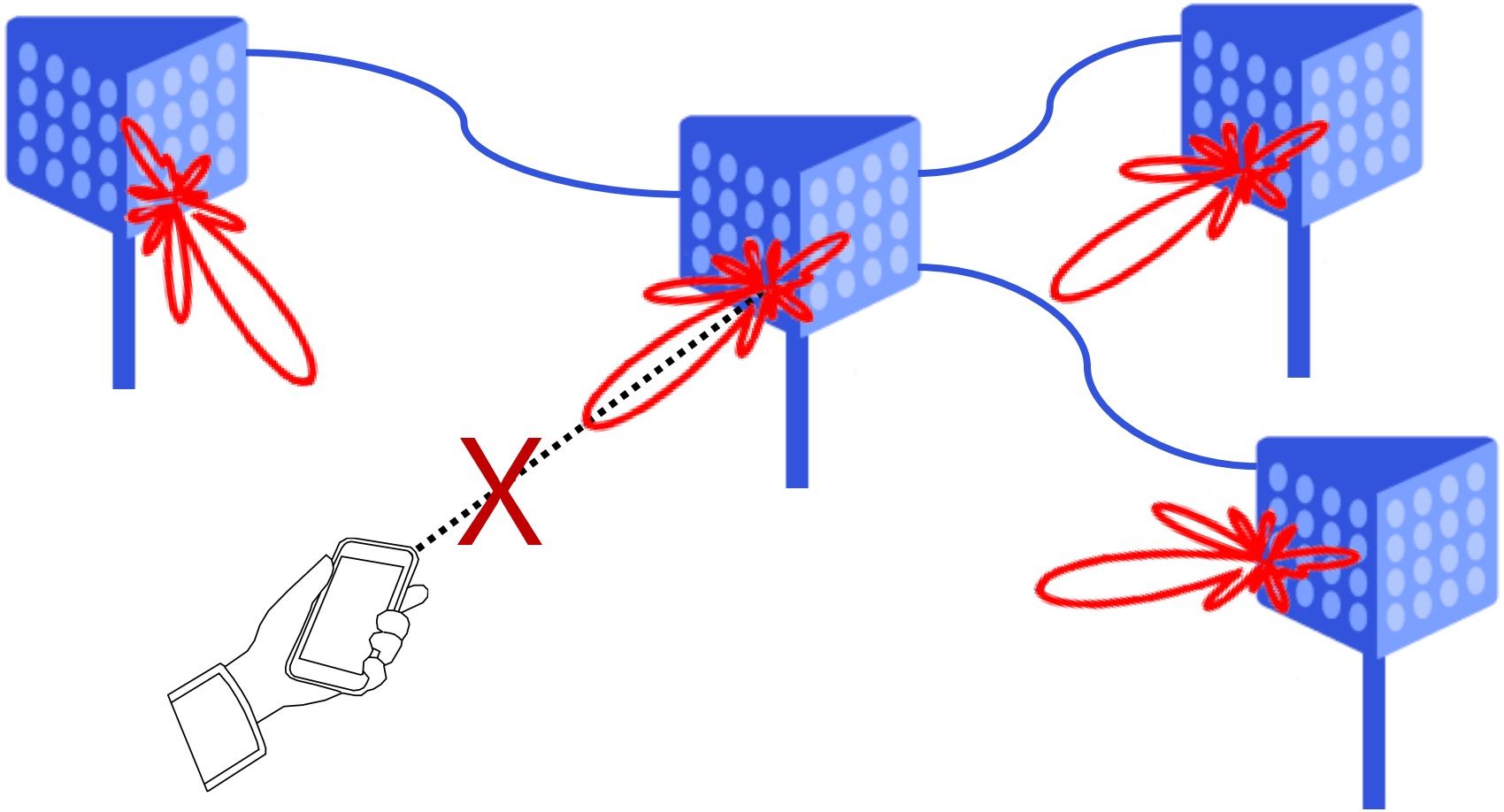
Simple antenna switching

- Random Switching
- Throughput Maximization

Antenna switching challenges

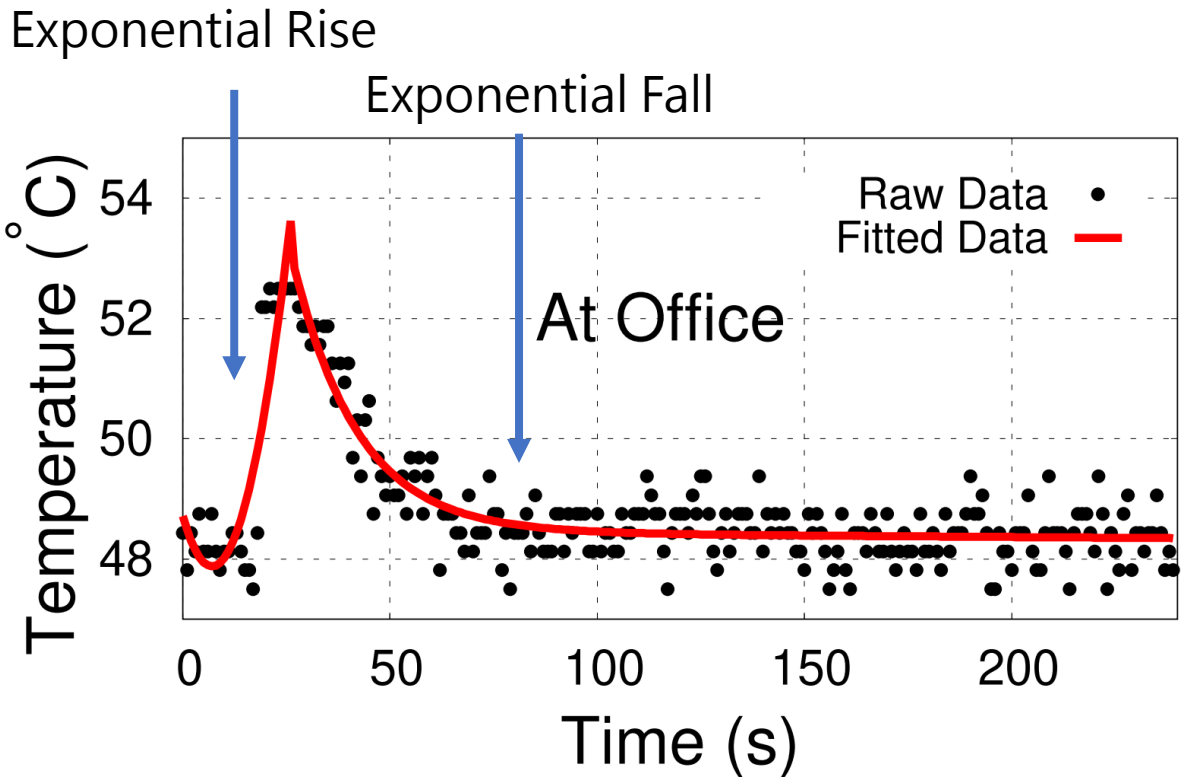
Millimeter-Wave link: *Very unreliable*

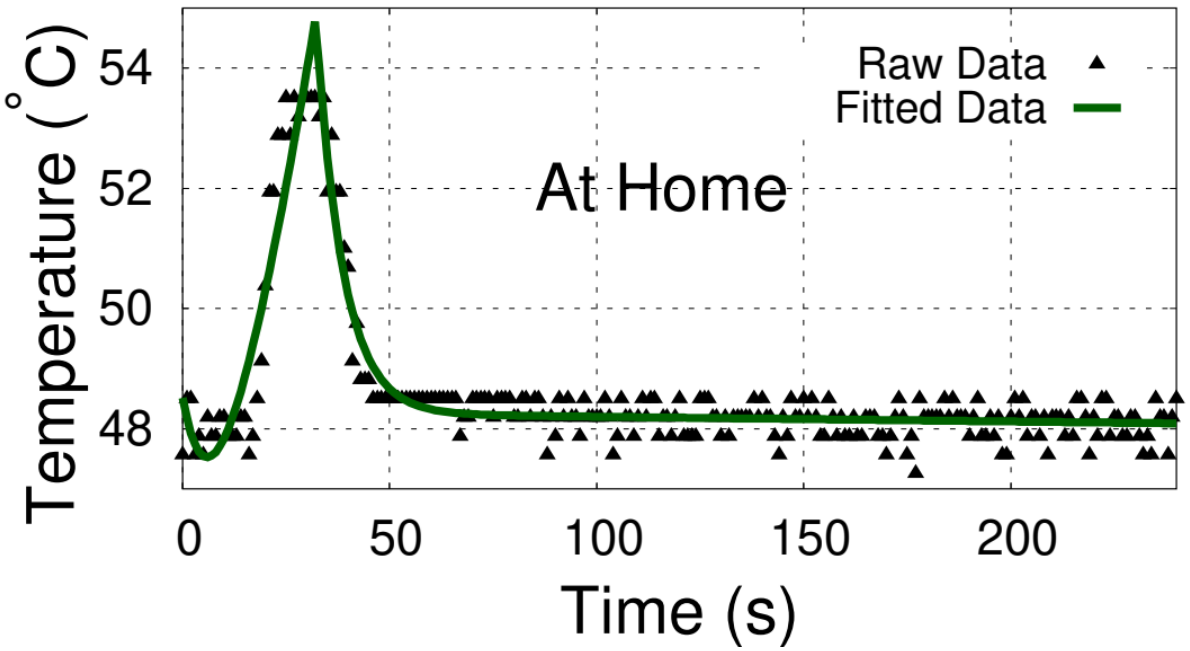
- No guaranteed link at any antenna at all times



Temperature profile: *Varies in space-time*

- No pre-determined temperature rise and fall model



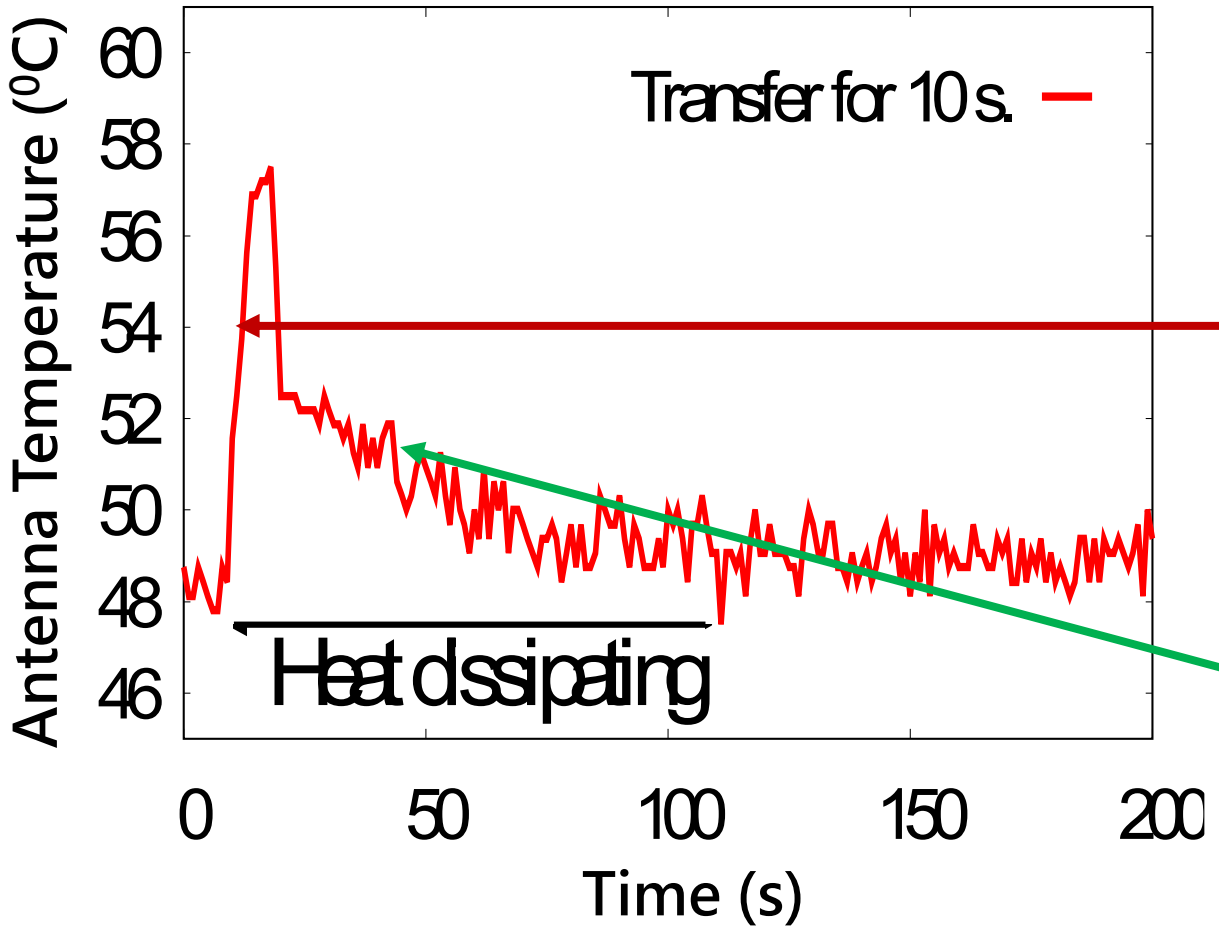


Dissipation after a 10 s transmission

Design components of *Aquilo*

- Online thermal profile estimation
- Generating look-ahead schedules

Online thermal profile estimation



Model parameters α and β are derived from **online measurements**

Rising Temperature
Modelled as an exponential gain:

$$e^{\alpha t}$$

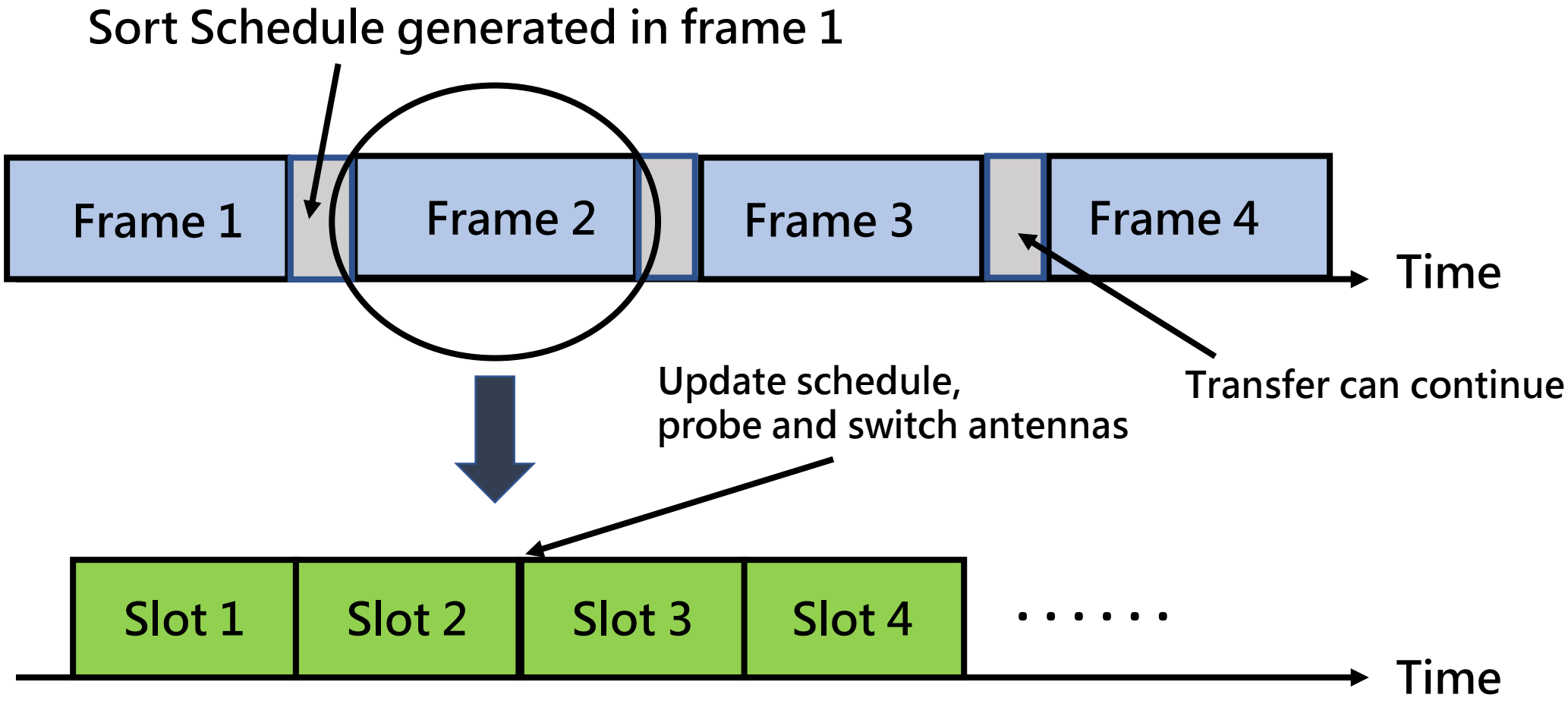
Falling Temperature
Modelled as an exponential fall:

$$e^{-\beta t}$$

Generating look-ahead schedules

Schedule No	Schedule	Peak Temperature (^{0}C)
1	{2, 3, 1, 4}	59
2	{1, 2, 1, 4}	62
3	{2, 1, 4, 3}	54
…	…	…

Aquilo antenna execution sequence

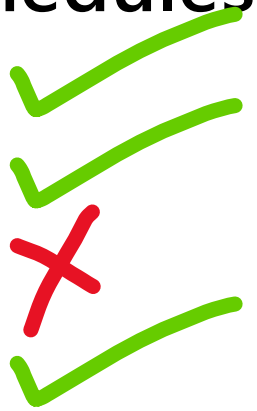


Non-Adjacency Criteria

3 Slot System

Antenna Schedules:

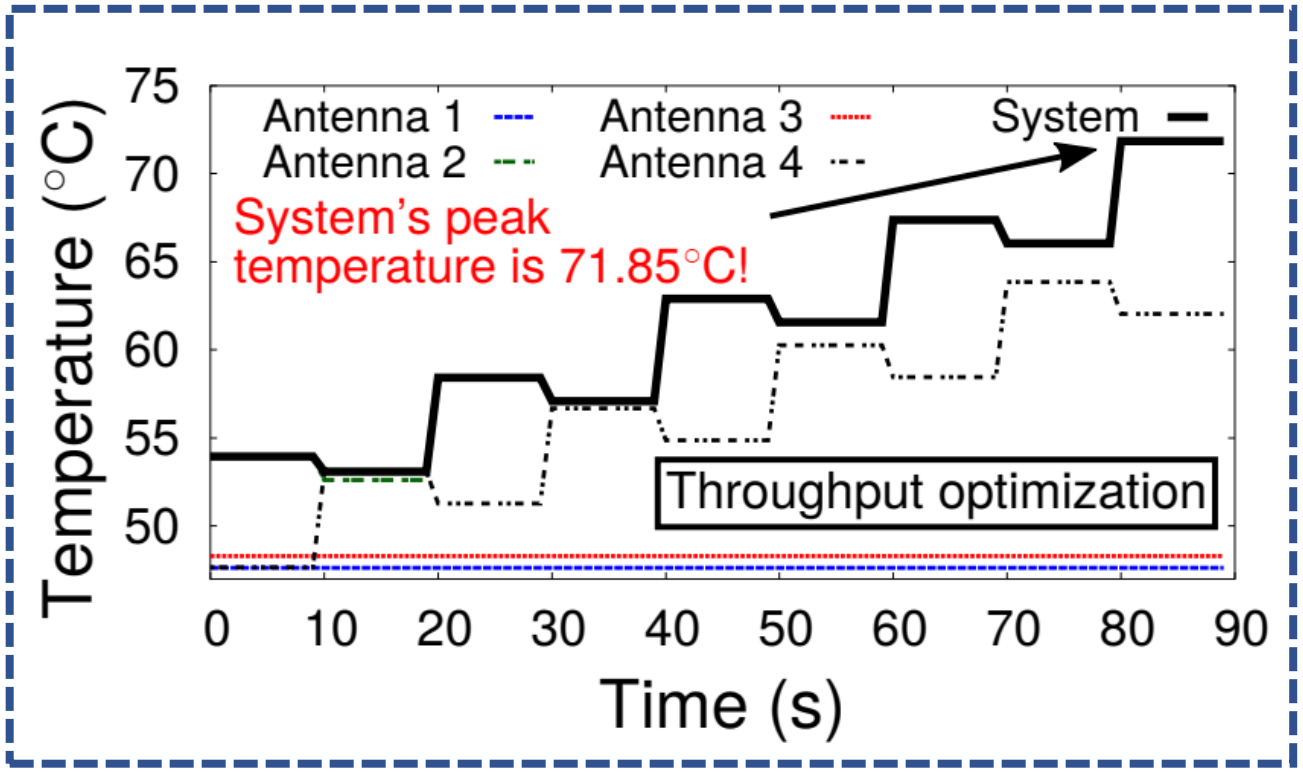
(3, 2, 4)
(1, 3, 4)
(2, 3, 3)
(2, 4, 1)

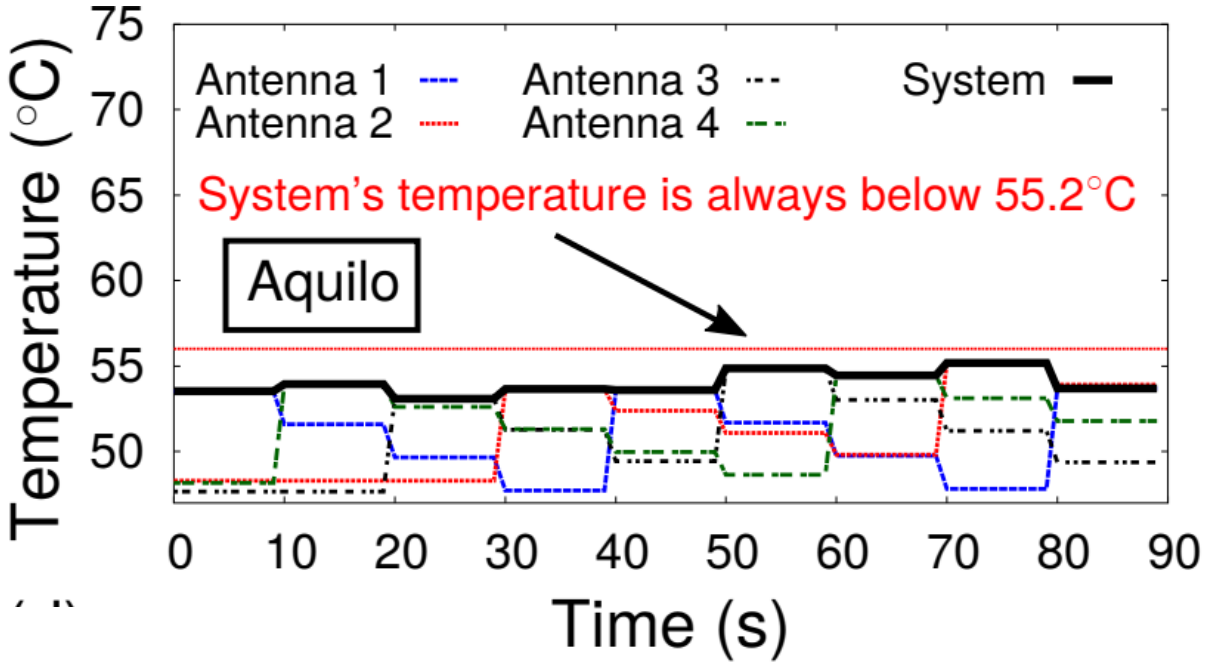


No antenna can be scheduled in consecutive time slot

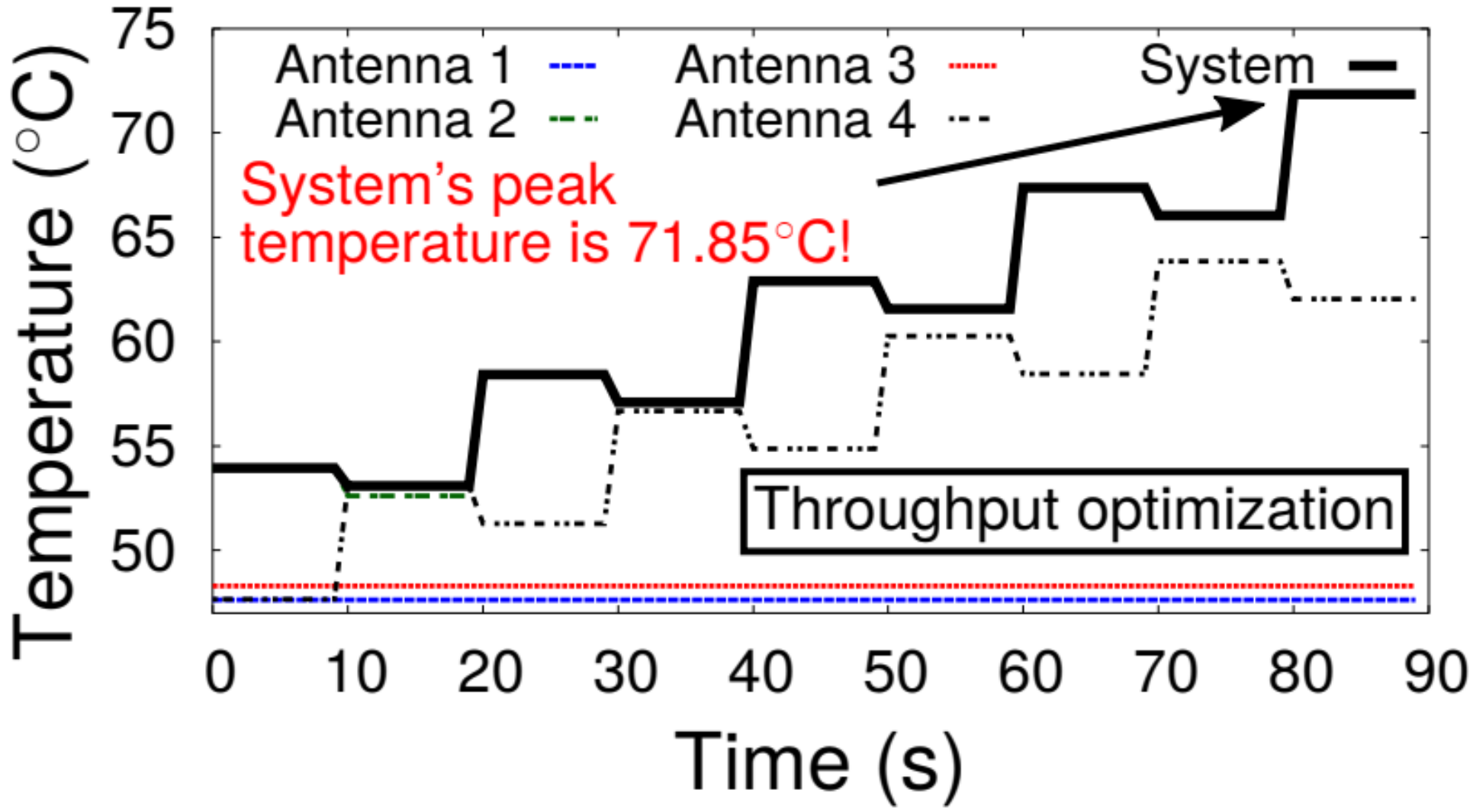
Performance Evaluation

Throughput Optimization vs. Aquilo

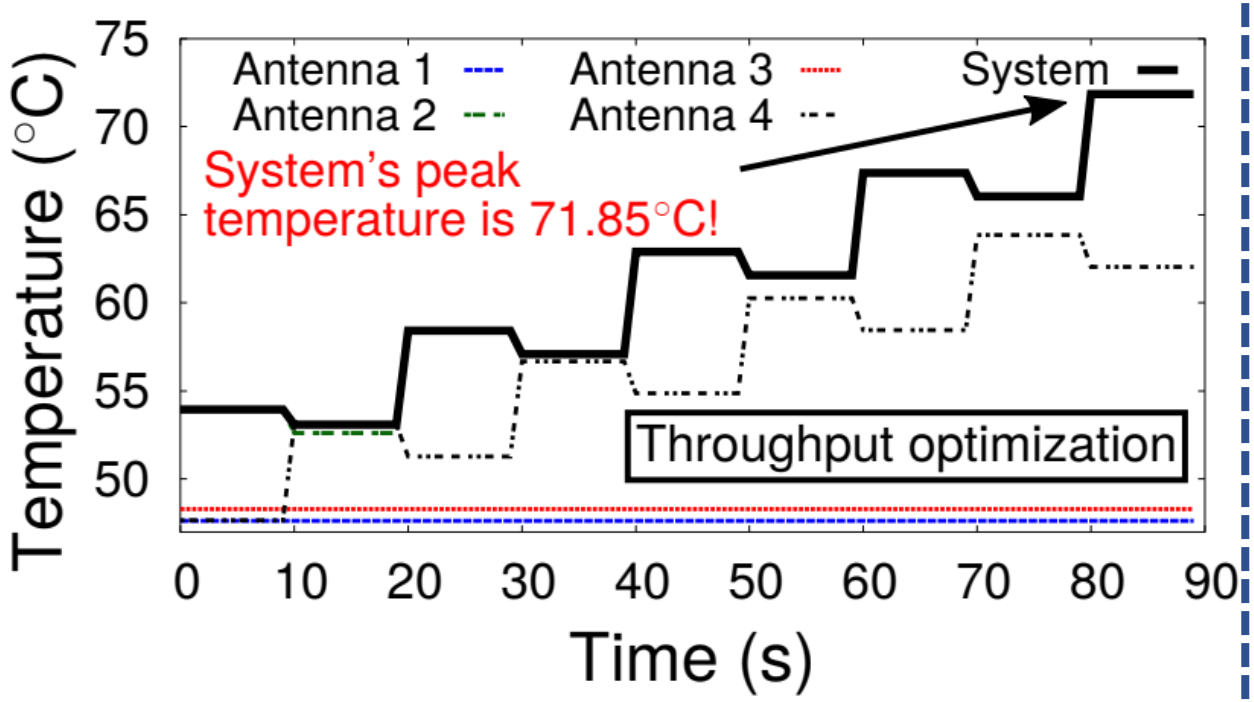


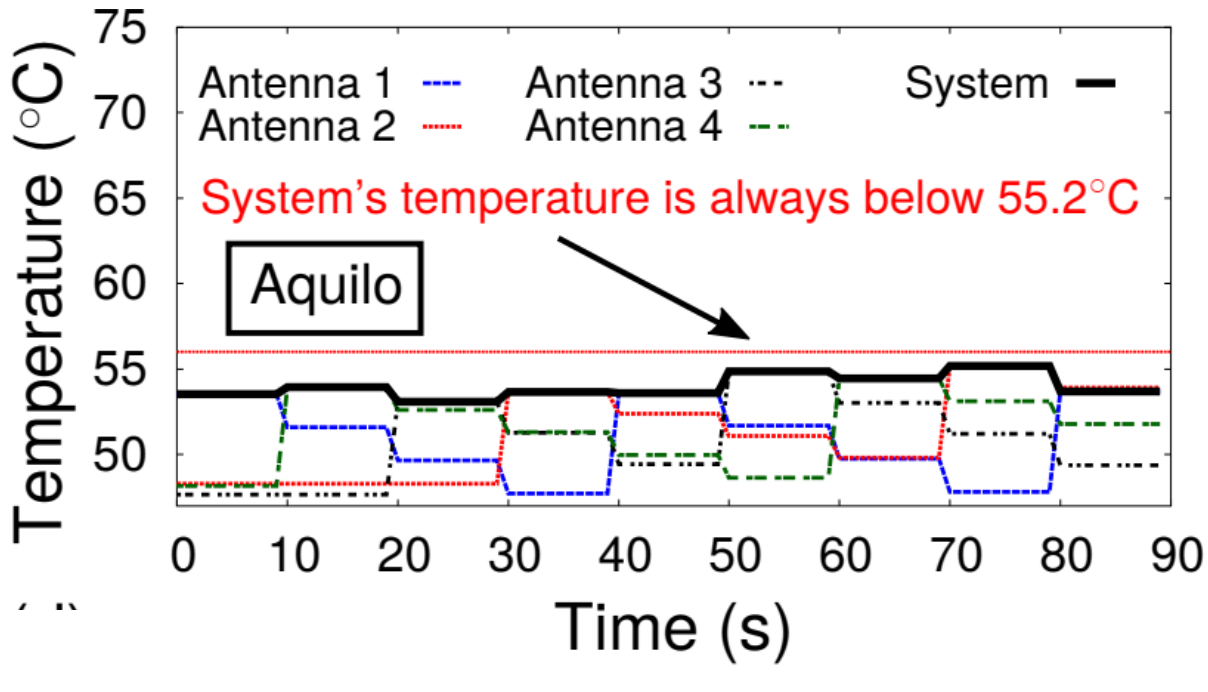


Evaluate Throughput Optimization

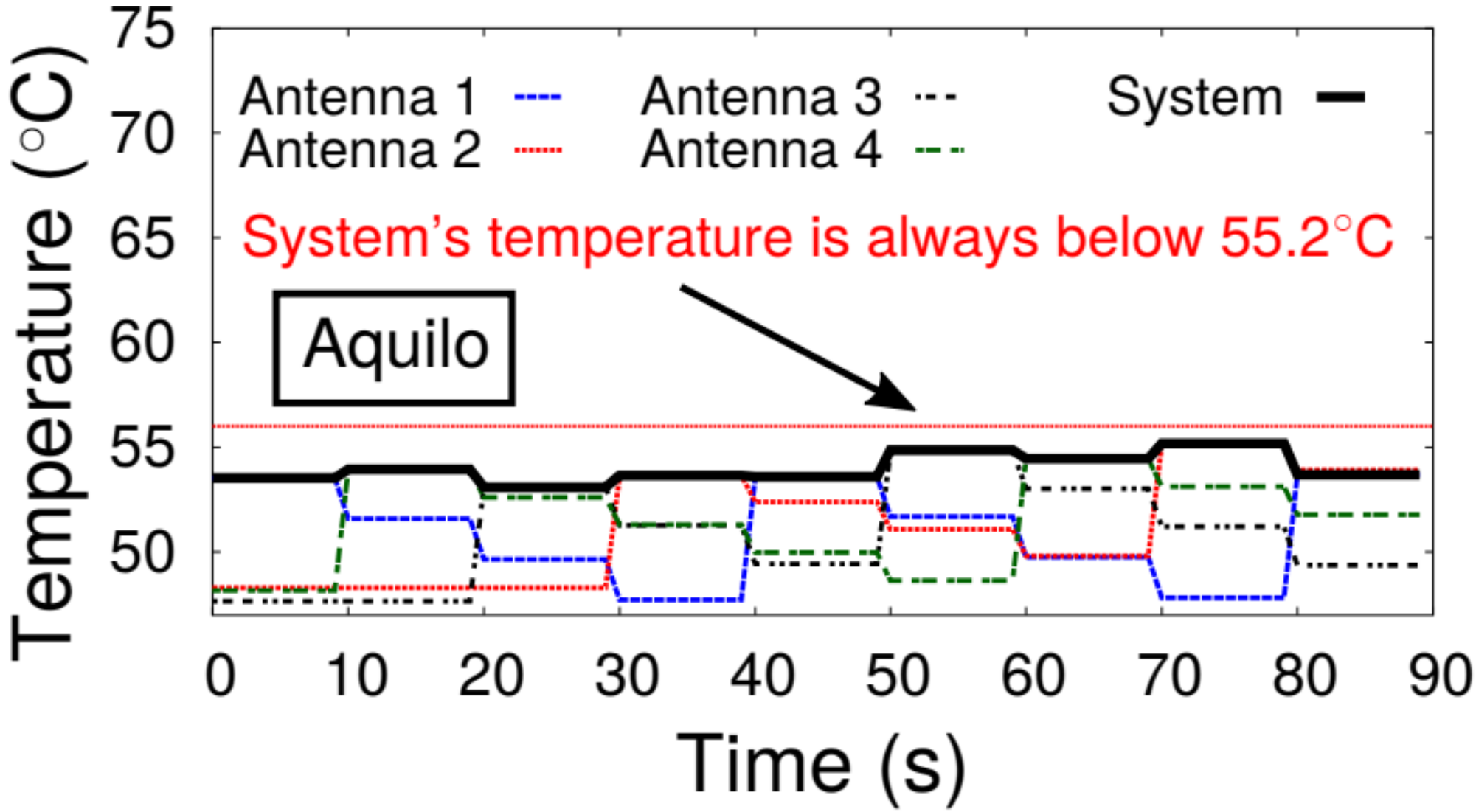


Throughput Optimization vs. Aquilo

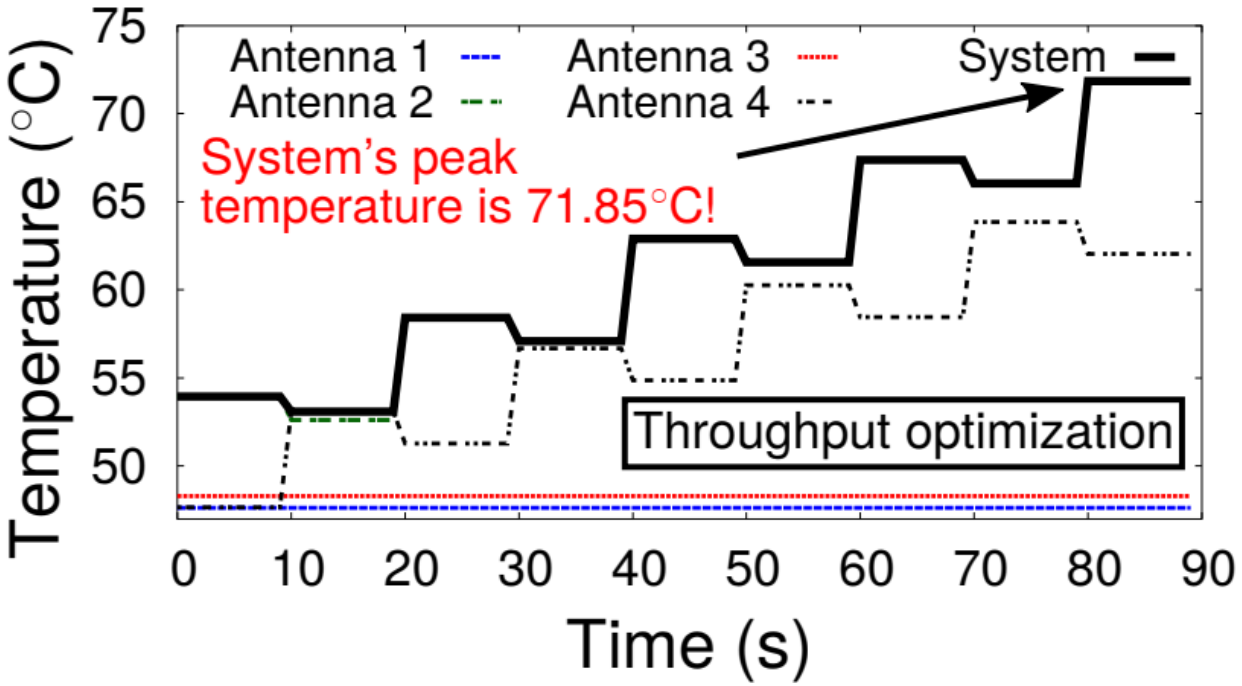


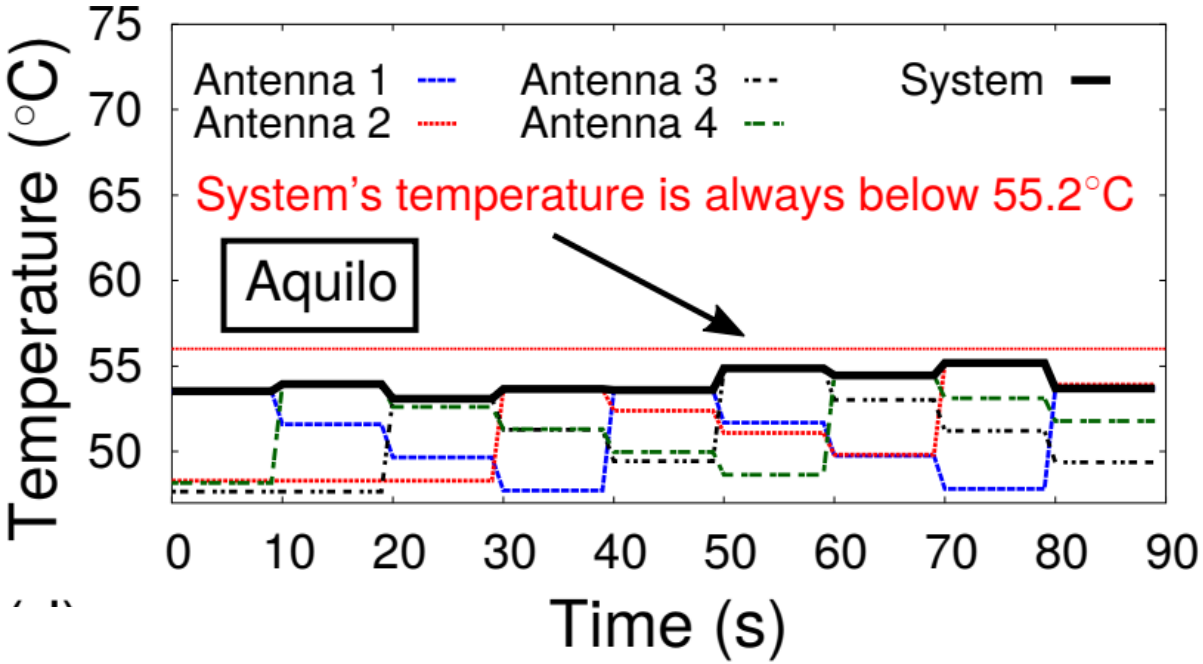


Evaluate Aquilo



Throughput Optimization vs. Aquilo

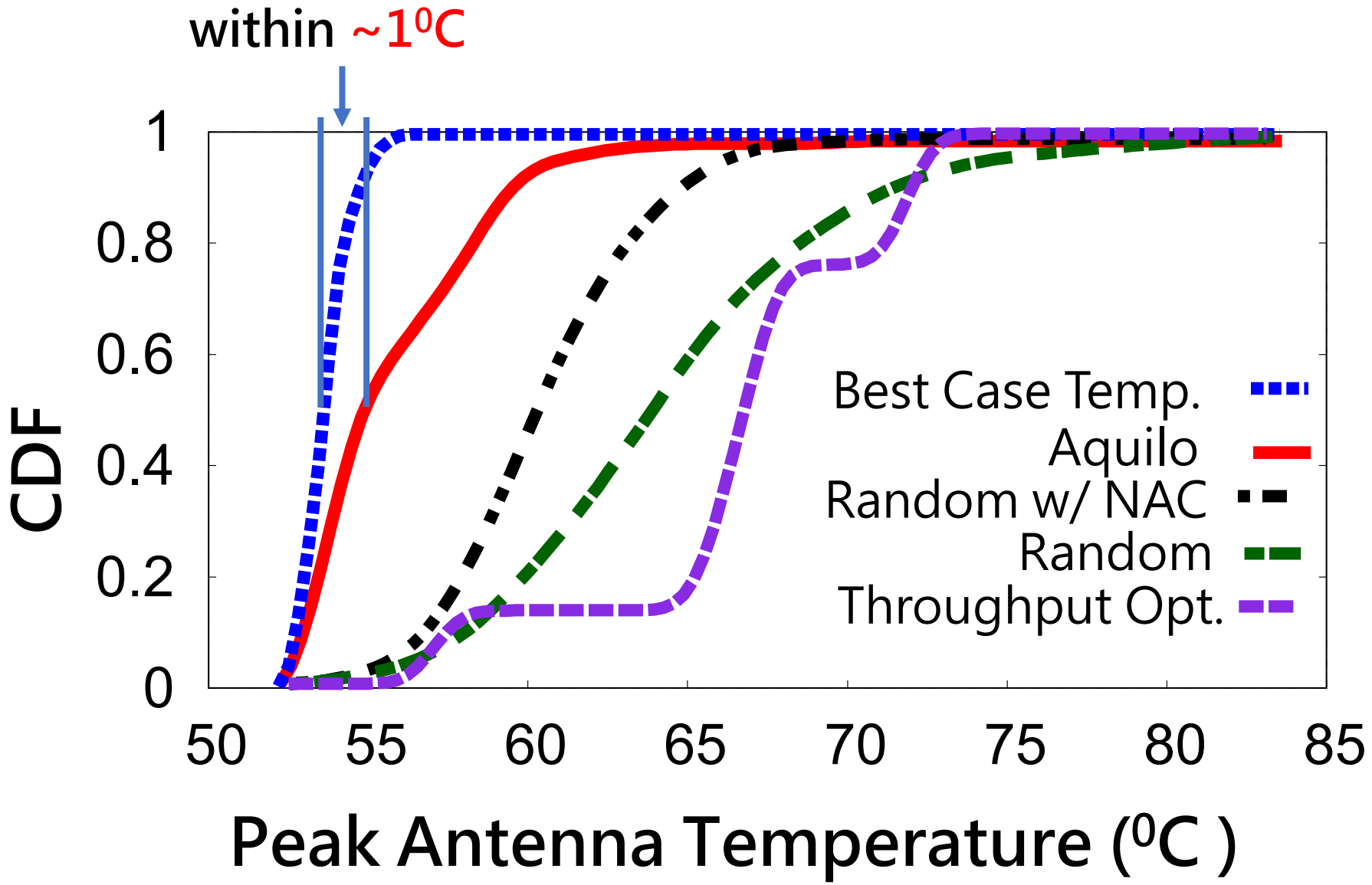




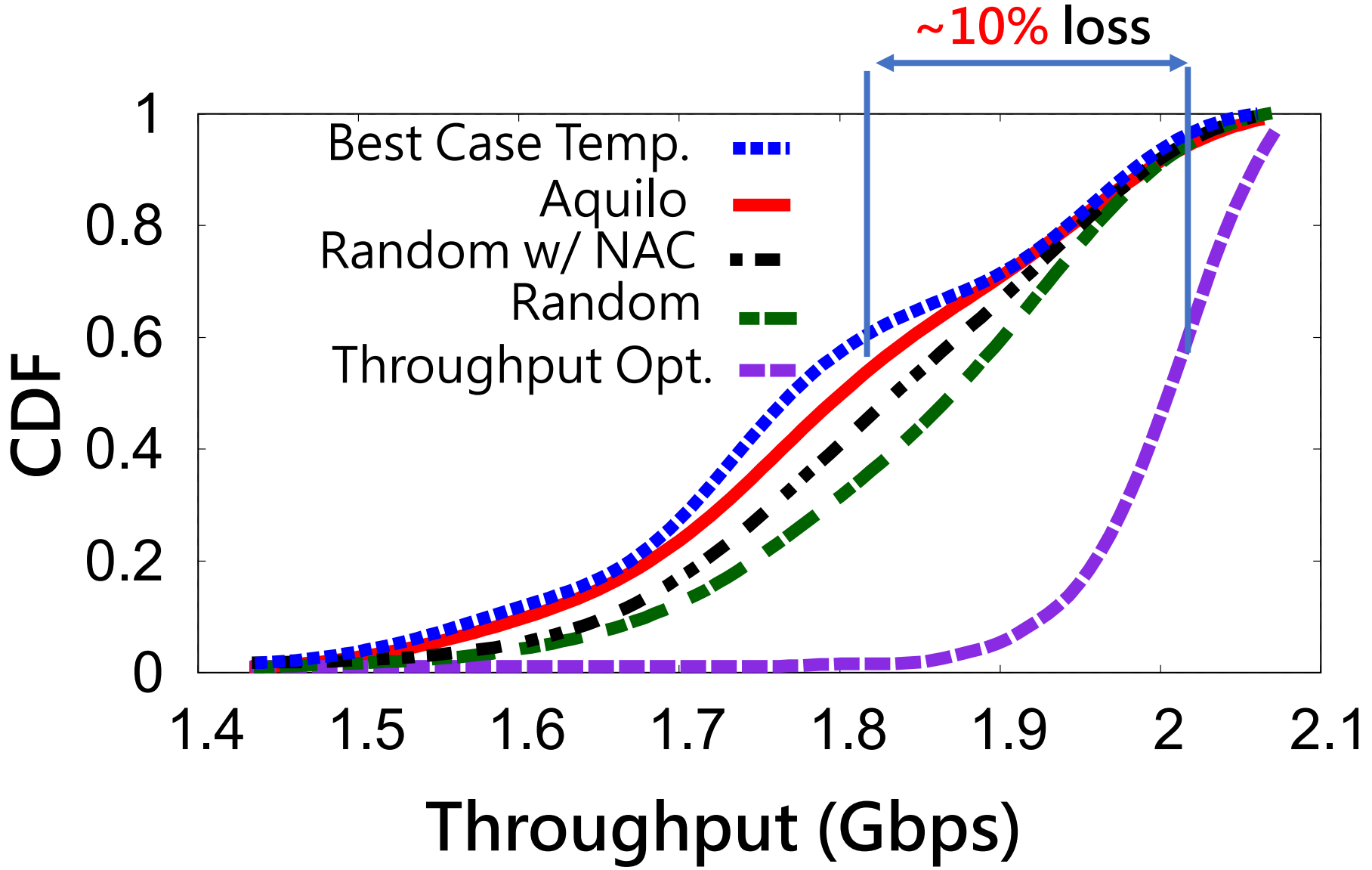
Comparative schemes with Aquilo

- **Best Case:** Achieves the best temperature performance
- **Random:** An antenna is selected at random
- **Random with NAC:** Random with Non-Adjacency Criteria
- **Throughput Opt.:** Achieves the maximum throughput

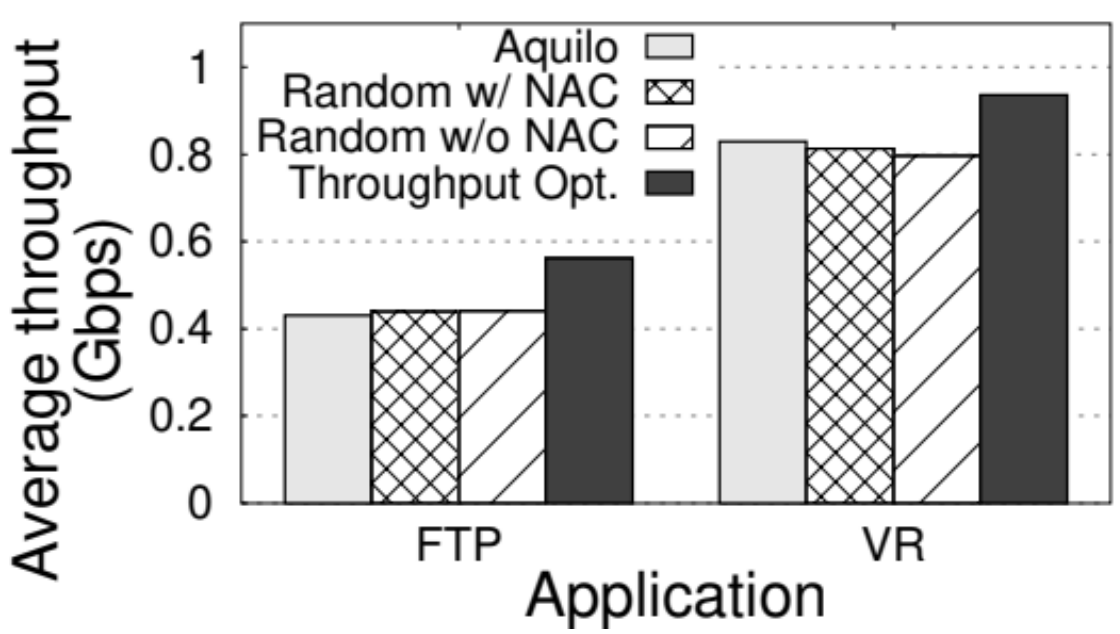
Temperature performance

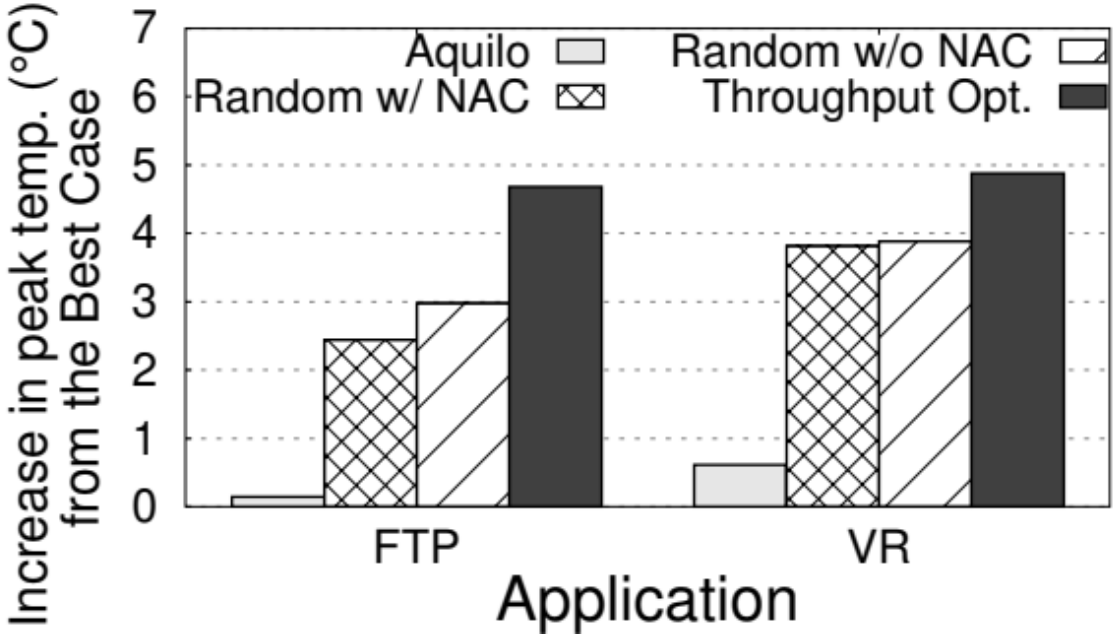


Throughput performance

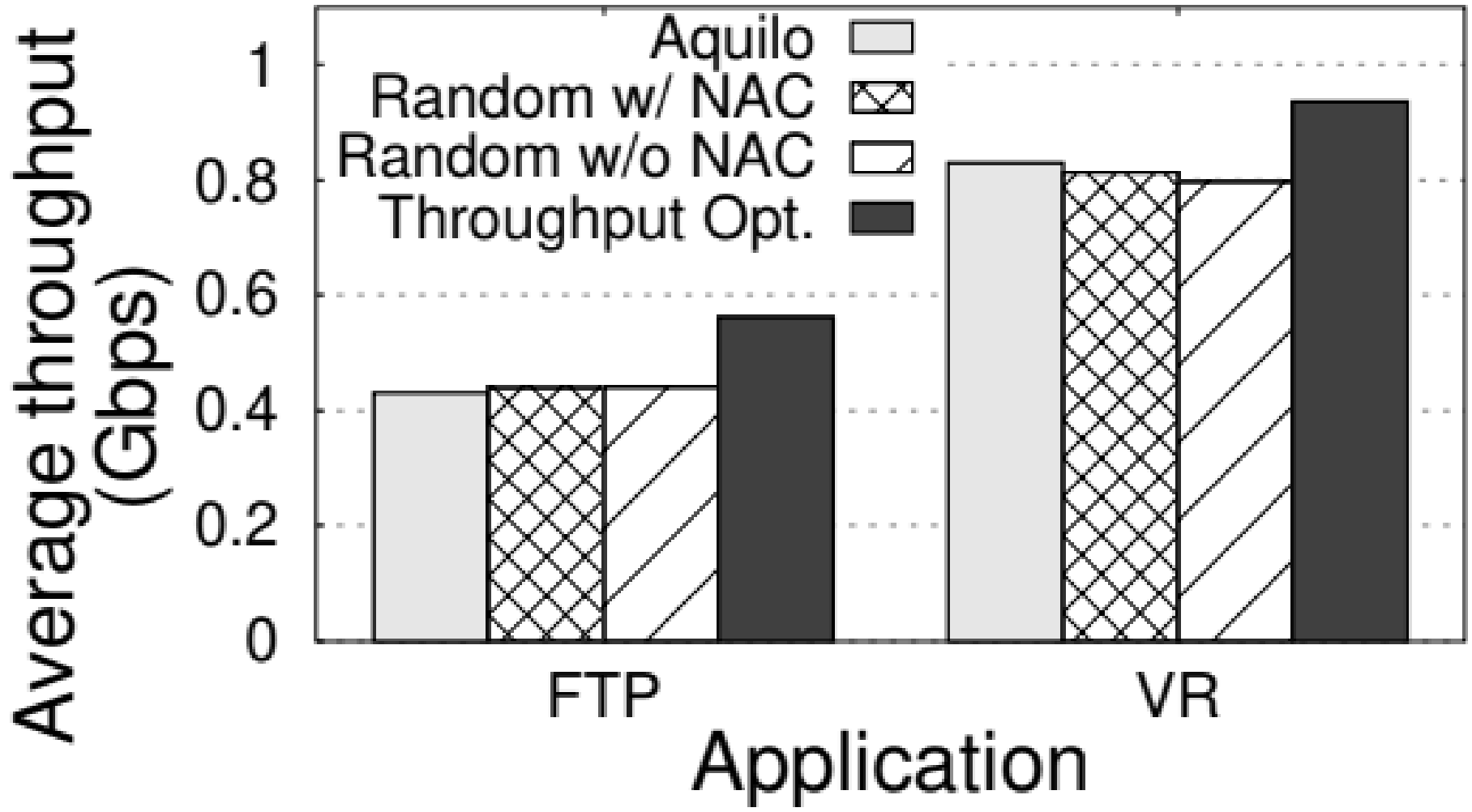


Field trial of Aquilo





Field trial: *Throughput performance*



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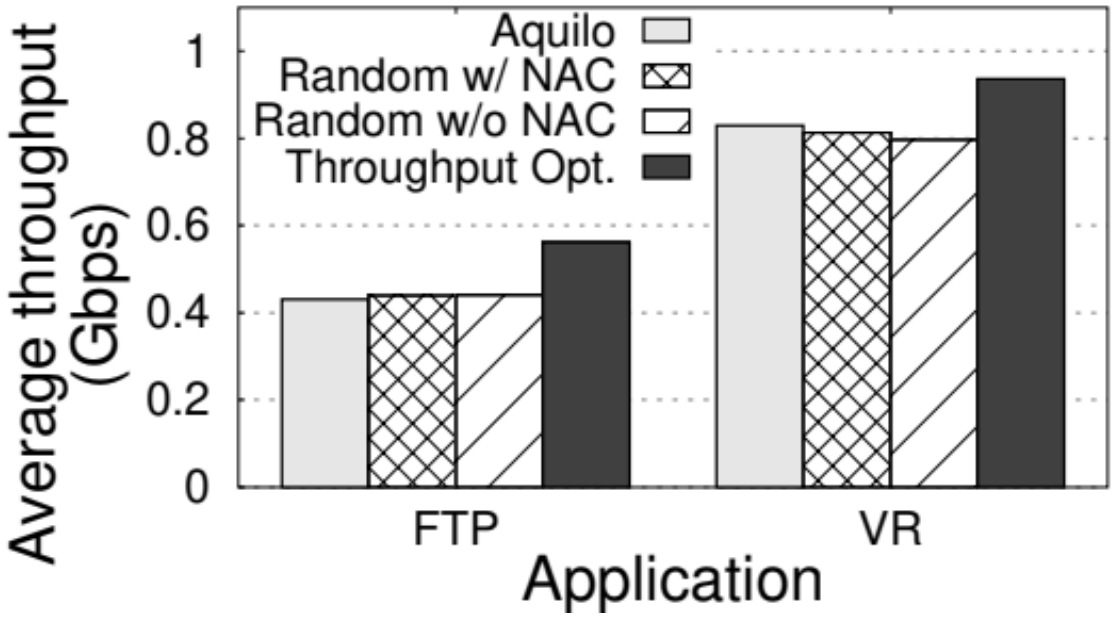
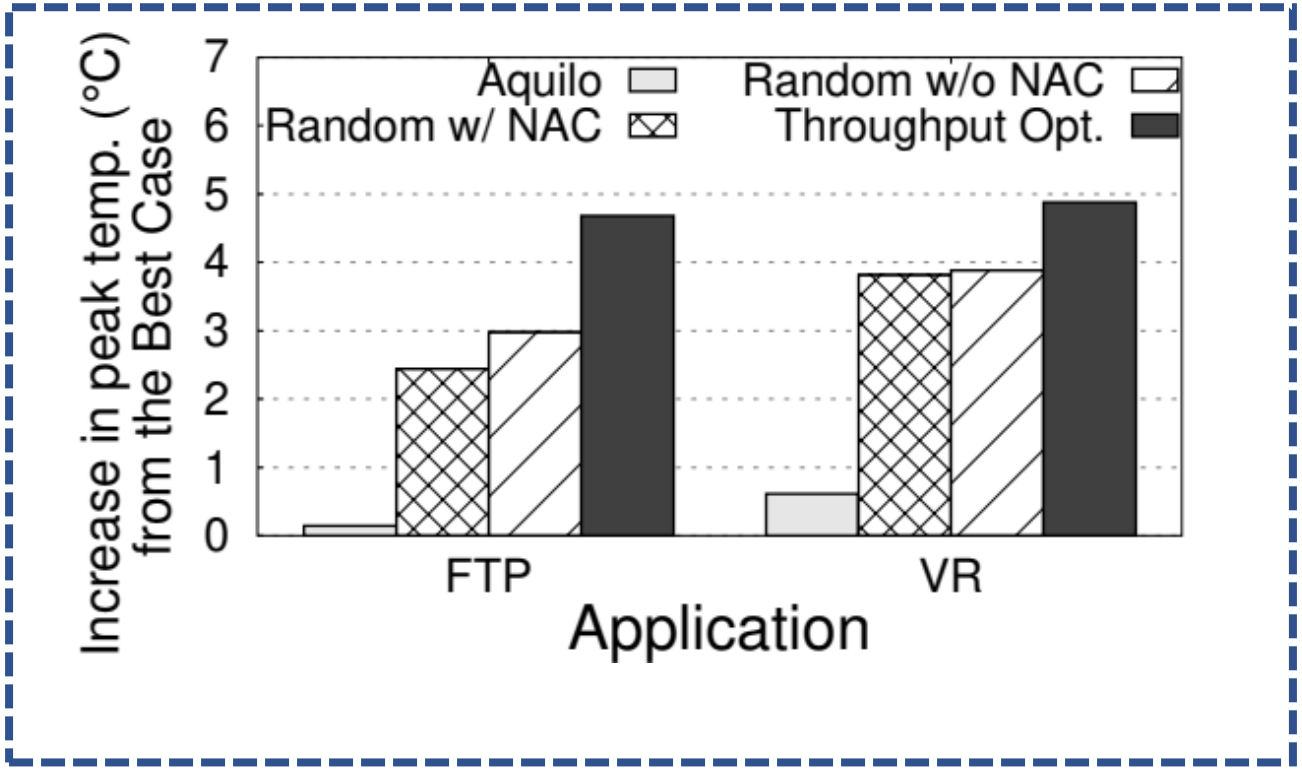
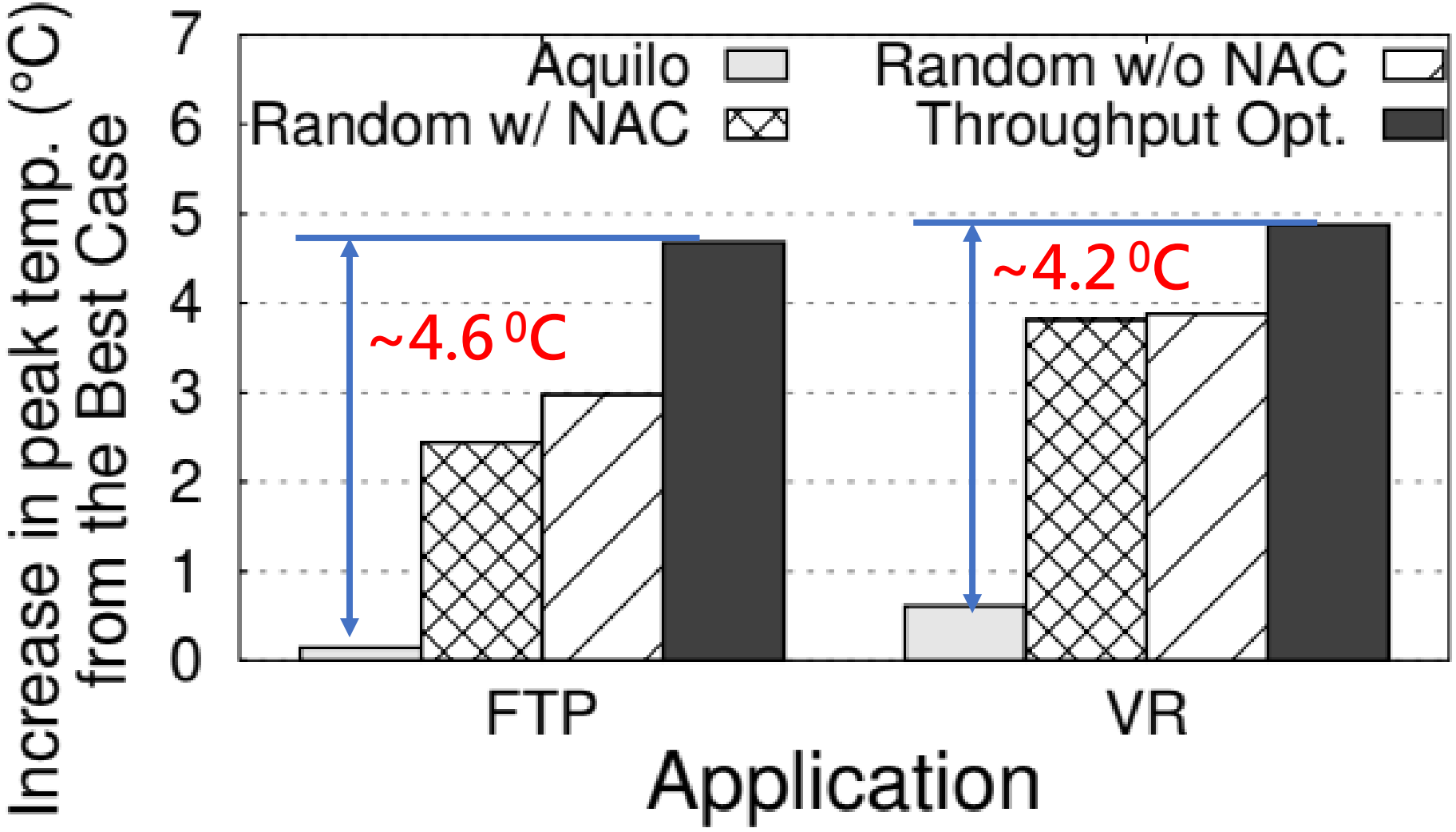




Field trial: *Temperature performance*



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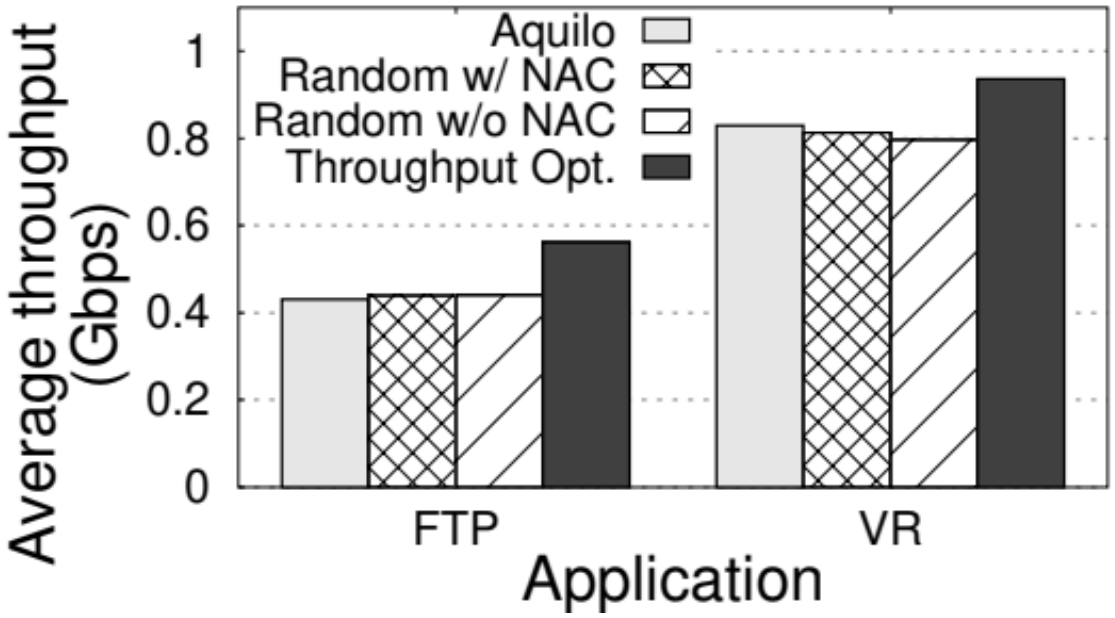

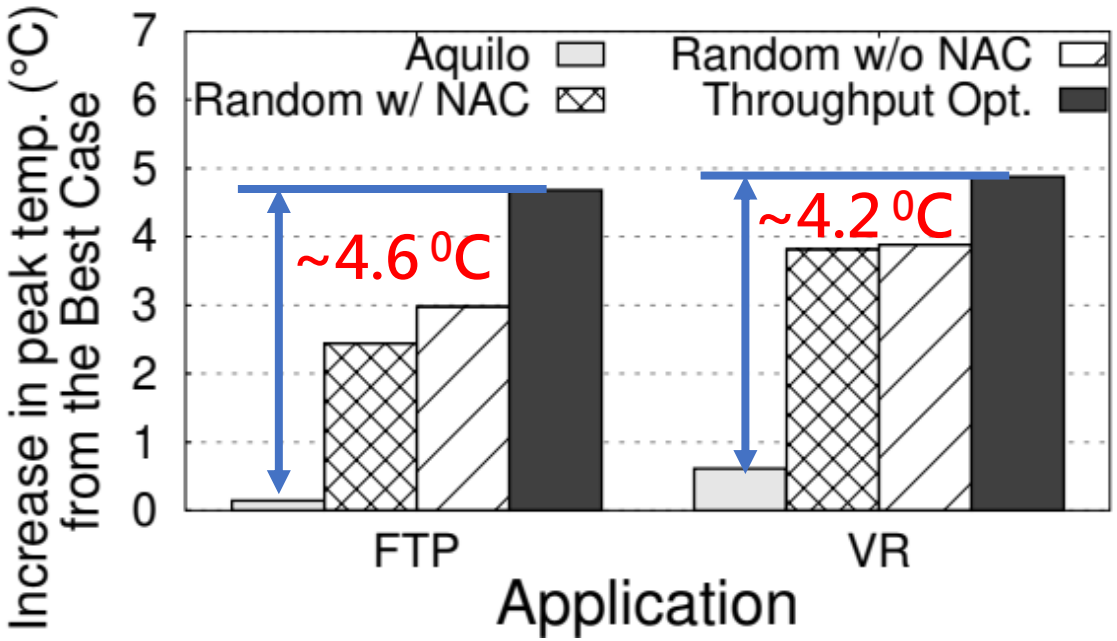

Summary and Conclusions

Problem and challenges

- Device overheating in mmWave poses health hazards and cause poor network performance
- Design is challenging – *unreliable network connectivity* and *non-deterministic temperature model*

Aquilo Summary

- Thermal characterization of mmWave network: *first-of-its-kind*
- *Aquilo:* A scheduler for multi-antenna devices based on temperature-awareness
- *Aquilo* achieves chip temperature within 1^0C of best temperature case while sacrificing only 10% throughput

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