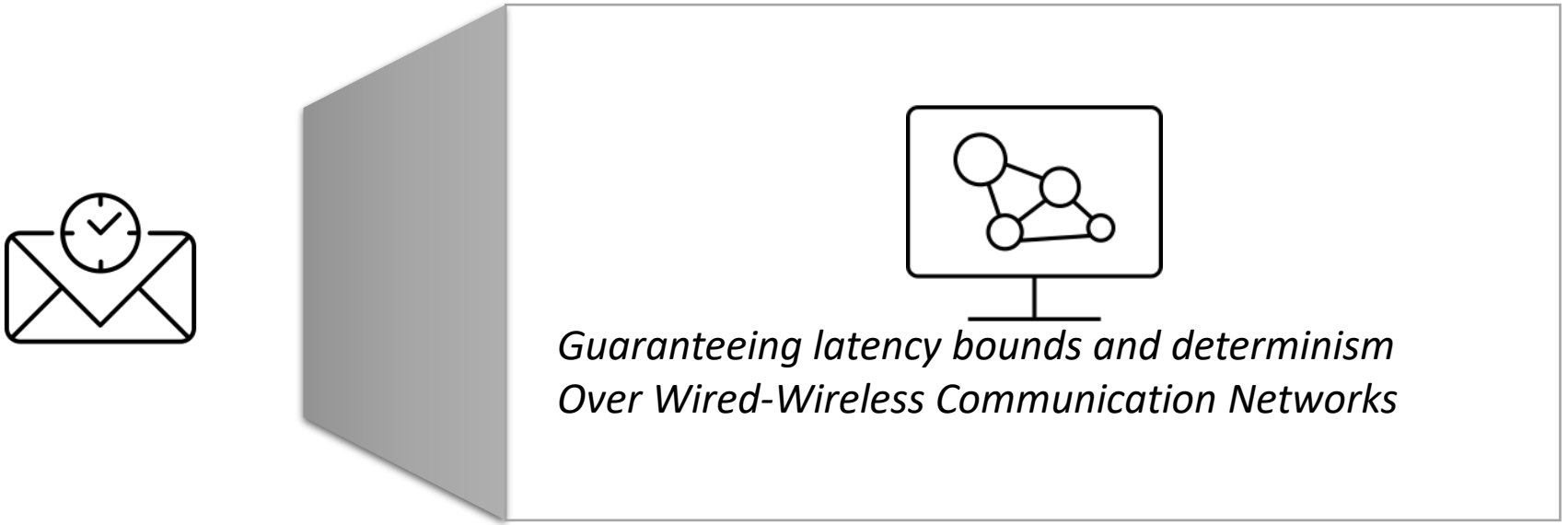
Guaranteeing Latency Bounds & Determinism| *Over Wired-Wireless Communication Networks*

Presentation

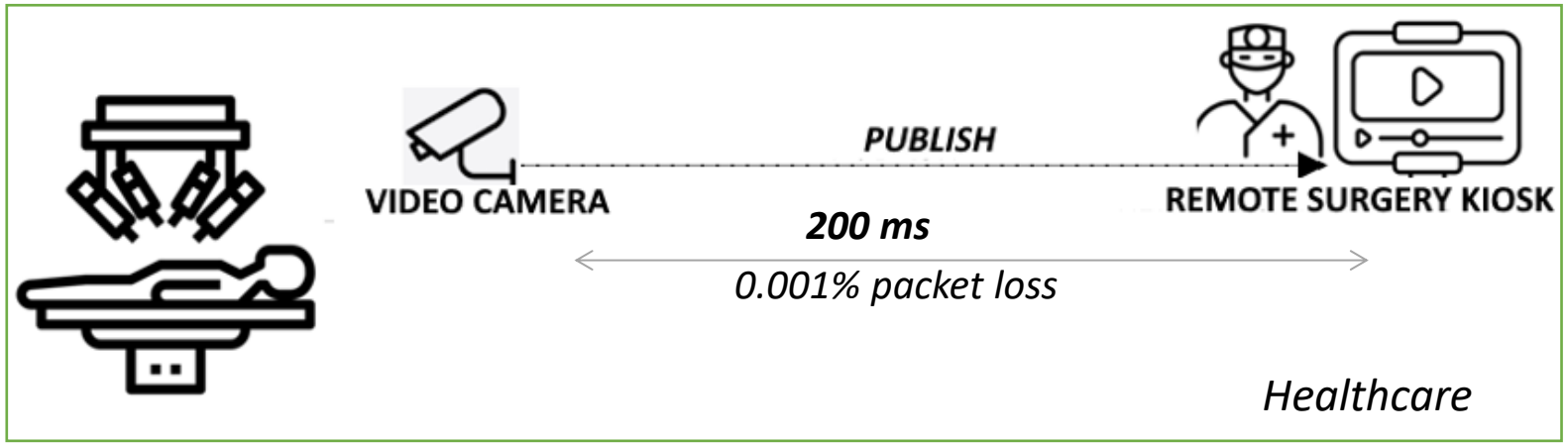


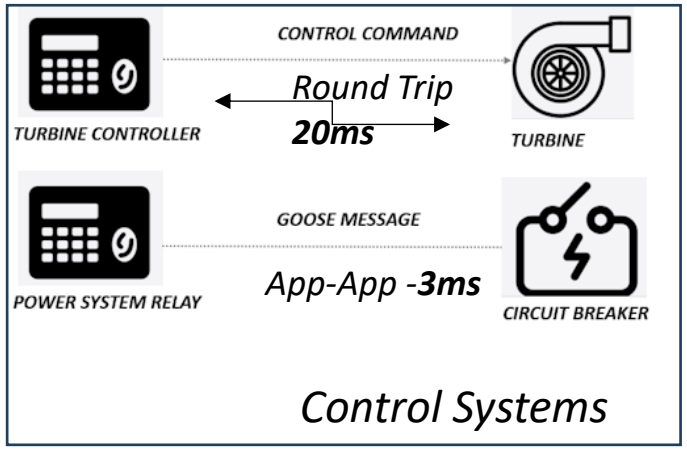
Abhilash Gopalakrishnan, Research Scholar
Supervisor: Dr. Subhasri Duttagupta
Amrita Vishwa Vidyapeetham, Amritapuri Campus
21 July 2025 – Presentation to Doctoral Committee

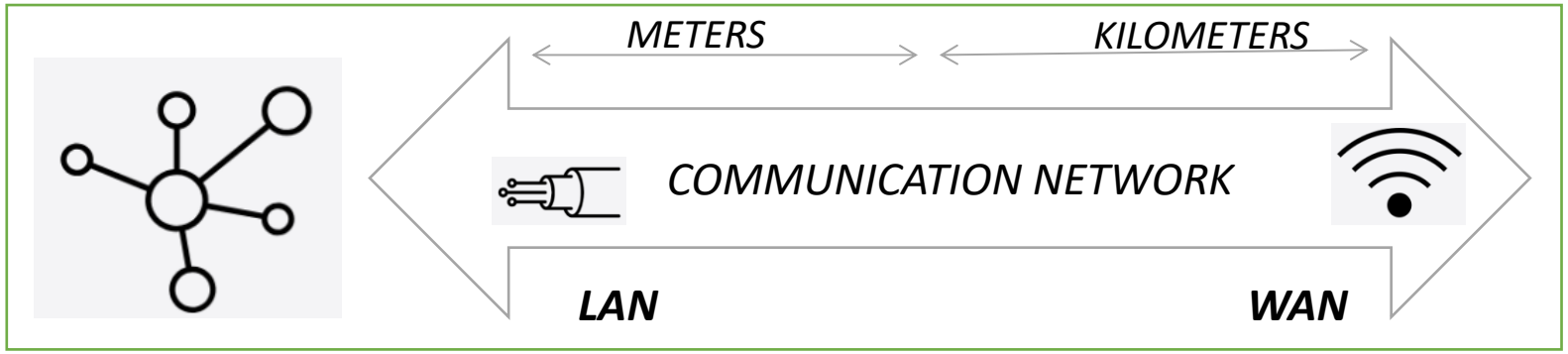
Agenda

Motivation | The Problem & Context | Challenges | Research Gaps and Plan | Our Work | Conclusion and Future Work

Motivation| *Technology in Healthcare/Automation & Control Systems*







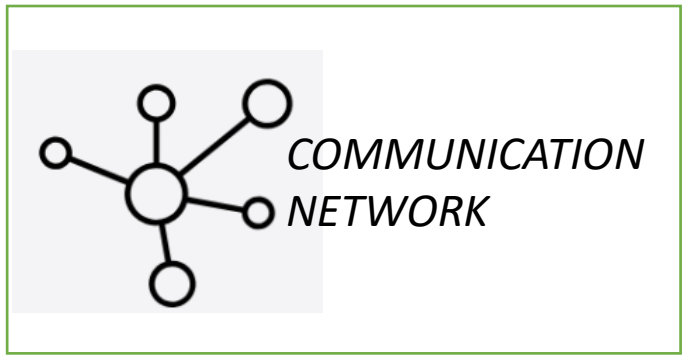


Figure 3: Remote Surgery and underlying communication network backbone

Figure 4: Control Systems

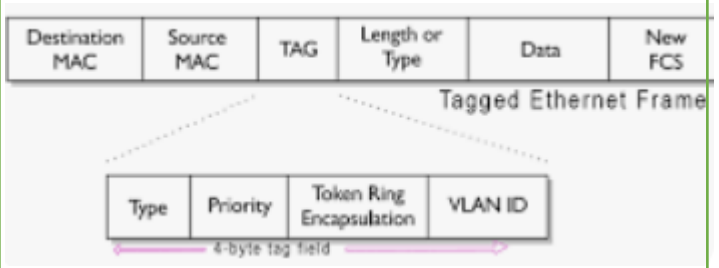
The underlying telecommunication network is often taken for granted!
Typically these are Wired-Wireless networks!

Ethernet| *Time Sensitive Networking*

Traditional

Using special interfaces/connectors like PROFINET, ETHERCAT, AFDX

Or Using Ethernet with VLAN Priority together with Publish – Subscribe



In order to ensure reliability the message is often send multiple times.

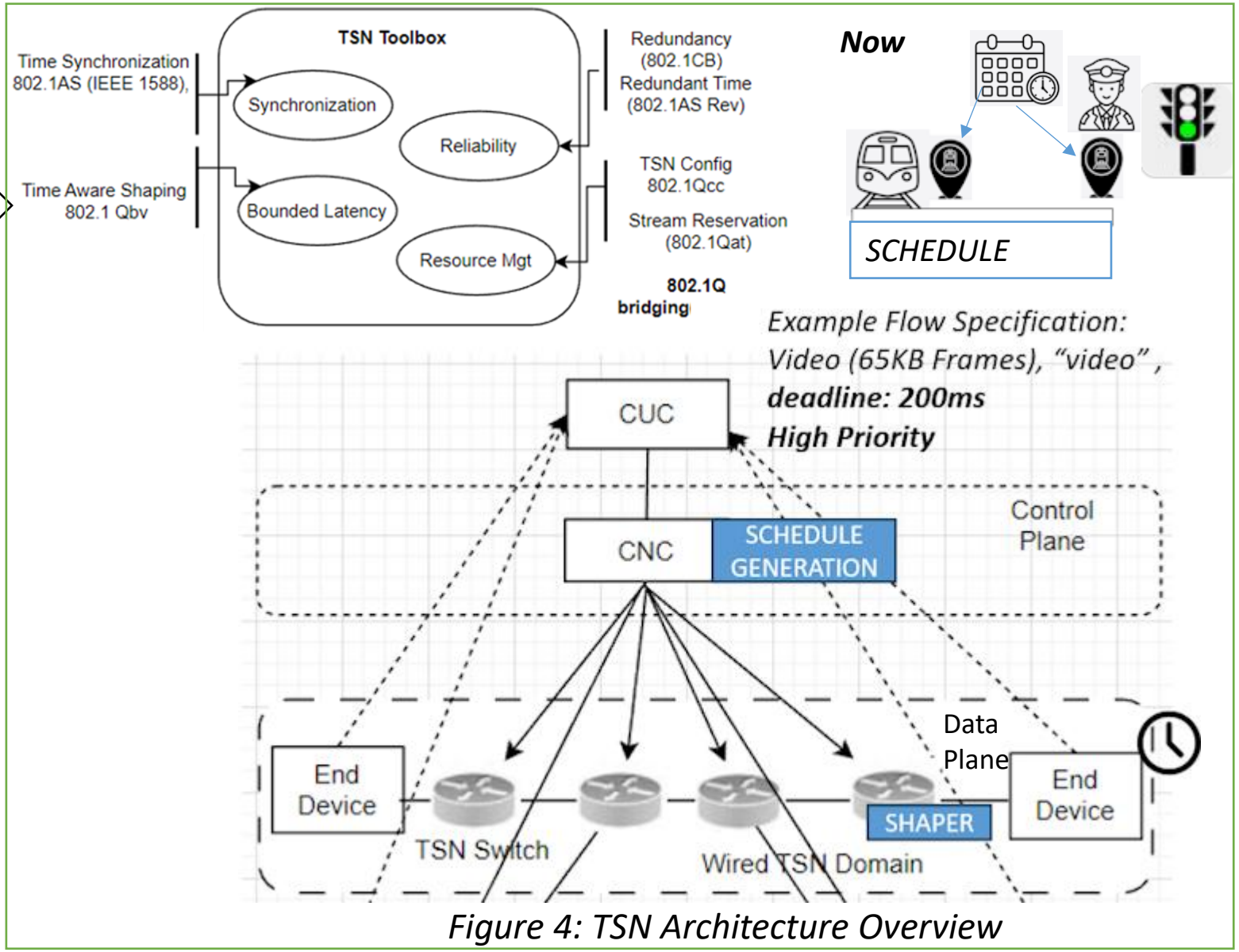
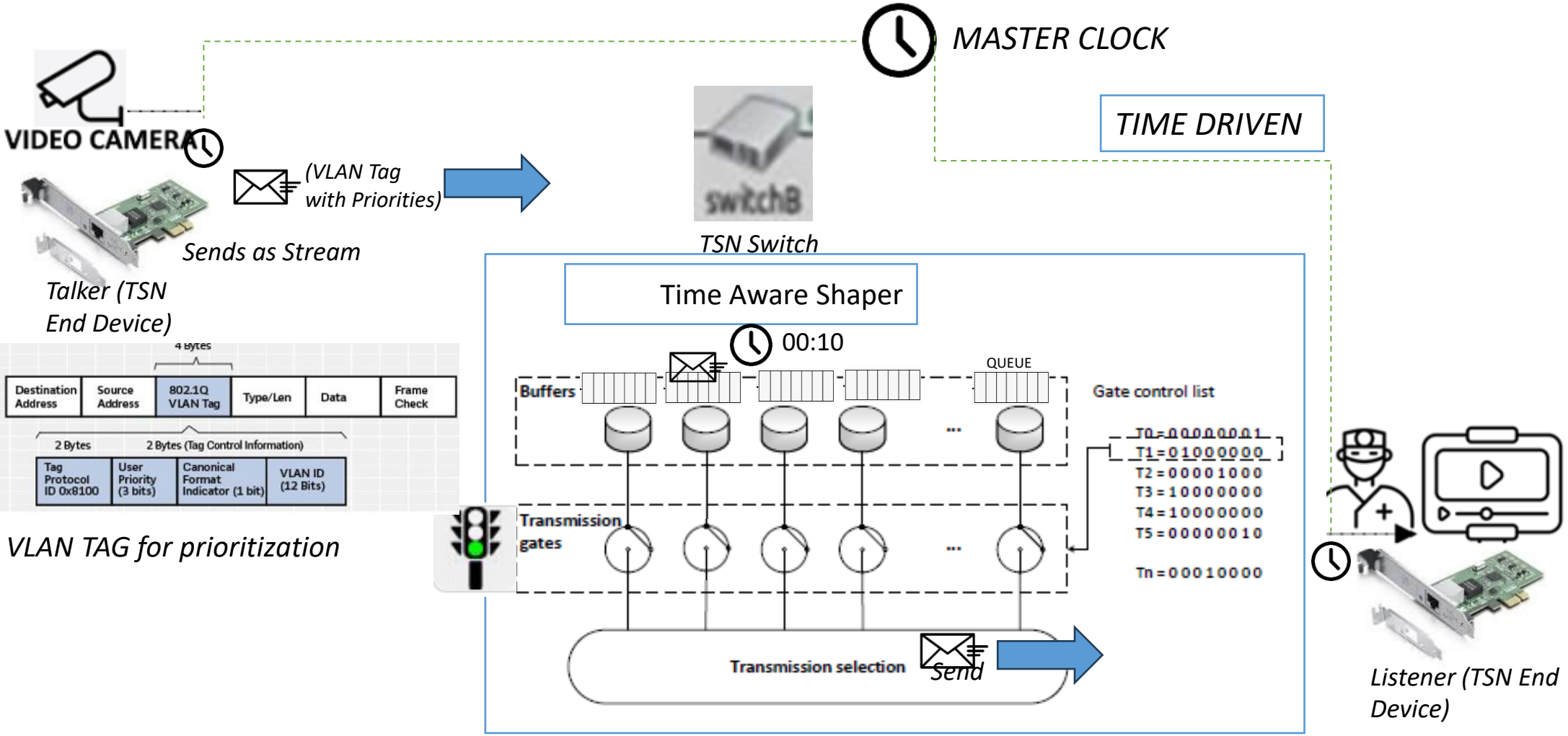


Figure 4: TSN Architecture Overview

Ethernet| *Time Aware Shaper*



Wireless | *Challenges*

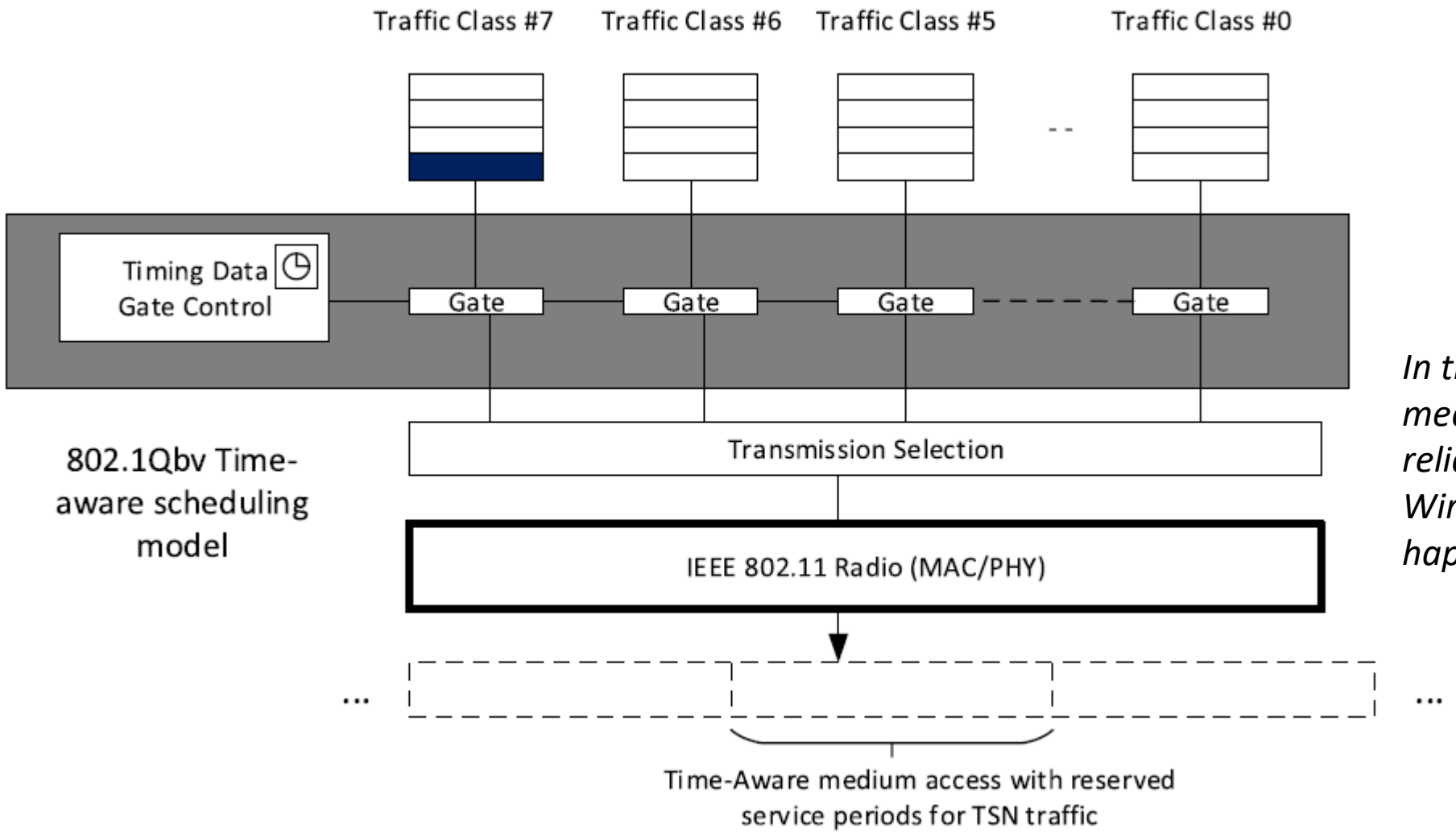


Fig. 7. *802.1Qbv time-aware scheduling over the 802.11 MAC.*

In the case of Ethernet, the medium is wired and highly reliable.
Wireless communication happens over a Shared Medium

Focus| *Research Questions*

3.1 Research Questions

RQ2 : How can Time Aware Shaping (TAS) be extended to Wi-Fi access points and integrated with wired TSN networks to provide deterministic, low-latency communication for mixed-priority traffic in dynamic environments using machine learning?

RQ4: How to enhance the existing frameworks for integrating wired and wireless networks in industrial and healthcare scenarios? What additional considerations have to be taken into account to offer deterministic low-latency communications?

3.1 Research Objectives

RO2 : To develop a strategy enabling a wireless aware gate schedule and access point placement strategies to accommodate mixed-priority traffic while ensuring bounded delay and limited packet loss.

Focus| *Research Questions*

TABLE 1
Communication QoS requirements for the multi-modality sensory data in robotic telesurgery

	Data types	Latency	Jitter	Packet Loss Rate	Data Rate	Ref
Real-time multimedia stream	2D camera flow	< 150 ms	3-30 ms	$< 10^{-3}$	< 10 Mbps	[4], [7]
	3D camera flow	< 150 ms	3-30 ms	$< 10^{-3}$	137 Mbps - 1.6Gbps	[4], [7]
	Audio flow	< 150 ms	< 30 ms	$< 10^{-2}$	22 – 200 Kbps	[7], [8]
Physical vital signs	Temperature	< 250 ms	-	$< 10^{-3}$	< 10 kbps	[9]
	Blood pressure	< 250 ms	-	$< 10^{-3}$	< 10 kbps	[9]
	Heart rate	< 250 ms	-	$< 10^{-3}$	< 10 kbps	[9]
	Respiration rate	< 250 ms	-	$< 10^{-3}$	< 10 Kbps	[9]
	ECG	< 250 ms	-	$< 10^{-3}$	72 kbps	[9]
	EEG	< 250 ms	-	$< 10^{-3}$	86.4 kbps	[9]
	EMG	< 250 ms	-	$< 10^{-3}$	1.536 Mbps	[9]
Haptic feedback	Force	3 – 10 ms	< 2 ms	$< 10^{-4}$	128 – 400 Kbps	[7], [8]
	Vibration	< 5.5 ms	< 2 ms	$< 10^{-4}$	128 – 400 Kbps	[7], [8], [10]

[Tele-assessment of bandwidth limitation for remote robotics surgery - PMC]

Robotic Tele-surgery requirements

2D Camera flow, Vital Signs

2D Camera flow
Permitted Latency <150ms
Jitter -3-30ms
Packet Loss Rate - 0.1% packet loss
Data Rate <10 Mbps

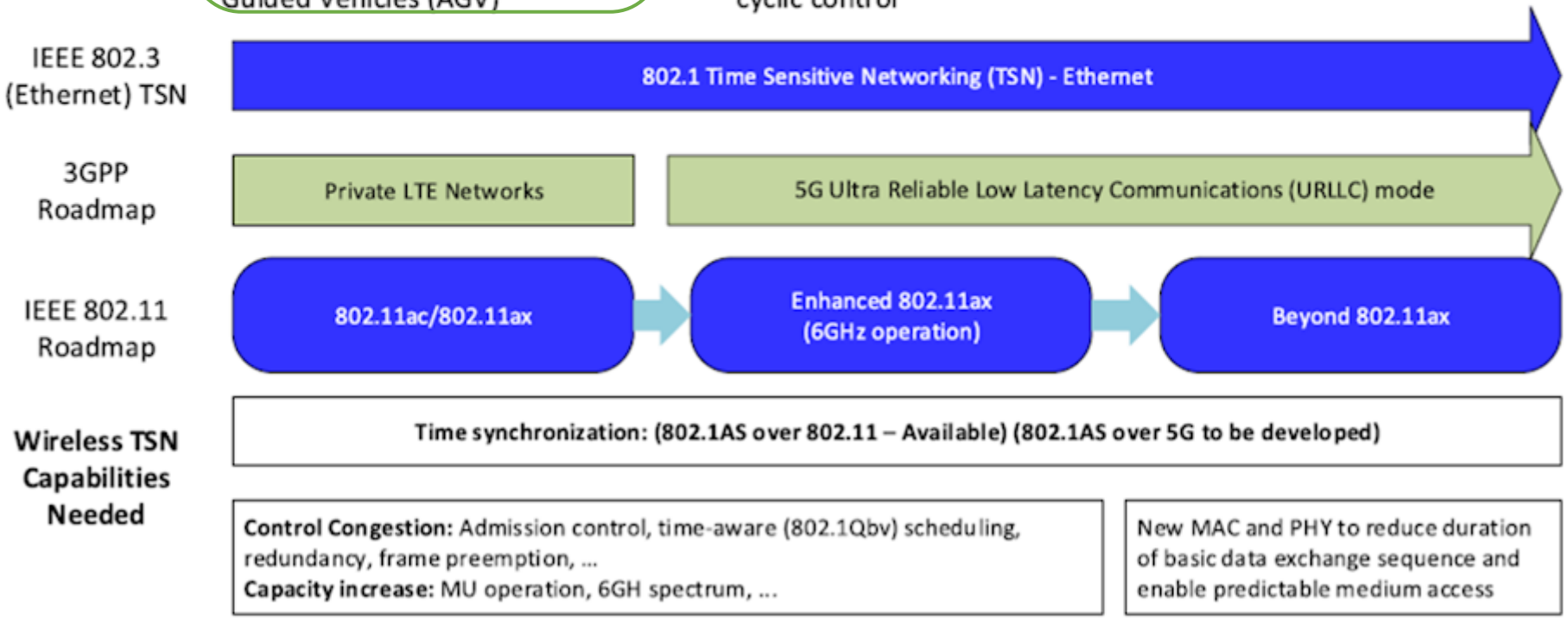
Vital Signs
Permitted Latency <250ms
Jitter -3-30ms
Packet Loss Rate - 0.1% packet loss
Data Rate <10 Kbps ECG etc 72-87Kbps

[1803.03586] Towards 5G Enabled Tactile Robotic Telesurgery

As of now haptic feedback is not considered.

Focus| *Roadmap Aligned to Wireless Roadmaps*

Class of Service	Class A	Class B	Class C
Latency	50 – 10 ms	10 – 1 ms	1 ms - ...
Reliability	99% - 99.9%	99.9% - 99.99%	99.999% - ...
Application Examples	High quality AV, soft-real-time control, mobile robotics/Automated Guided Vehicles (AGV)	AR/VR, Professional AV, gaming, HMI, hard-real-time cyclic control	Hard-real-time isochronous control, motion control



A Measurement Strategy to Align

Cavalcanti, D. et al, Extending accurate time distribution and timeliness capabilities over the air to enable future wireless industrial automation systems. [11]

And how much can we get closer to Class B Requirements?

Part 1| *Contributions*

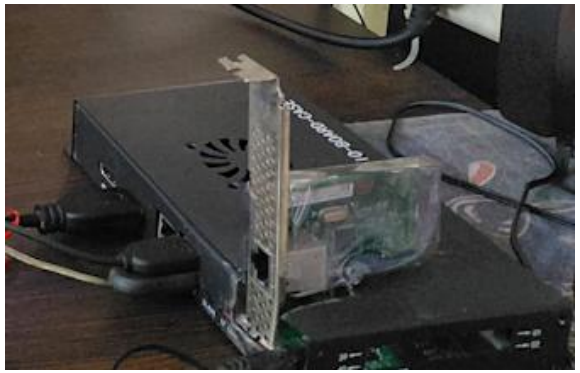
A wireless – tightened or wireless –aware gate scheduling as to ensure tighter schedule over Ethernet while wireless needs to have tolerance for variations.

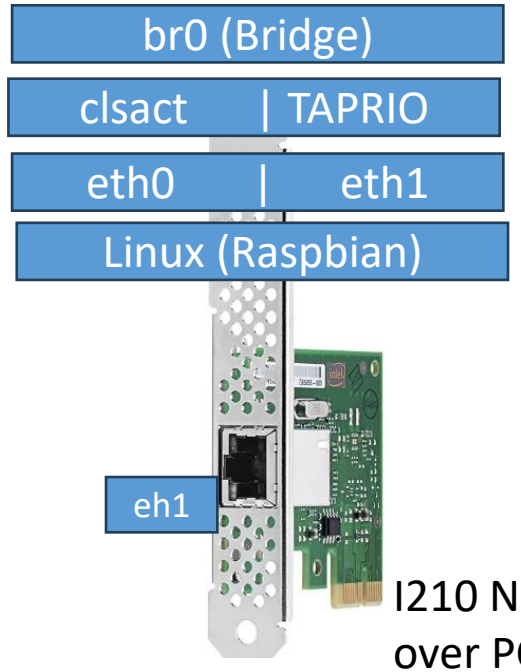
A novel approach combining Time Aware Shaper on Ethernet together with priority in Wireless (WMM) to achieve latency and packet loss guarantees over a 4 hop hybrid network consisting of 2 hops ethernet and 2 hops over Wi-Fi verified on close to real hardware.

A novel algorithm for placement of Wi-Fi access points and end devices to ensure latency bounds and packet loss within control.

Steps| *Step 0: Building TSN Switch using Raspberry Pi CM4 + I210 NIC*

This is





Compute Module 4 IO Board

Steps:

1. Setting up the Bridge and Static IP Address
2. Setting up clsact and filters for QoS Mapping to QDisc
3. Setting up TAPRIO gate schedule

Steps| *Step 0: Setting up IEEE 1588 – Precision Time Protocol (PTP)*

What all devices need to be in Sync?

1. Talker and Listener in TSN perspective (Source and Destination) for sure
2. They should have both Hardware Time Synchronization Support
3. Then we could install linuxptp (ptp4l) and get the clocks working

https://tsn.readthedocs.io/timesync.html

Pre-requistes

1.NIC Cards at both ends to have (ideally) hardware time synchronization. The supported hardware today includes: Intel i210 Gigabit NIC card, Broadcom NIC which comes with Rpi CM4

2.Many Standard NICs do have PTP support today check using: ethtool -T <interface_name>

3.Decide how to setup the Master and slave. In our case we are setting up Master on Linux PC(Sender) and Slave on Linux Laptop (thinkpad) Linux PC has added i210 GB NIC card, while the Linux Laptop Intel card as well supports PTP.

4.All firewalls set of: sudo ufw disable and sudo systemctl stop firewalld (In our case firewalld was filtering and hence sync was not happening)

Steps| *Step 0: Setting up IEEE 1588 – Precision Time Protocol (PTP)*

PTP Working (Sender as Master and Receiver as Slave)

Master

```
abhilash@abhilash-B760M-D2H-DDR4:~$ sudo ptp4l -i enp3s0 -f /etc/linuxptp/ptp4l-
master.conf -m
[sudo] password for abhilash:
ptp4l[37885.901]: selected /dev/ptp0 as PTP clock
ptp4l[37885.903]: port 1 (enp3s0): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[37885.904]: port 0 (/var/run/ptp4l): INITIALIZING to LISTENING on INIT_COM
PLETE
ptp4l[37885.904]: port 0 (/var/run/ptp4lro): INITIALIZING to LISTENING on INIT_C
OMPLETE
ptp4l[37893.618]: port 1 (enp3s0): LISTENING to MASTER on ANNOUNCE_RECEIPT_TIMEO
UT_EXPIRES
ptp4l[37893.618]: selected local clock 1cfd08.fffe.79729c as best master
ptp4l[37893.618]: port 1 (enp3s0): assuming the grand master role
```

Slave

```
abhilash@KalamE16:~$ sudo ptp4l -i enp0s31f6 -f /etc/linuxptp/ptp4l-client.conf
-m
ptp4l[27786.648]: selected /dev/ptp0 as PTP clock
ptp4l[27786.649]: port 1: INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[27786.649]: port 0: INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[27787.167]: port 1: new foreign master 1cfd08.fffe.79729c-1
ptp4l[27791.167]: selected best master clock 1cfd08.fffe.79729c
ptp4l[27791.167]: port 1: LISTENING to UNCALIBRATED on RS_SLAVE
ptp4l[27793.168]: master offset -128130351 s0 freq -1601550 path delay     119947
ptp4l[27794.168]: master offset -128175616 s1 freq -1646880 path delay     107885
ptp4l[27795.168]: master offset     -28985 s2 freq -1675865 path delay     107885
ptp4l[27795.168]: port 1: UNCALIBRATED to SLAVE on MASTER_CLOCK_SELECTED
ptp4l[27796.169]: master offset      47177 s2 freq -1608399 path delay     107885
ptp4l[27797.168]: master offset     -88423 s2 freq -1729846 path delay     119947
ptp4l[27798.169]: master offset      33419 s2 freq -1634531 path delay     119947
```

Steps| *Step 0: The Traffic Model – Aligned to*

2D Video Traffic expects 30 Frames per second to 60 frames per second

In alignment to that

1. *Video – 1400 bytes per 10 milliseconds*
2. *Vitals – 1200 bytes per 10 milliseconds*
3. *Electronic Health Record (HER) – 1400 bytes per 1 milliseconds (Best Effort)*
4. *PTP as traffic needs to be provided a queue*

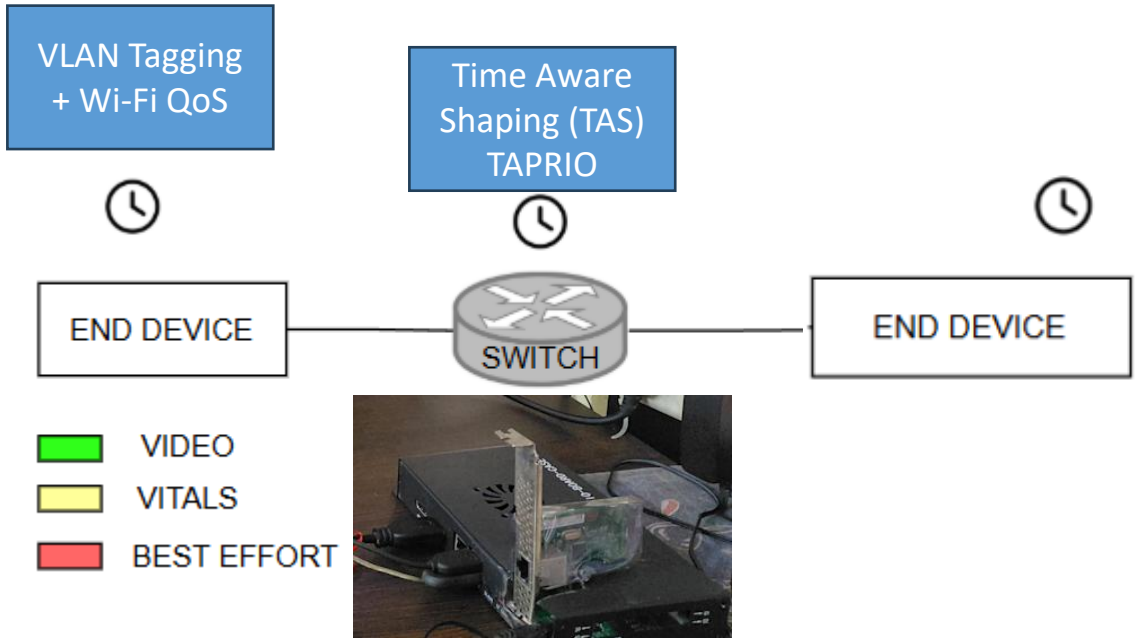
I210 NIC supports 4 Tx Queues. Hence limitation of 4 types of traffic only

Base case – 11.2 Mbps traffic (1,2,3,4)

My Link speed is 490Mbps (effective)

Hence based on that to reach 5% traffic is 25Mbps, 10% traffic is 50Mbps
And 20% traffic is 100Mbps. Keeping the base traffic (1,2,3,4) live, add extra traffic as to create this kind of best effort traffic.

Part 2| *Time Sensitive Networking – over Integrated Networks*



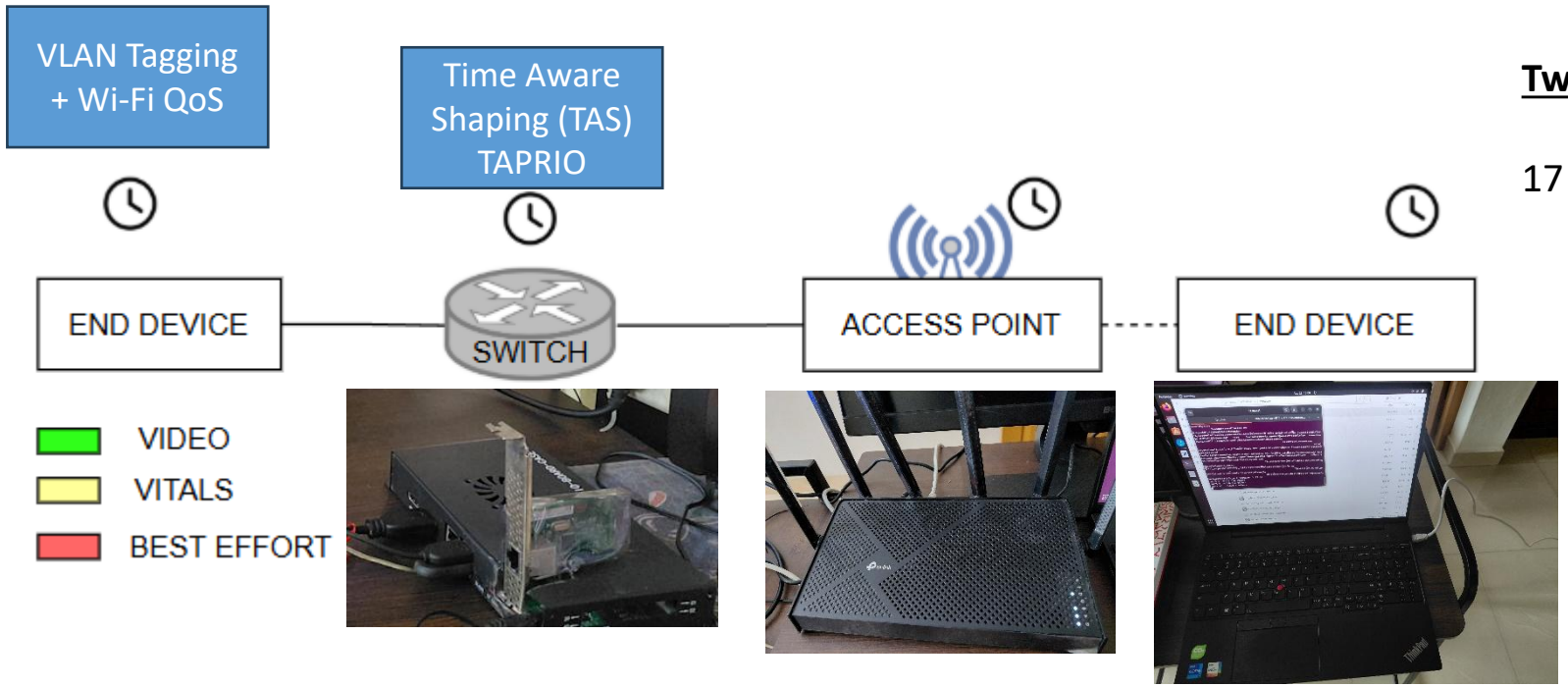
Step1: Tightening the schedule over 2 Ethernet Hops. Synchronisation using PTP

SCENARIO 1

In a Remote surgery case, the videos over the wireless to a room where doctors may control the surgery. Considers multiple times of crossing wired and wireless domains.

{tsnEthernetHost1 → tsnSwitch1 → tsnEthernetHost2}

Part 2| *Time Sensitive Networking – over Integrated Networks*



Two Configurations

17 Feet Not Line of Sight (NLoS)

SCENARIO 1

In a Remote surgery case, the videos over the wireless to a room where doctors may control the surgery. Considers multiple times of crossing wired and wireless domains.

{tsnEthernetHost1 → tsnSwitch1 → tsnAccessPoint1 → tsnWifiHost1}

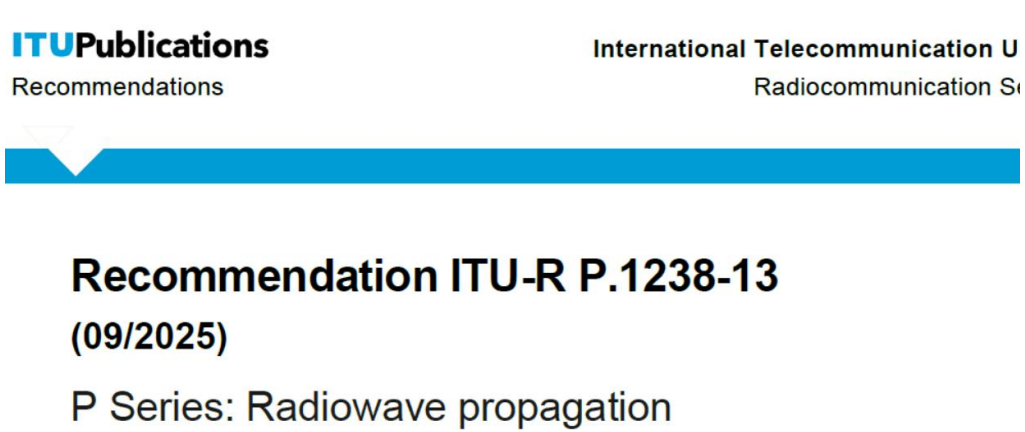
Packet Loss is significant (5% or more) and RSSI is low when in NLOS.

Part 2| *Coverage Area Analysis – Using Path Loss Model defined in ITU P 1238*

Two Configurations

17 Feet Not Line Of Sight (NLOS)

30 Feet Not Line of Signt (NLOS) (10m is max distance in good range of Wi-Fi 6 with Concrete wall indoor)


ITUPublications
Recommendations

International Telecommunication U
Radiocommunication S

Recommendation ITU-R P.1238-13
(09/2025)

P Series: Radiowave propagation

Where to place the access point is important

3.1 Site-general models

The site-general model is applicable to situations where both the transmitting and receiving stations are located on the same floor. The median basic transmission loss is given by:

$$L_b(d,f) = 10\alpha \log_{10}(d) + \beta + 10\gamma \log_{10}(f) \quad \text{dB} \quad (1)$$

with an additive zero mean Gaussian random variable $N(0,\sigma)$ with a standard deviation σ (dB), where:

d : 3D direct distance between the transmitting and receiving stations (m)

f : operating frequency (GHz)

α : coefficient associated with the increase of the basic transmission loss with distance

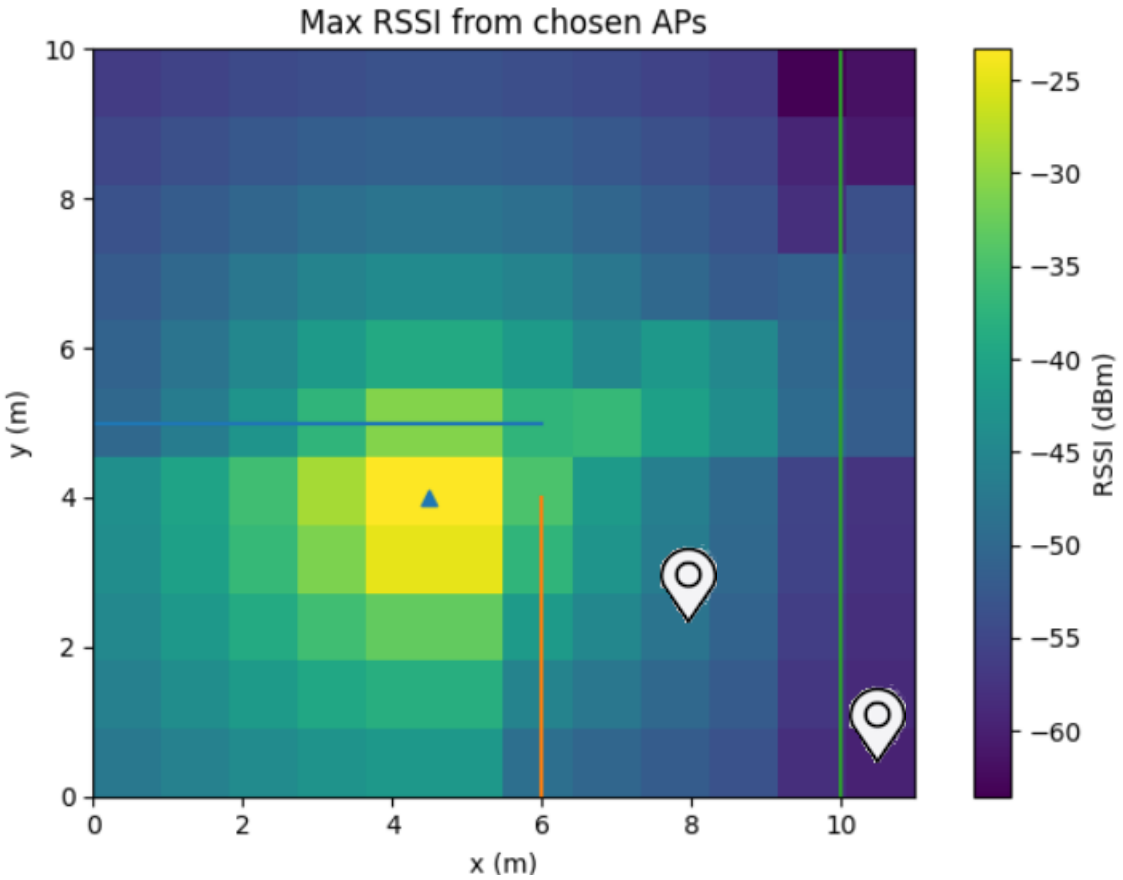
β : coefficient associated with the offset value of the basic transmission loss

γ : coefficient associated with the increase of the basic transmission loss with frequency.

For non-line-of-sight (NLoS) Monte Carlo simulations, the excess basic transmission loss with respect to free-space basic transmission loss, L_{FS} ($L_{FS} = 20\log_{10}(4 \times 10^9 \pi df/c)$ where c is the speed of light in m/s), will not exceed $10\log_{10}(10^{0.1A} + 1)$ (dB), where A is a random variable with a normal distribution $N(\mu,\sigma)$, with mean $\mu = L_b(d,f) - L_{FS}$ and standard deviation of σ.

The recommended coefficient values for indoor propagation environments are provided in Table 2.

Part 2| *Coverage Area Analysis – Using Path Loss Model defined in ITU P 1238*



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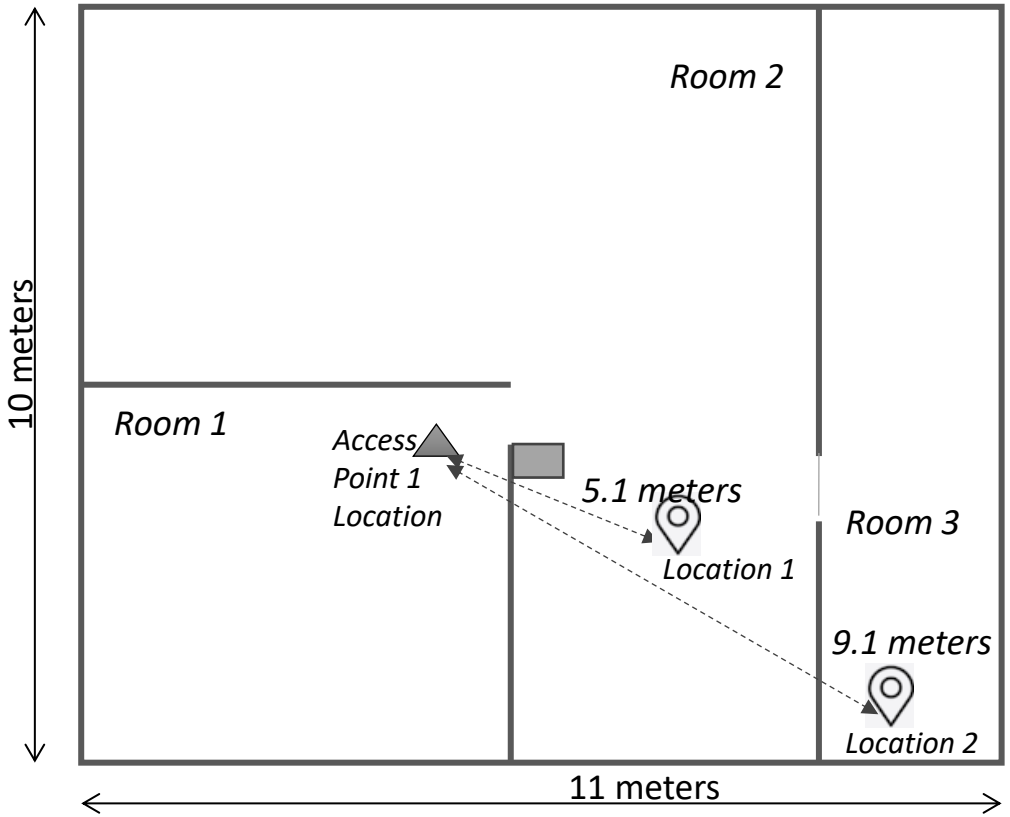

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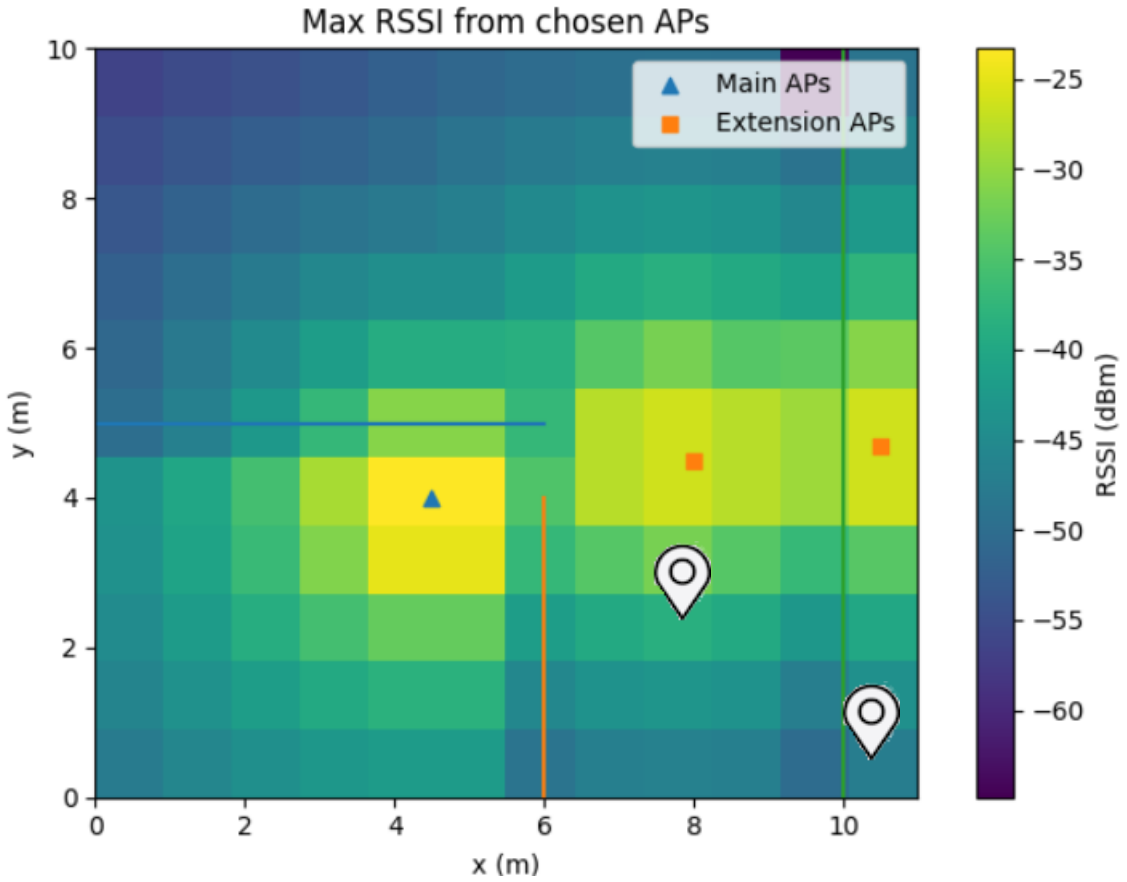

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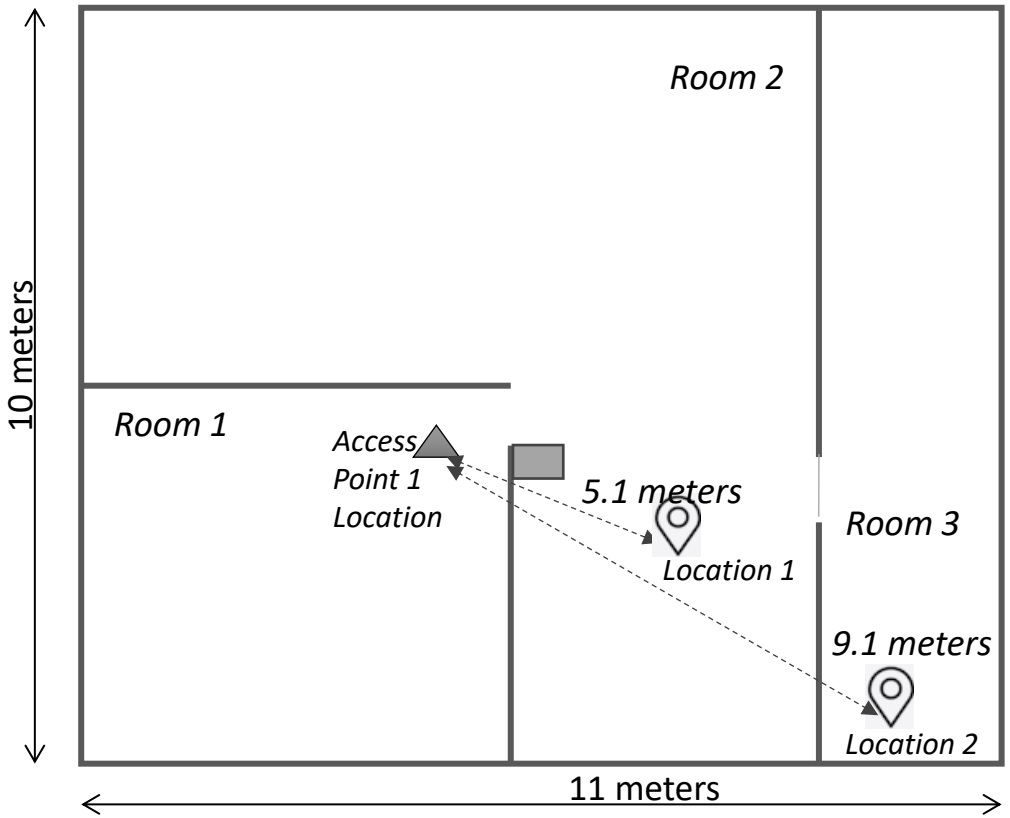
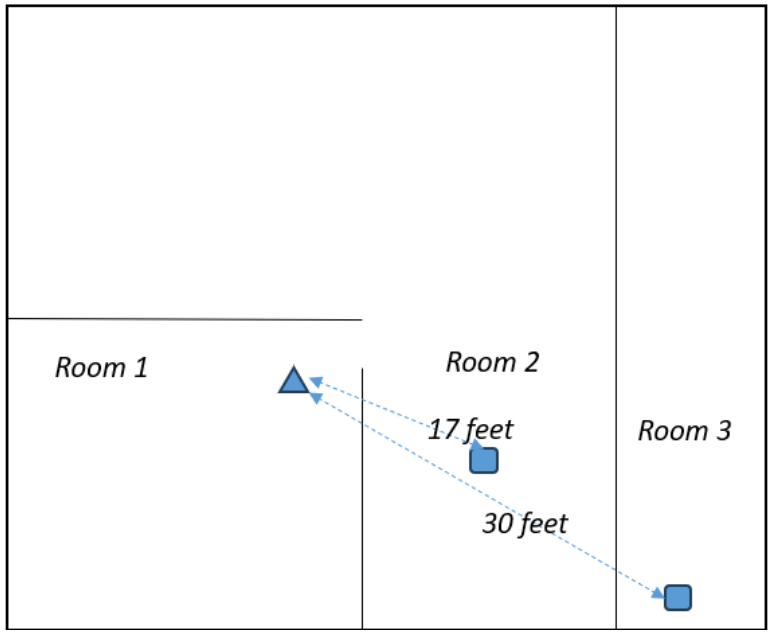
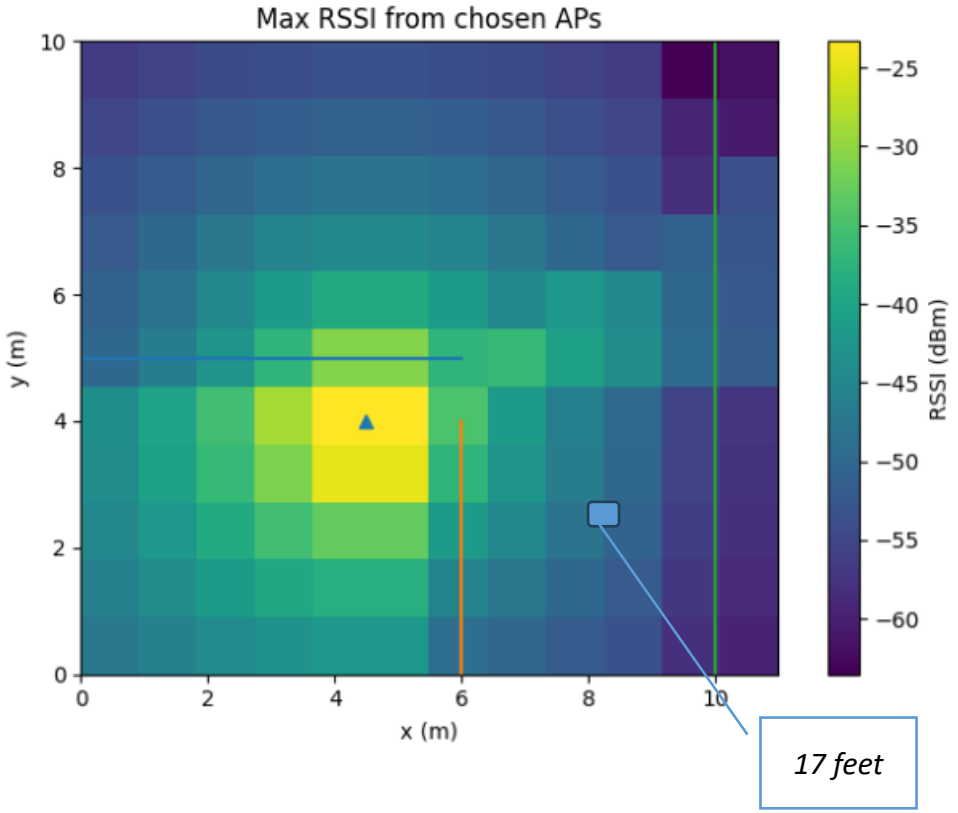


Part 2| *17 Feet – Additional Access Point in Line of Sight*





Where to place the access point is important

One AP only -17 feet away & NLOS

One AP + Extender at 12 feet away and LOS of Main and only 5 feet away in LOS of Extender

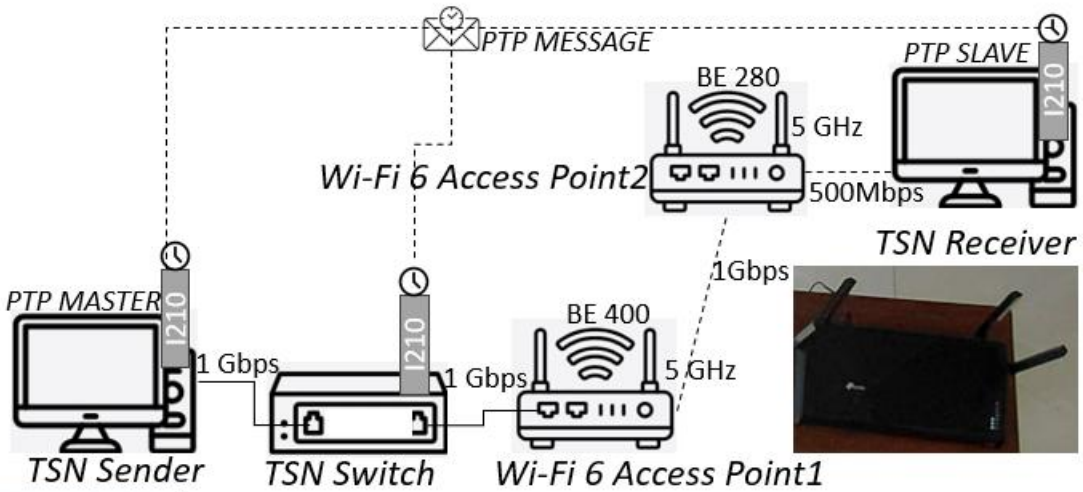
Part 2| *Time Sensitive Networking – over Integrated Networks – with 2 AP*

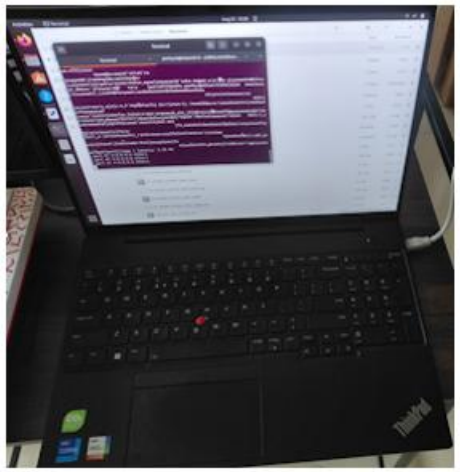
VLAN Tagging + Wi-Fi QoS

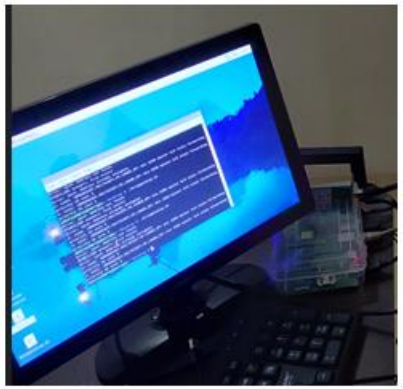
Time Aware Shaping (TAS) TAPRIO

Two Configurations

17 Feet (5.1m) Not Line of Sight (NLoS)







In a Remote surgery case, the videos over the wireless to a room where doctors may control the surgery. Considers multiple times of crossing wired and wireless domains.

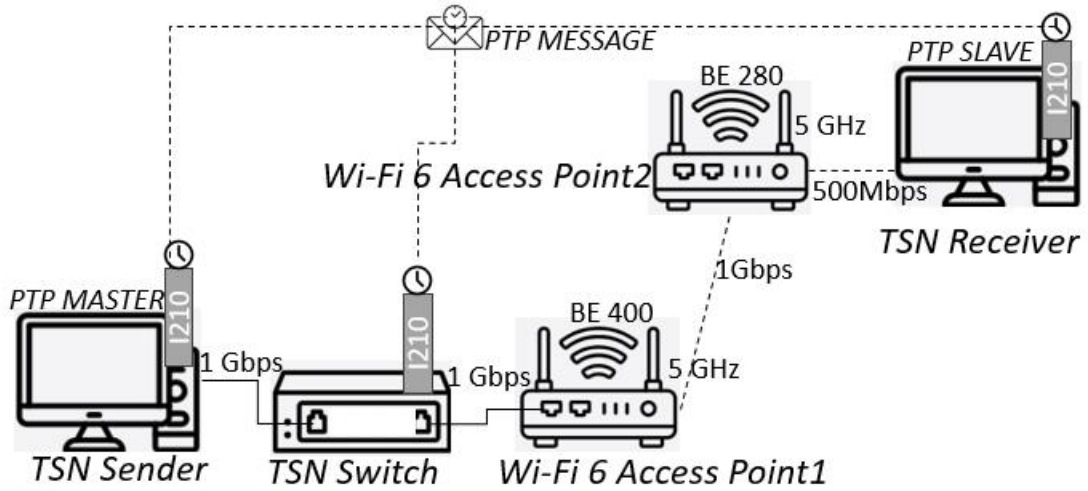
{tsnEthernetHost1 → tsnSwitch1 → AccessPoint1 → AccessPoint2-> tsnWifiHost1}

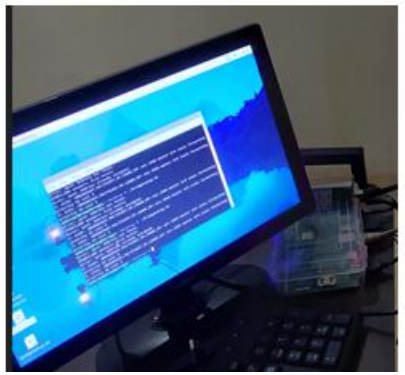
Packet Loss is in control and RSSI is low

Part 2| *Time Sensitive Networking – over Integrated Networks – with 2 AP*

VLAN Tagging + Wi-Fi QoS

Time Aware Shaping (TAS) TAPRIO





Two Configurations

17 Feet (5.1m) Not Line of Sight (NLoS)

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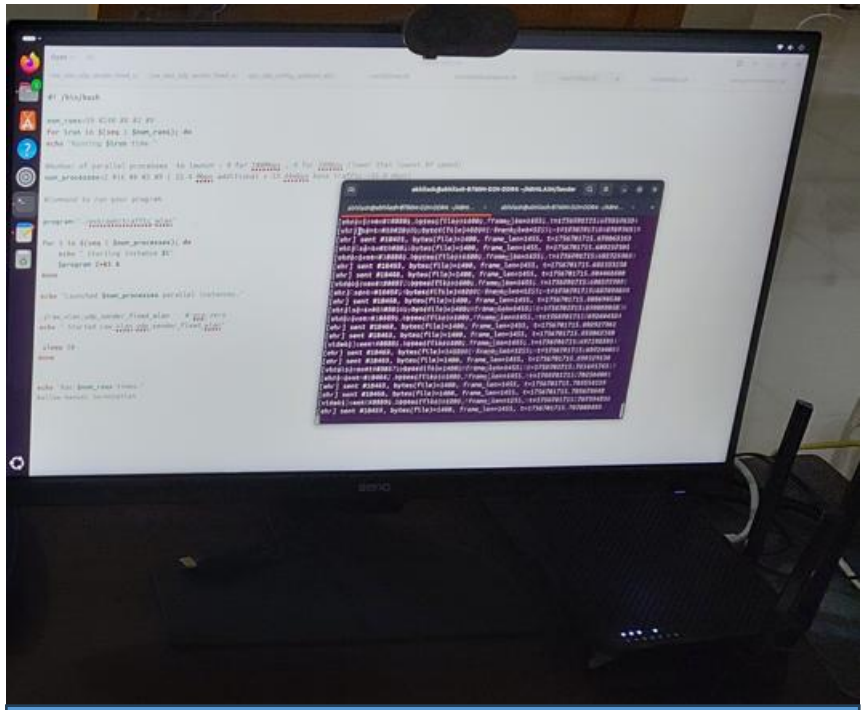
'tsnEthernetHost1 → tsnSwitch1 → AccessPoint1 → AccessPoint2-> 'snWifiHost1}

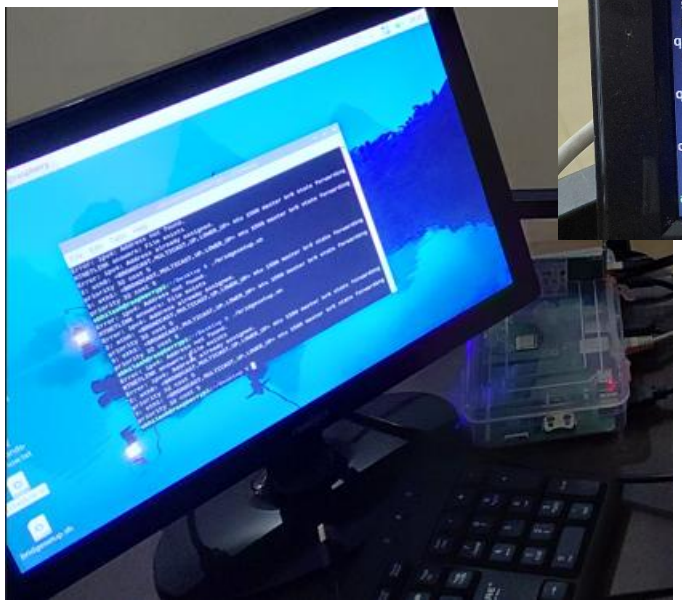
Packet Loss is in control and RSSI is low

Part 2| *Elements of the Setup*

These are all in room 1



1. TSN Sender



2. TSN Switch with Raspberry Pi CM4 + I210 card with HDMI based Display

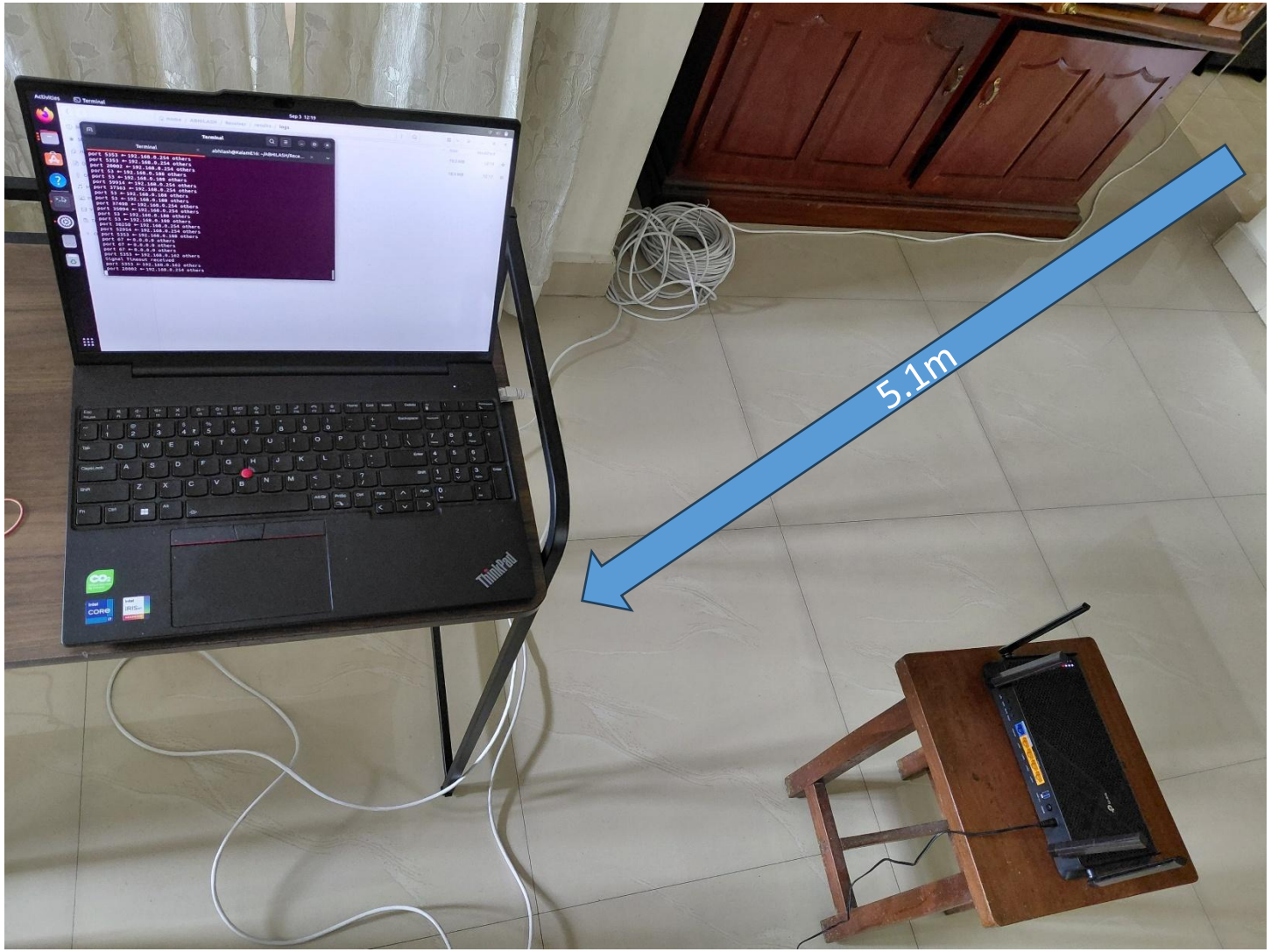
2.1 TAPRIO SCHEDULE RUNNING on Rpi CM4

```
qdisc pfifo 0: parent 100:2 limit 1000p
 Sent 18750000 bytes 15000 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
qdisc pfifo 0: parent 100:1 limit 1000p
 Sent 21750000 bytes 15000 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
abhilash@raspberrypi:~ $ sudo tc -s qdisc show dev eth1
qdisc taprio 100: root refcnt 9 tc 4 map 3 2 2 2 1 1 1 0 3 2 2 2 1 1 1 0
queues offset 0 count 1 offset 1 count 1 offset 2 count 1 offset 3 count 1
clockid TAI flags 0x1   base-time 1000000000 cycle-time 211000 cycle-time-extension 0
        index 0 cmd S gatemask 0 interval 13000
        index 1 cmd S gatemask 0x1 interval 13000
        index 2 cmd S gatemask 0 interval 24000
        index 3 cmd S gatemask 0x2 interval 13000
        index 4 cmd S gatemask 0x4 interval 12000
        index 5 cmd S gatemask 0x8 interval 12000
        index 6 cmd S gatemask 0 interval 124000

 Sent 4363216987 bytes 3055355 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
qdisc pfifo 0: parent 100:4 limit 1000p
 Sent 3317965521 bytes 2314524 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
qdisc pfifo 0: parent 100:3 limit 1000p
 Sent 761751466 bytes 530831 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
qdisc pfifo 0: parent 100:2 limit 1000p
 Sent 131250000 bytes 105000 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
qdisc pfifo 0: parent 100:1 limit 1000p
 Sent 152250000 bytes 105000 pkt (dropped 0, overlimits 0 requeues 0)
 backlog 0b 0p requeues 0
abhilash@raspberrypi:~ $
```

3. TPLink Archer BE 400 (Same make in Amrita Lab)

Part 2| *Elements of the Setup*



Location 1

5.1 m away from Access Point 1

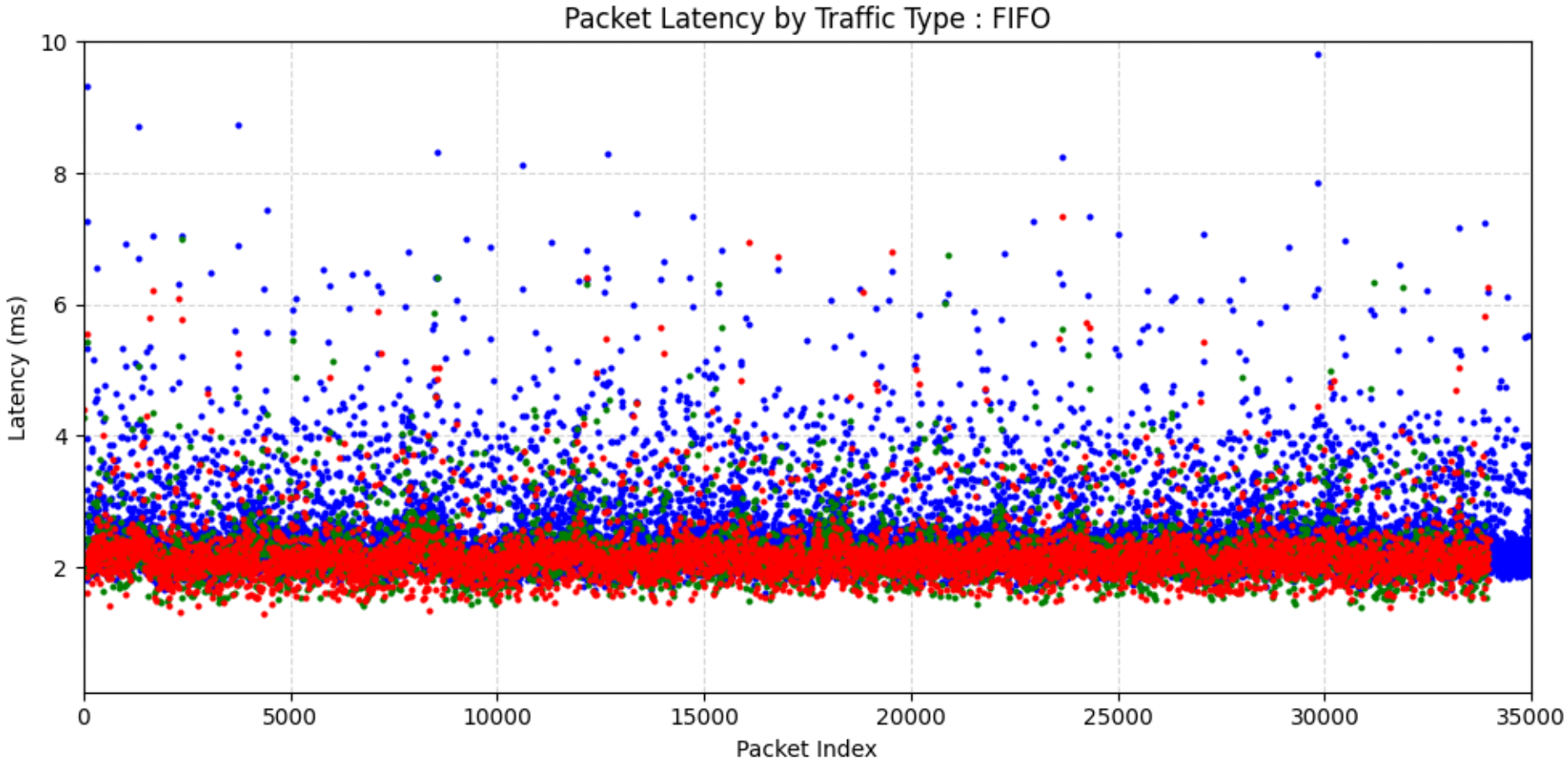
Access Point placed as per signal strength

Part 2| *Elements of the Setup*

Location 1
9.1 m away from Access Point 1

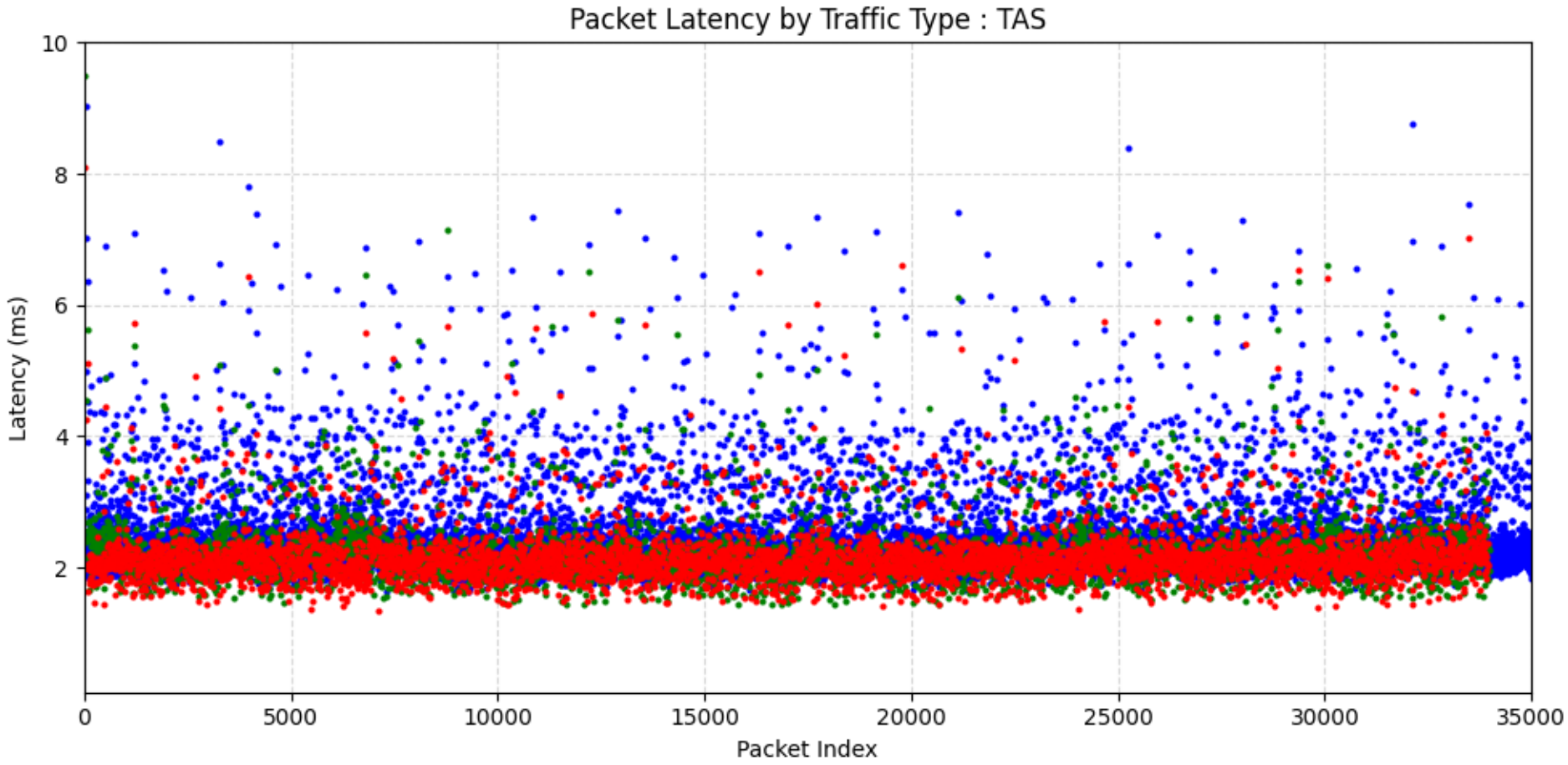
Access Point placed as per signal strength

Part 2| *17 Feet - Base case : 11.2 Mbps - Run #1 – FIFO* *(using traffic_log2)*



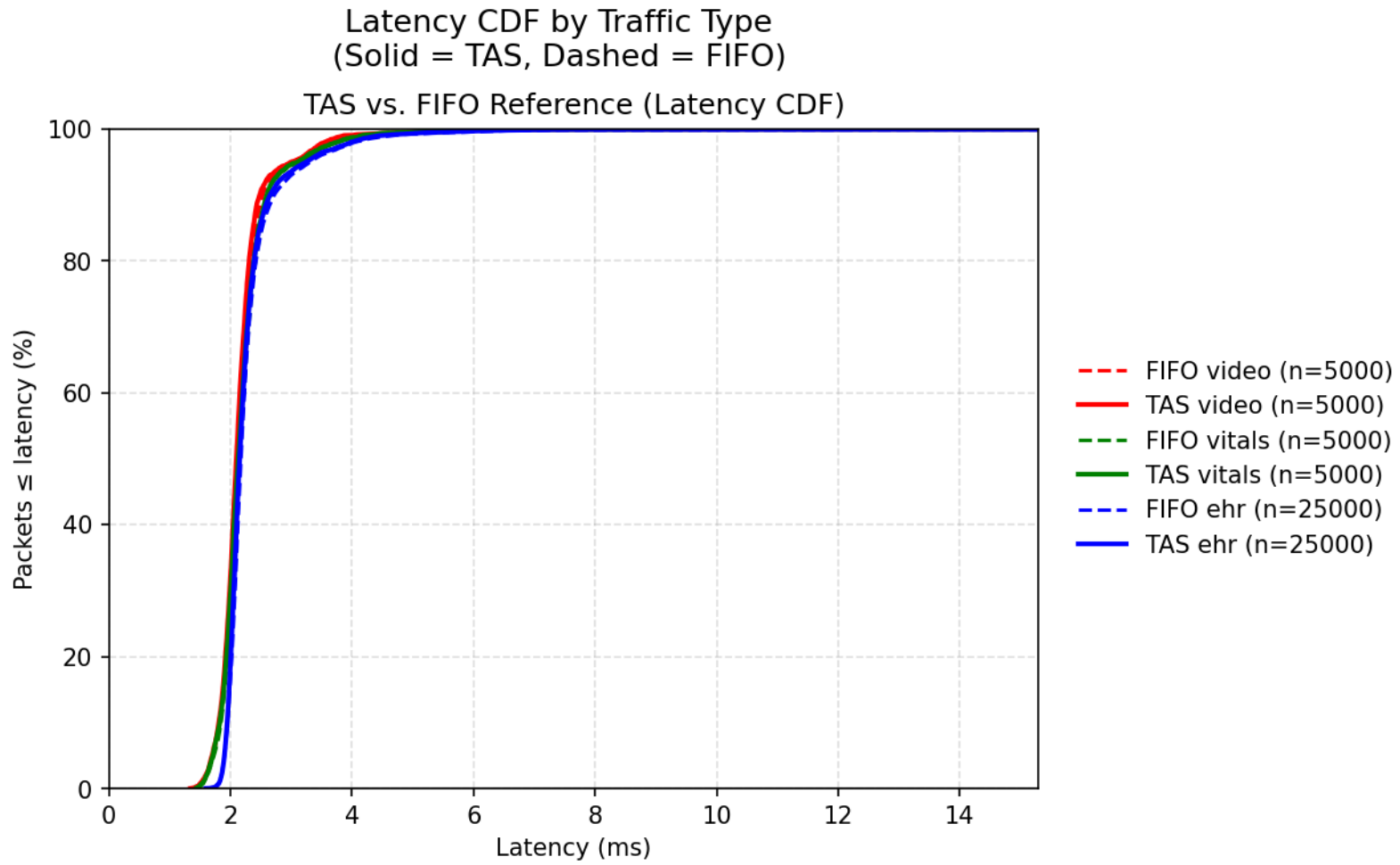
Part 2| *17 Feet - Base case : 11.2 Mbps - Run #1 - TAS*

TAS (Most of it within 8ms)

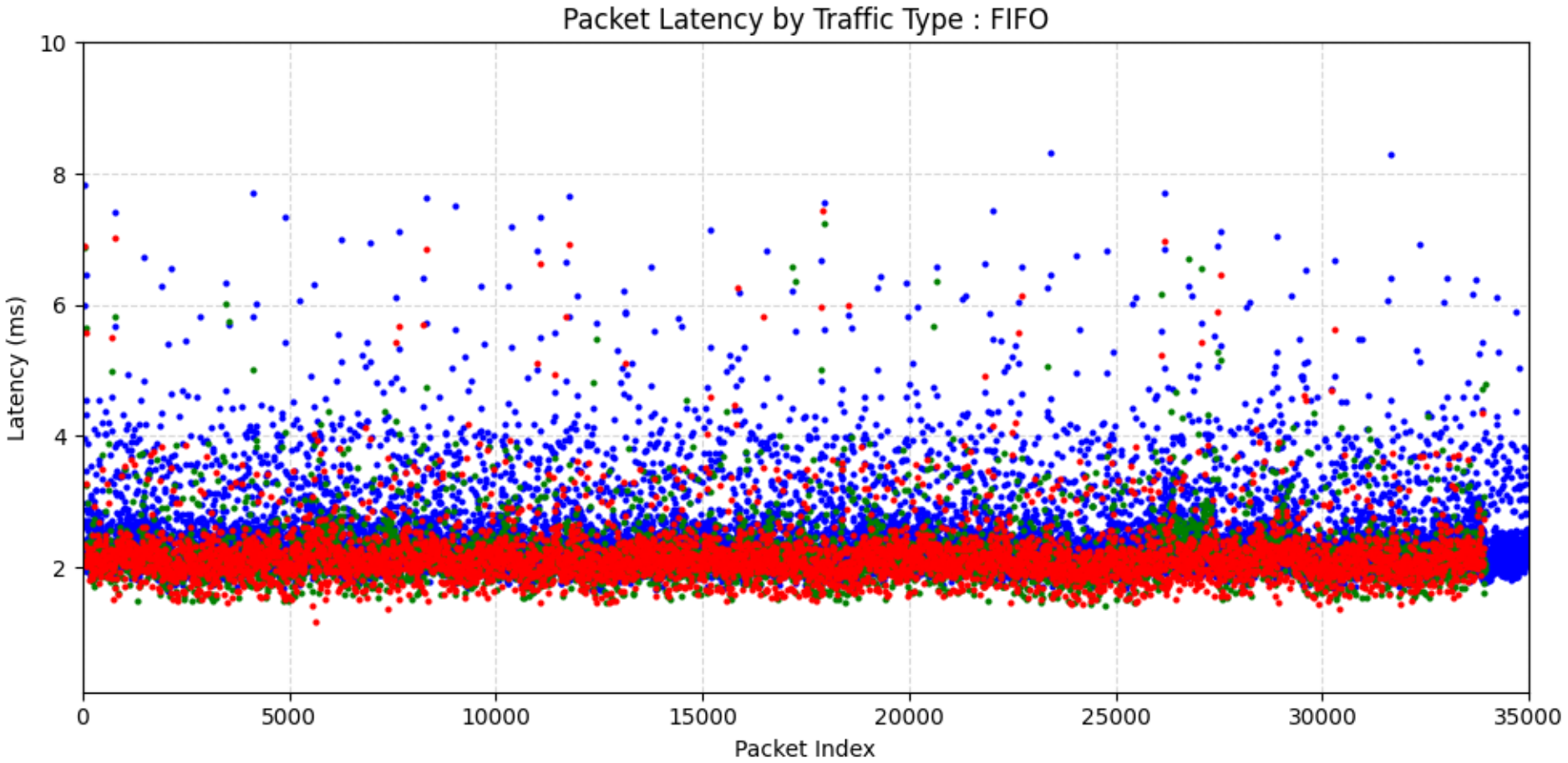


Part 2| *17 Feet - Base case : 11.2 Mbps - Run #1 – FIFO vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

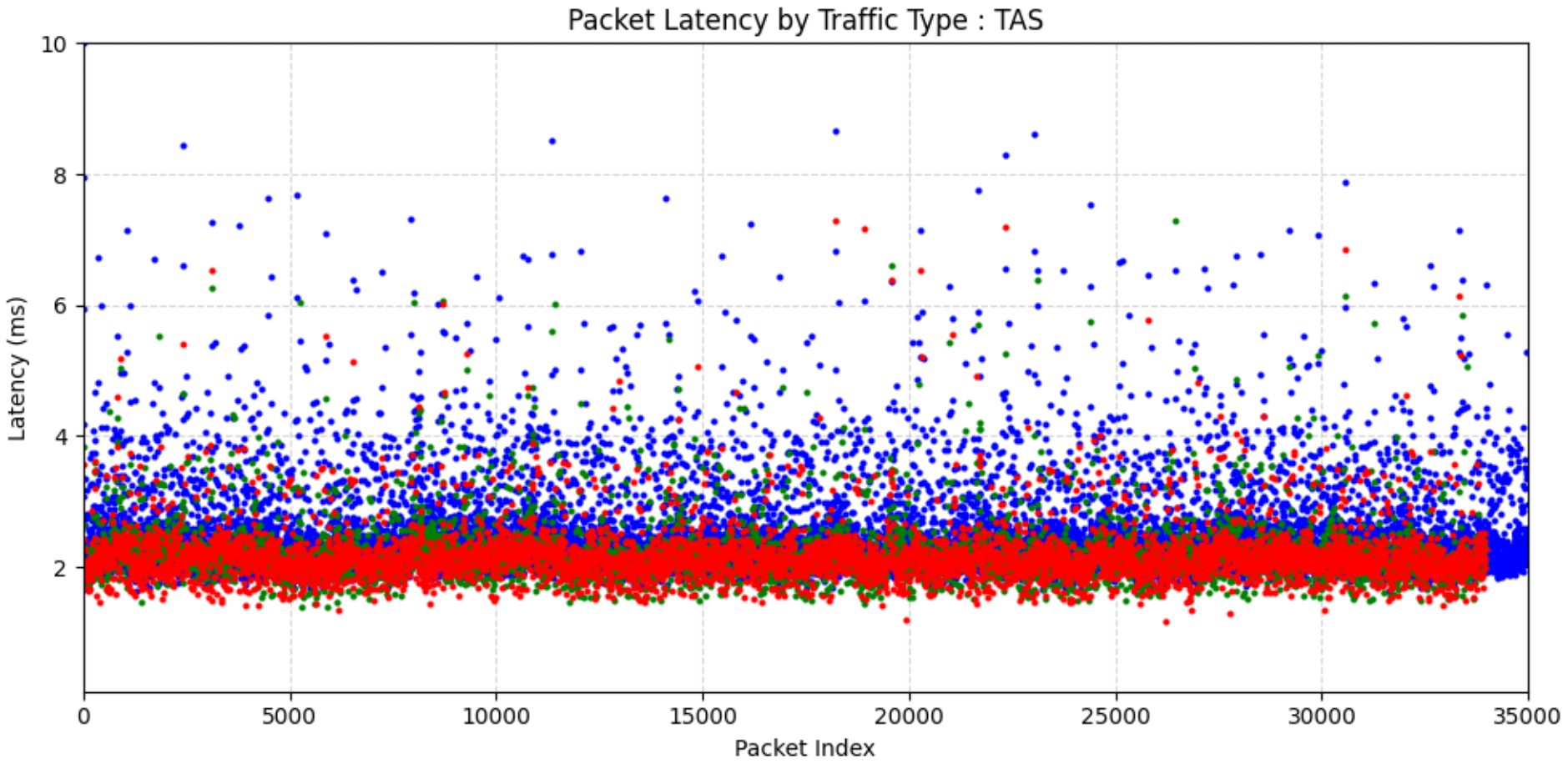


Part 2| *17 Feet - Base case : 11.2 Mbps - Run #2 - FIFO*



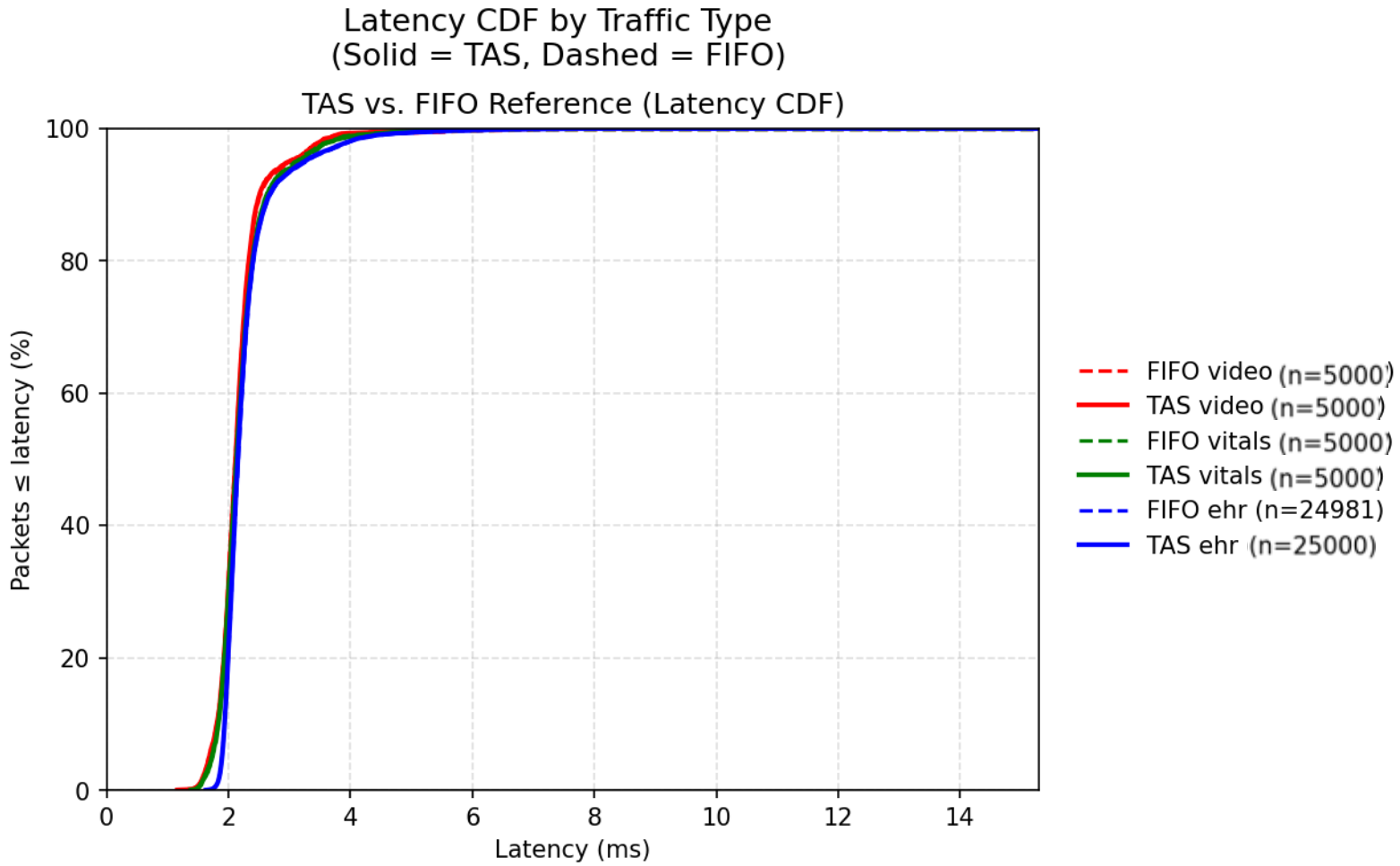
Part 2| *17 Feet - Base case : 11.2 Mbps - Run #2 - TAS*

TAS (Most of it within 8ms)



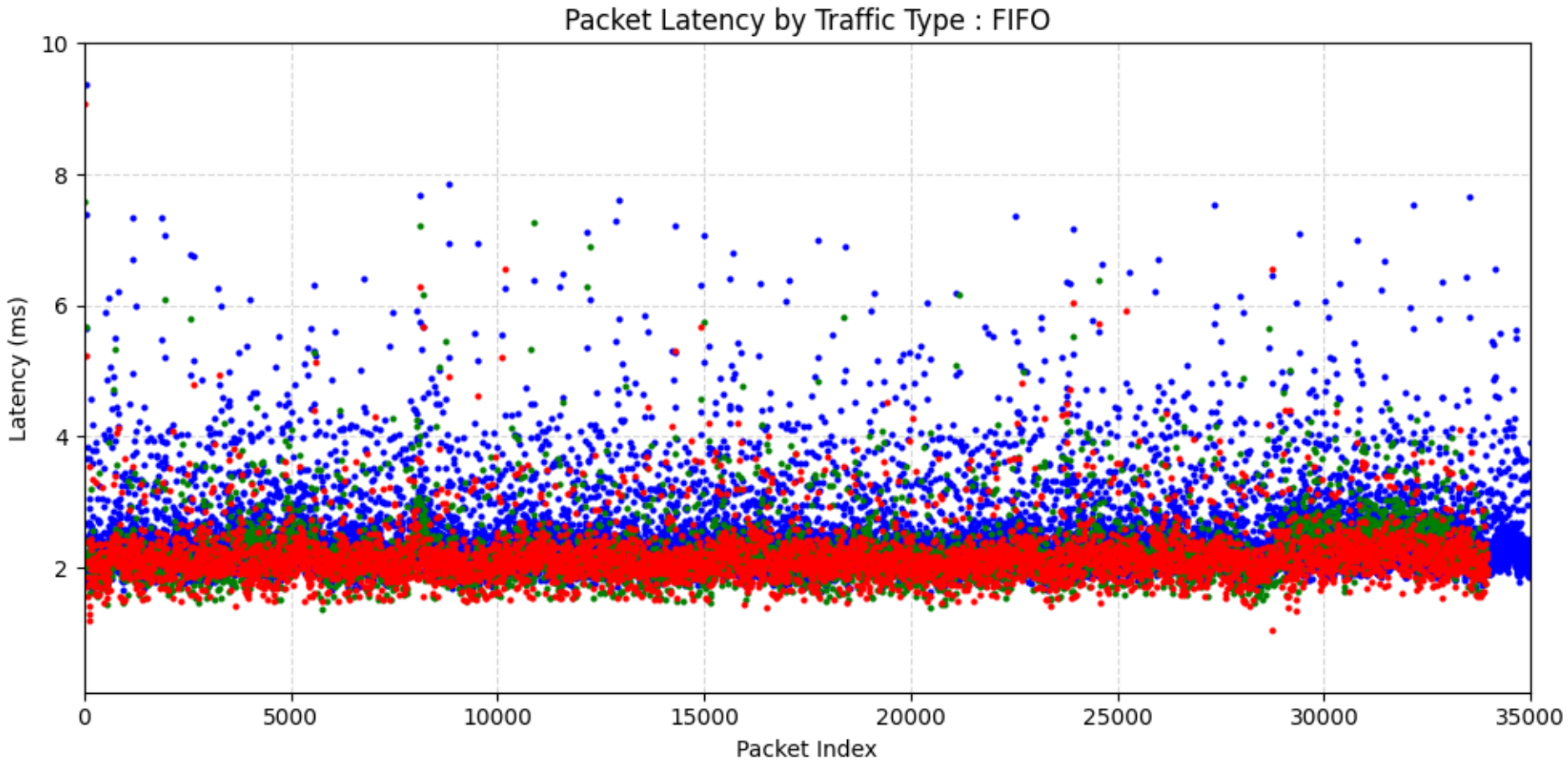
Part 2| *17 Feet - Base case : 11.2 Mbps - Run #1 – FIFO vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

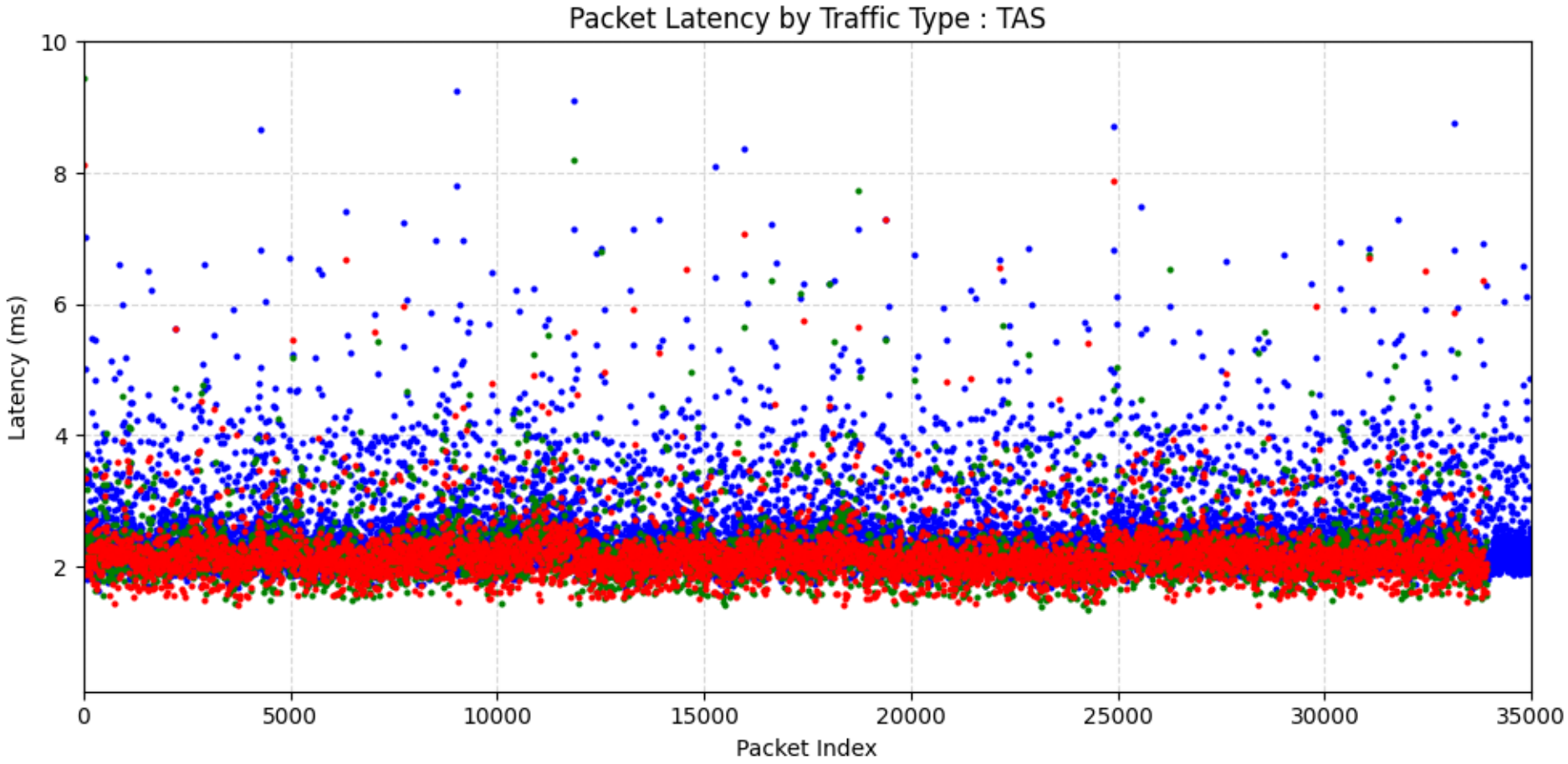


Part 2| *17 Feet - Base case : 11.2 Mbps - Run #3 - FIFO*

FIFO ()

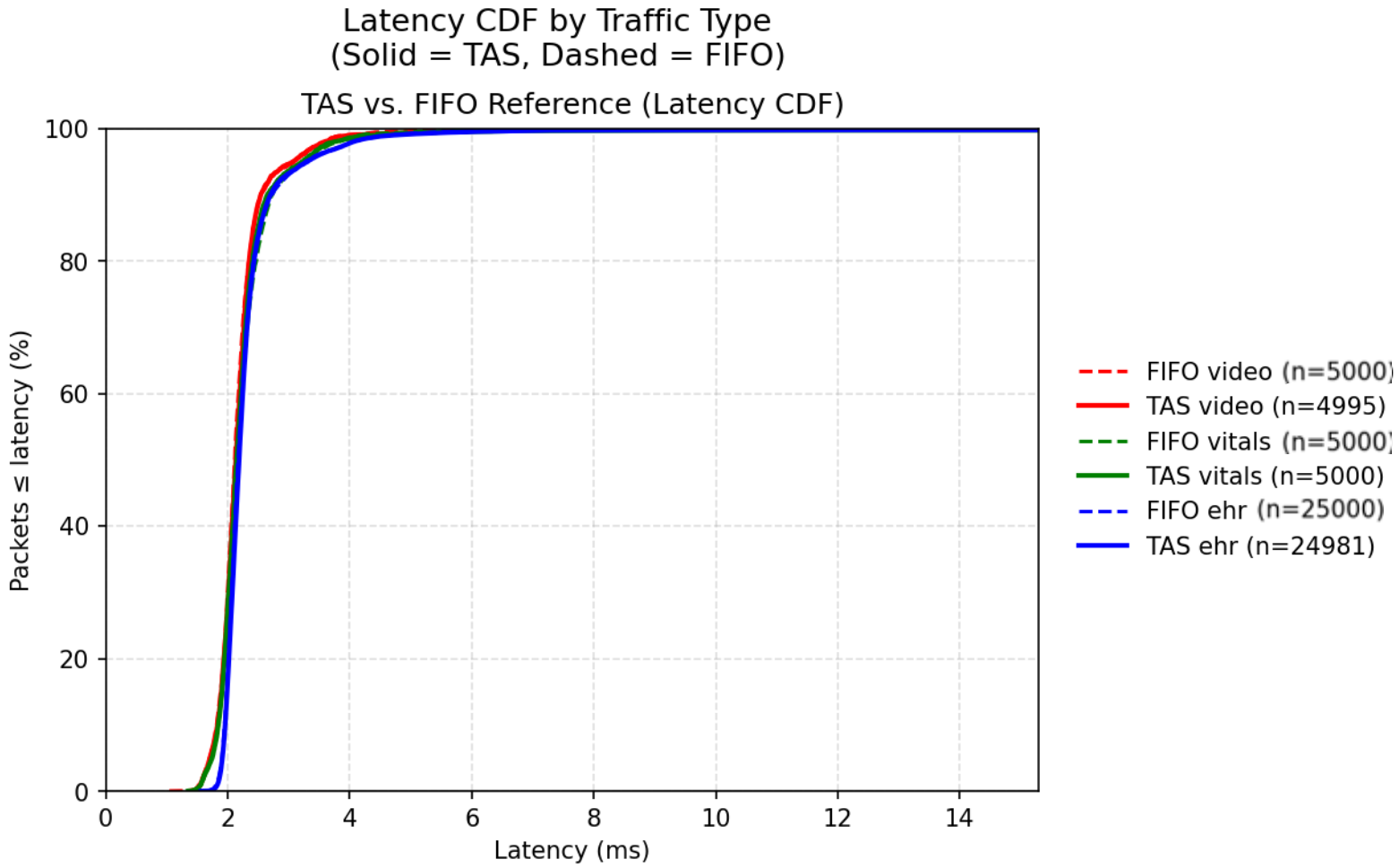


Part 2| *17 Feet - Base case : 11.2 Mbps - Run #3 - TAS*

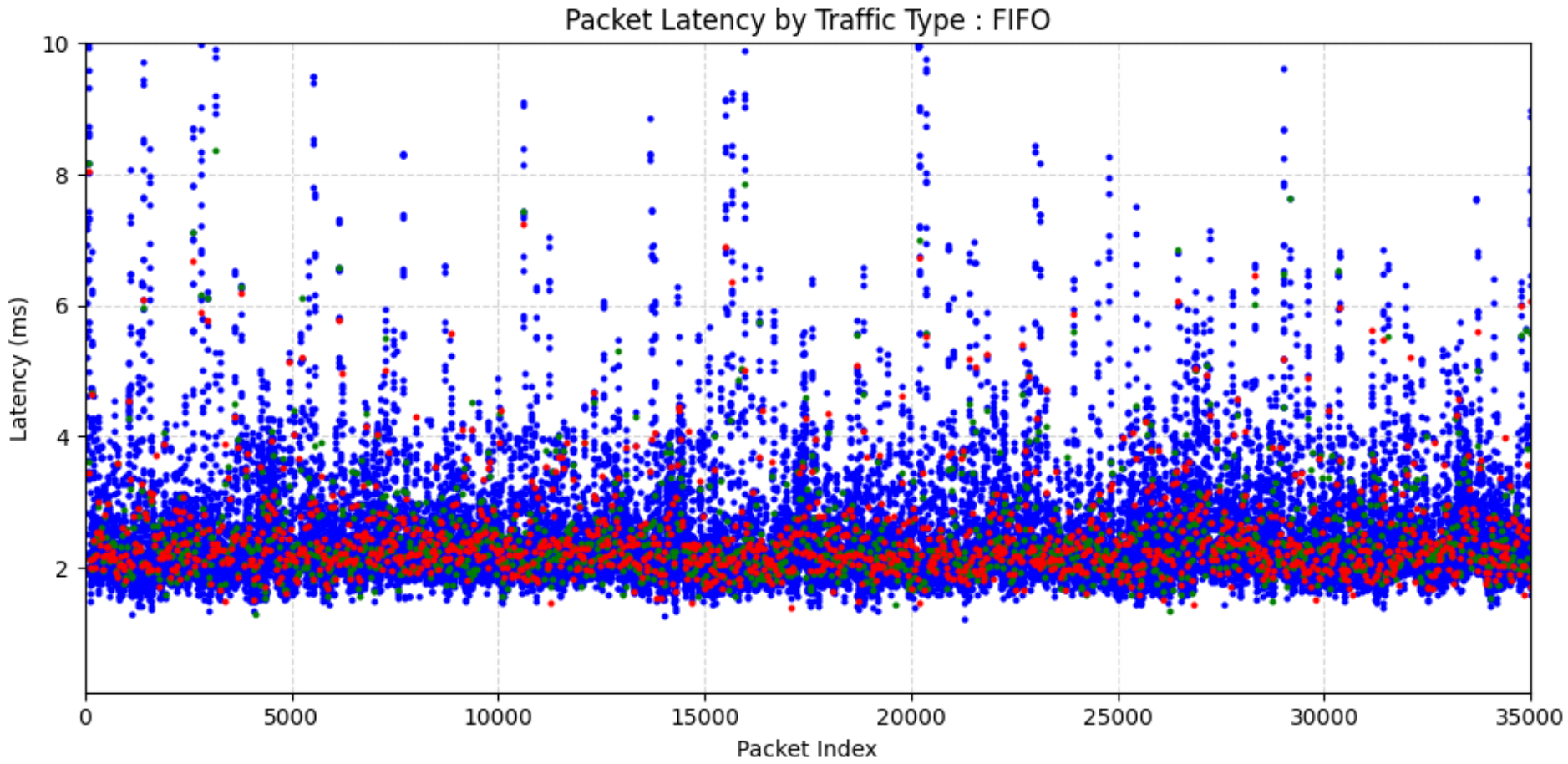


Part 2| *17 Feet - Base case : 11.2 Mbps - Run #3 – FIFO vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

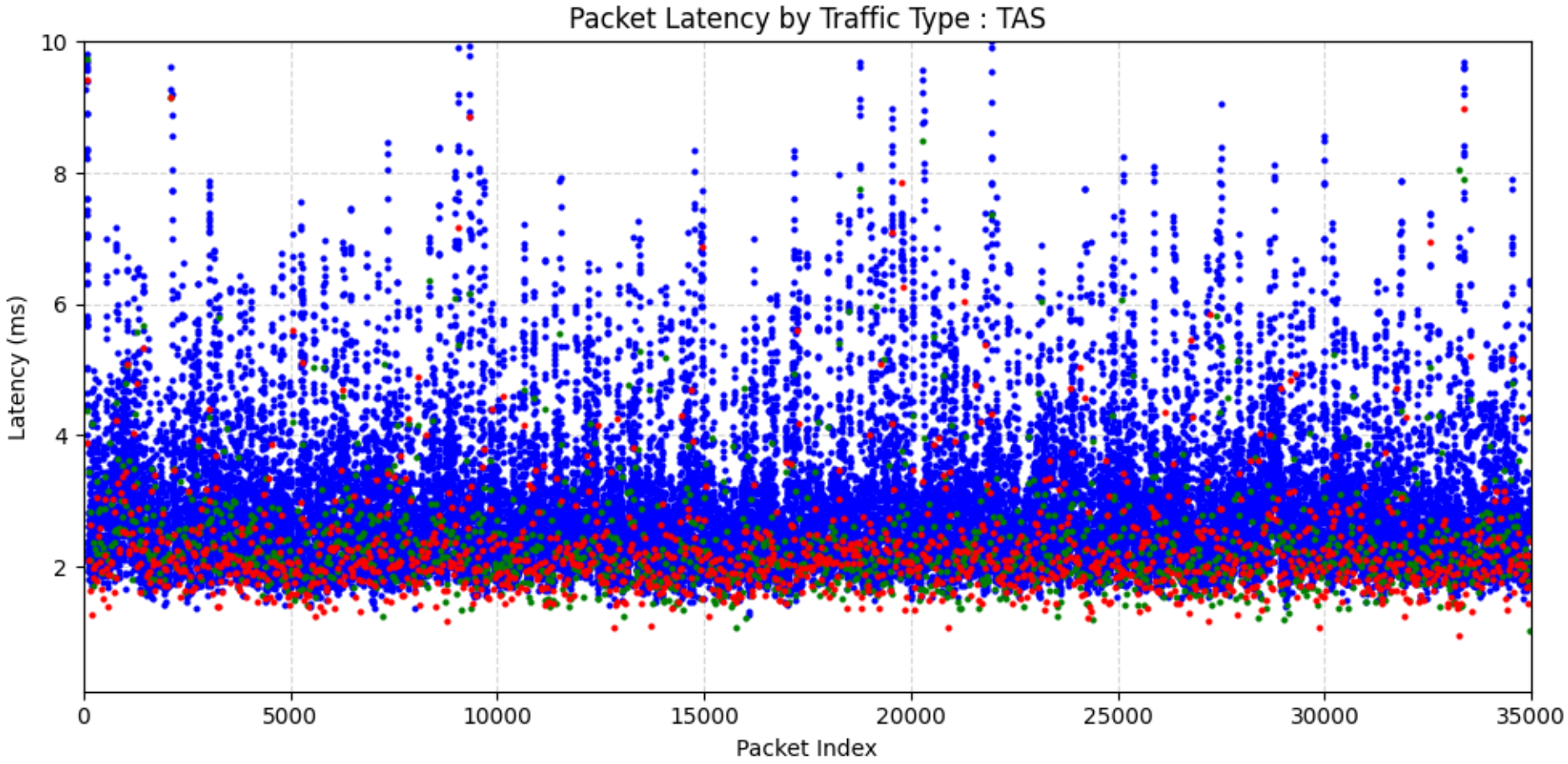


Part 2| *17 Feet - 5% of Linkspeed -25 Mbps - Run #1 – FIFO* *(using traffic_log3)*



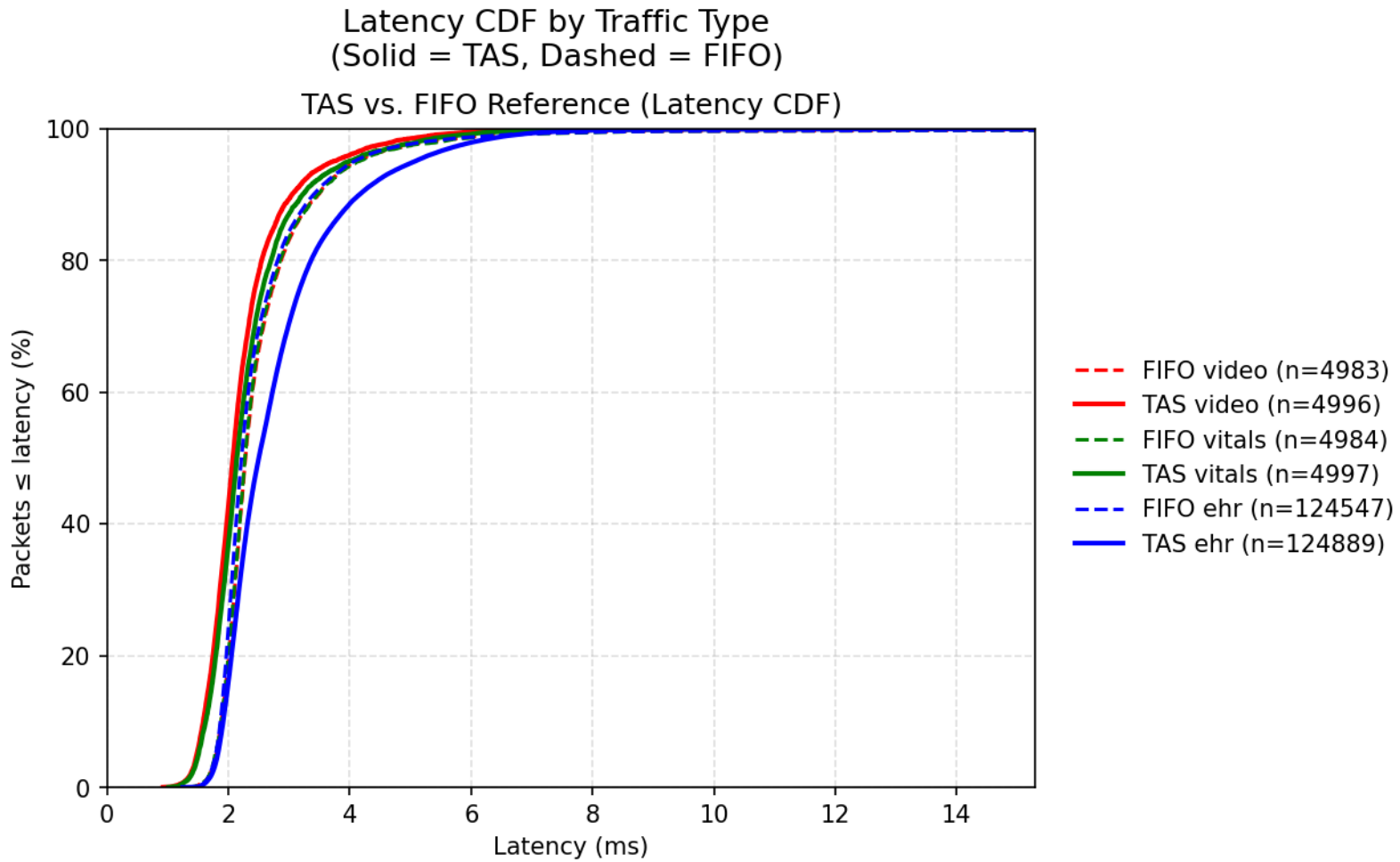
Part 2| *17 Feet - 25 Mbps - Run #1 - TAS*

TAS (Most of it within 8ms)

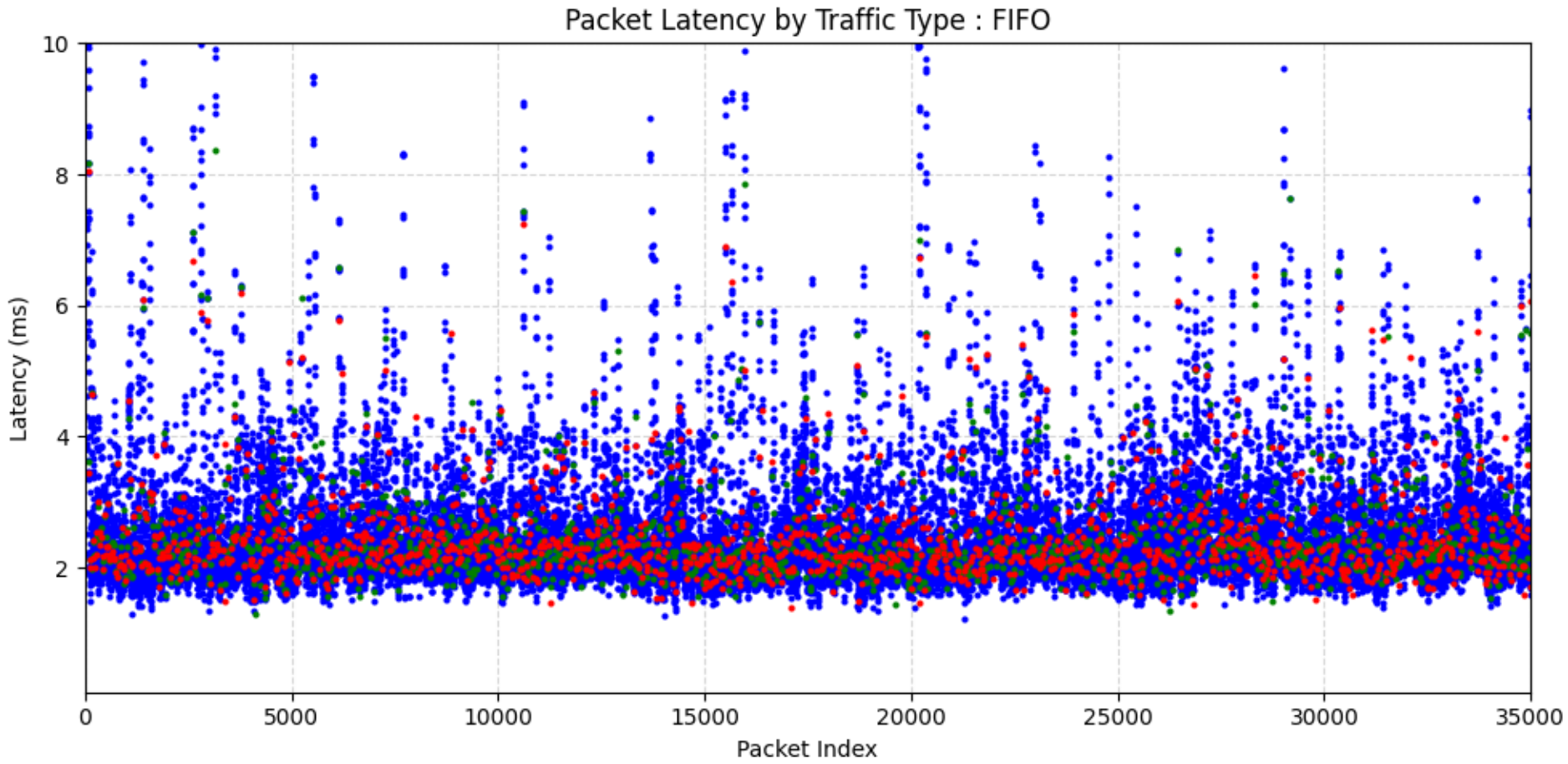


Part 2| *17 Feet - 25 Mbps - Run #1 – FIFO vs TAS*

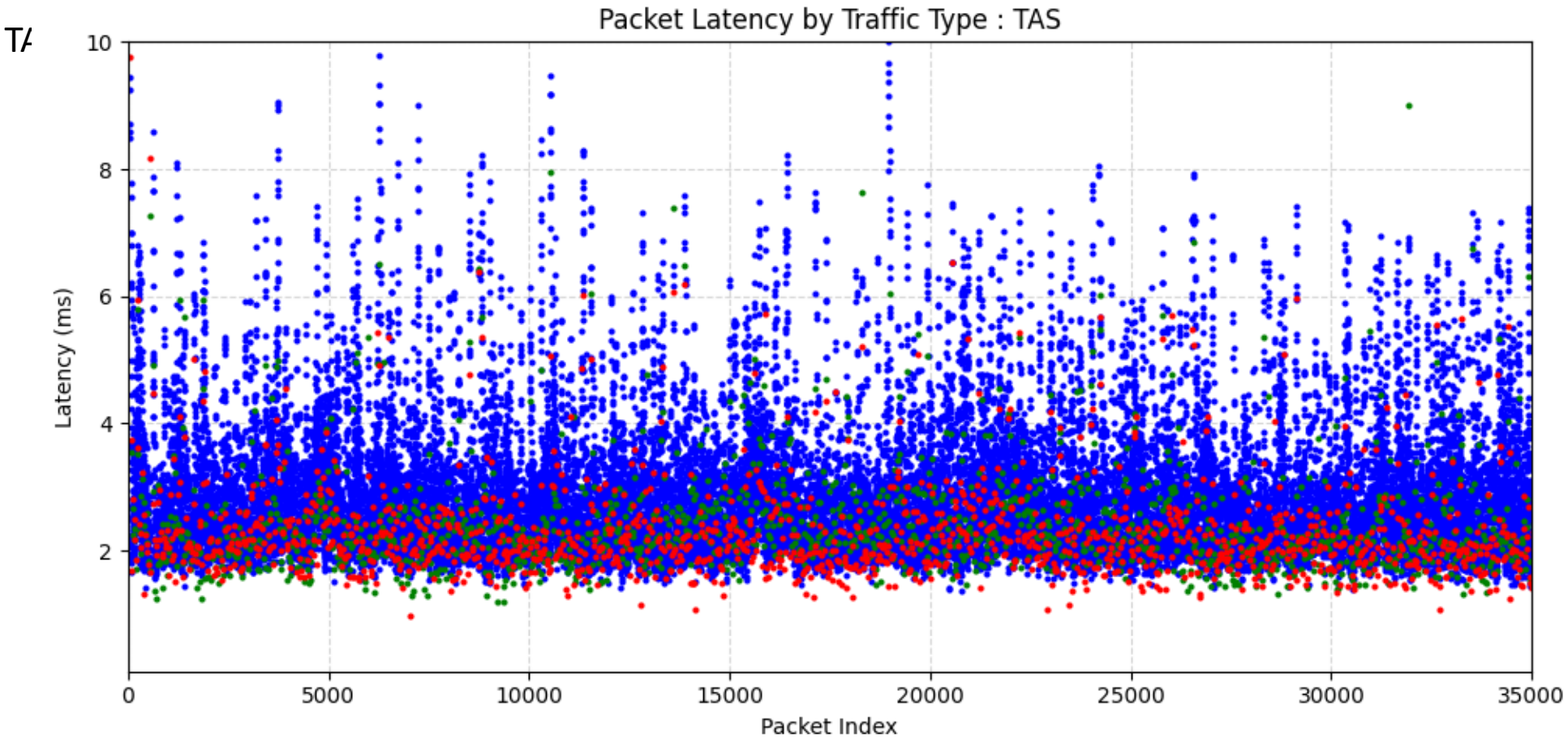
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



Part 2| *17 Feet - 5% of Linkspeed -25 Mbps - Run #2 – FIFO* *(using traffic_log3)*

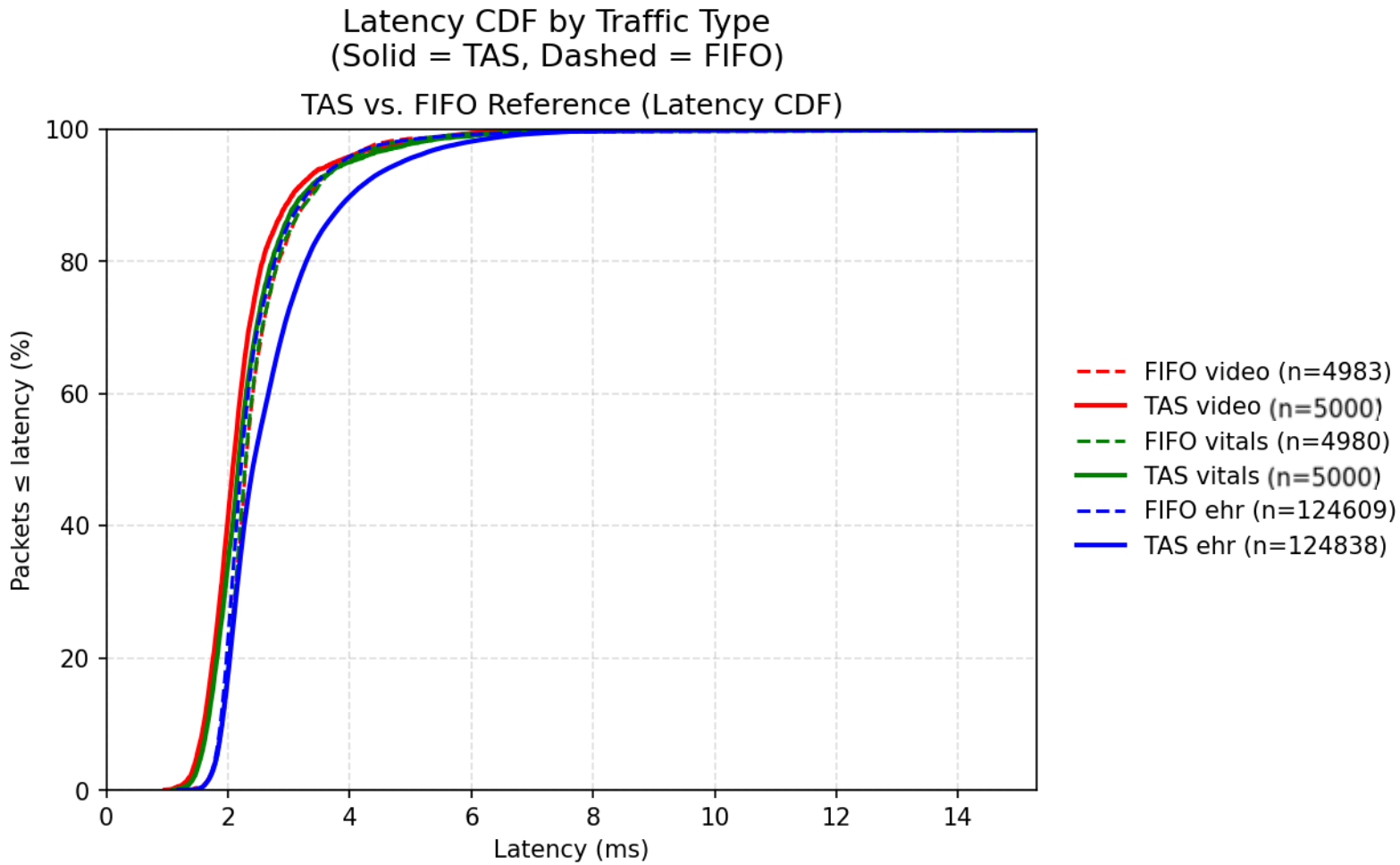


Part 2| *17 Feet - 25 Mbps - Run #2 - TAS*

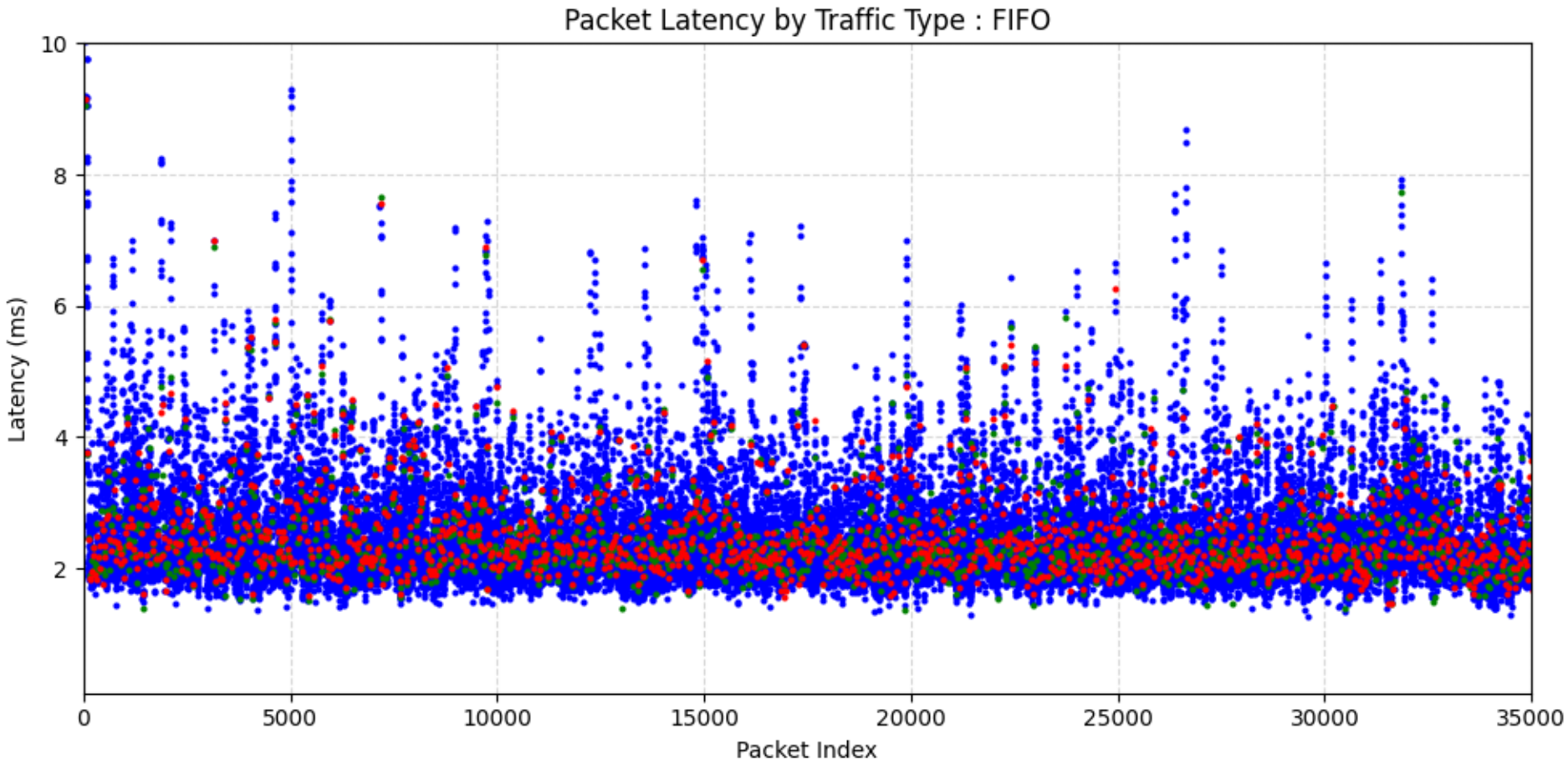


Part 2| *17 Feet - 25 Mbps - Run #2 – FIFO vs TAS*

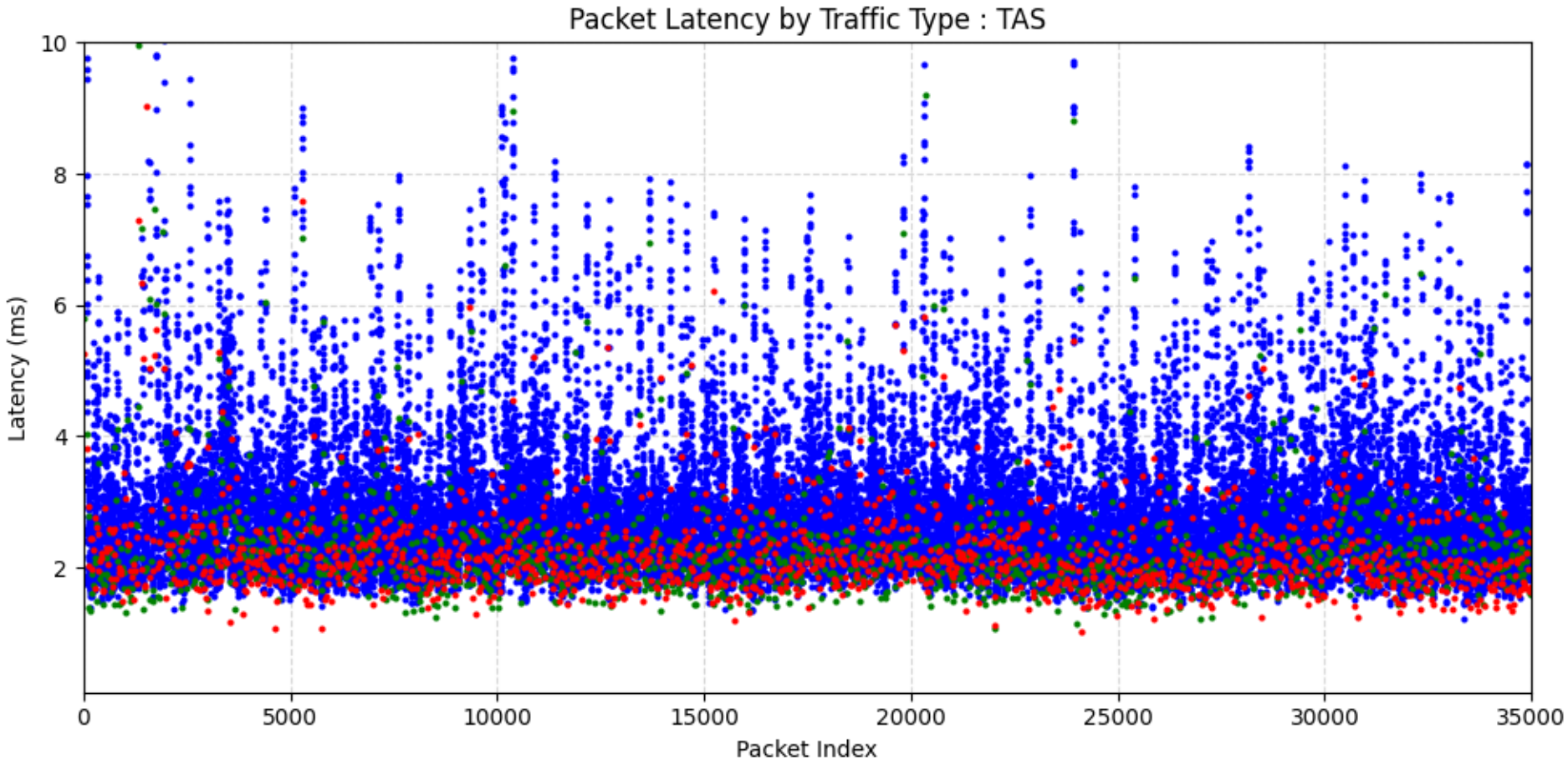
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



Part 2| *17 Feet - 5% of Linkspeed -25 Mbps - Run #3 – FIFO* *(using traffic_log3)*

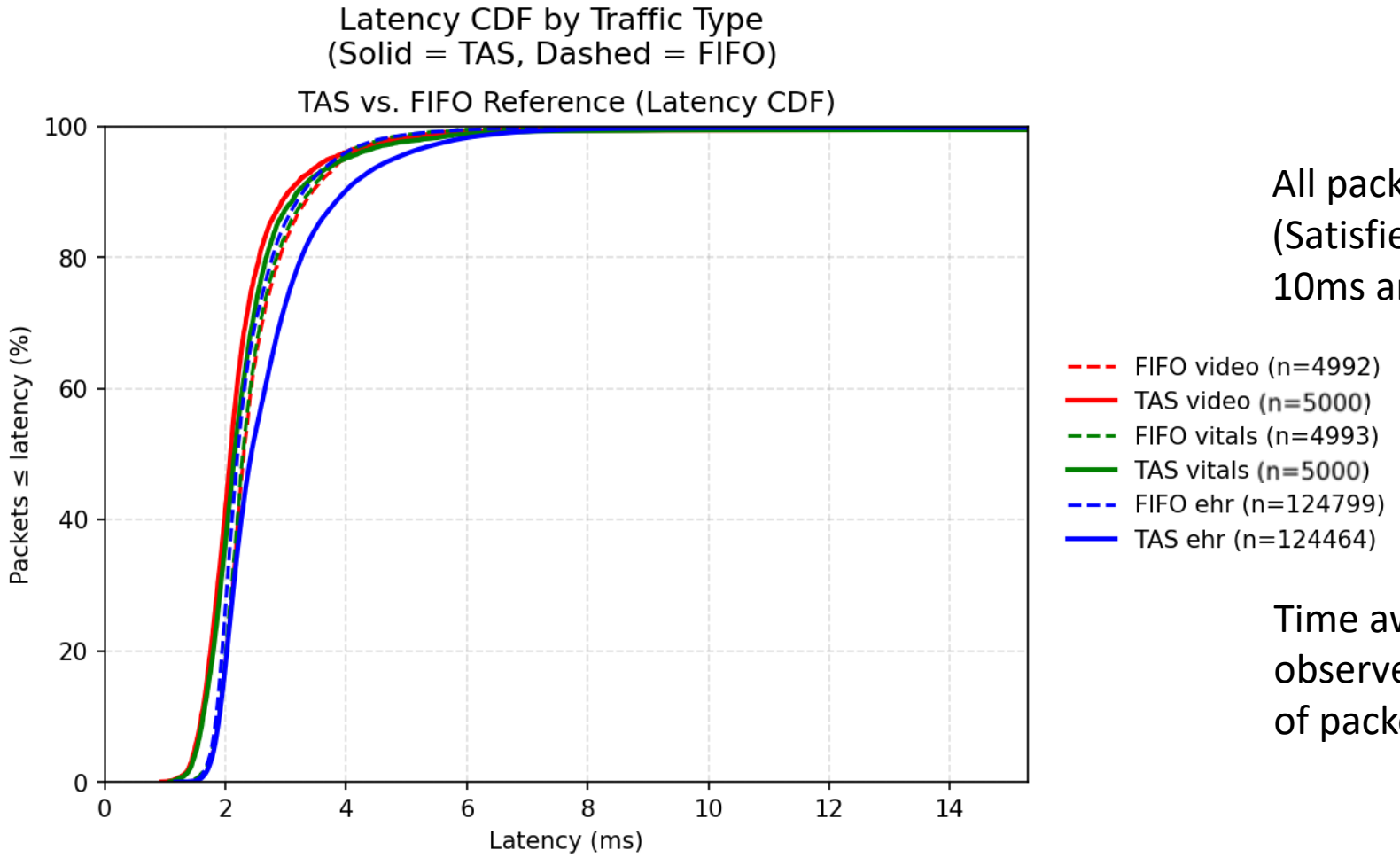


Part 2| *17 Feet - 25 Mbps - Run #3 - TAS*



Part 2| *17 Feet - 25 Mbps - Run #3 – FIFO vs TAS*

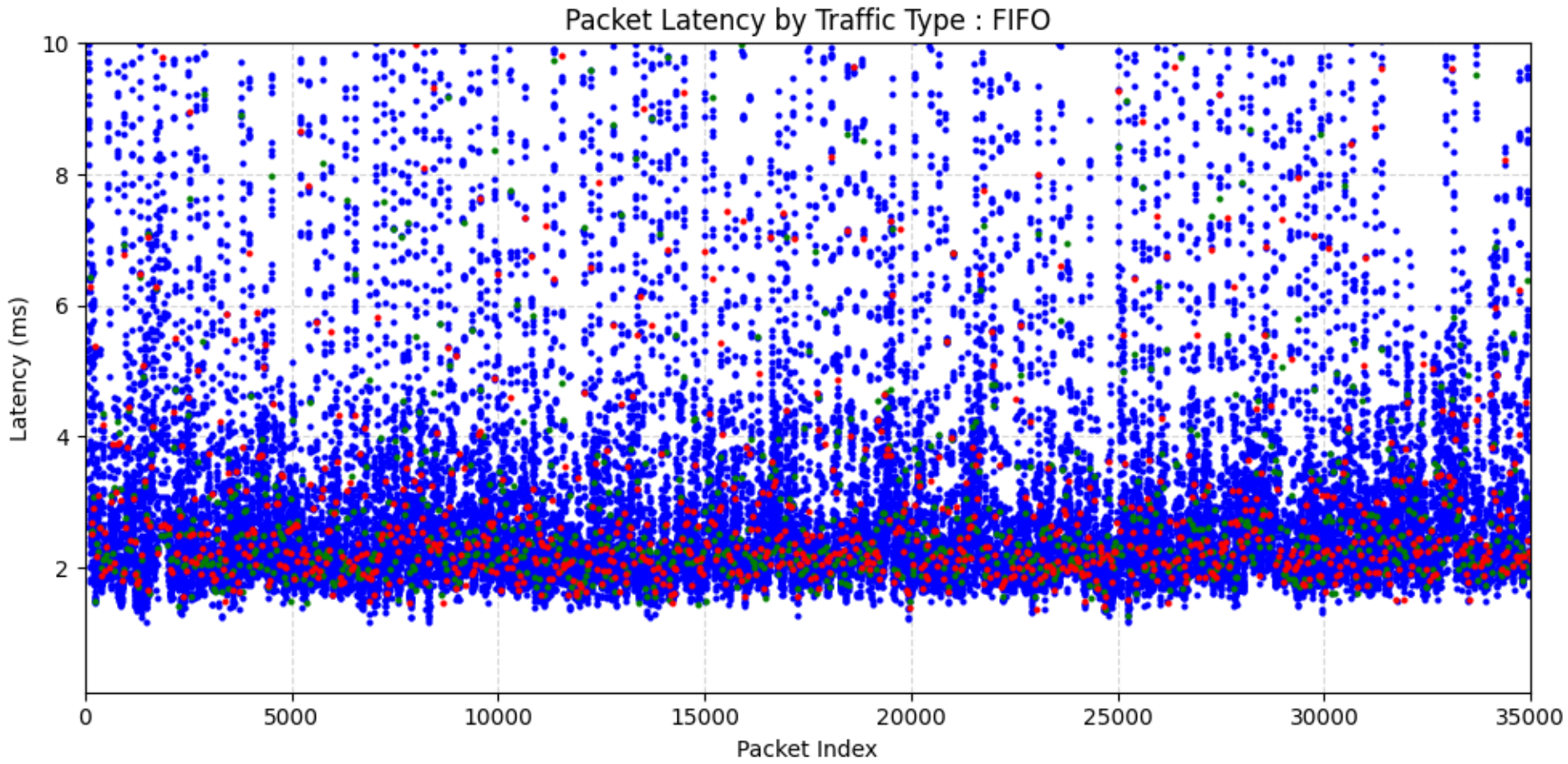
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



All packets bound within 10ms (Satisfies Class B requirements of 10ms and packetloss <.1%)

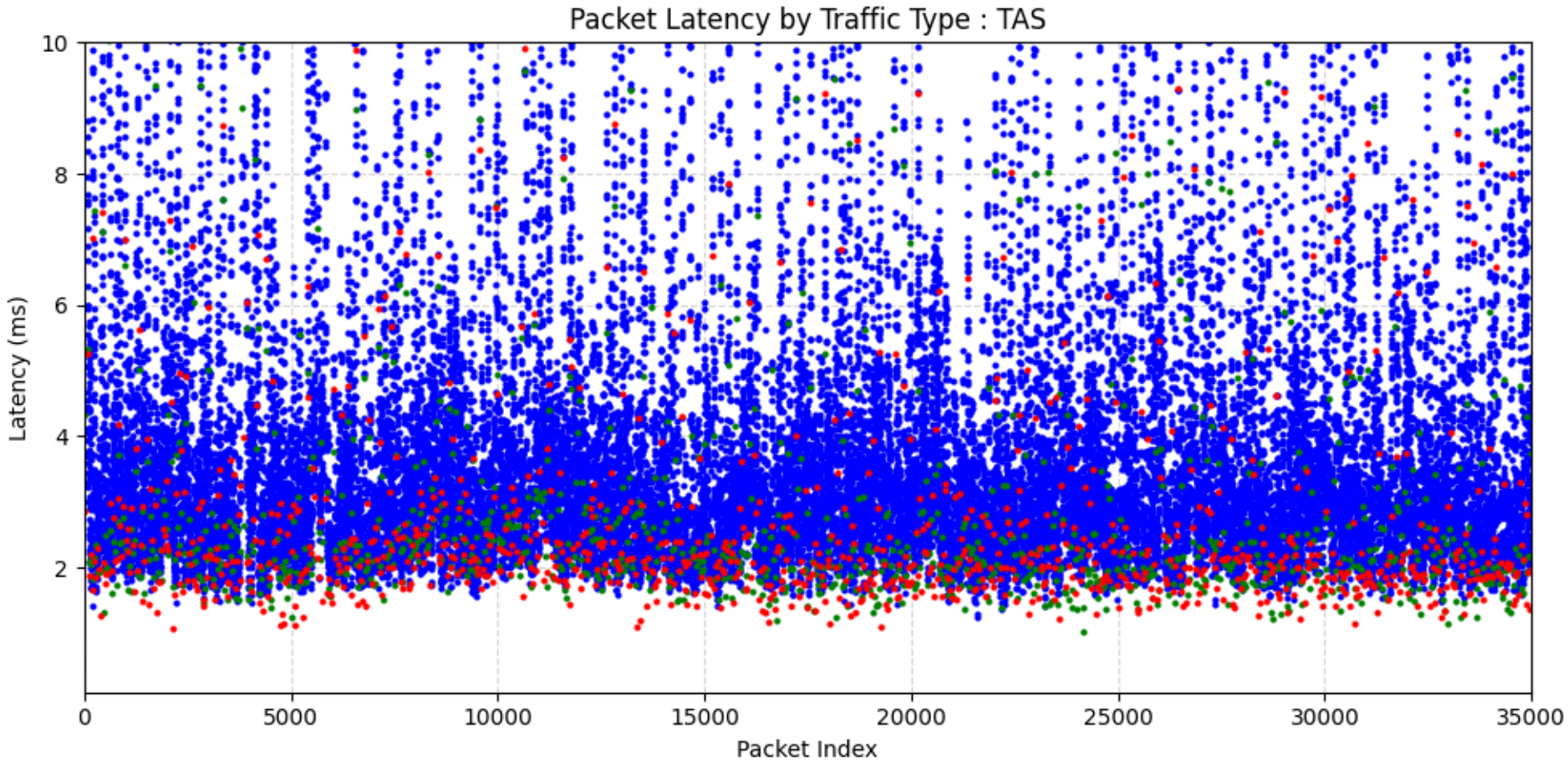
Time aware shaping is observed to reduce chances of packet loss

Part 2| *17 Feet - 10% of Linkspeed -50 Mbps - Run #1 – FIFO* *(using traffic_log2)*



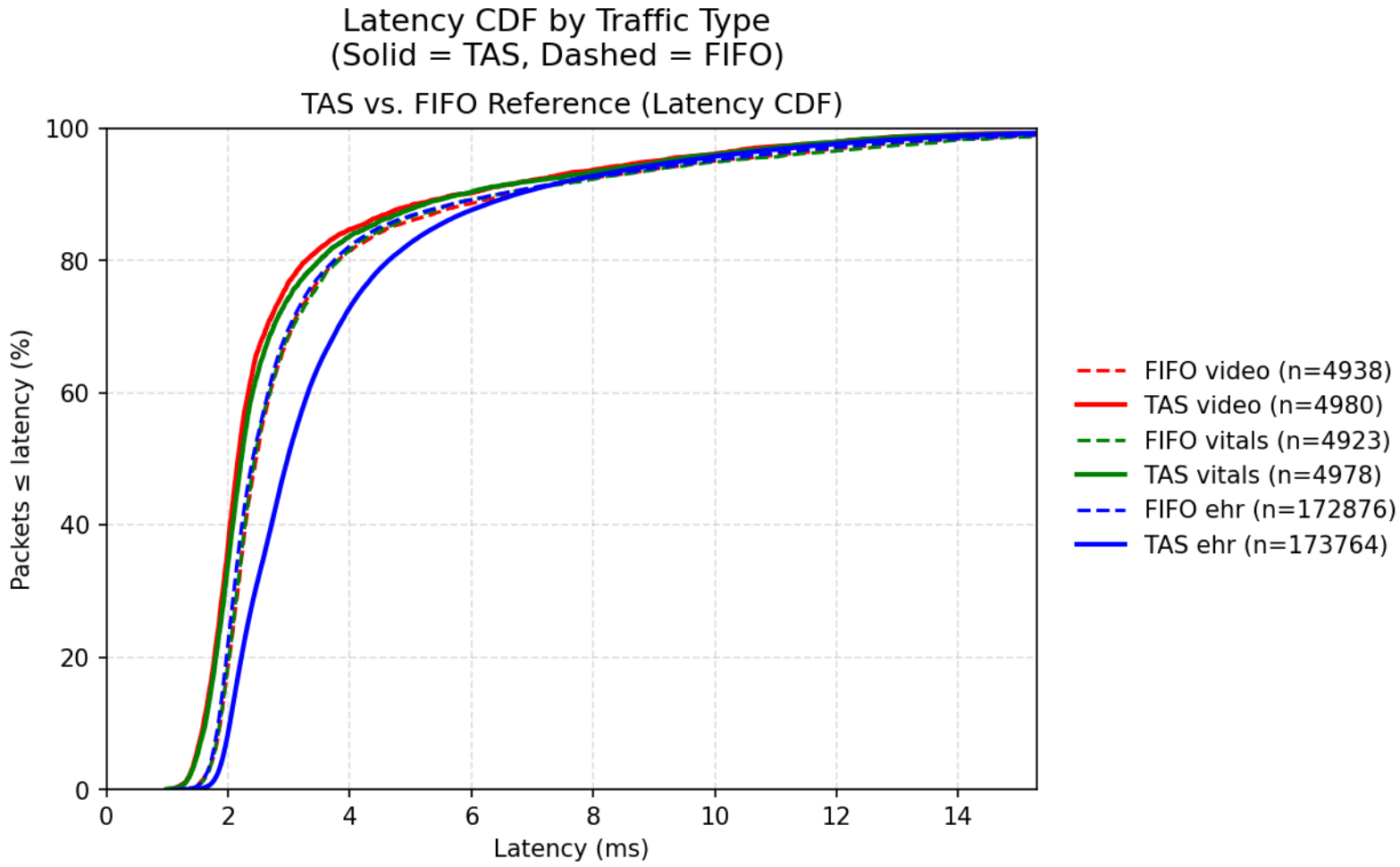
Part 2| *17 Feet - 50 Mbps - Run #1 - TAS*

TAS (Most of it within 8ms)

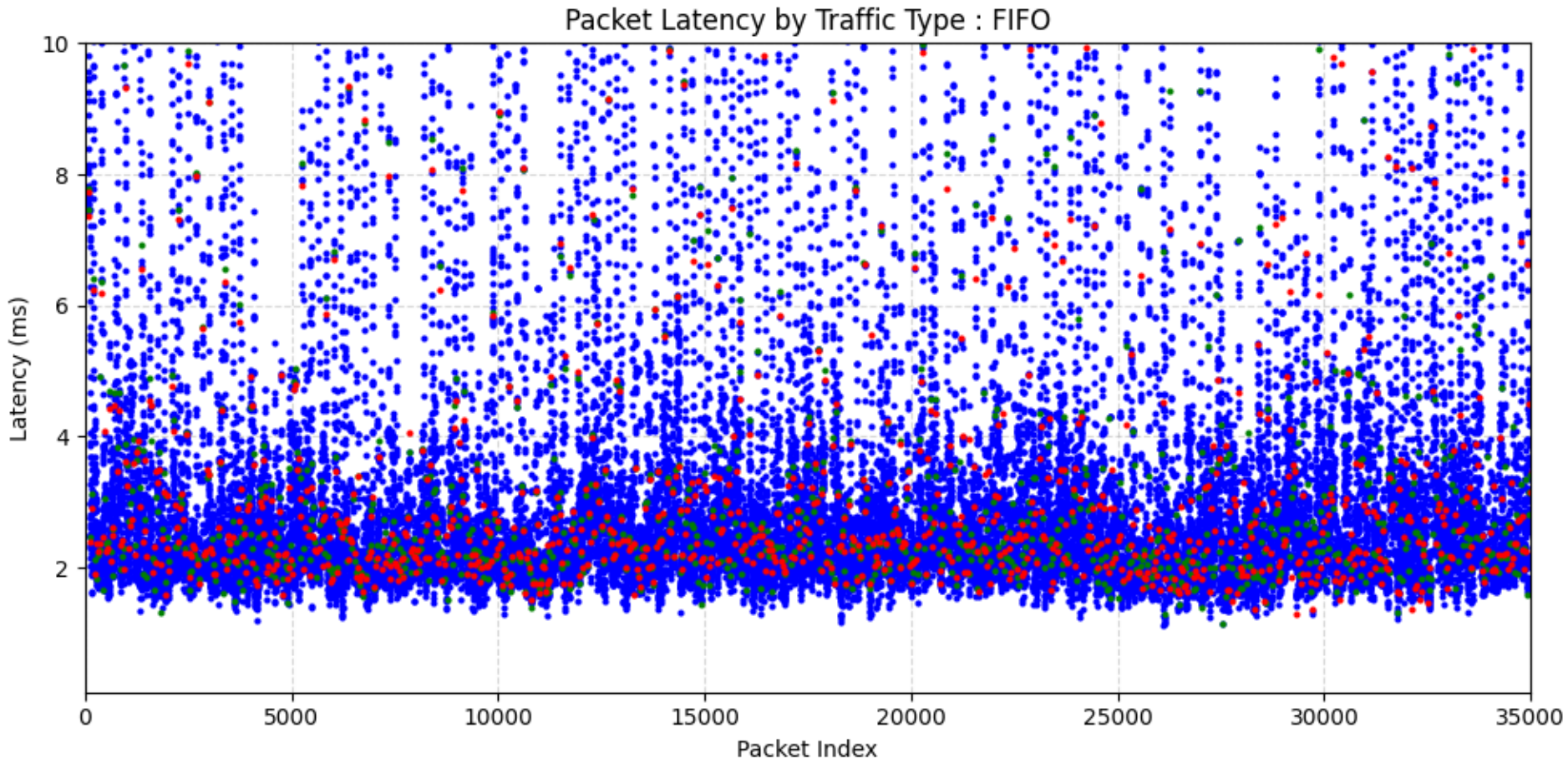


Part 2| *17 Feet - 50 Mbps - Run #1 – FIFO vs TAS*

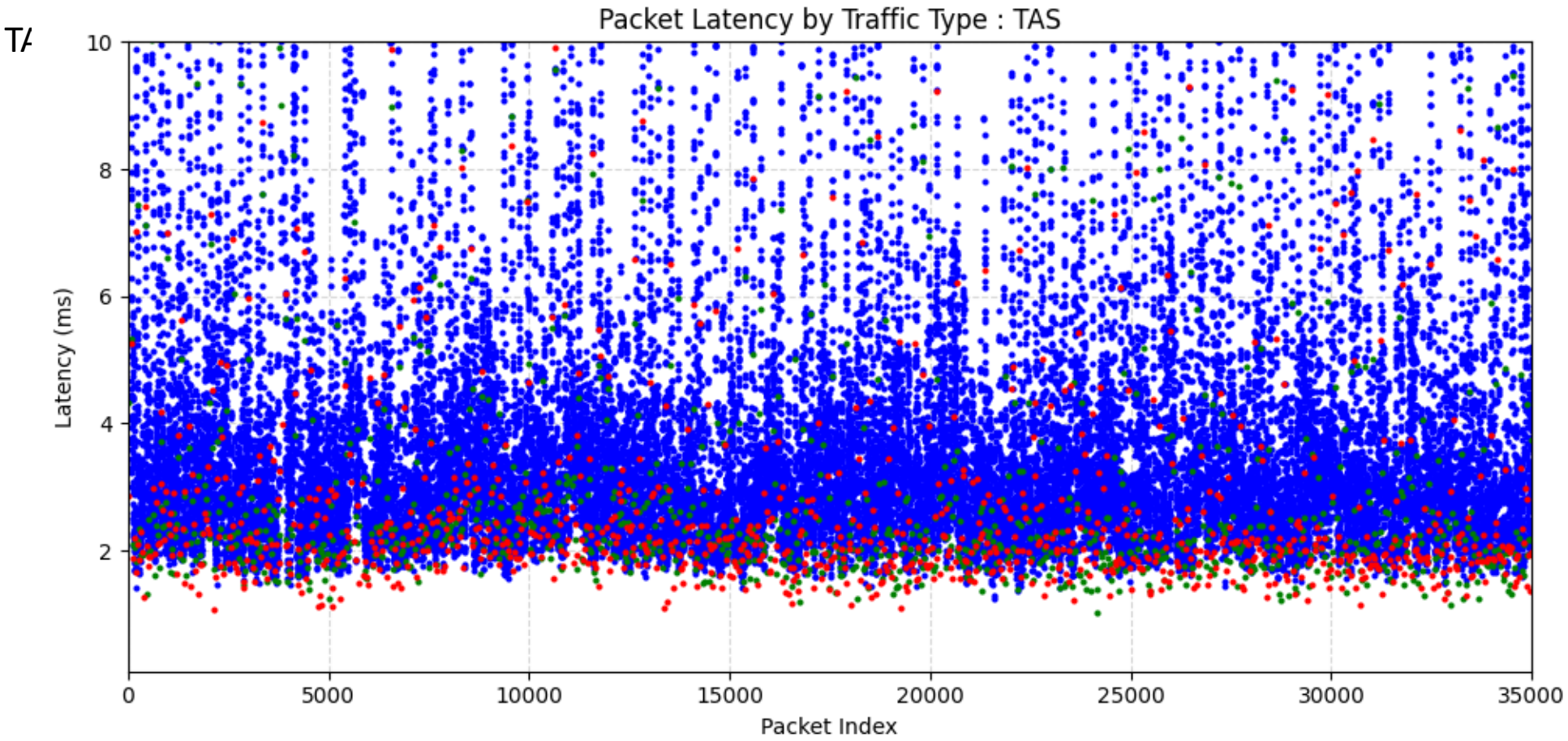
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



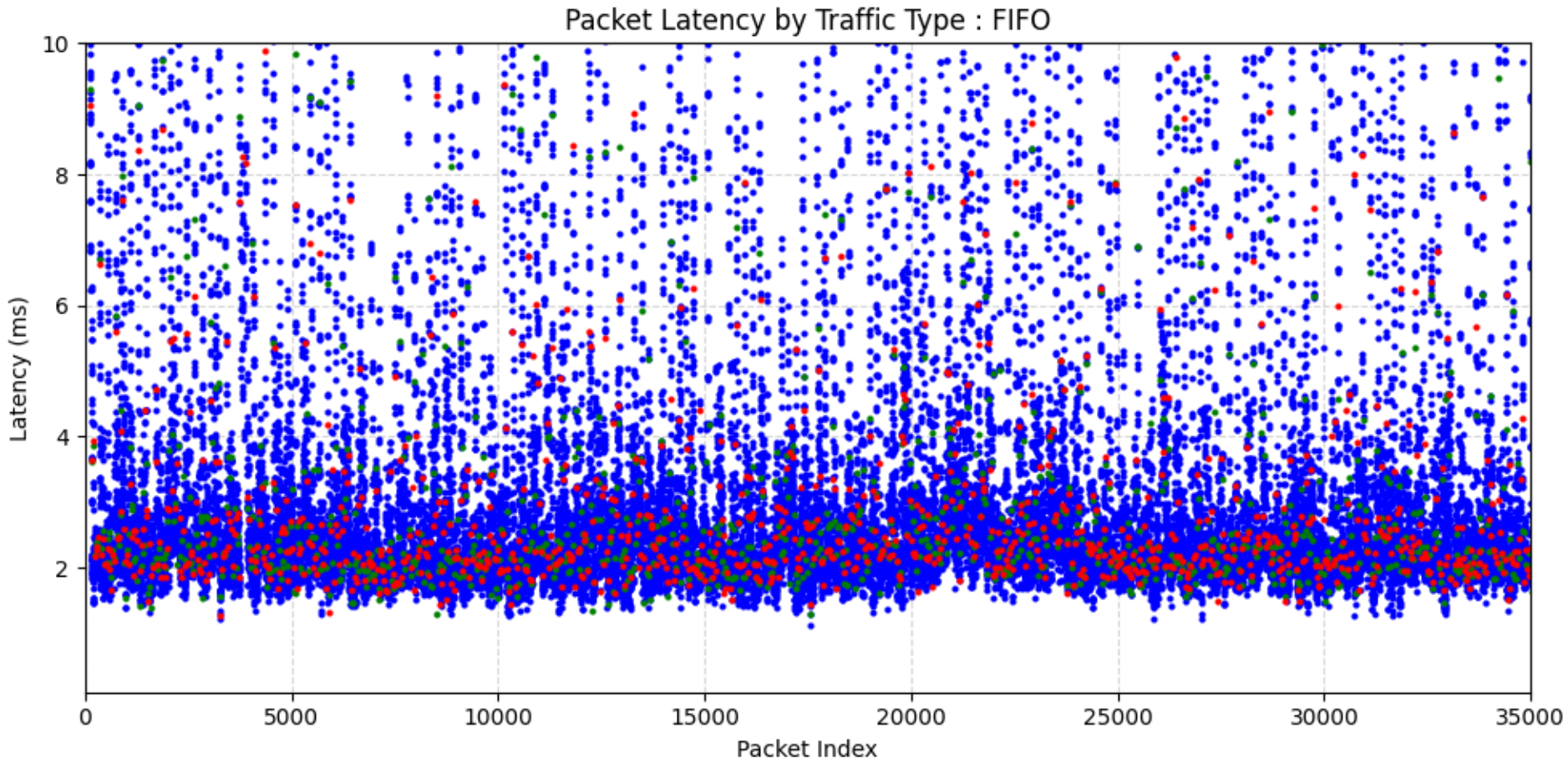
Part 2| *17 Feet - 10% of Linkspeed -50 Mbps - Run #2 – FIFO* *(using traffic_log2)*



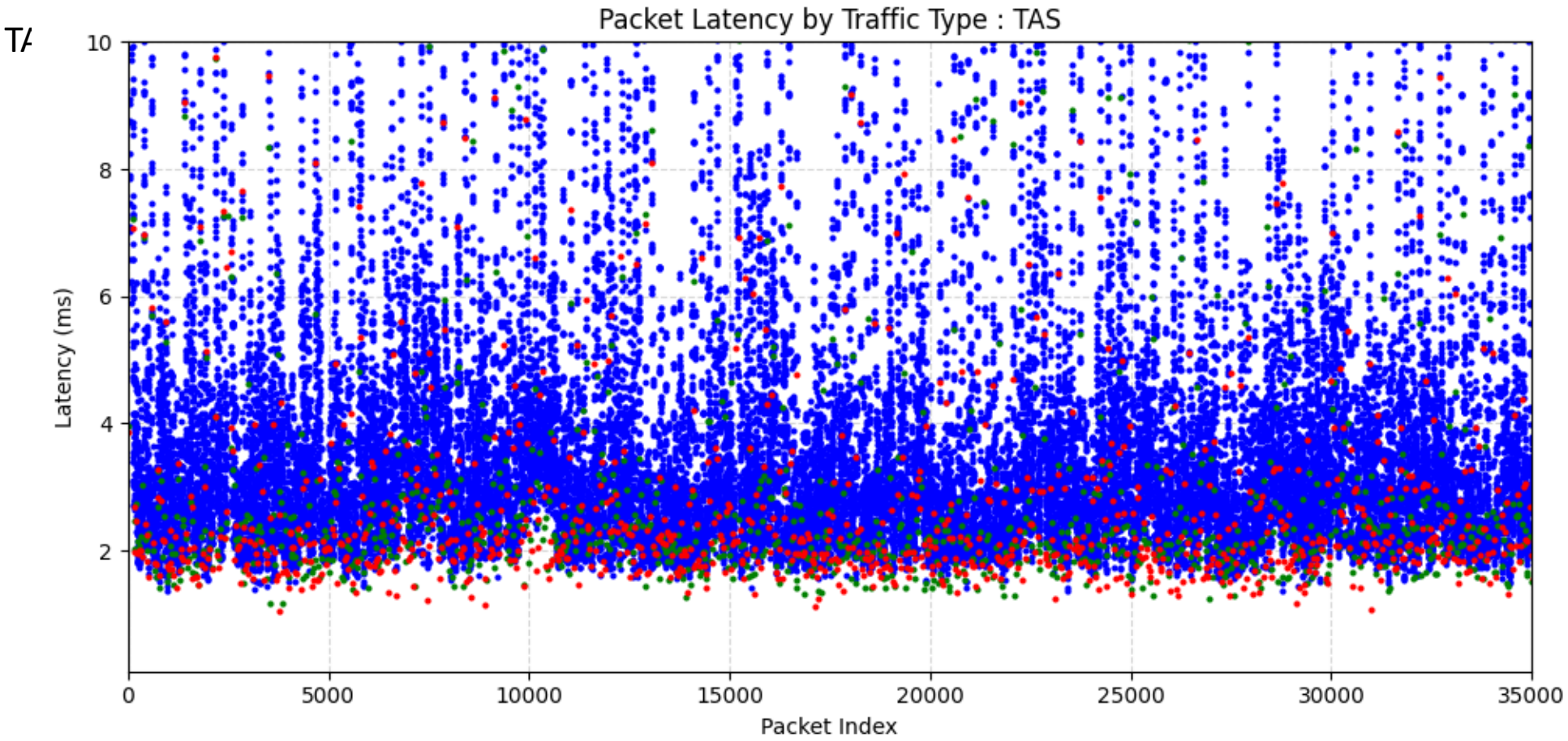
Part 2| *17 Feet - 50 Mbps - Run #2 - TAS*



Part 2| *17 Feet - 10% of Linkspeed -50 Mbps - Run #3 – FIFO* *(using traffic_log2)*

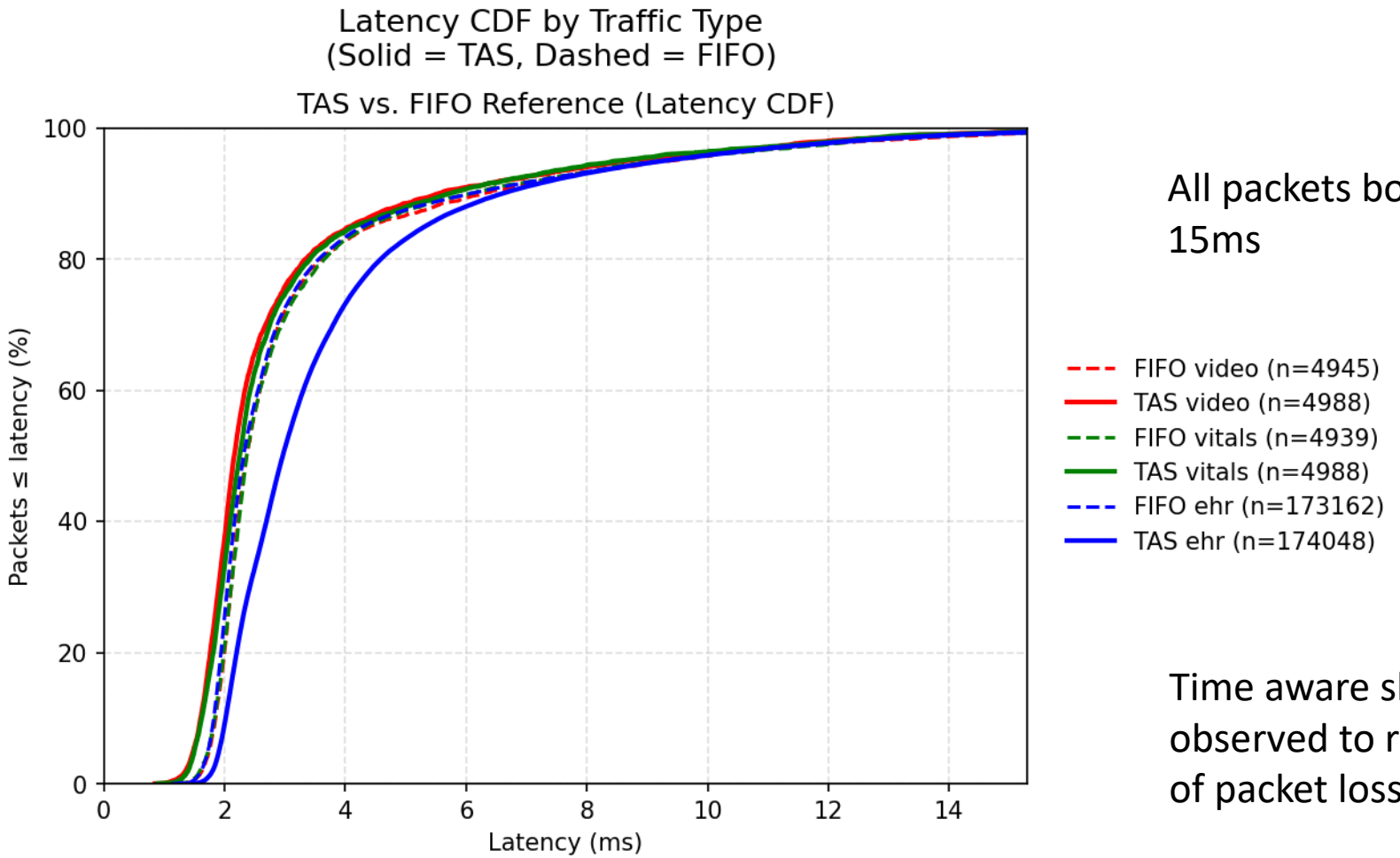


Part 2| *17 Feet - 50 Mbps - Run #3 - TAS*



Part 2| *17 Feet - 50 Mbps - Run #3 – FIFO vs TAS*

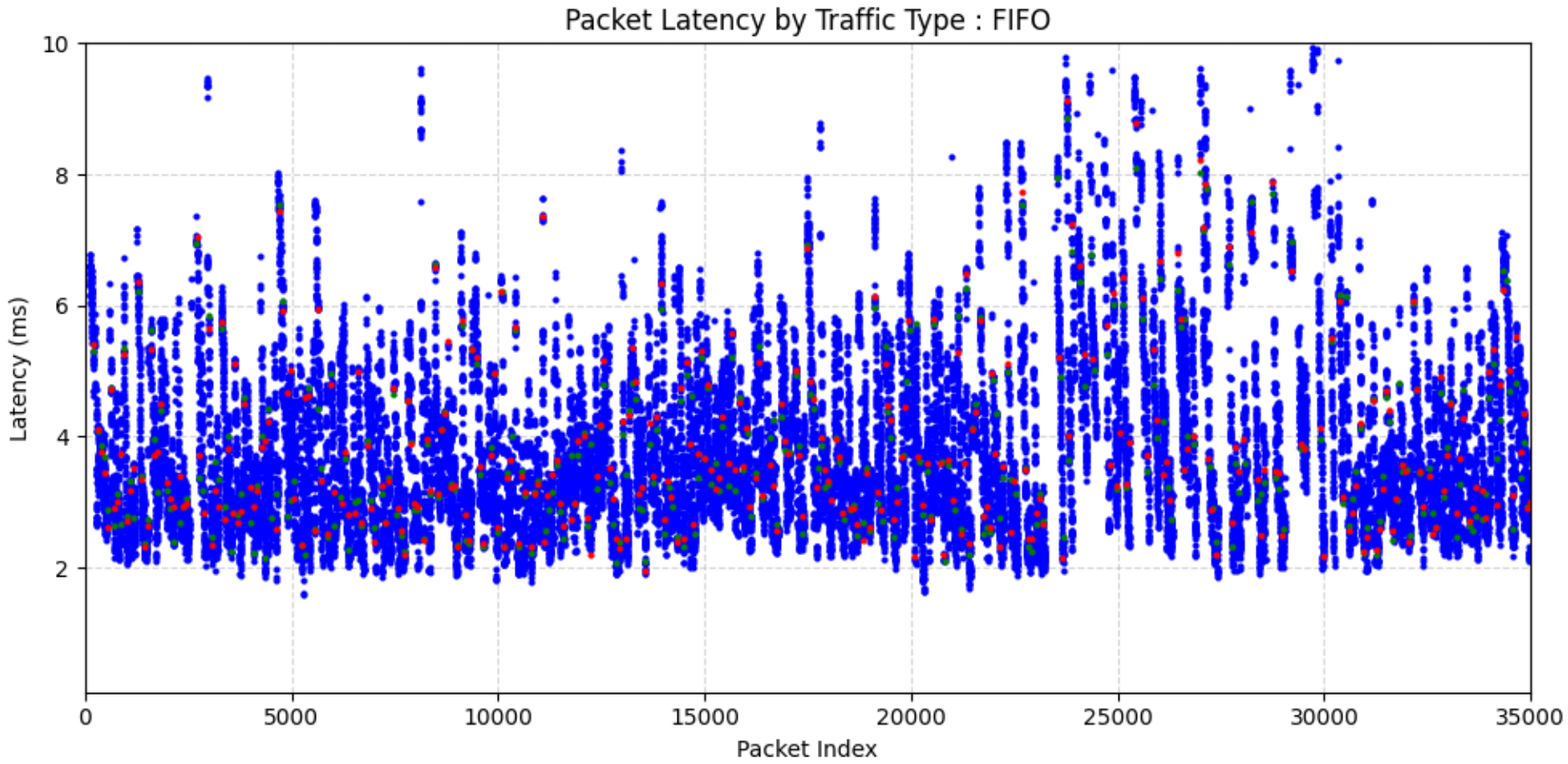
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



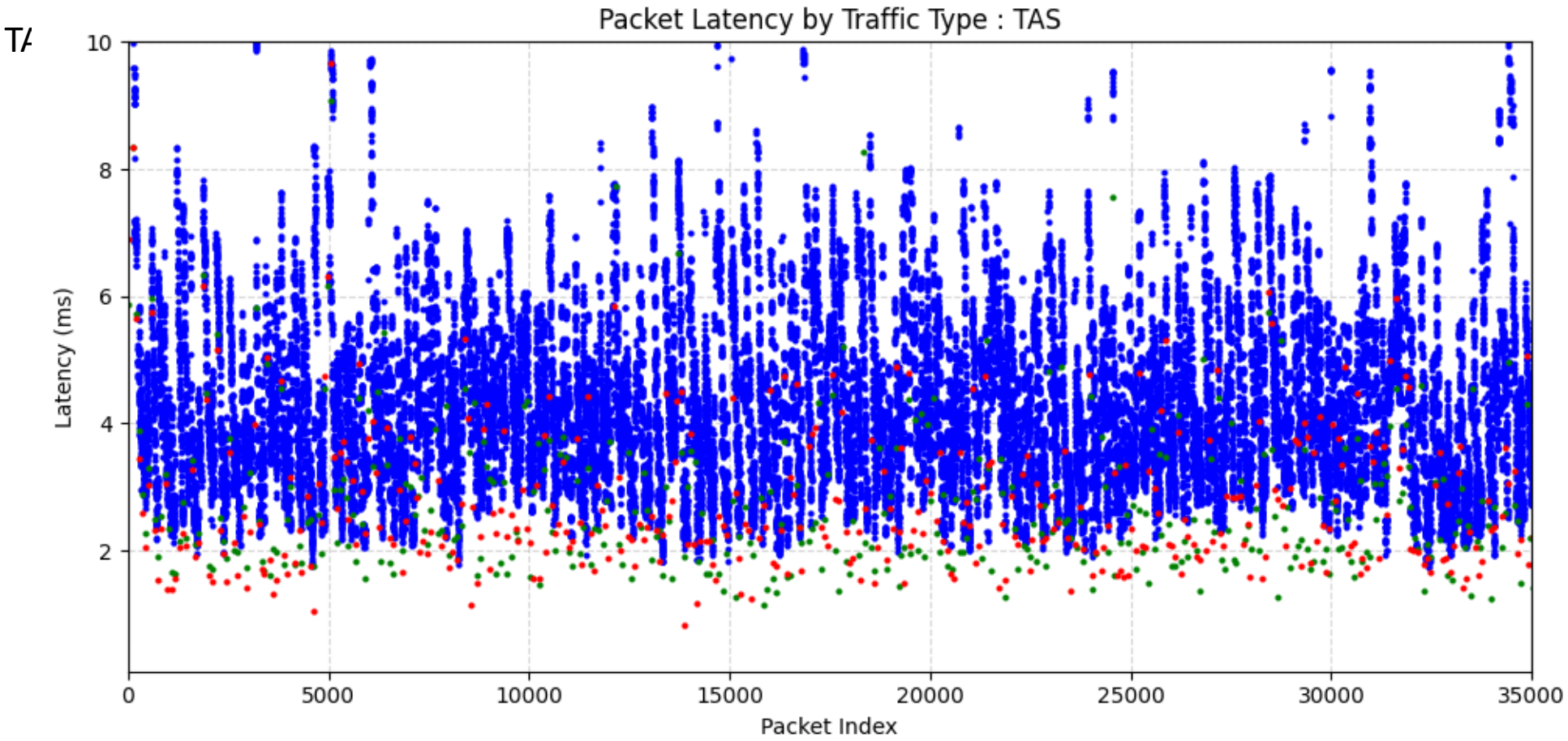
All packets bound within 15ms

Time aware shaping is observed to reducing chances of packet loss.

Part 2| *17 Feet - 20% of Linkspeed -100 Mbps - Run #1 – FIFO* *(using traffic_log2)*

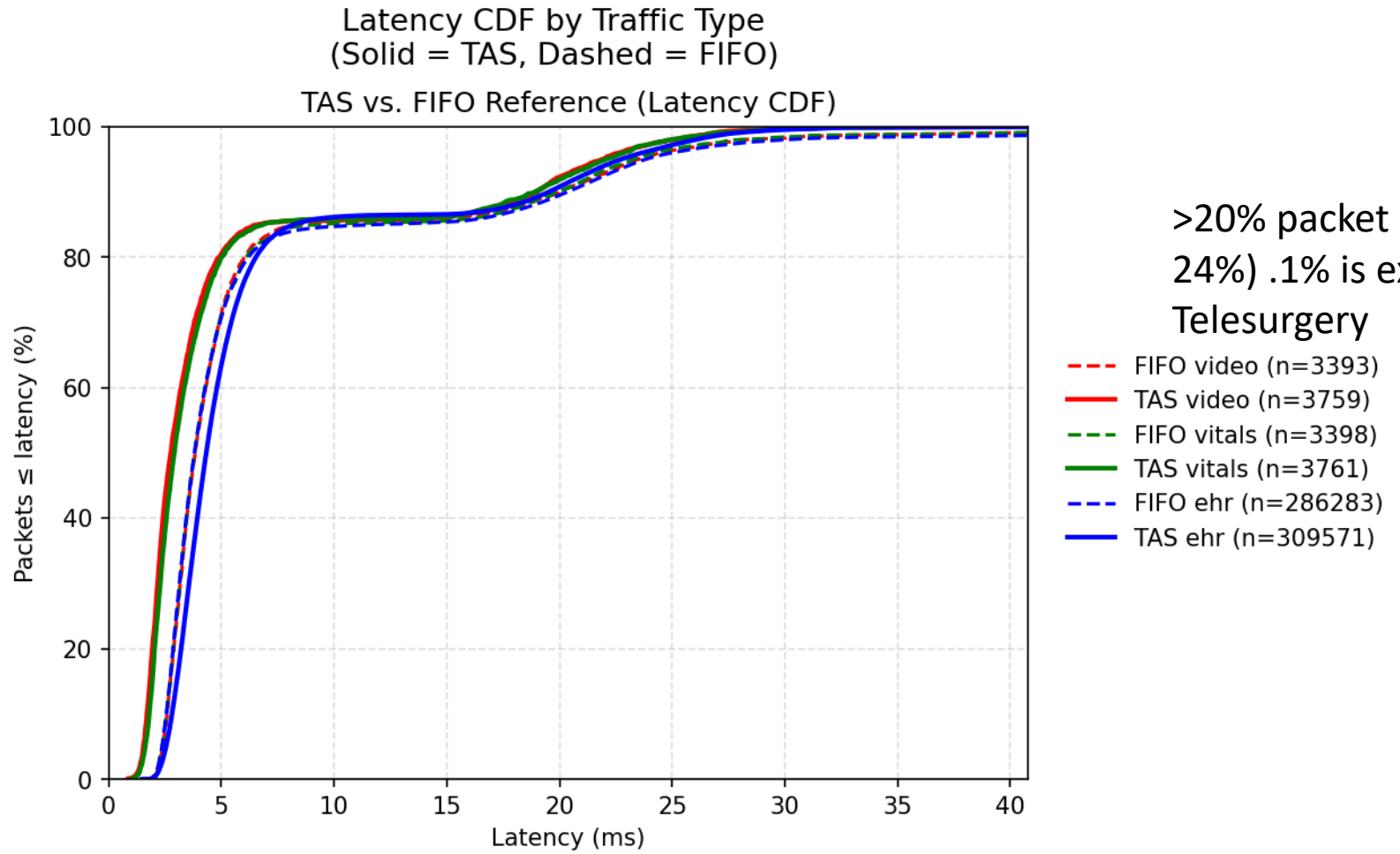


Part 2| *17 Feet - 100 Mbps - Run #1 - TAS*



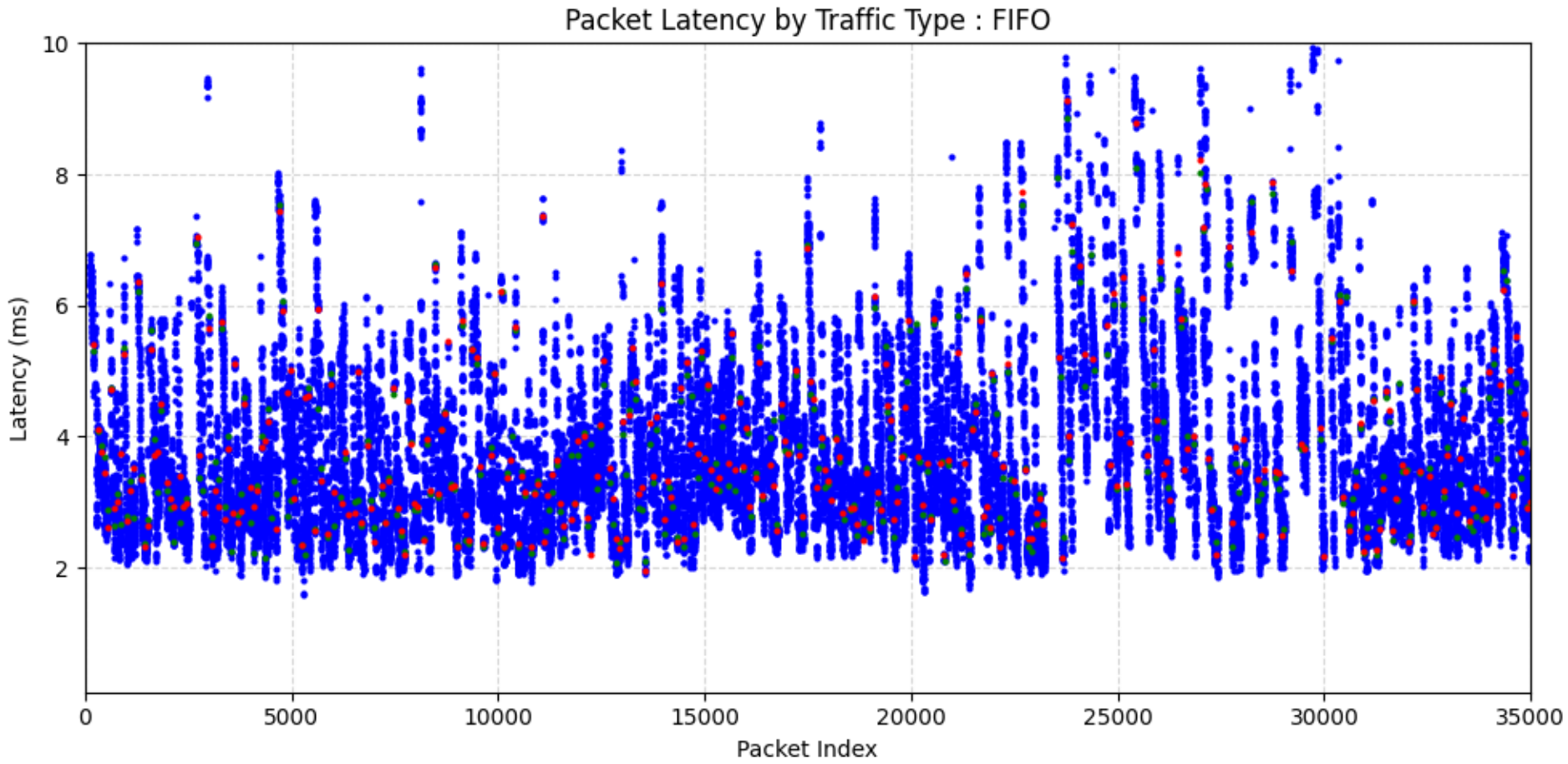
Part 2| *17 Feet - 100 Mbps - Run #1 – FIFO vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

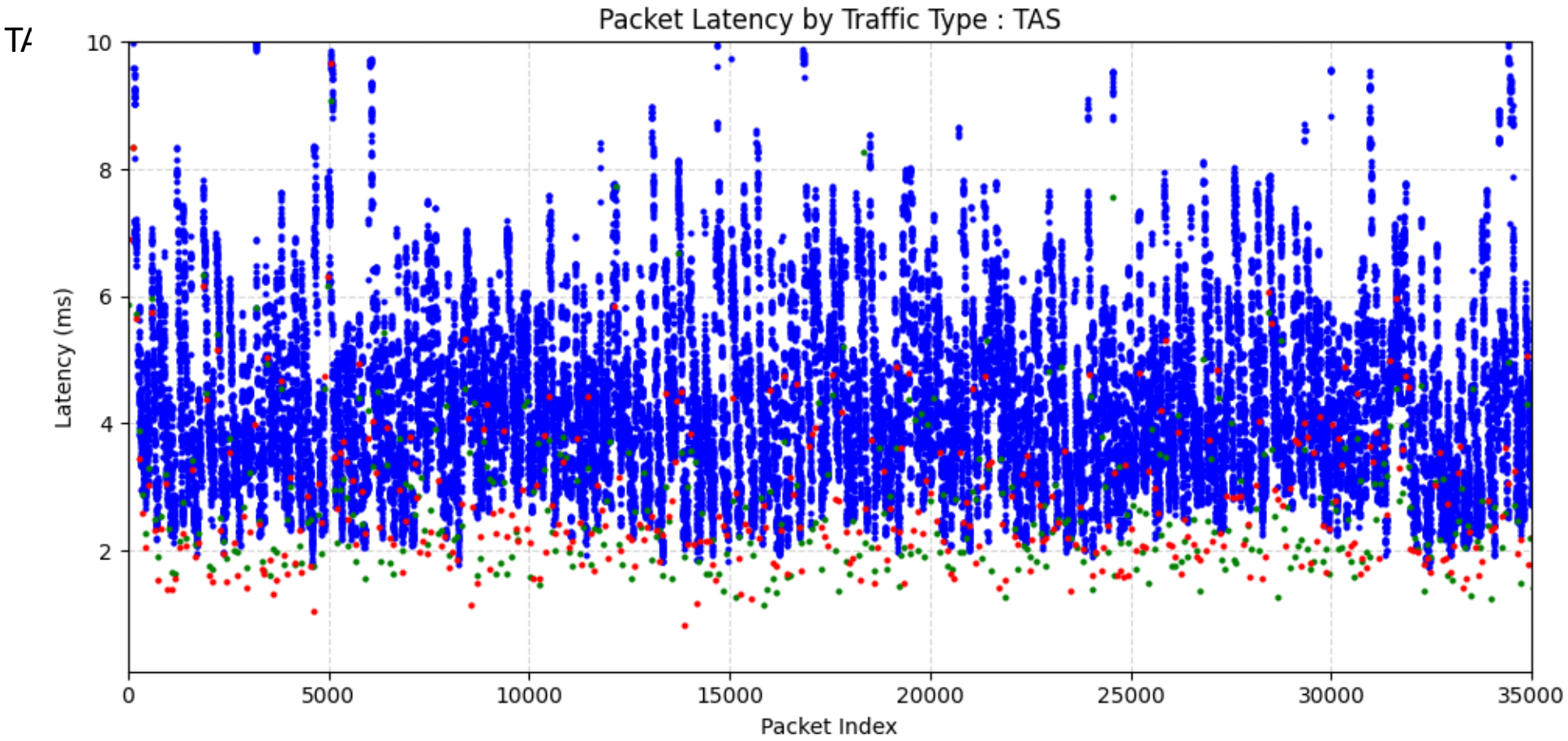


>20% packet loss for video (here 24%) .1% is expected by Telesurgery

Part 2| *17 Feet - 20% of Linkspeed -100 Mbps - Run #2 – FIFO* *(using traffic_log2)*

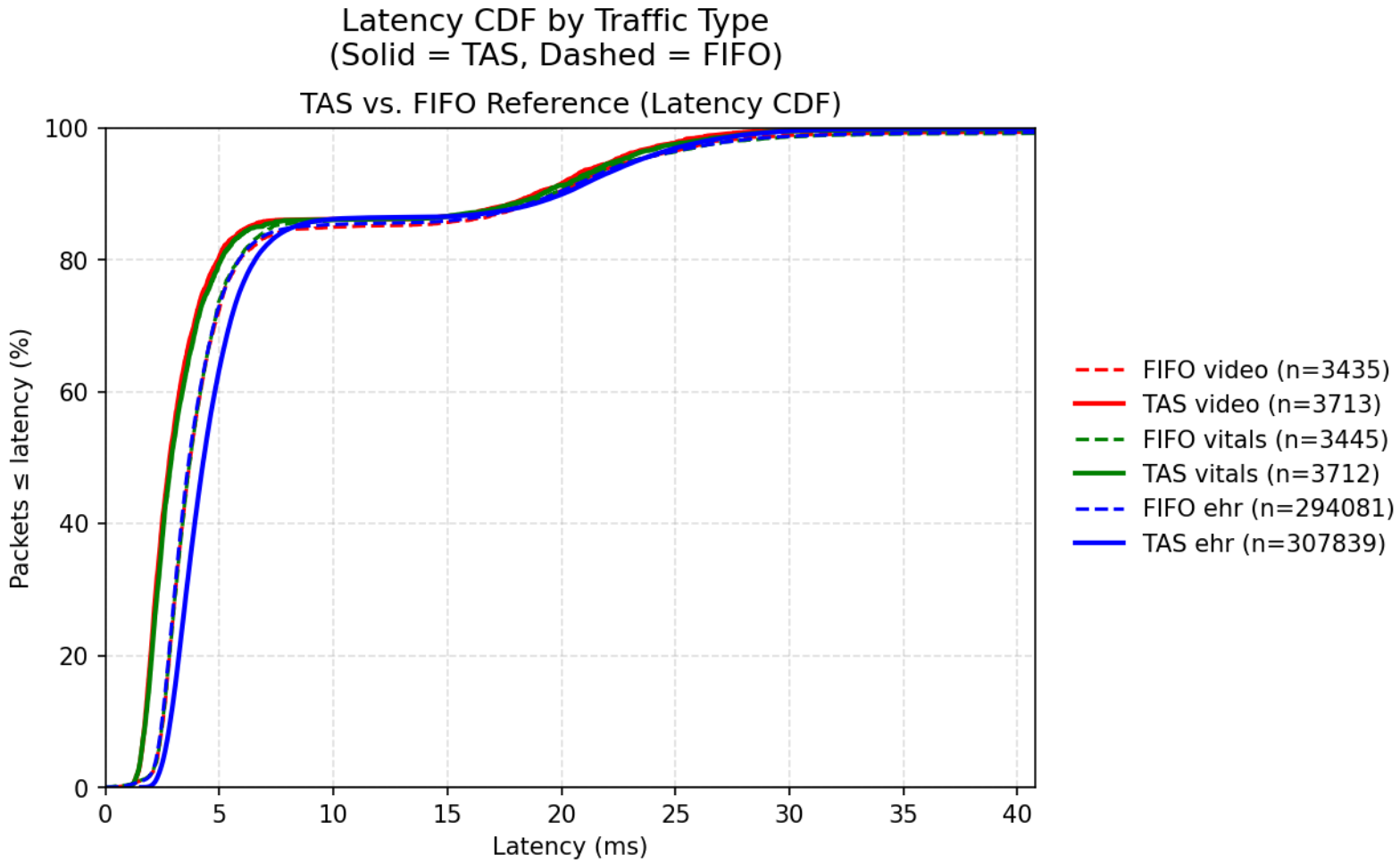


Part 2| *17 Feet - 100 Mbps - Run #2 - TAS*



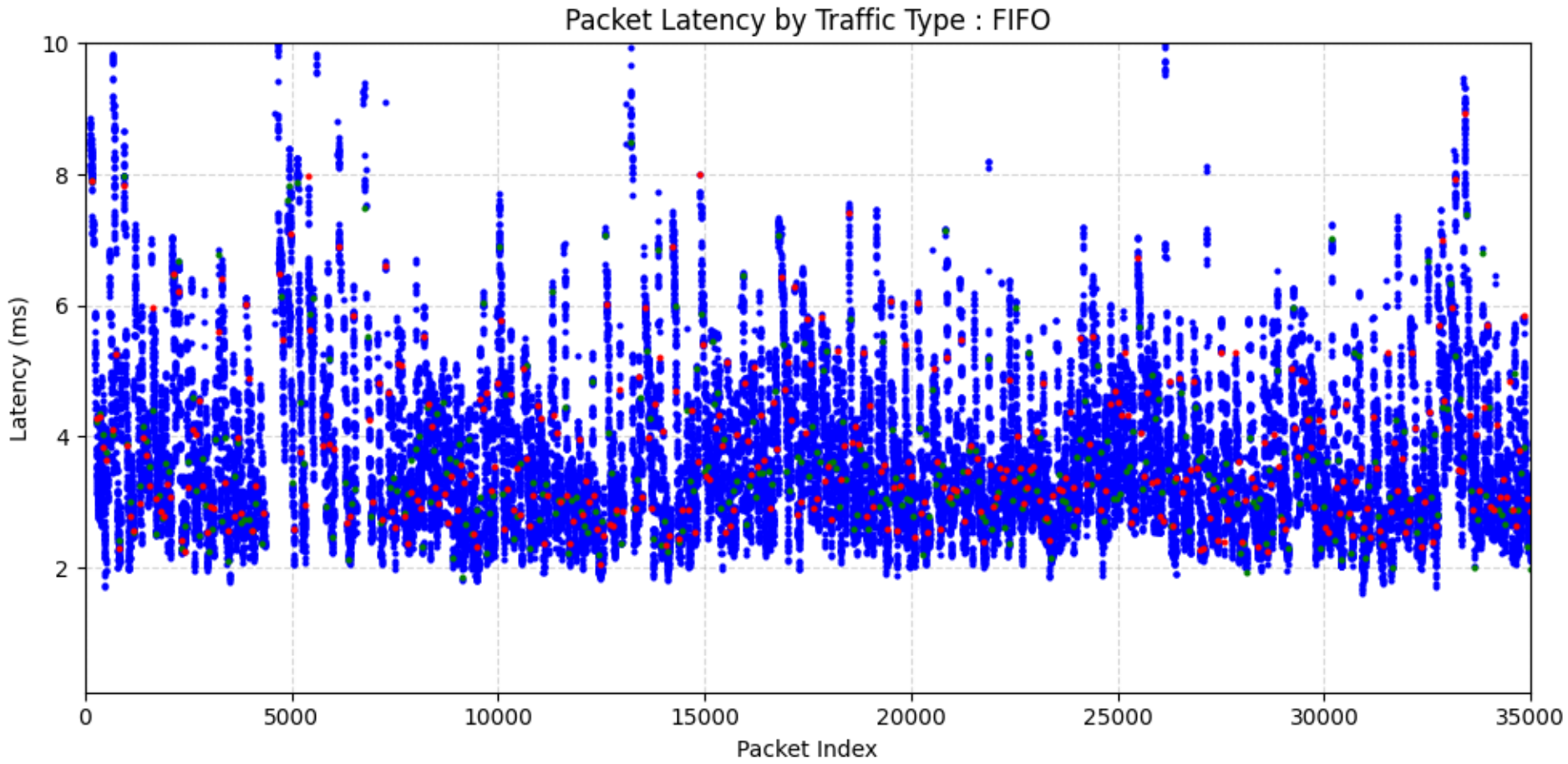
Part 2| *17 Feet - 100 Mbps - Run #2 – FIFO vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

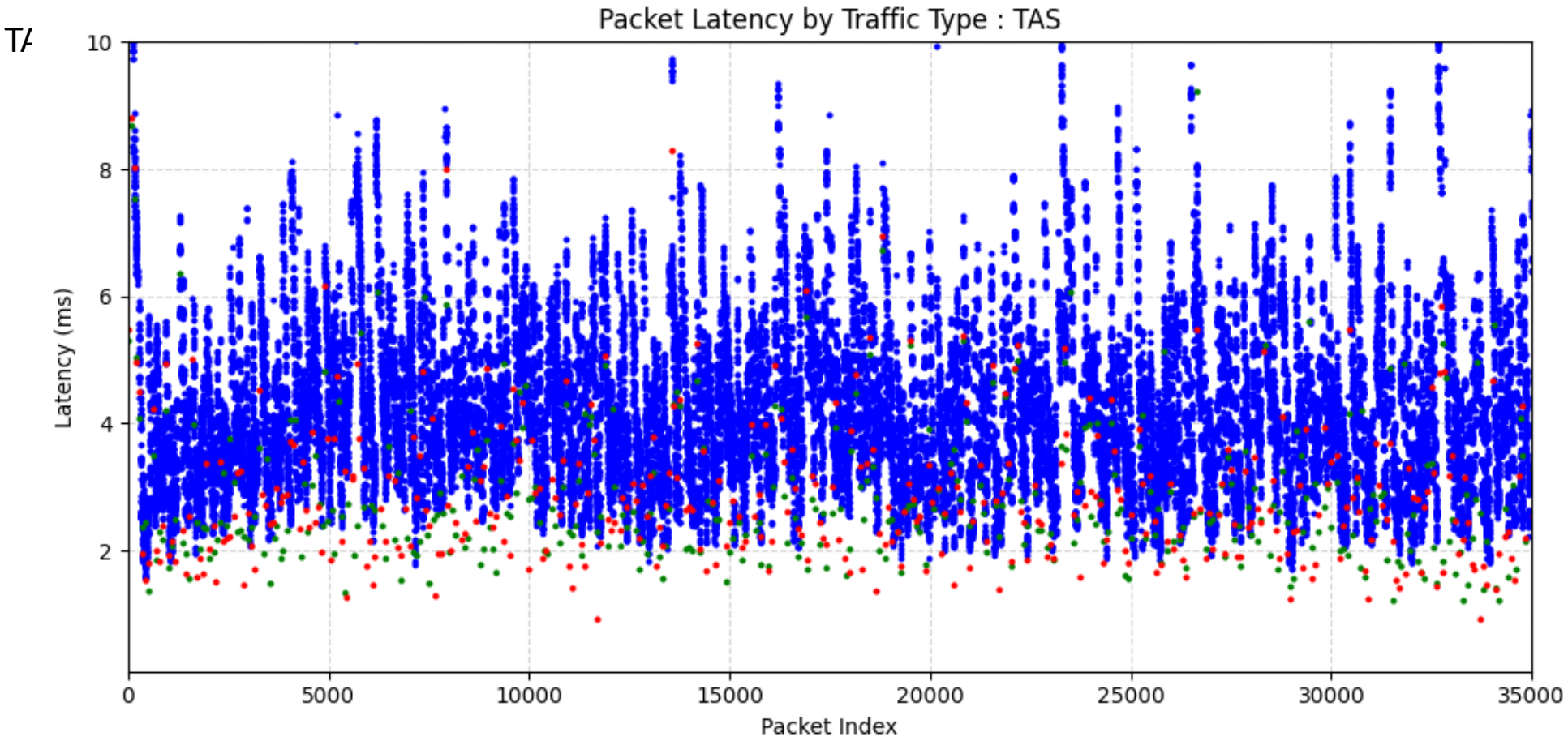


oss for video (here
xpected by

Part 2| *17 Feet - 20% of Linkspeed -100 Mbps - Run #3 – FIFO* *(using traffic_log2)*

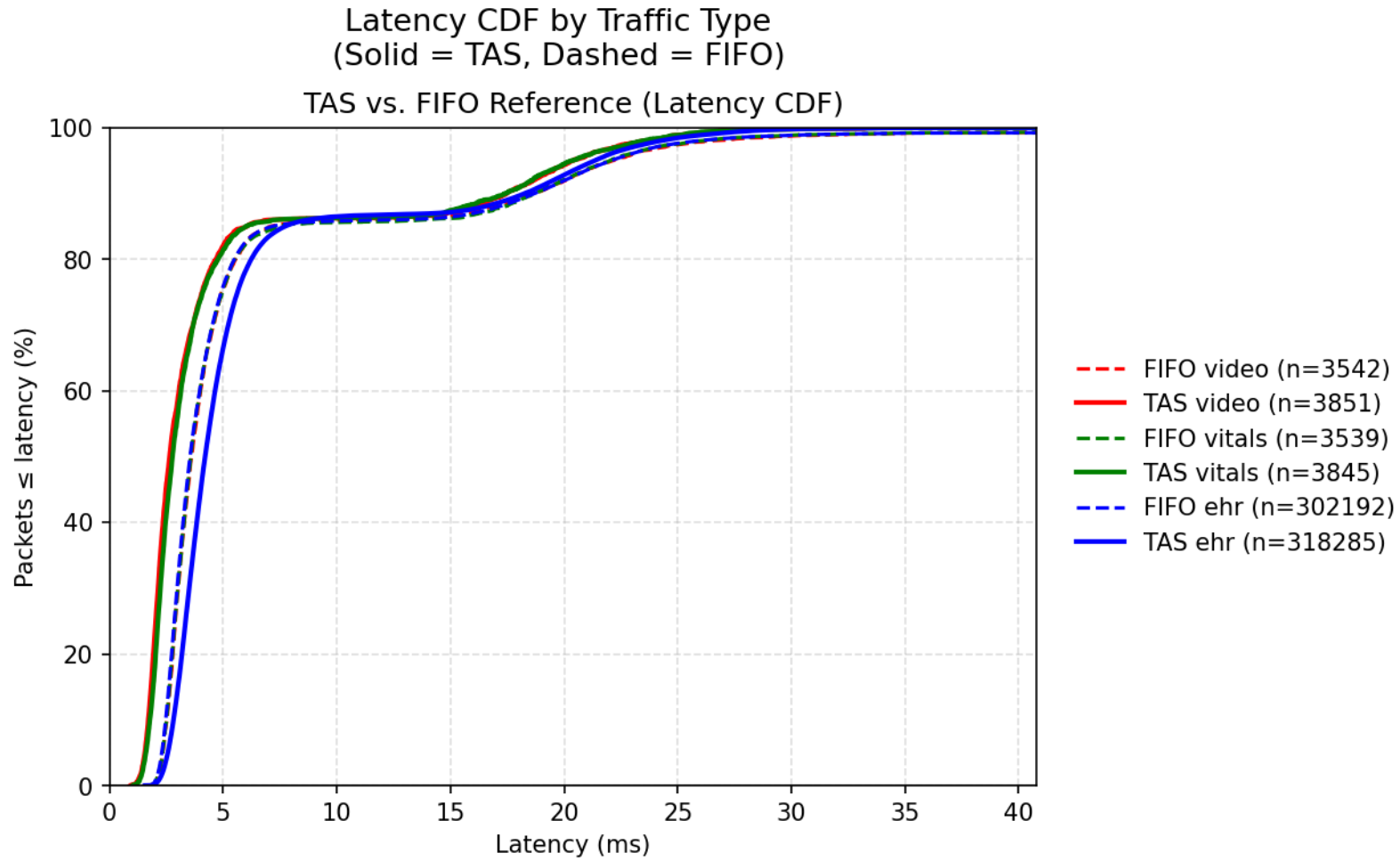


Part 2| *17 Feet - 100 Mbps - Run #3 - TAS*



Part 2| *17 Feet - 100 Mbps - Run #3 – FIFO vs TAS*

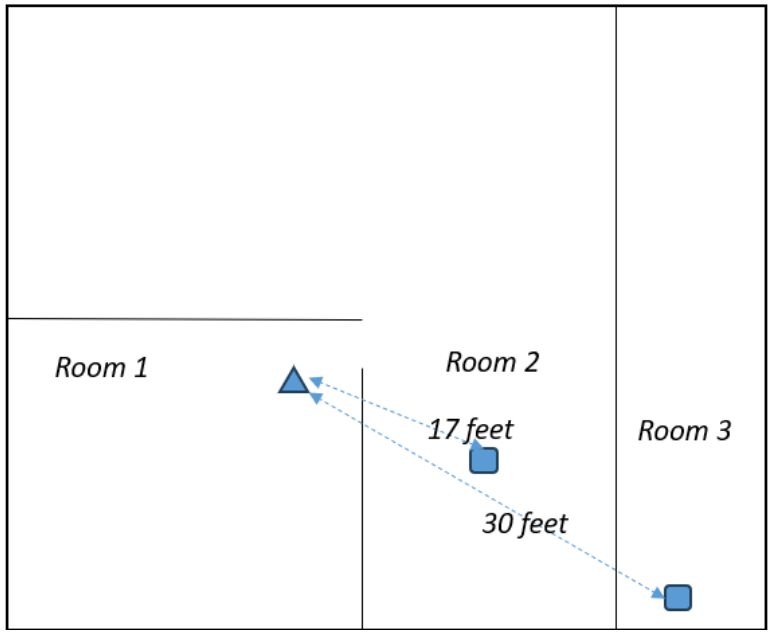
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

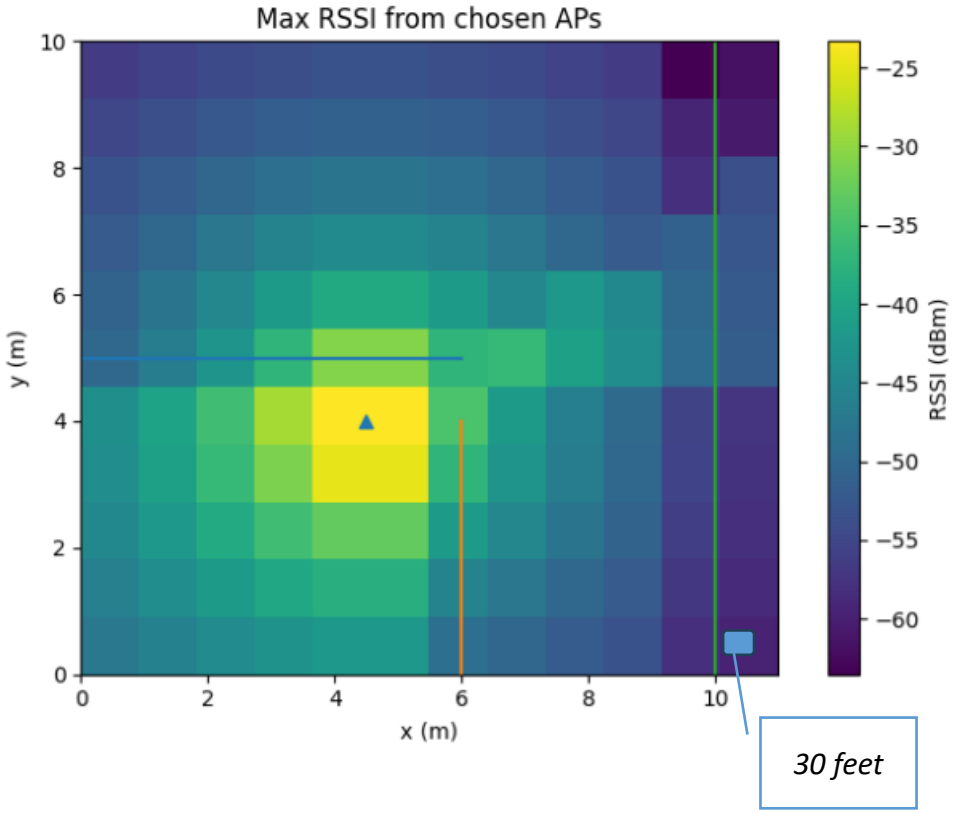


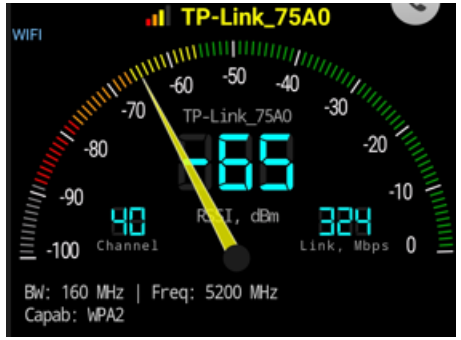
oss for video (here
xpected by

Part 2| *30 Feet – Additional Access Point in Line of Sight*

Where to place the access point is important





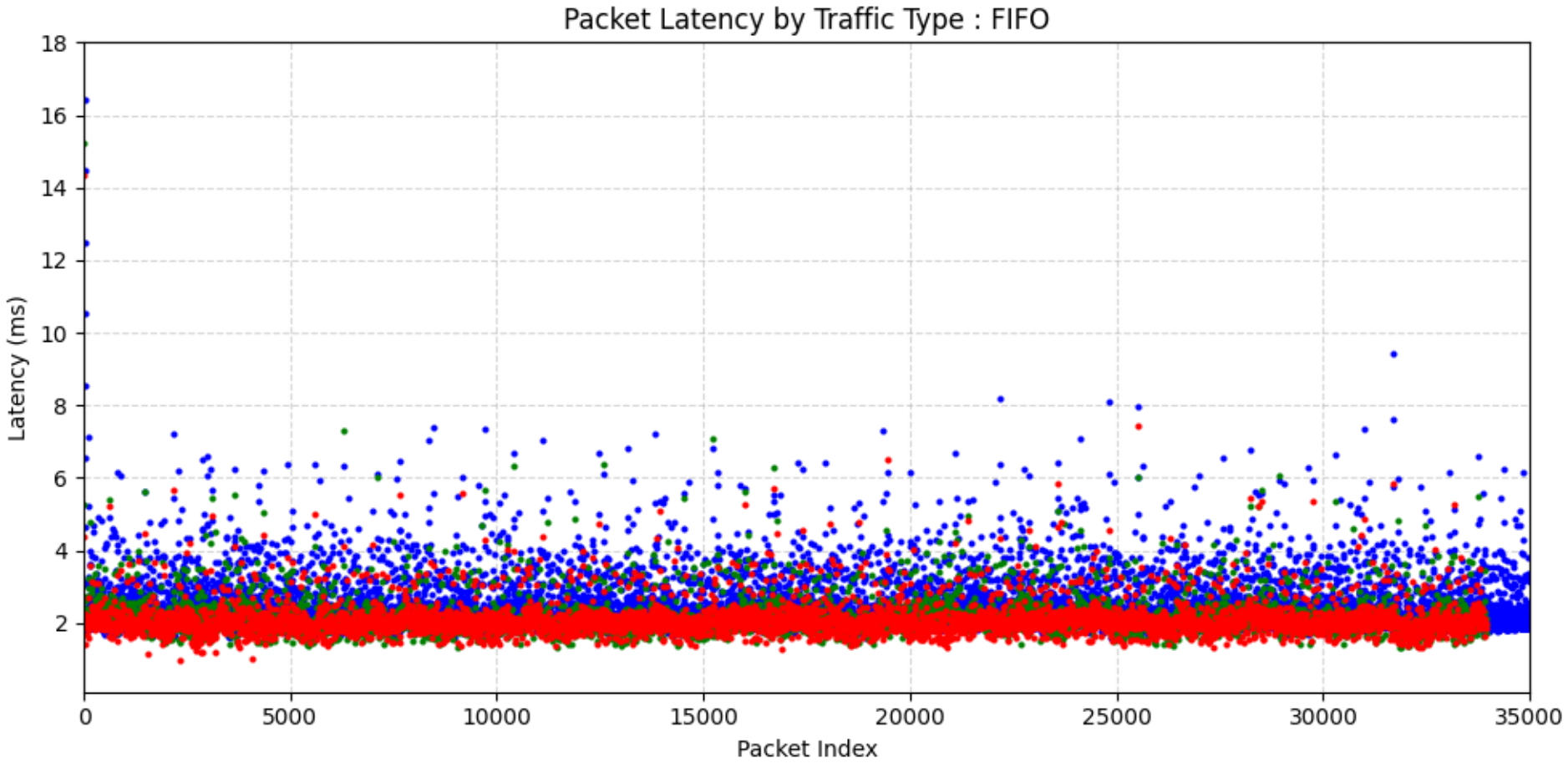


One AP only -30 feet away & NLOS(concrete wall)

One AP + Extender at 20 feet away and LOS of Main and only 10 feet away in LOS of Extender

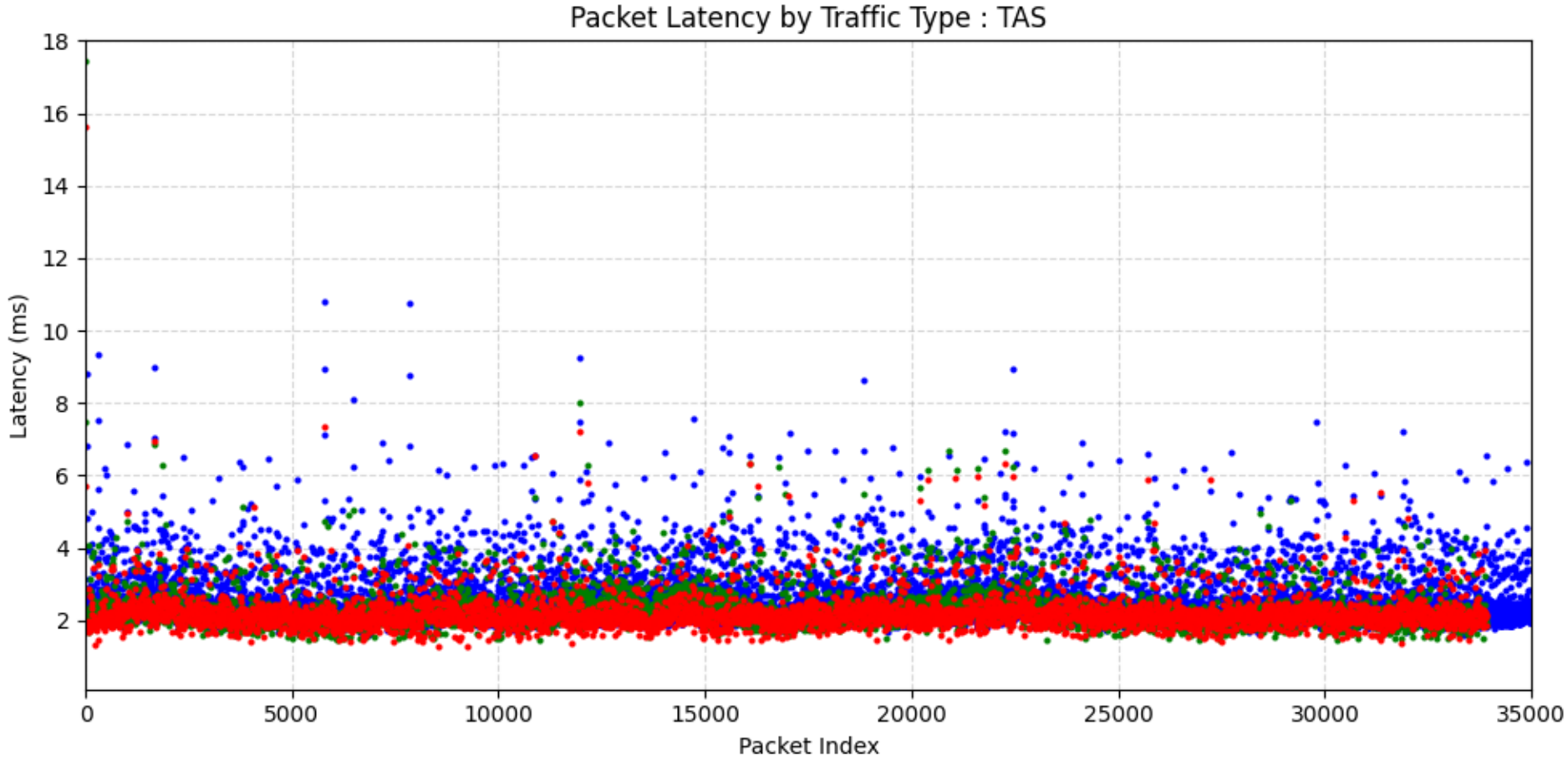
Part 2| *30 Feet – Base -11.2Mbps – FIFO Run#1*

Where to place the access point is important



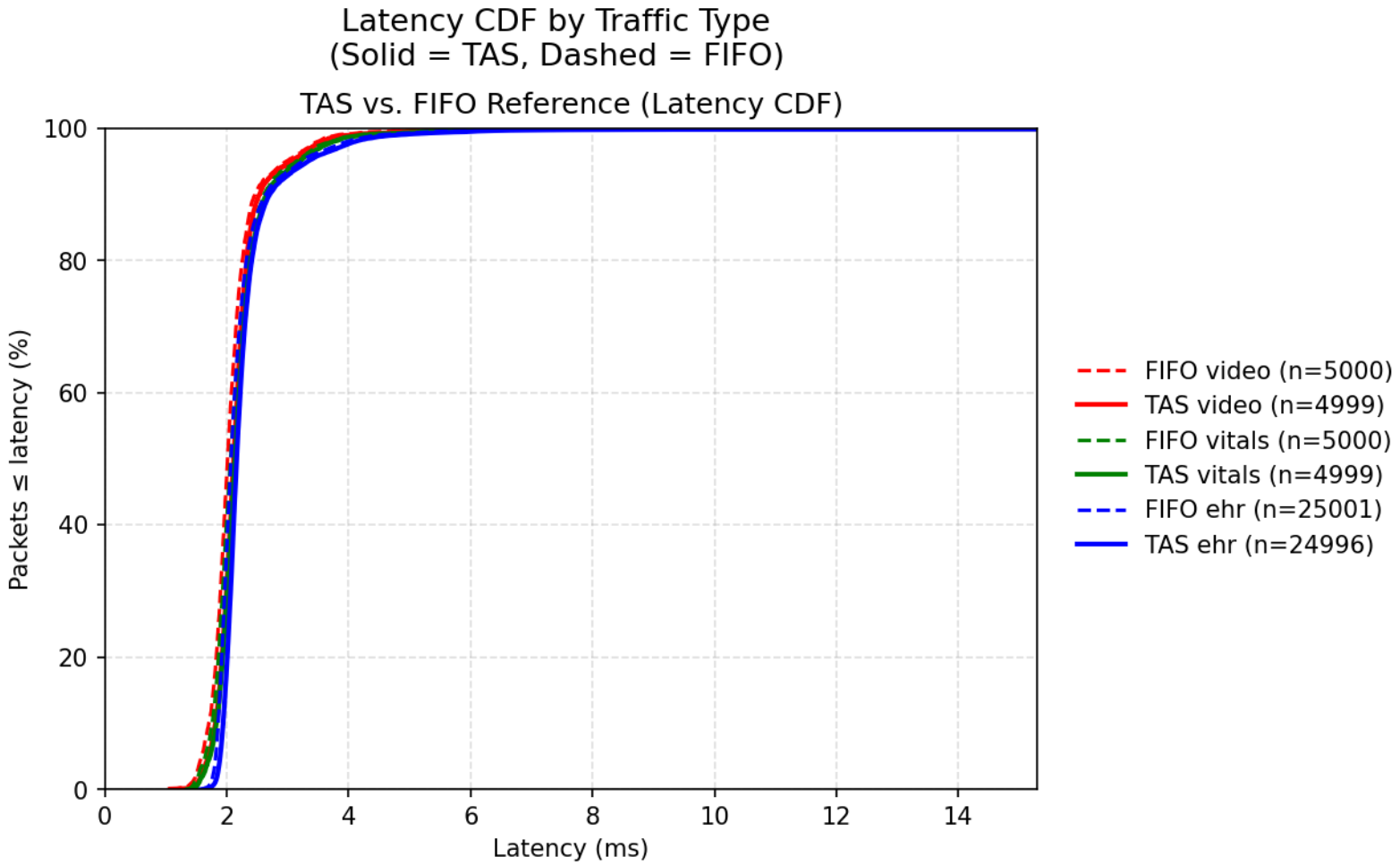
Part 2| *30 Feet – Base -11.2Mbps – TAS Run#1*

Where to place the access point is important



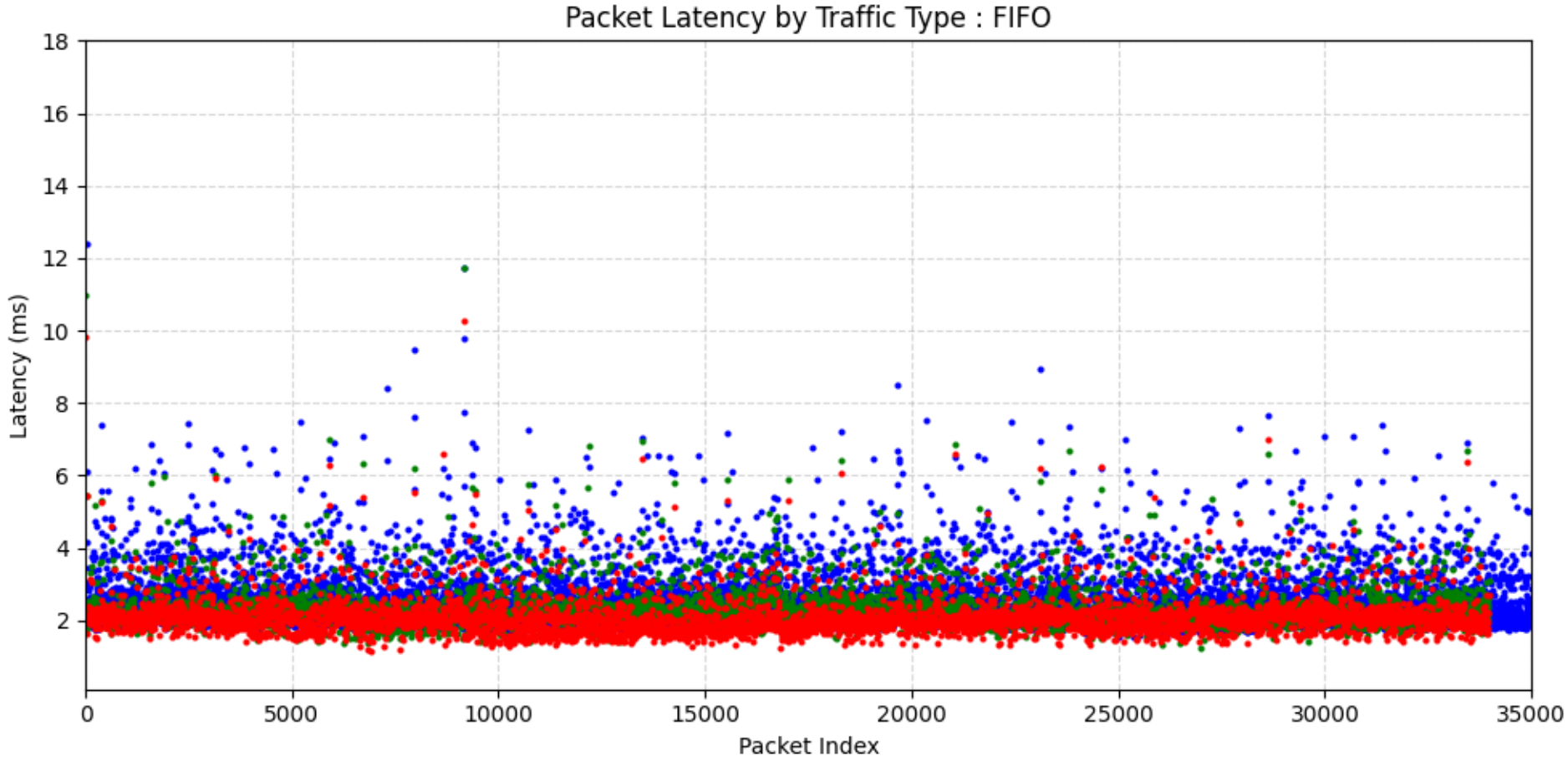
Part 2| *30 Feet – Base -11.2Mbps – FIFO vs TAS Run#1*

Where to place the access point is important



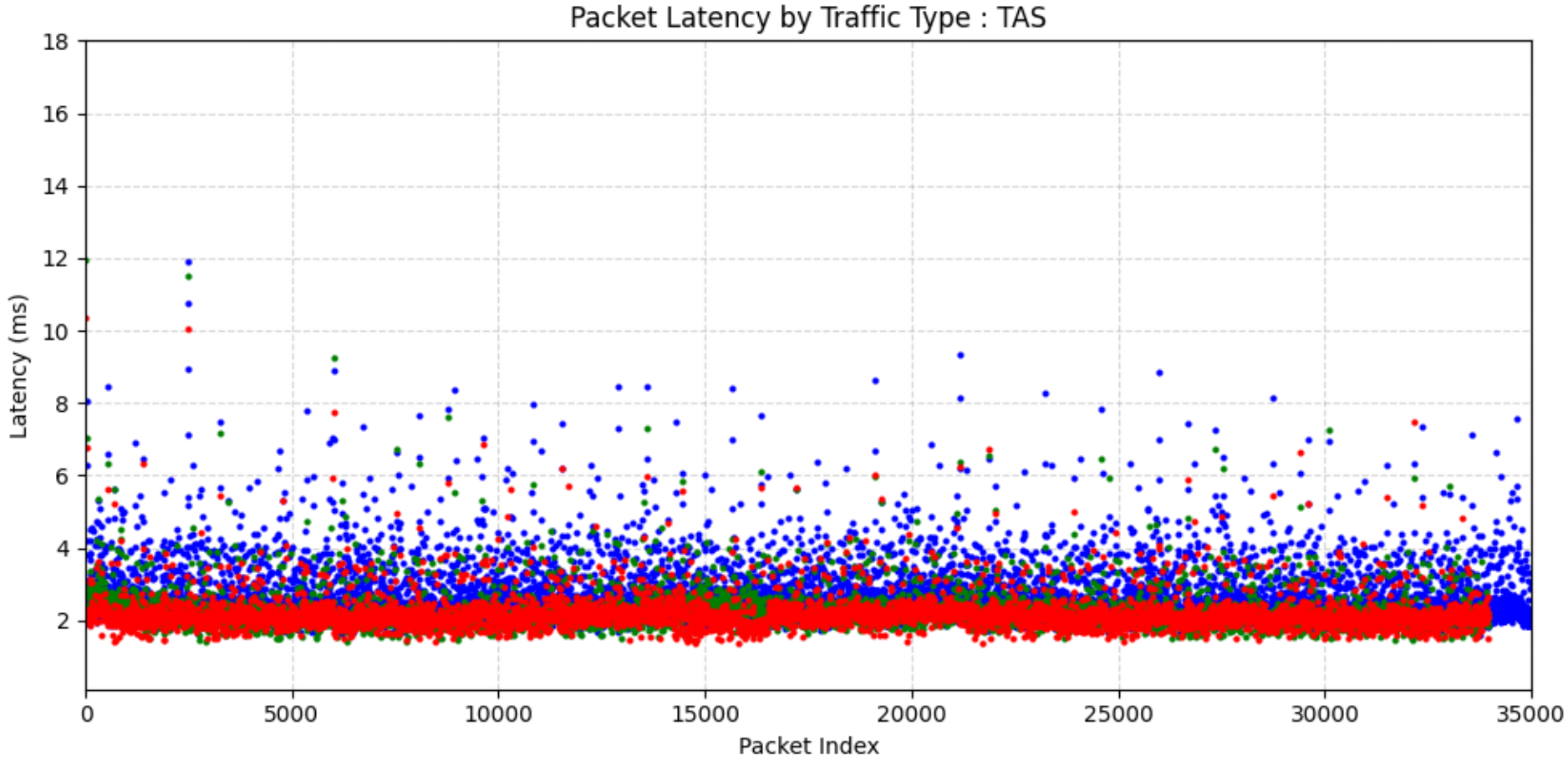
Part 2| *30 Feet – Base -11.2Mbps – FIFO Run#2*

Where to place the access point is important



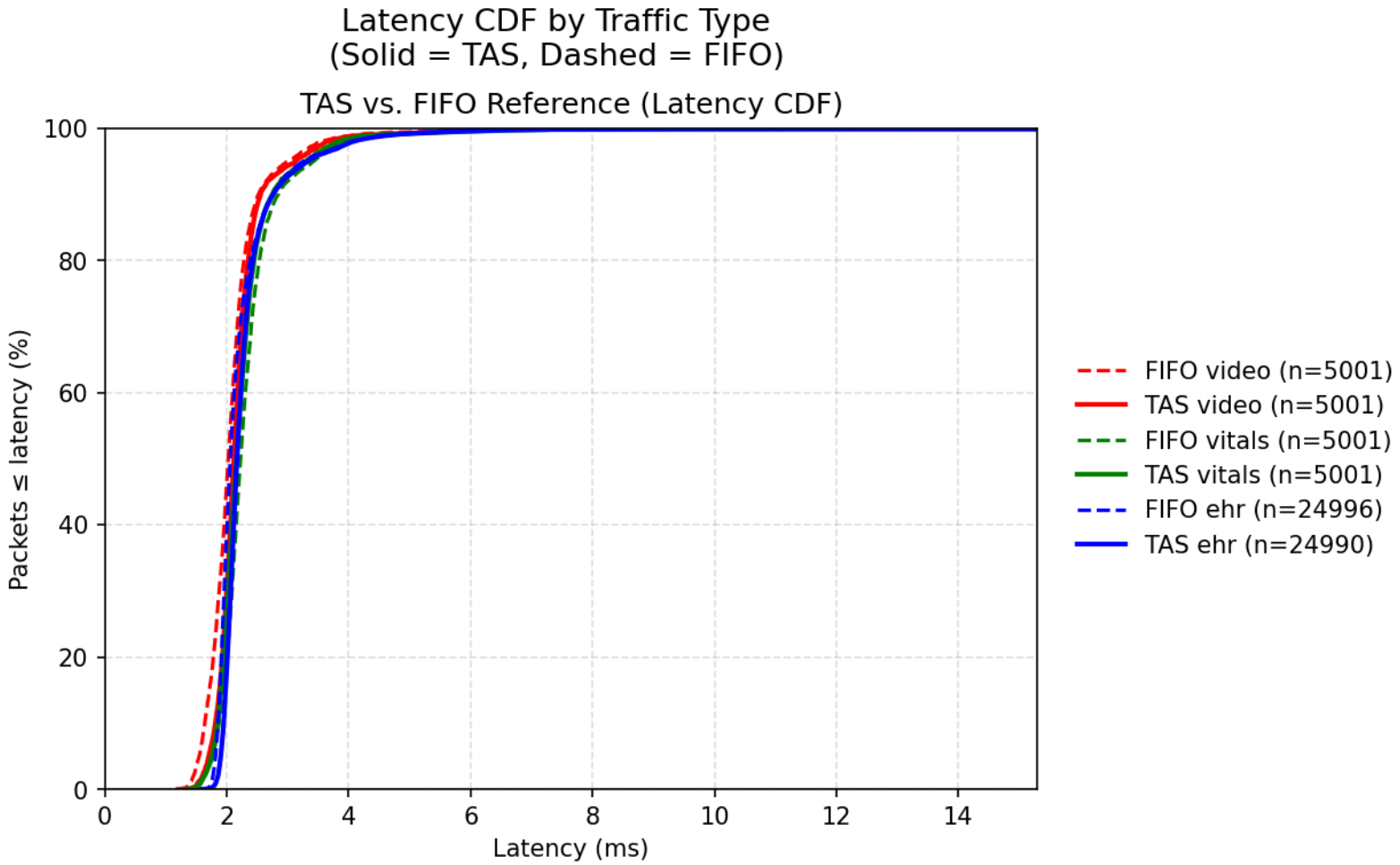
Part 2| *30 Feet – Base -11.2Mbps – TAS Run#2*

Where to place the access point is important



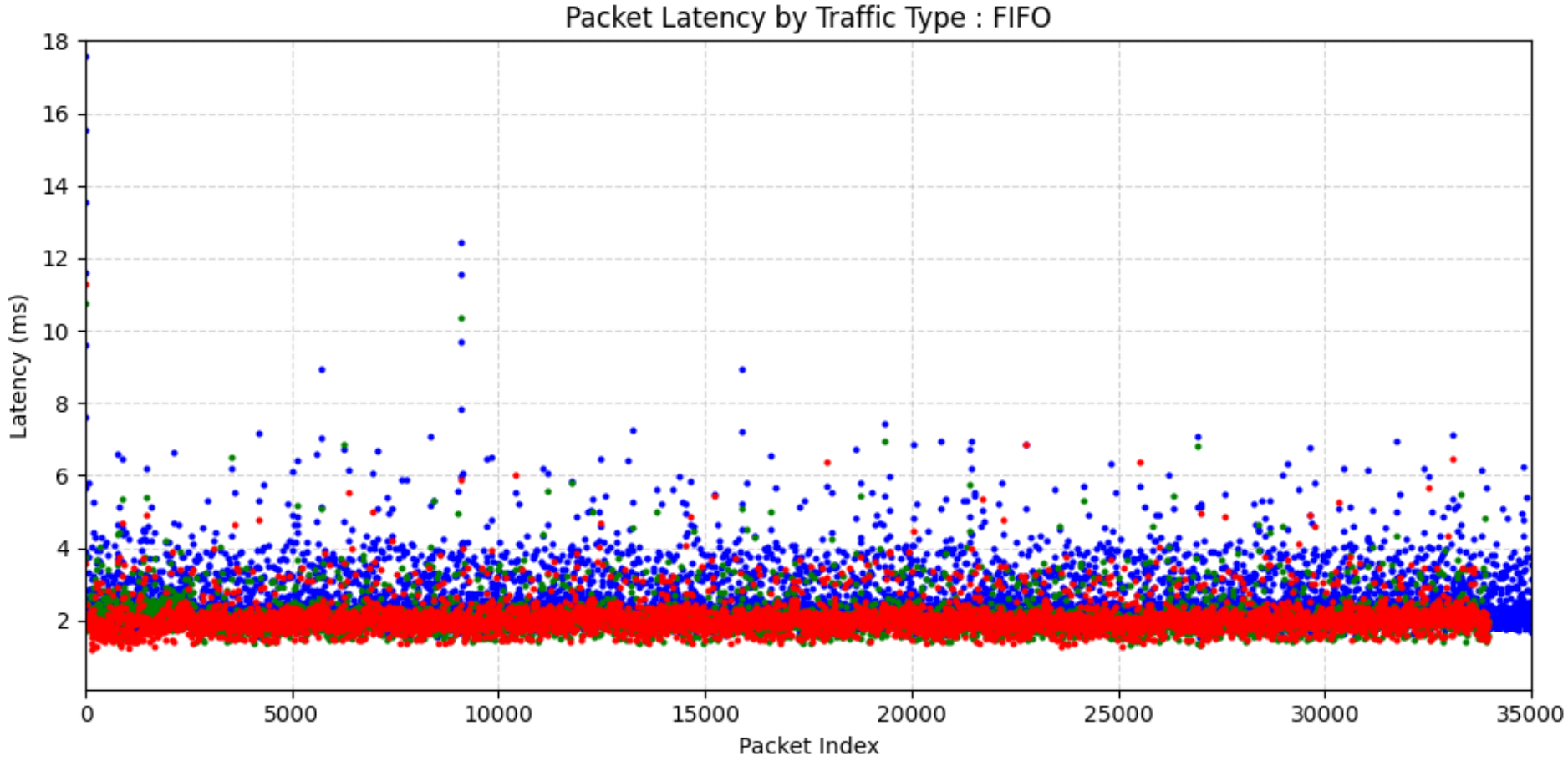
Part 2| *30 Feet – Base -11.2Mbps – FIFO vs TAS Run#2*

Where to place the access point is important



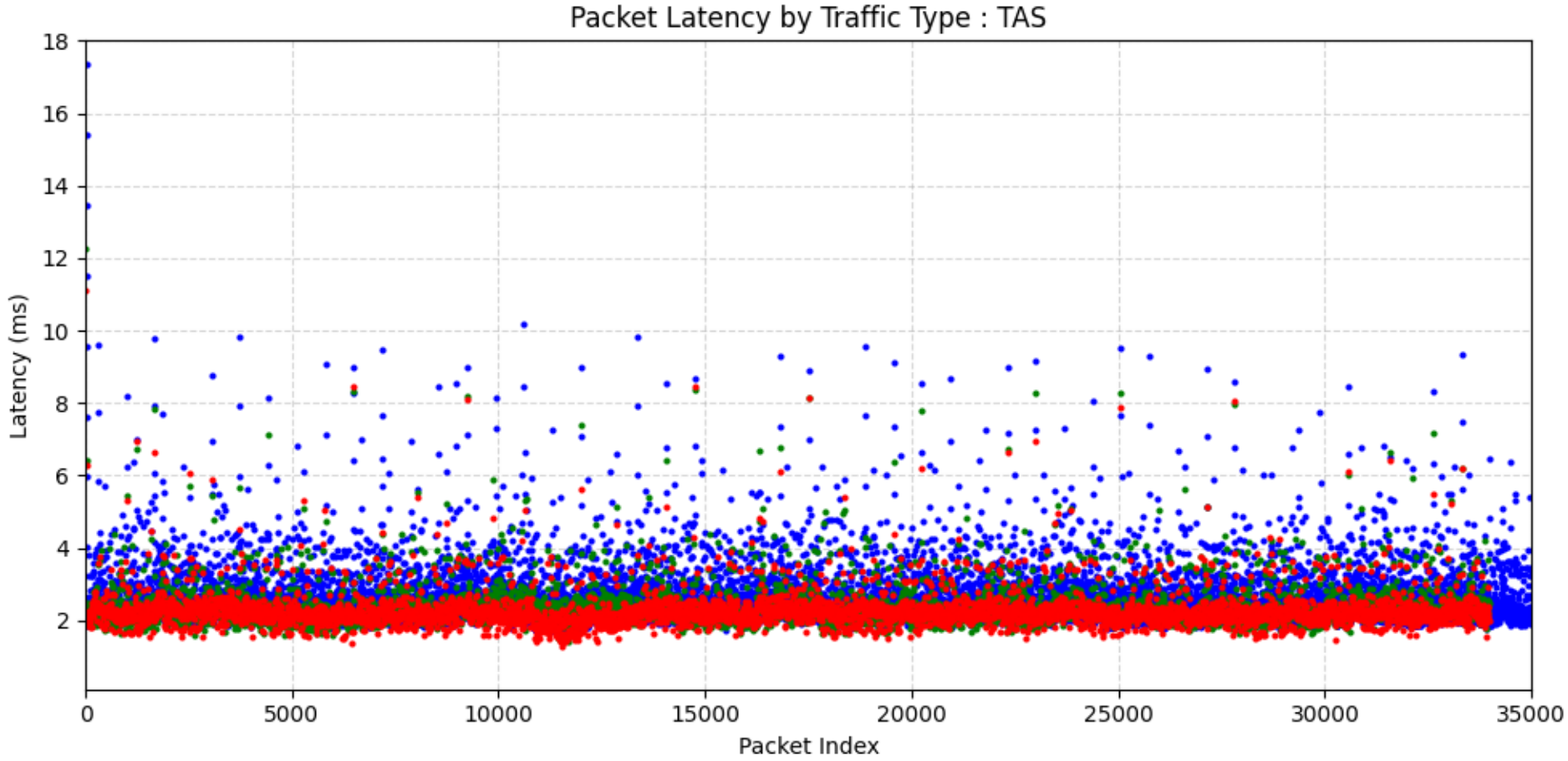
Part 2| *30 Feet – Base -11.2Mbps – FIFO Run#3*

Where to place the access point is important



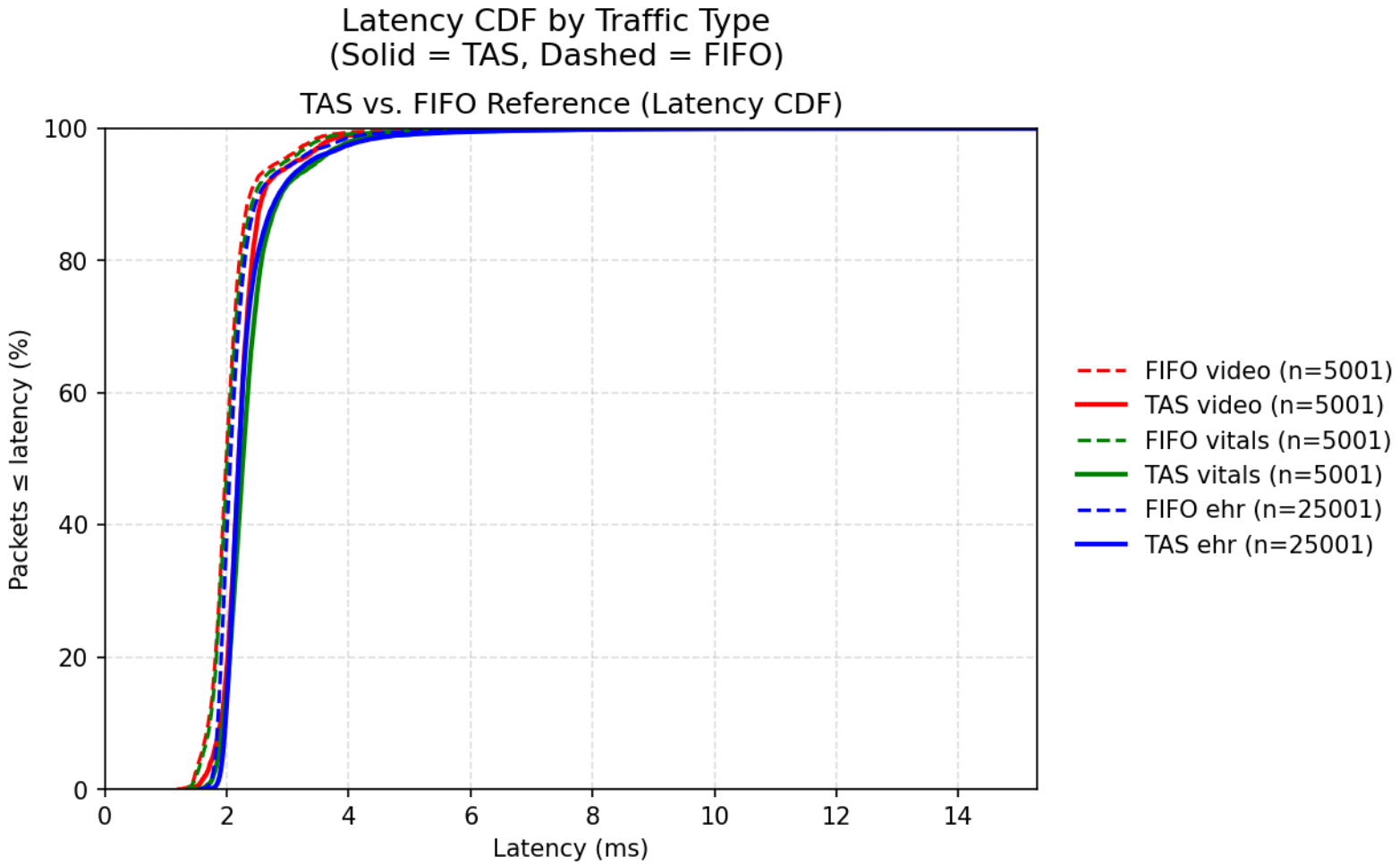
Part 2| *30 Feet – Base -11.2Mbps – TAS Run#3*

Where to place the access point is important



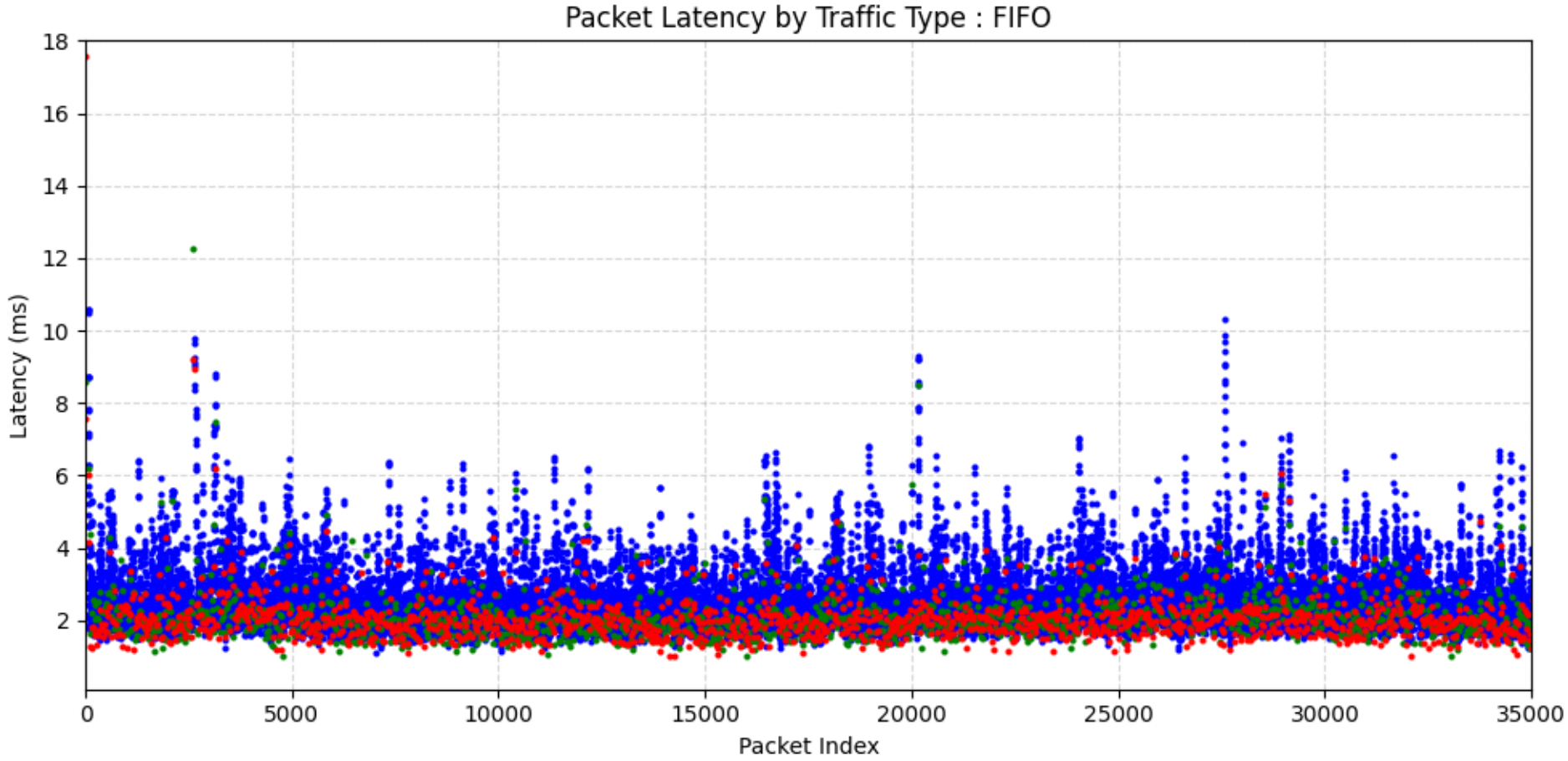
Part 2| *30 Feet – Base -11.2Mbps – FIFO vs TAS Run#3*

Where to place the access point is important



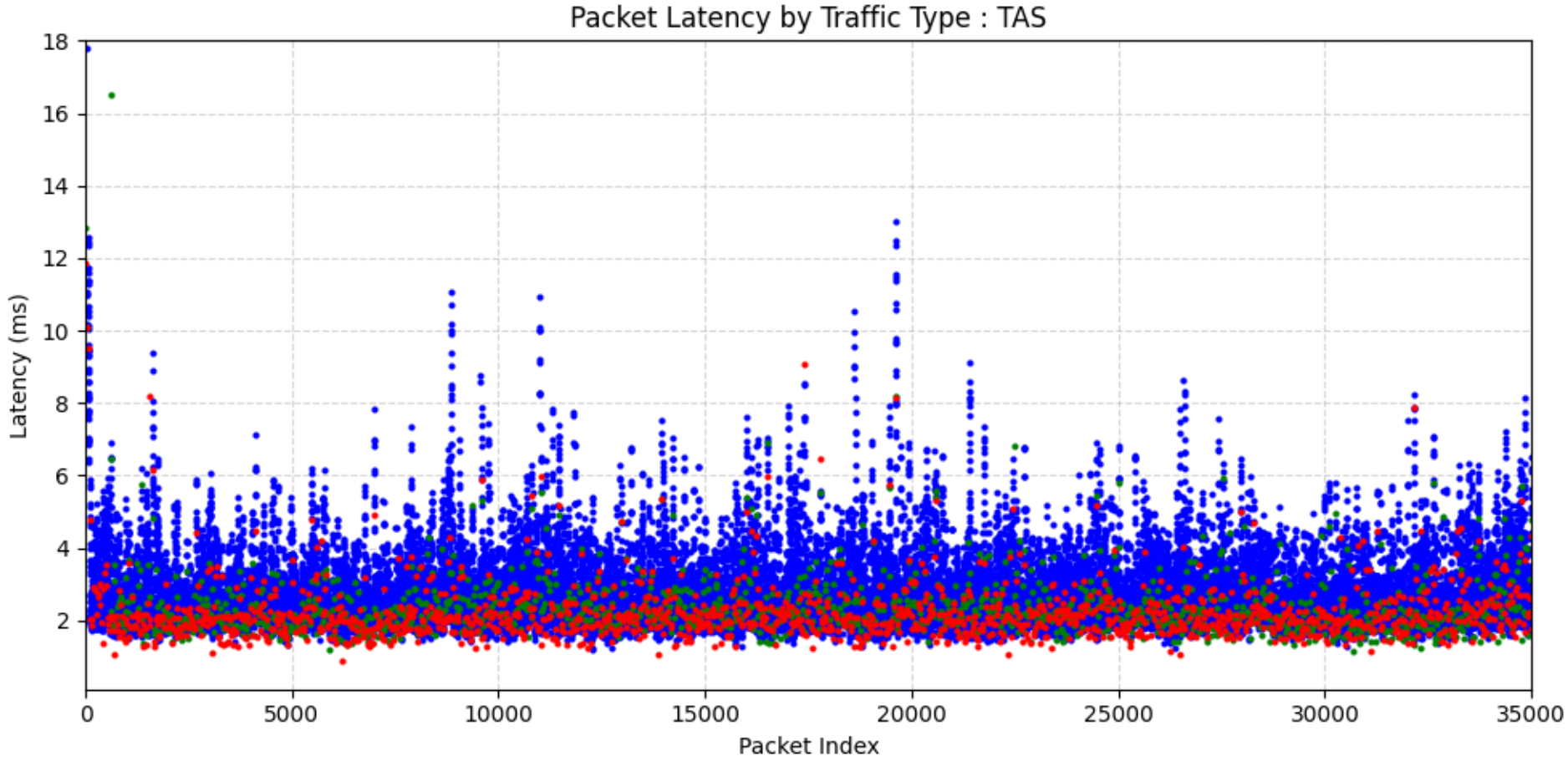
Part 2| *30 Feet – Base -25Mbps – FIFO Run#1*

Where to place the access point is important



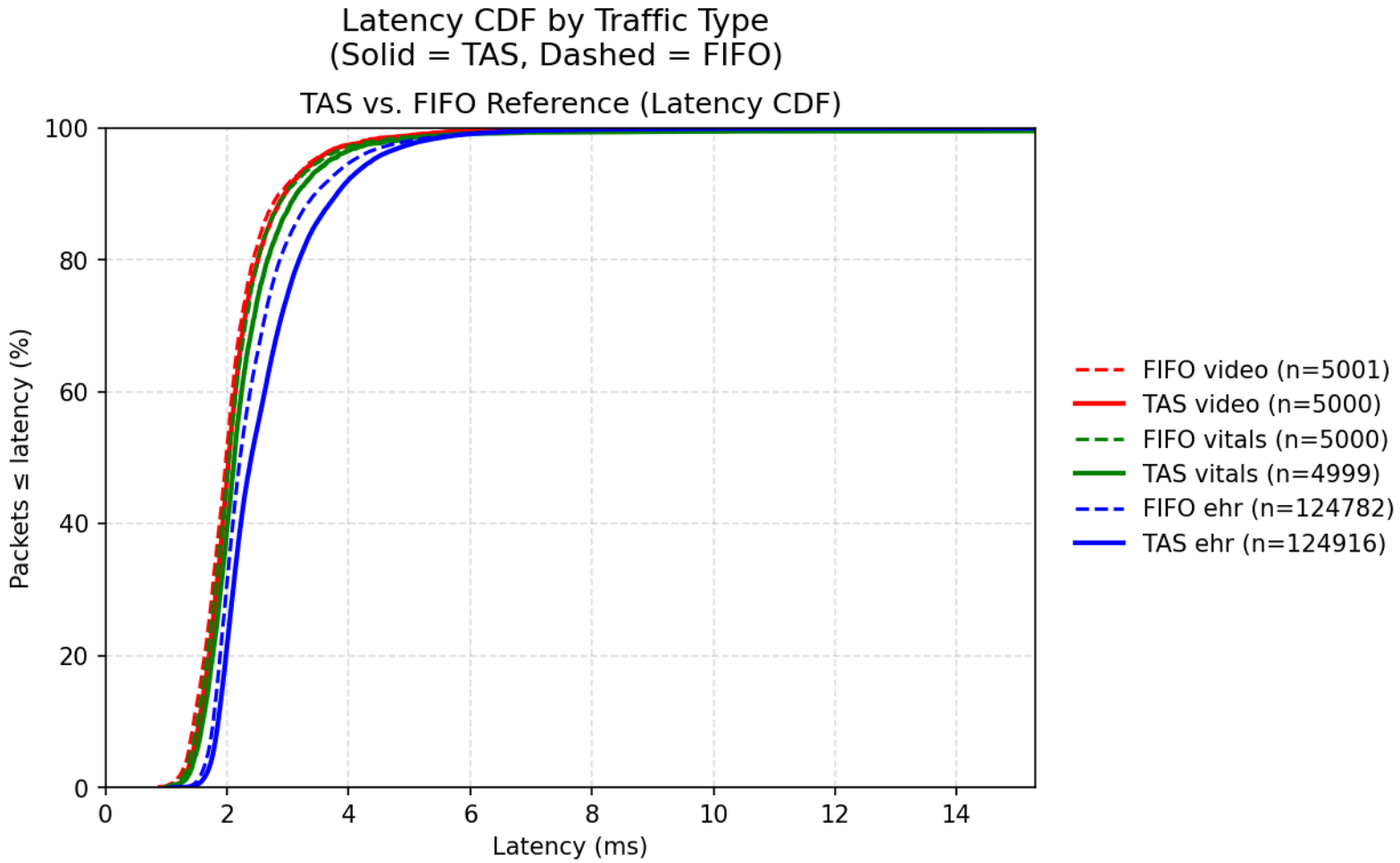
Part 2| *30 Feet – Base -25Mbps – TAS Run#1*

Where to place the access point is important



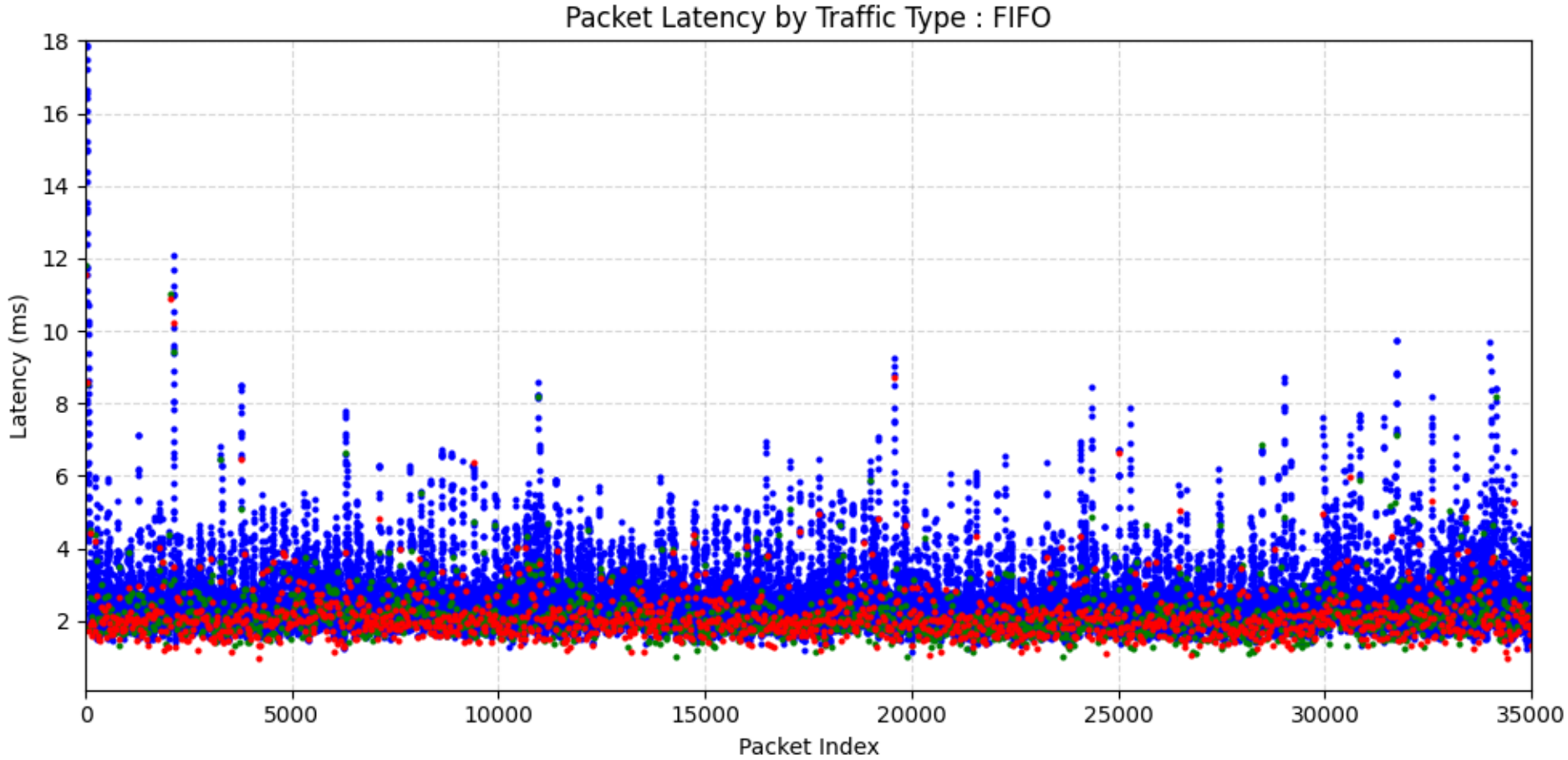
Part 2| *30 Feet – Base -25Mbps – FIFO vs TAS Run#1*

Where to place the access point is important



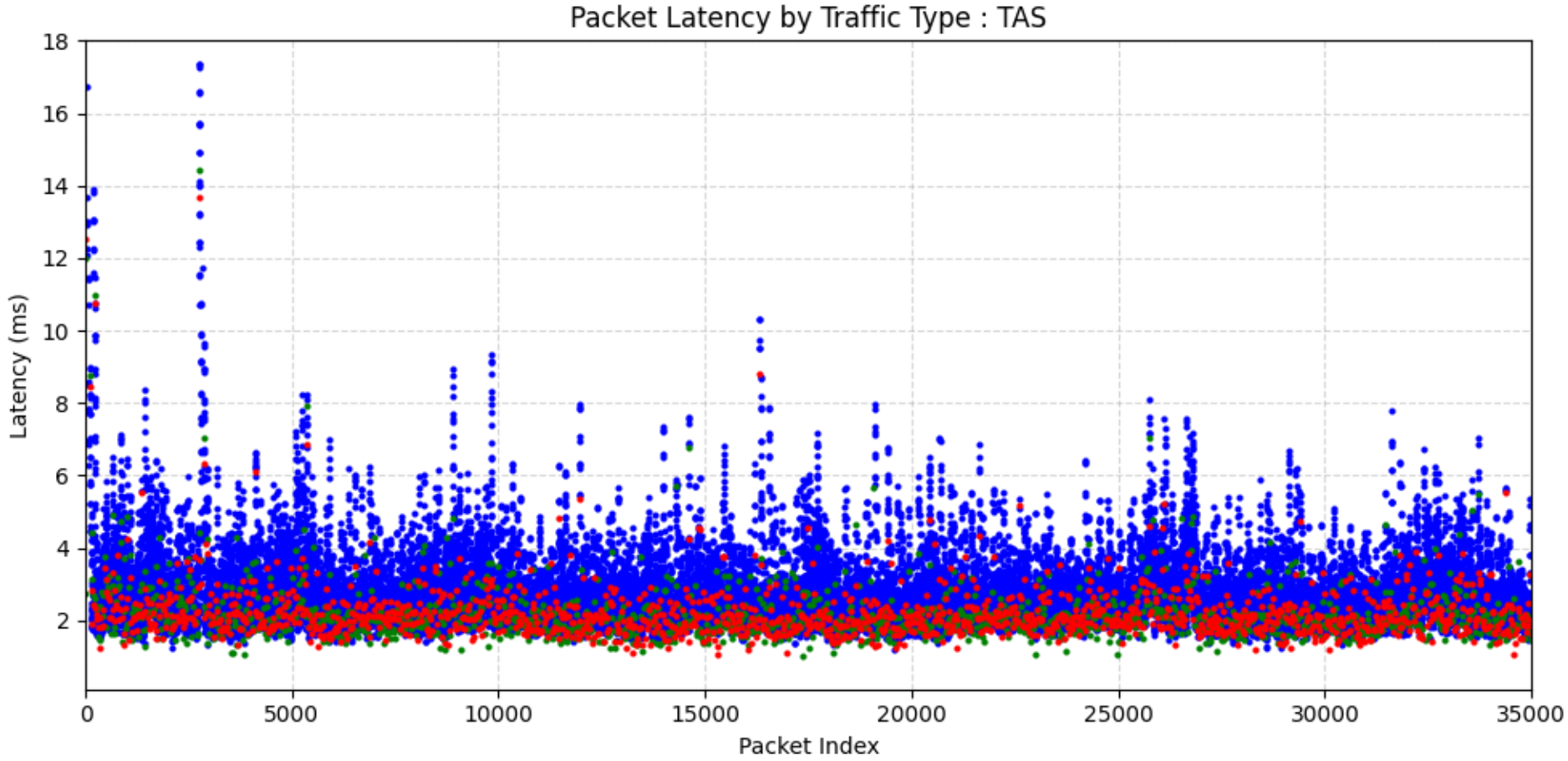
Part 2| *30 Feet – Base -25Mbps – FIFO Run#1*

Where to place the access point is important



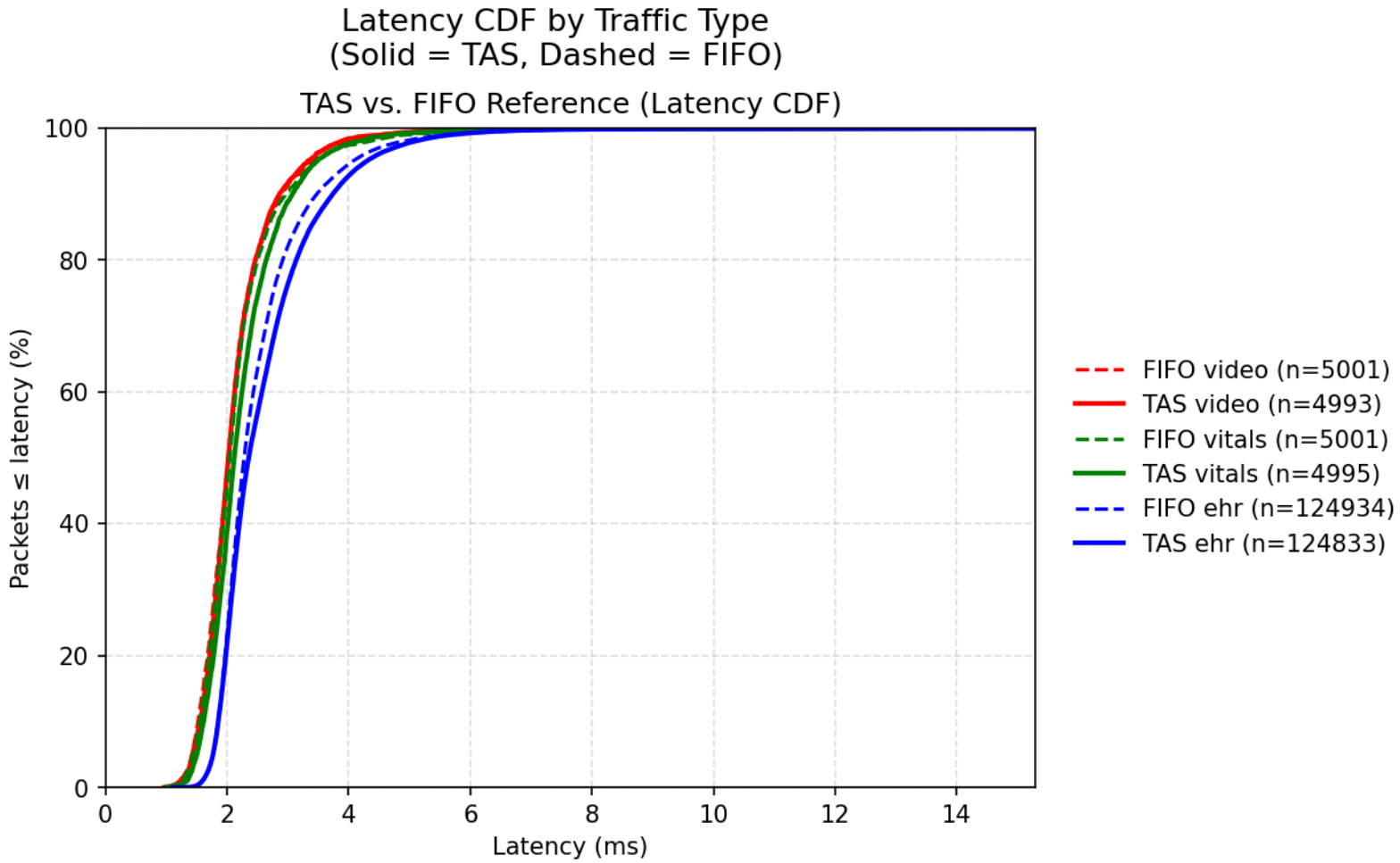
Part 2| *30 Feet – Base -25Mbps – TAS Run#2*

Where to place the access point is important



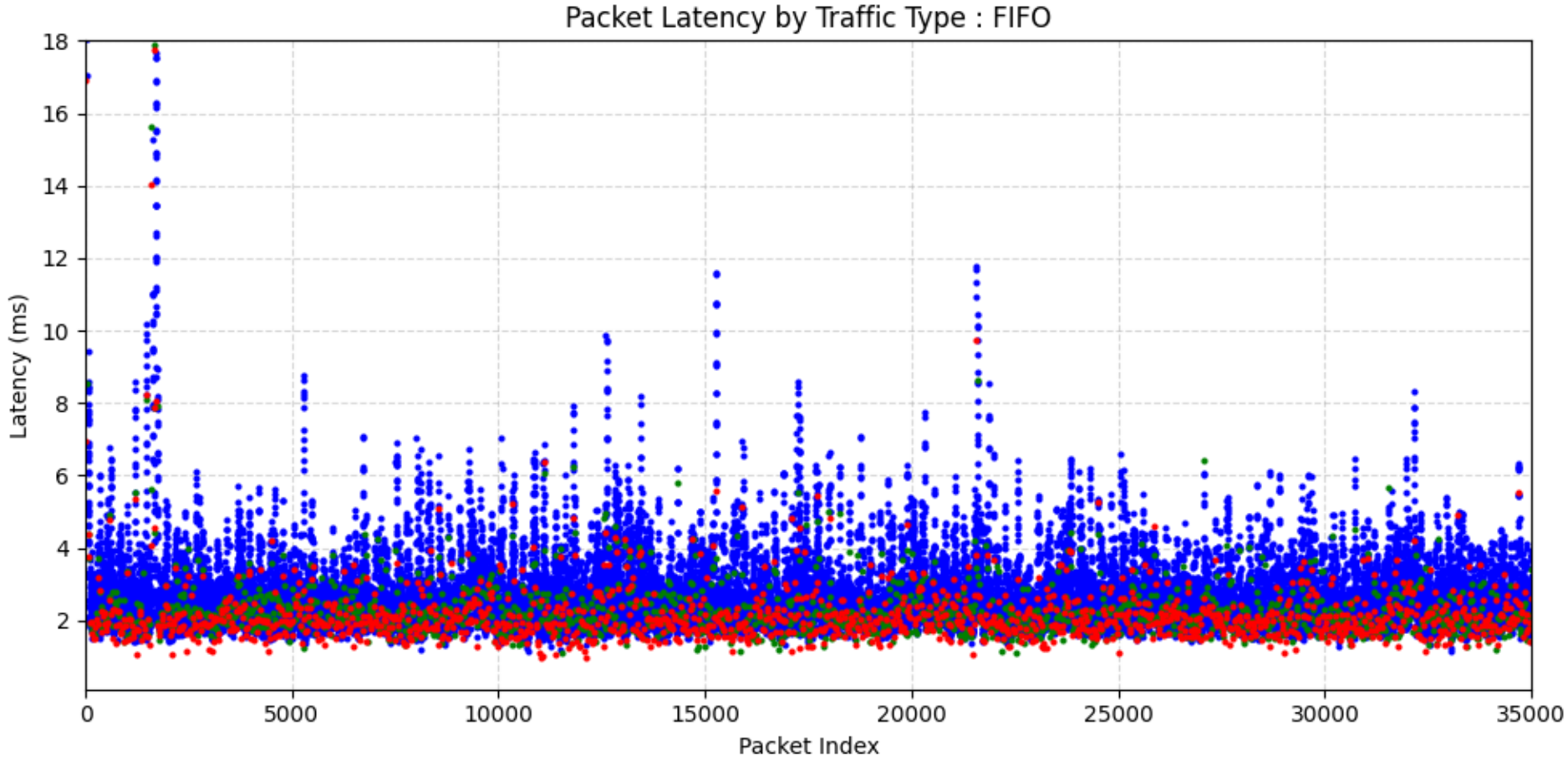
Part 2| *30 Feet – Base -25Mbps – FIFO vs TAS Run#2*

Where to place the access point is important



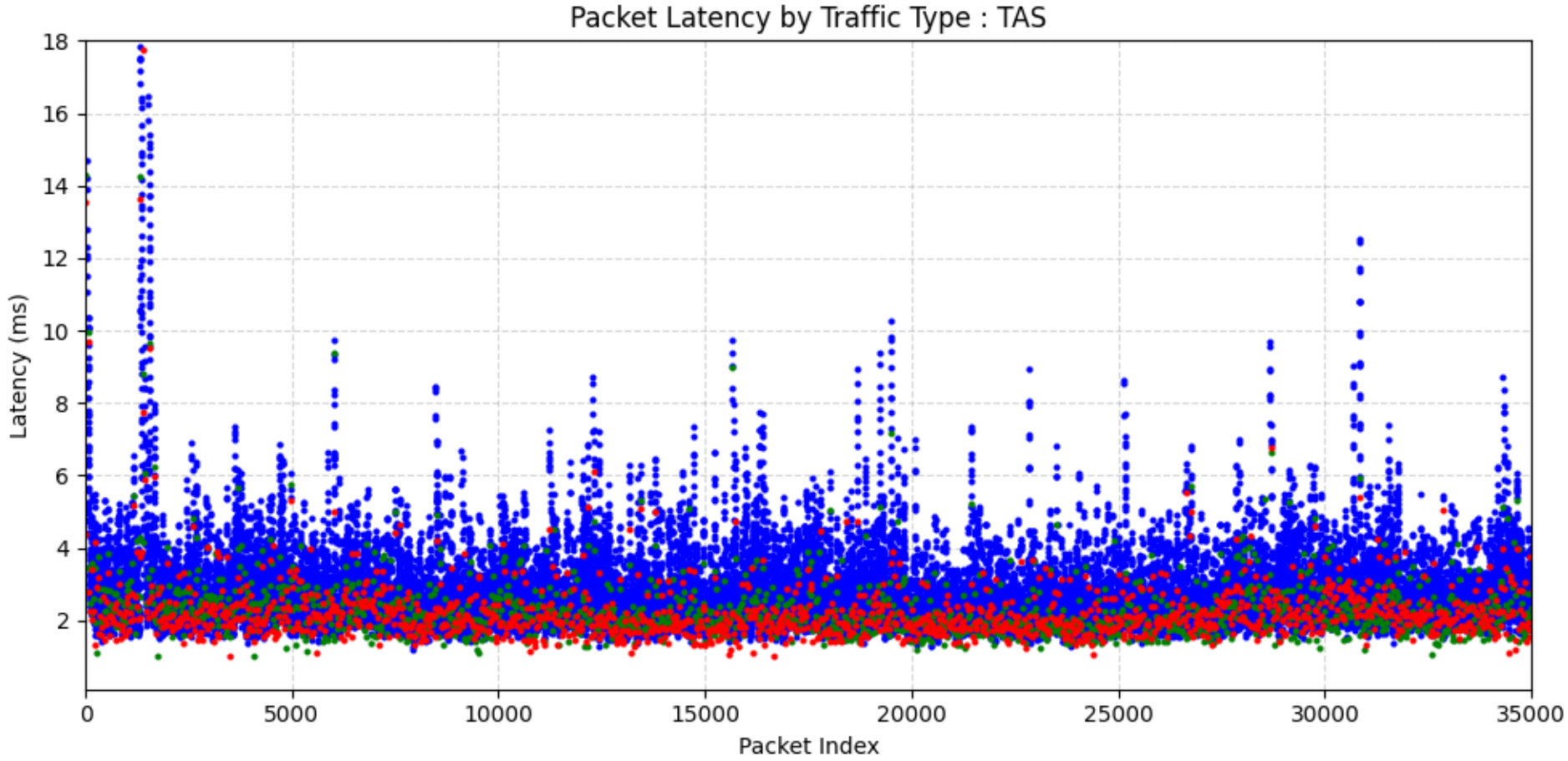
Part 2| *30 Feet – Base -25Mbps – FIFO Run#3*

Where to place the access point is important



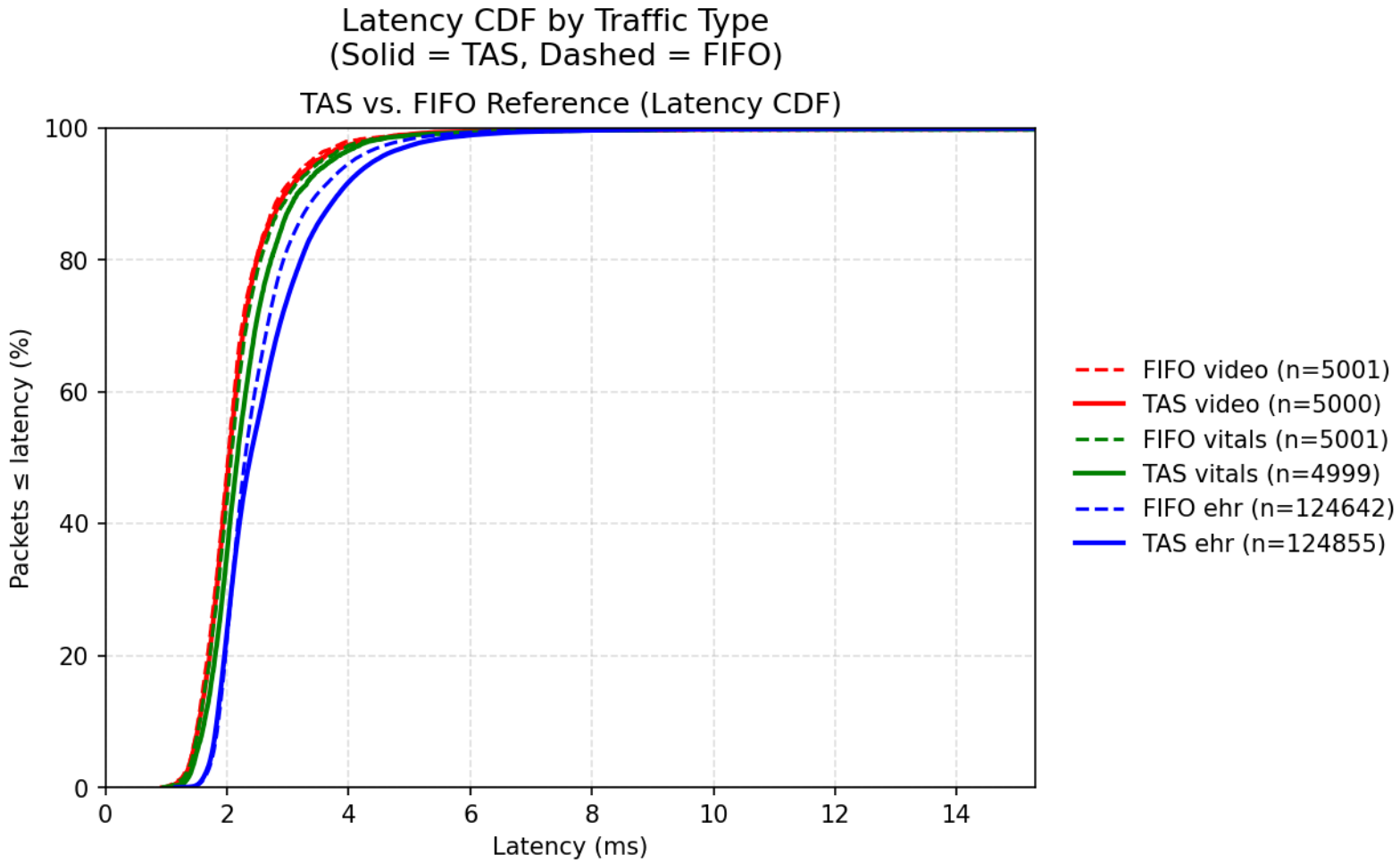
Part 2| *30 Feet – Base -25Mbps – TAS Run#3*

Where to place the access point is important



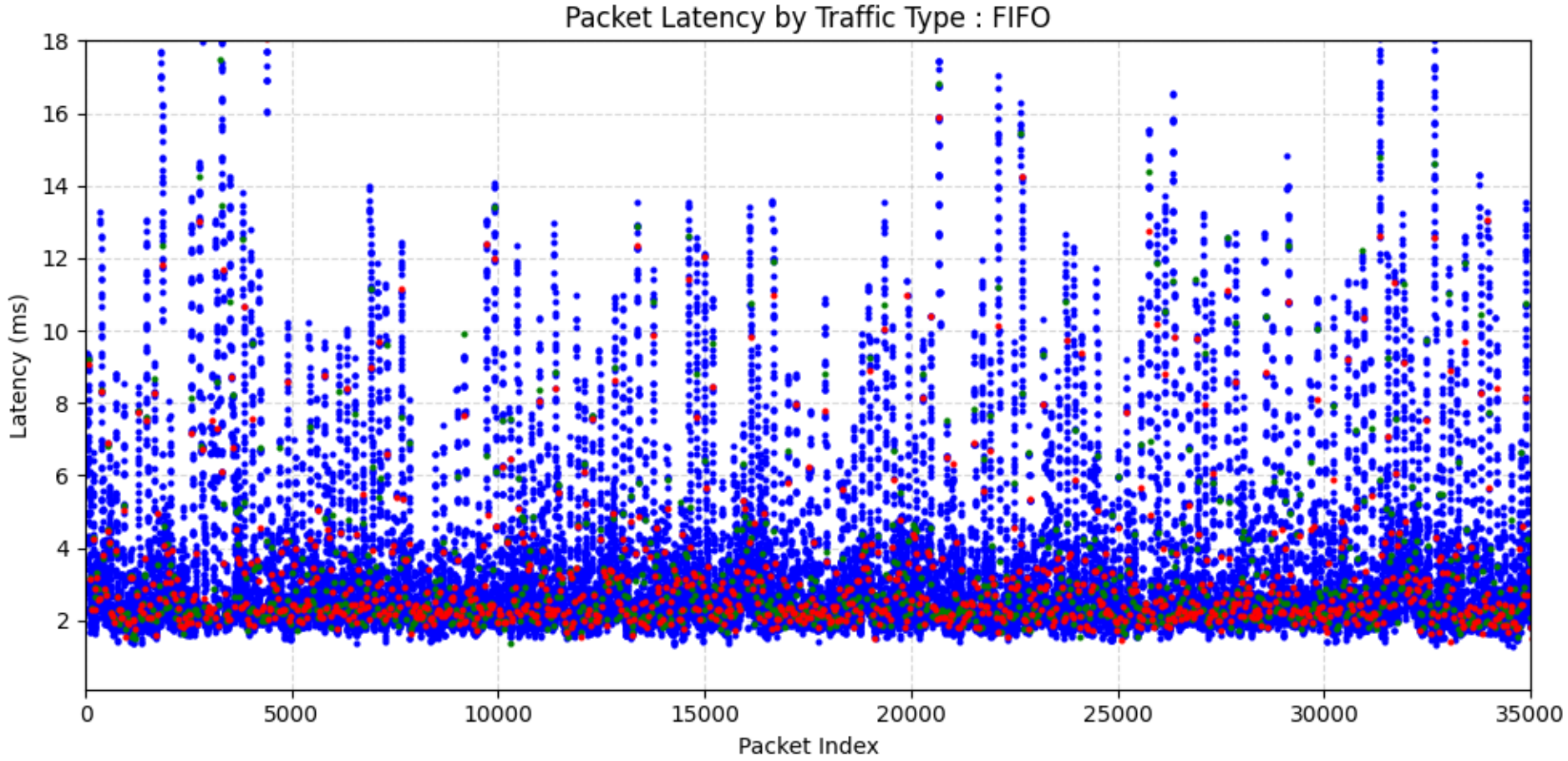
Part 2| *30 Feet – Base -25Mbps – FIFO vs TAS Run#3*

Where to place the access point is important



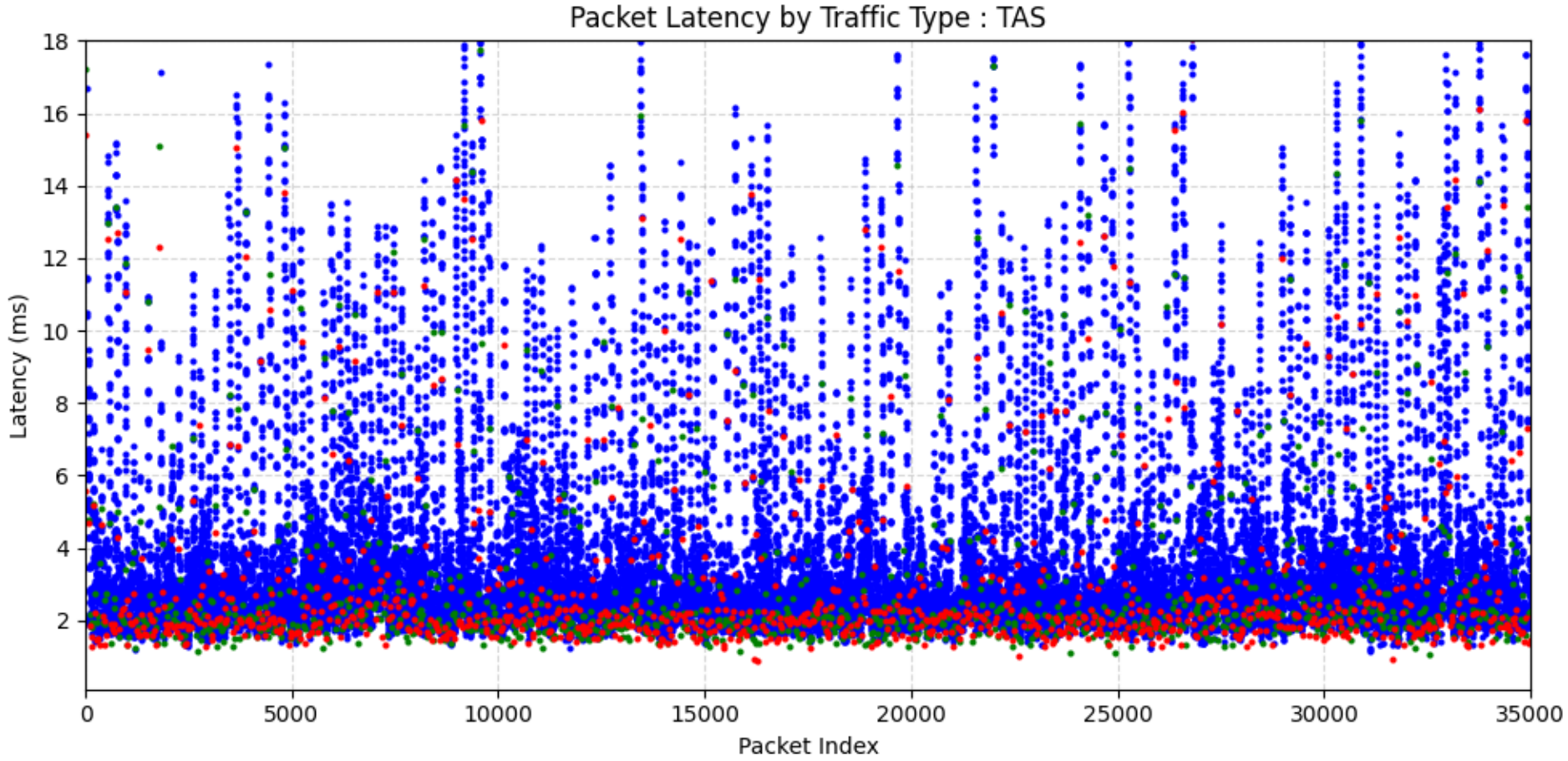
Part 2| *30 Feet –50Mbps – FIFO Run#1*

Where to place the access point is important



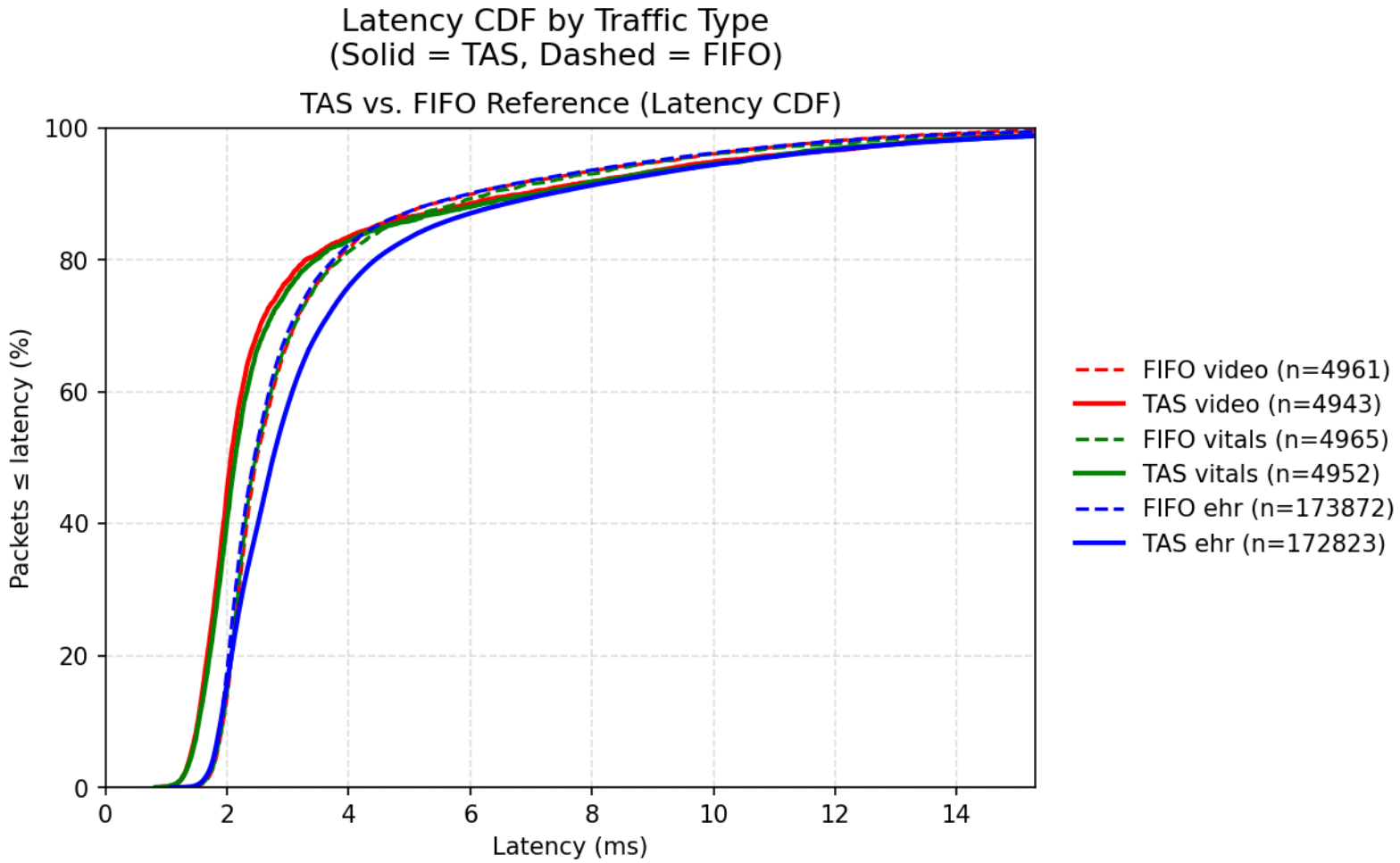
Part 2| *30 Feet – 50Mbps – TAS Run#1*

Where to place the access point is important



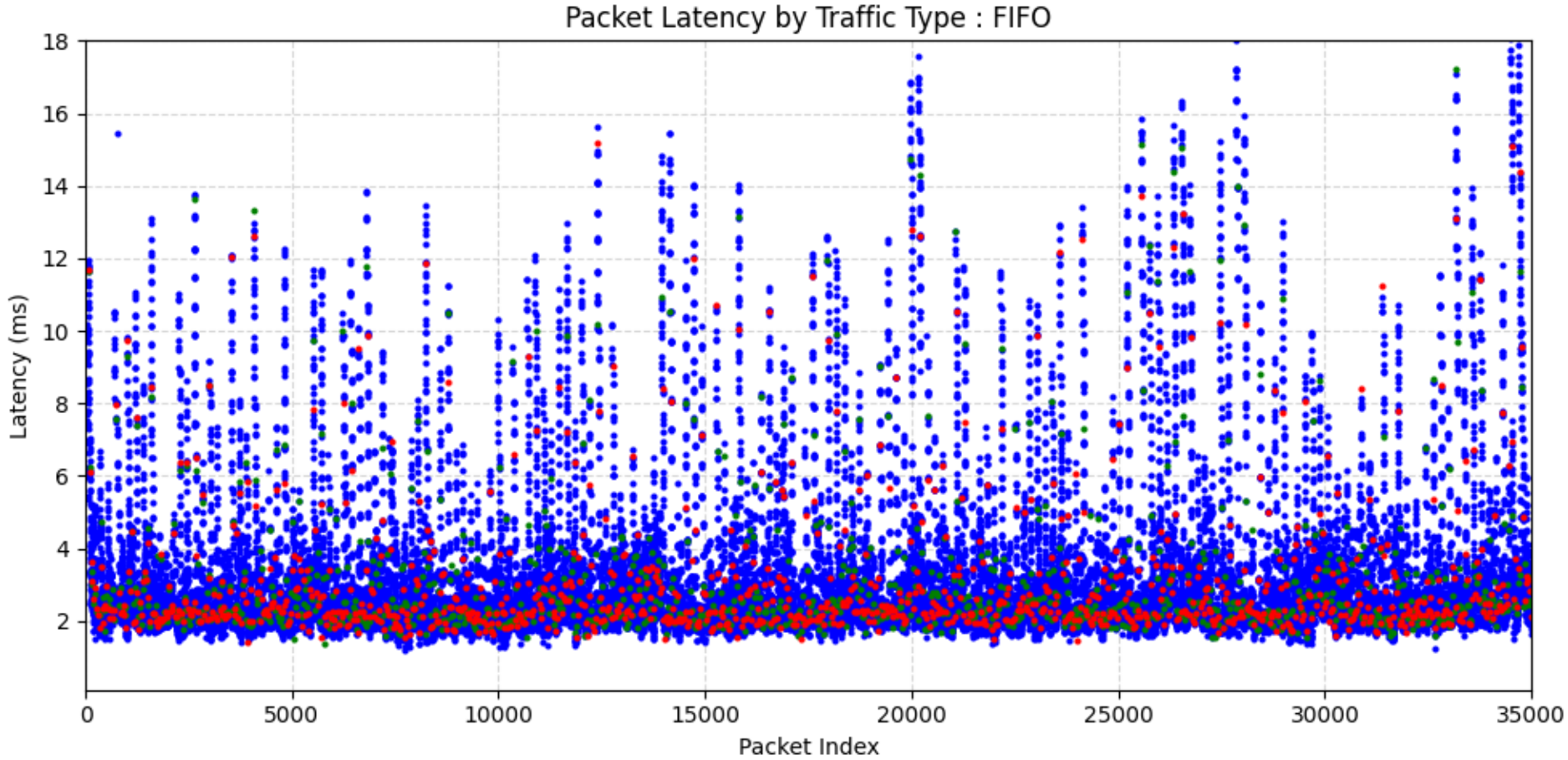
Part 2| *30 Feet – 50Mbps – FIFO vs TAS Run#1*

Where to place the access point is important



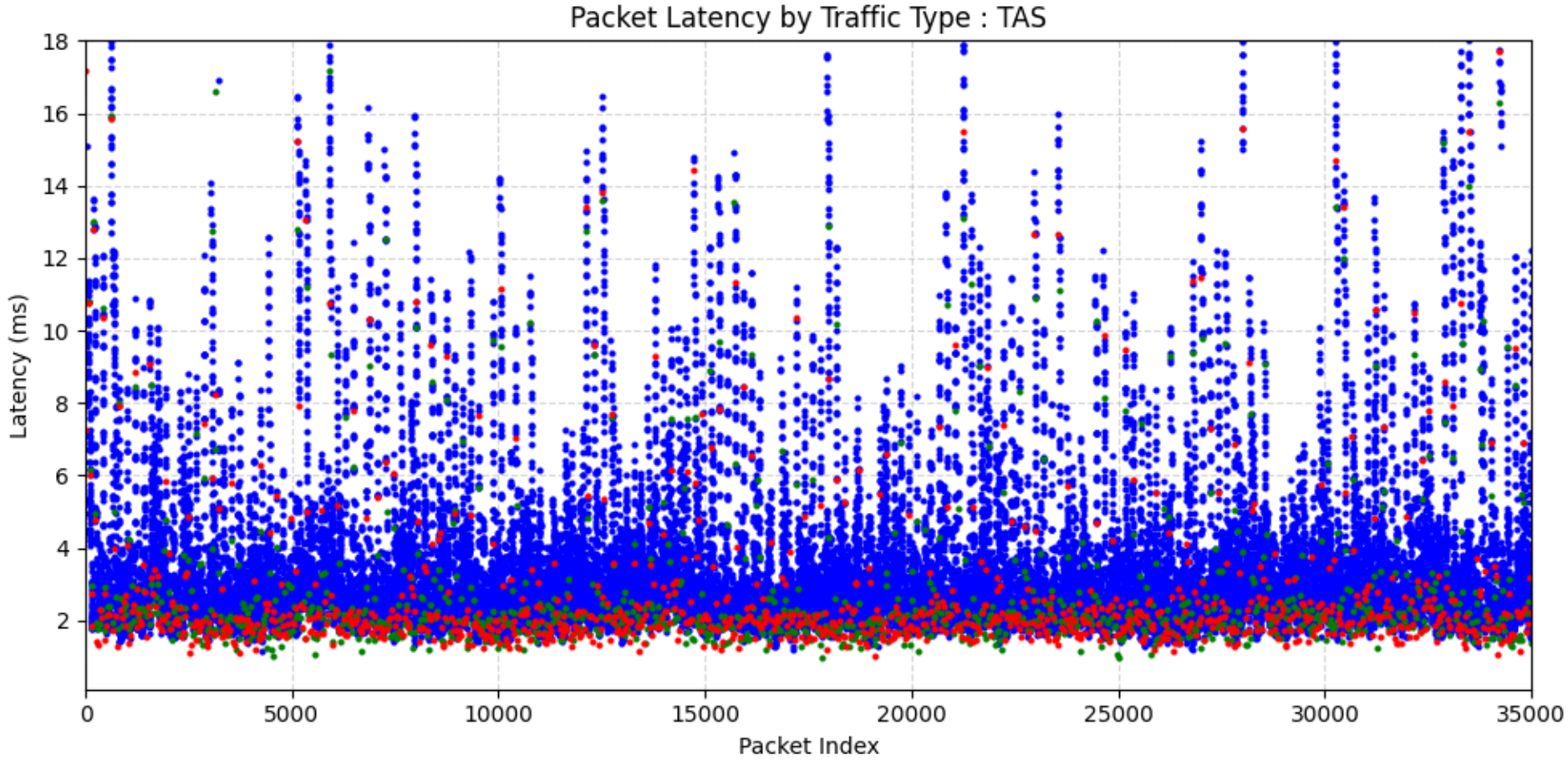
Part 2| *30 Feet –50Mbps – FIFO Run#2*

Where to place the access point is important



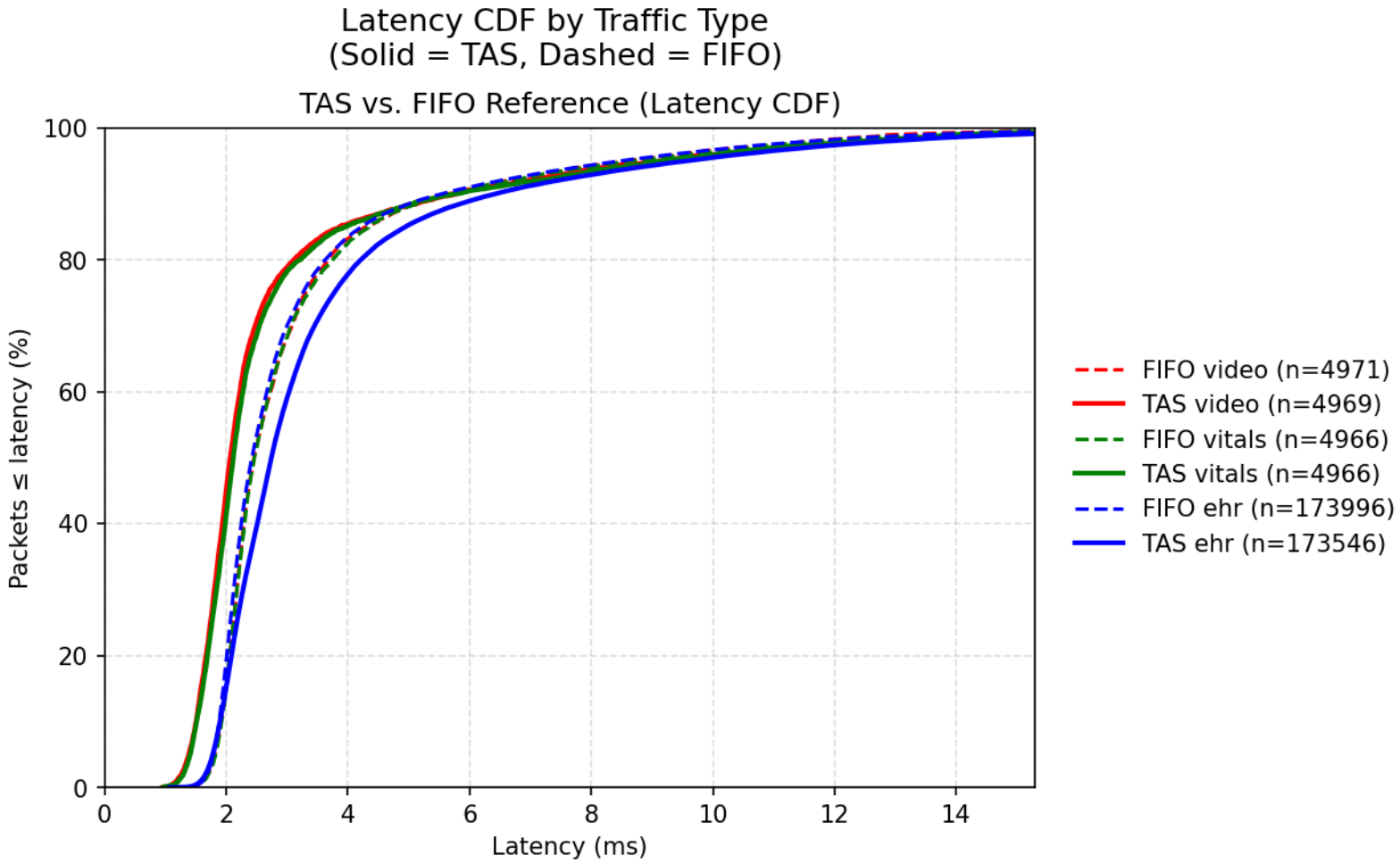
Part 2| *30 Feet – 50Mbps – TAS Run#2*

Where to place the access point is important



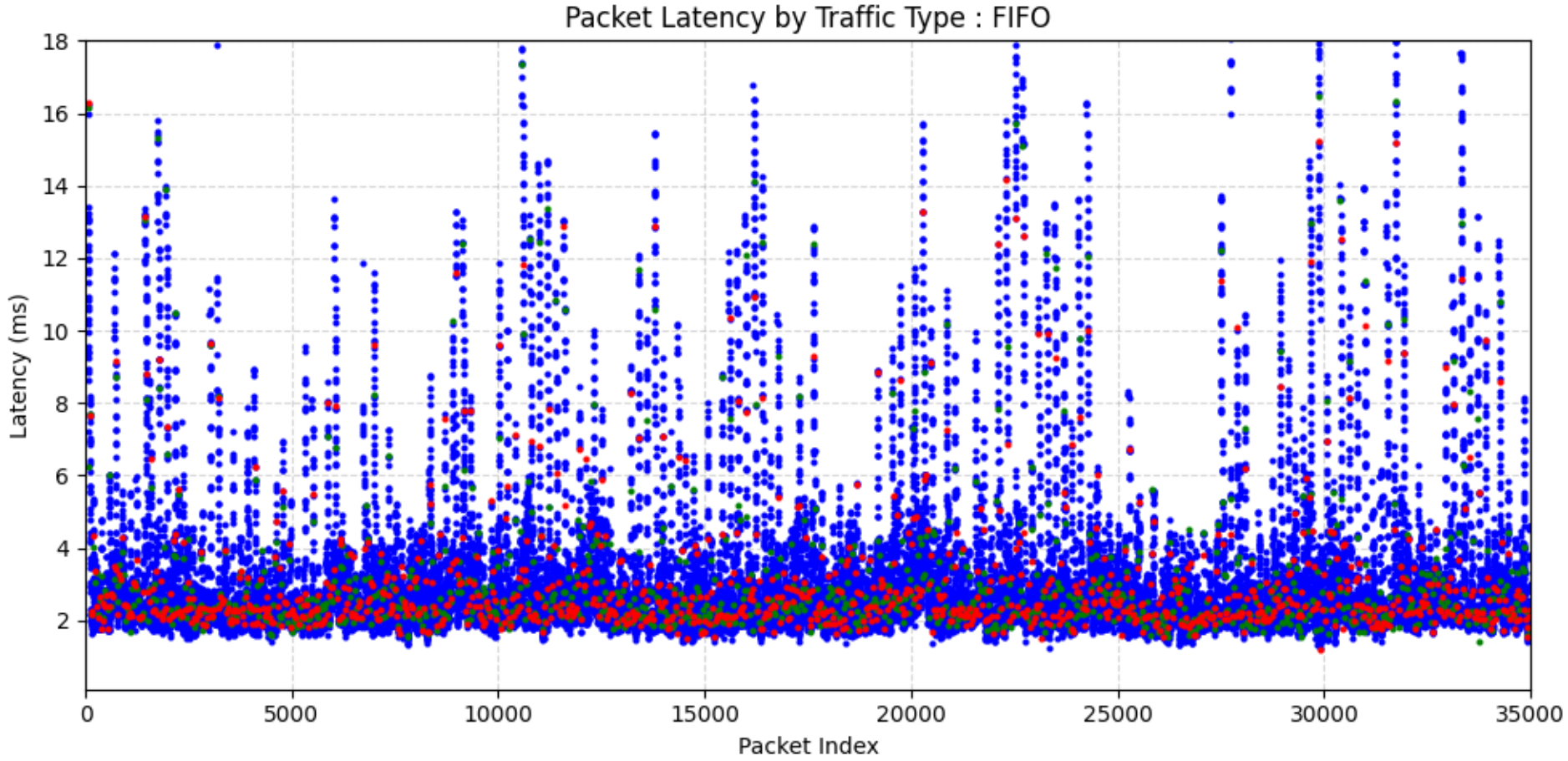
Part 2| *30 Feet – 50Mbps – FIFO vs TAS Run#2*

Where to place the access point is important



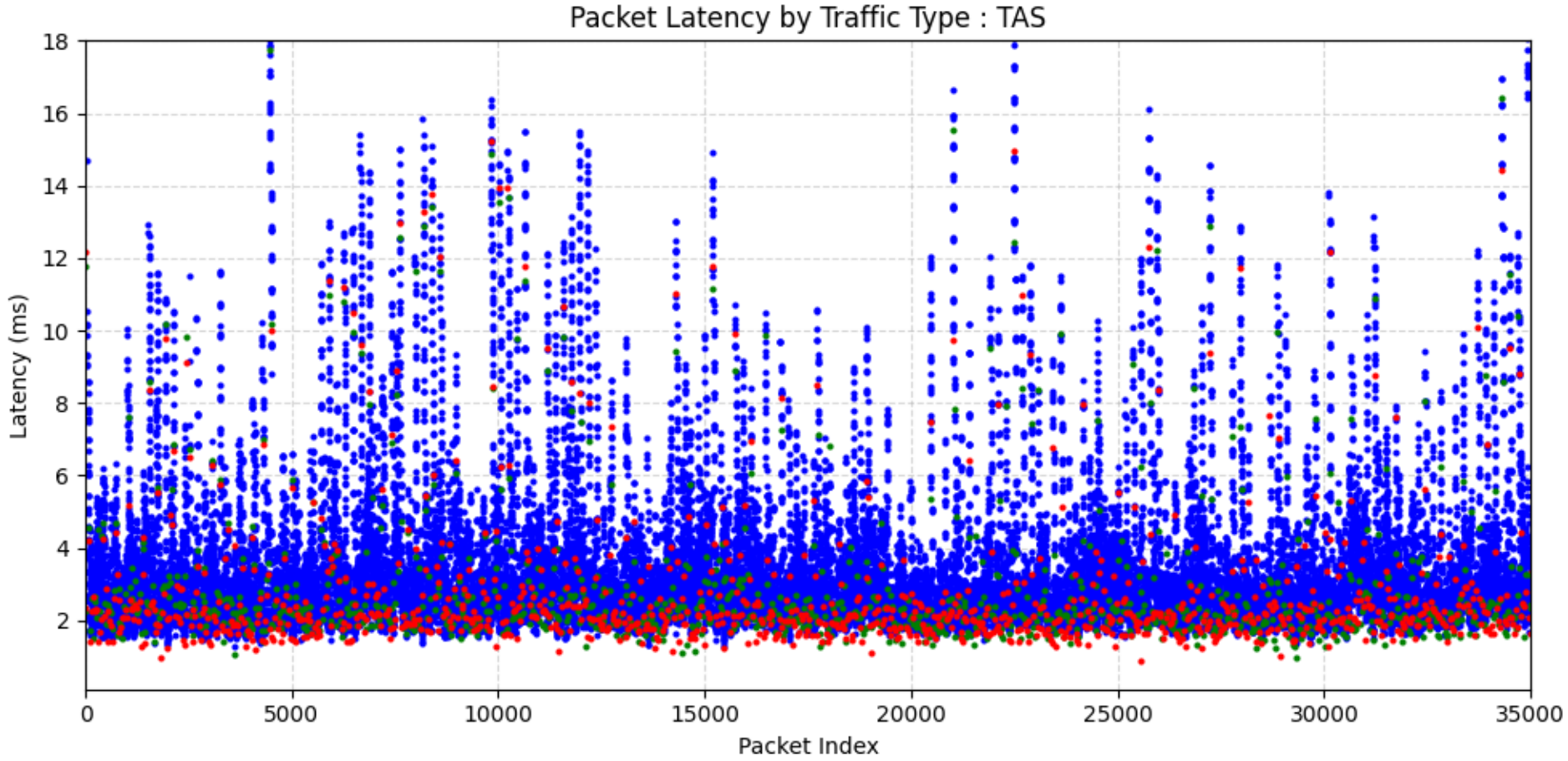
Part 2| *30 Feet –50Mbps – FIFO Run#3*

Where to place the access point is important



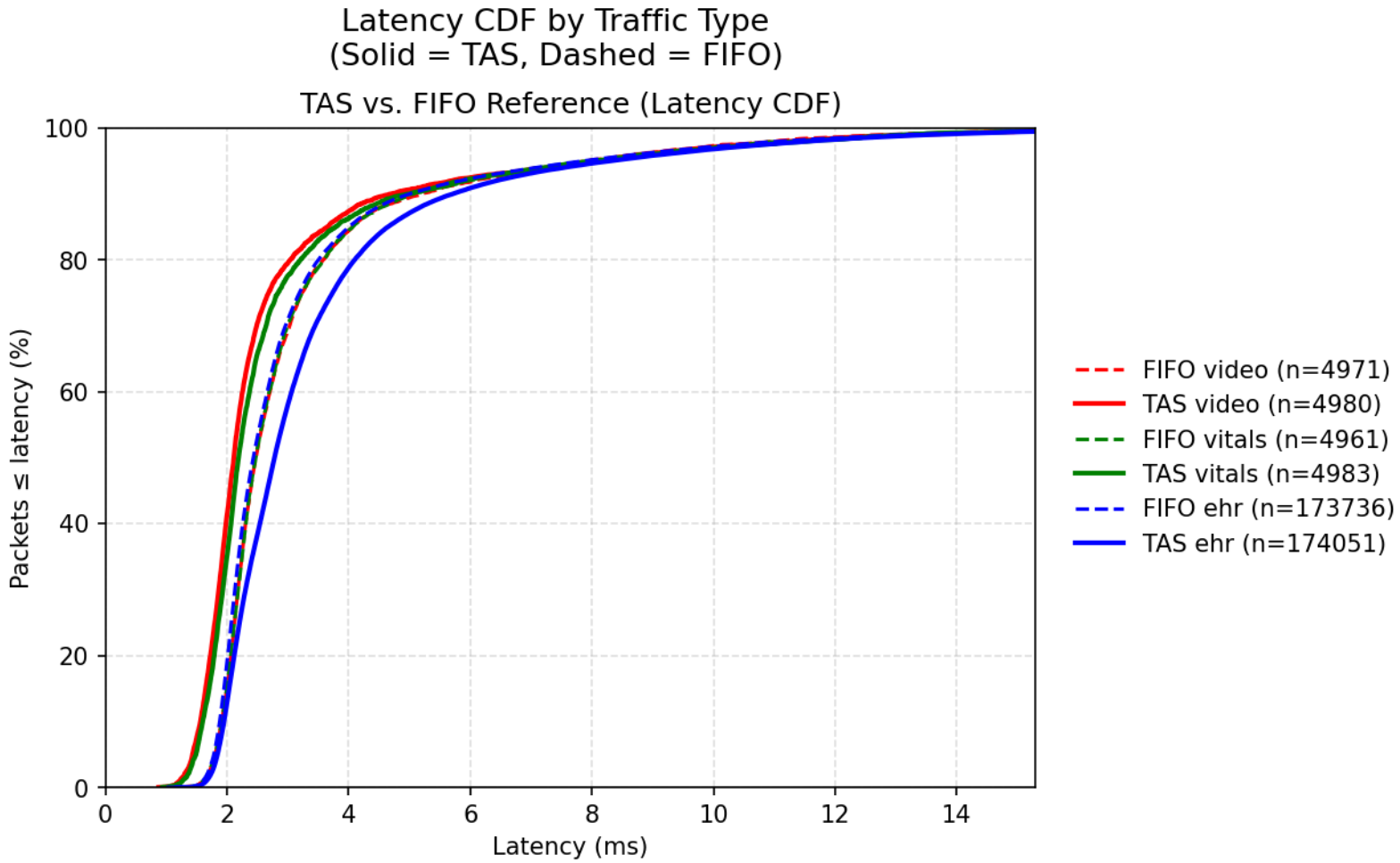
Part 2| *30 Feet – 50Mbps – TAS Run#3*

Where to place the access point is important



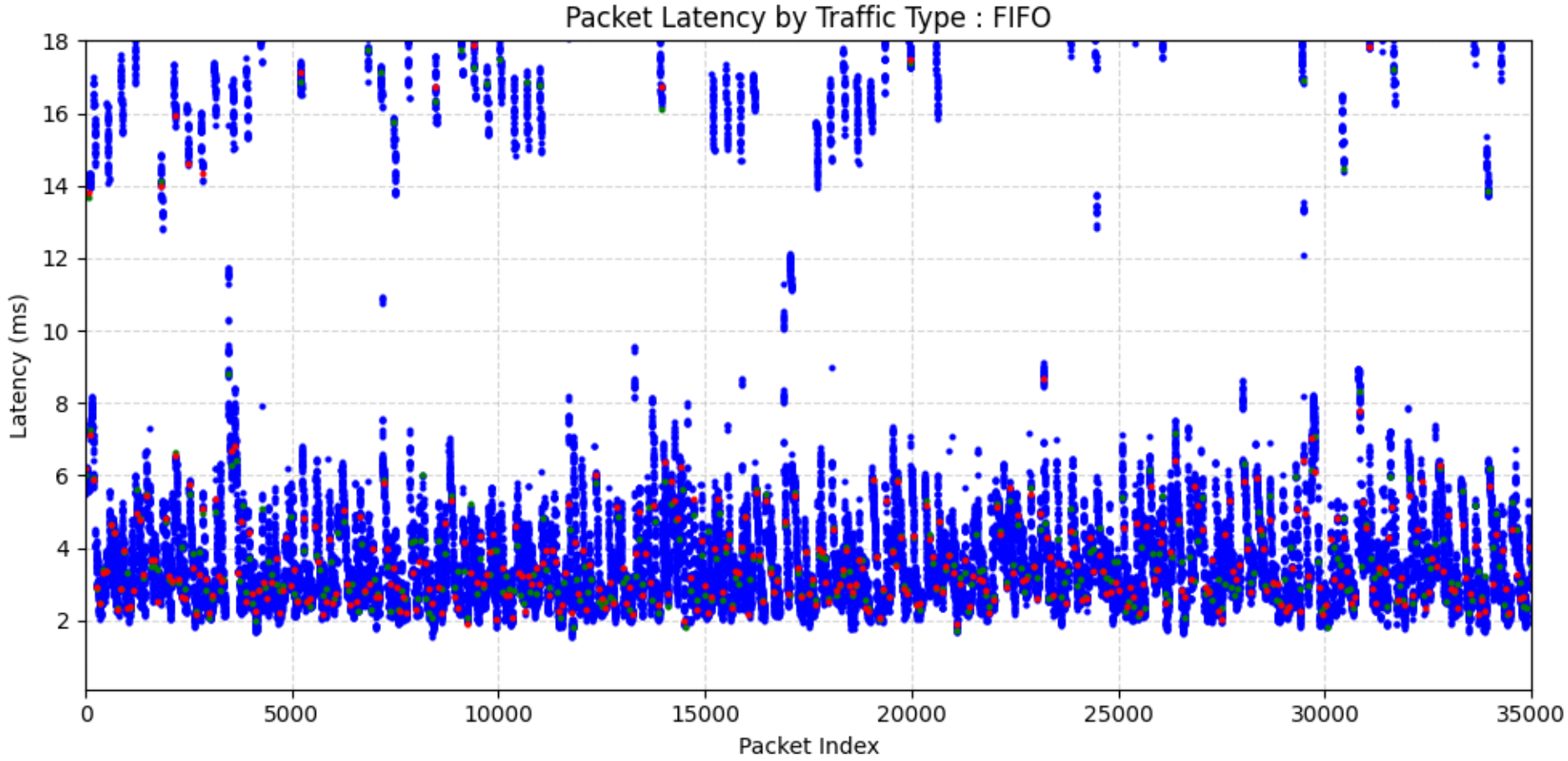
Part 2| *30 Feet – 50Mbps – FIFO vs TAS Run#3*

Where to place the access point is important



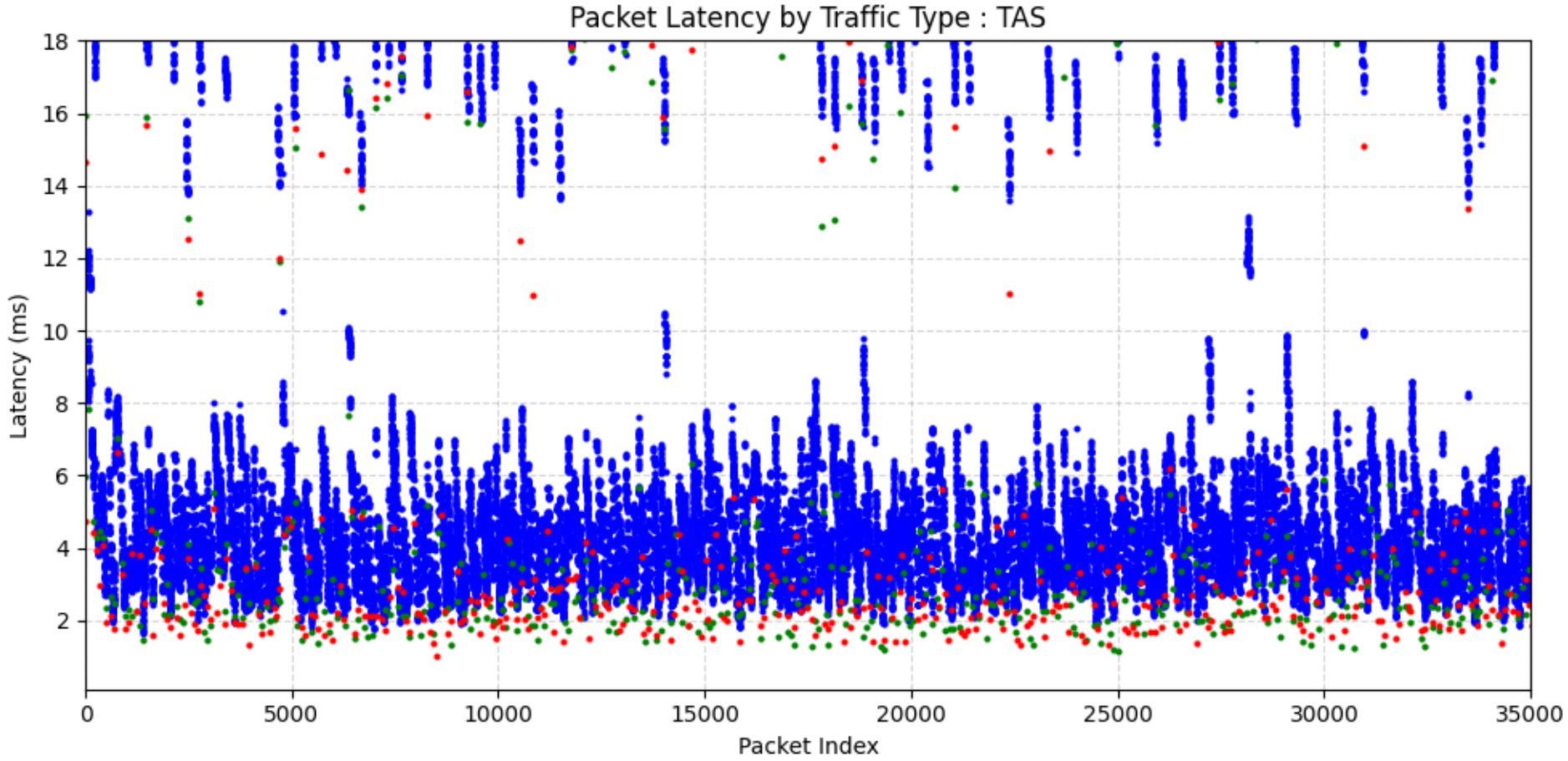
Part 2| *30 Feet –100Mbps – FIFO Run#1*

Where to place the access point is important



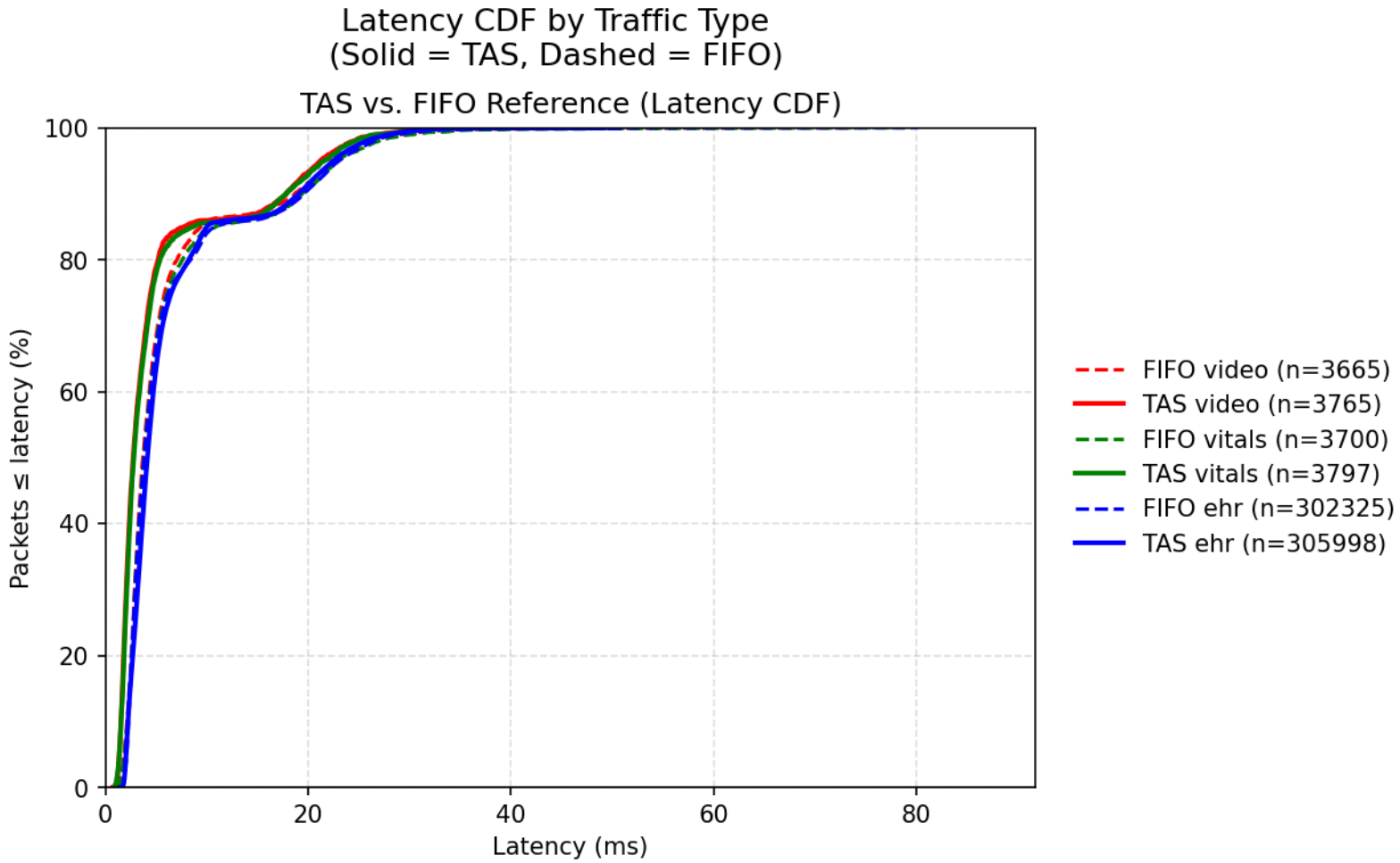
Part 2| *30 Feet – 100Mbps – TAS Run#1*

Where to place the access point is important



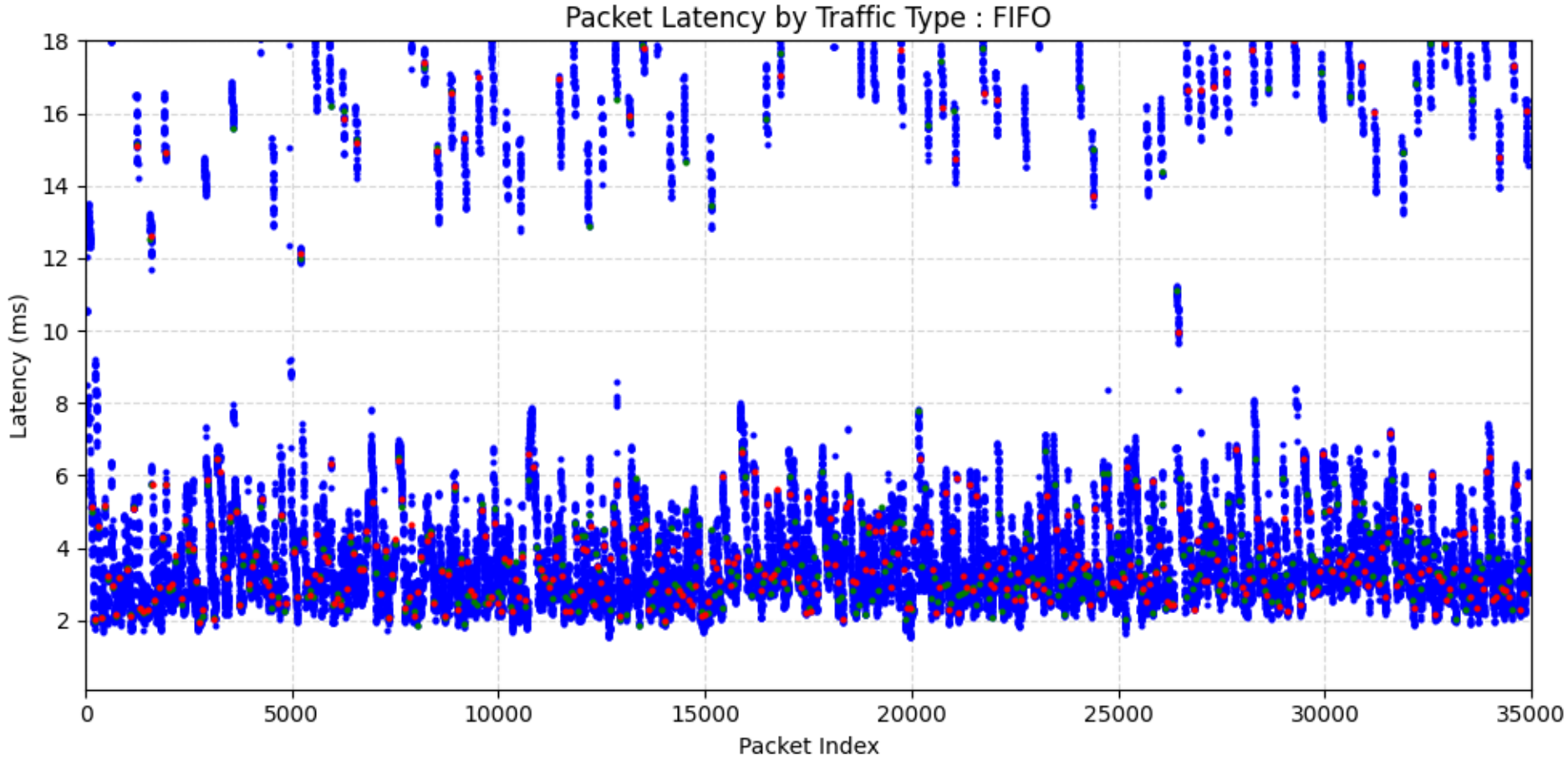
Part 2| *30 Feet – 100Mbps – FIFO vs TAS Run#1*

Where to place the access point is important



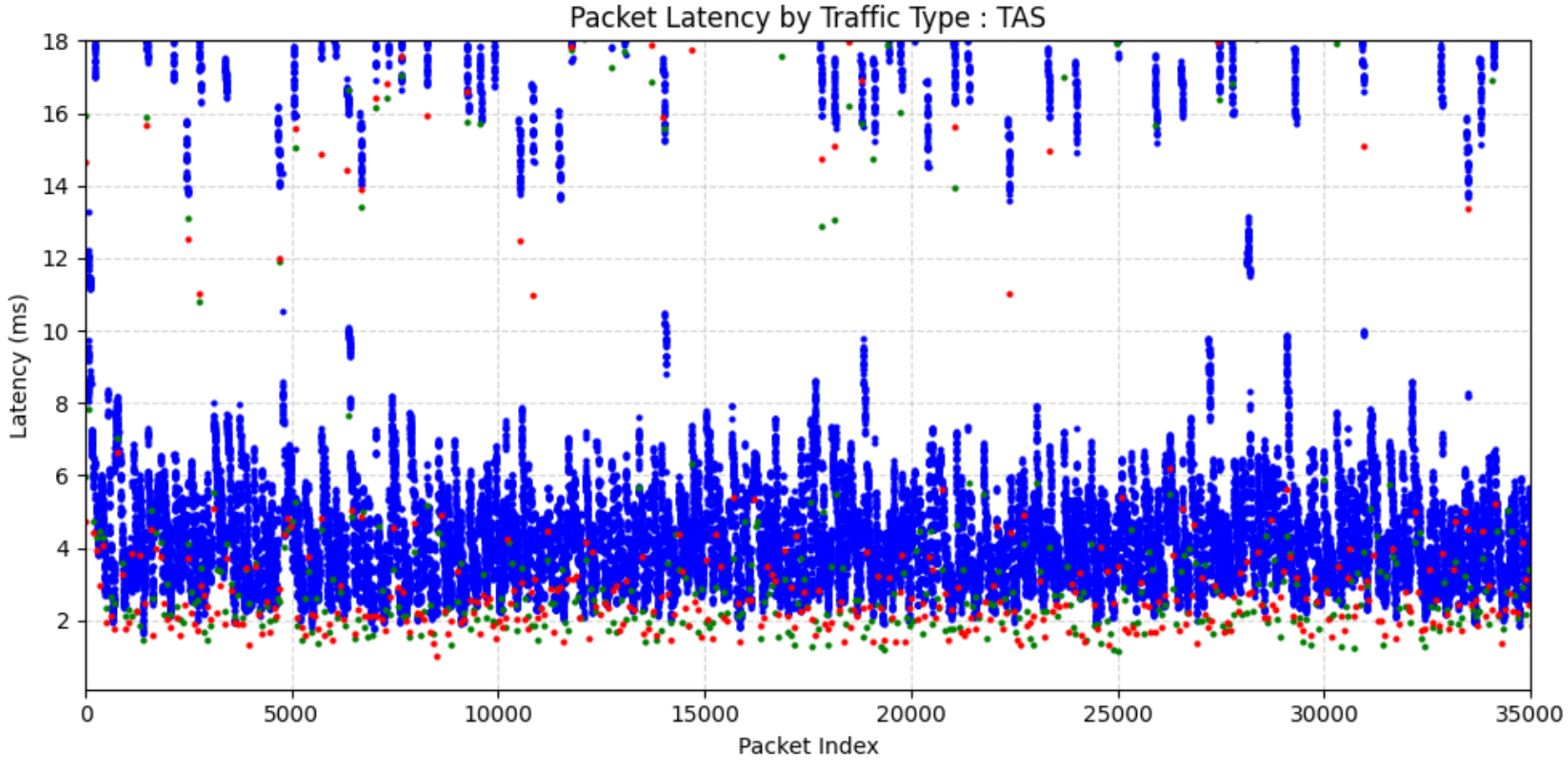
Part 2| *30 Feet –100Mbps – FIFO Run#2*

Where to place the access point is important



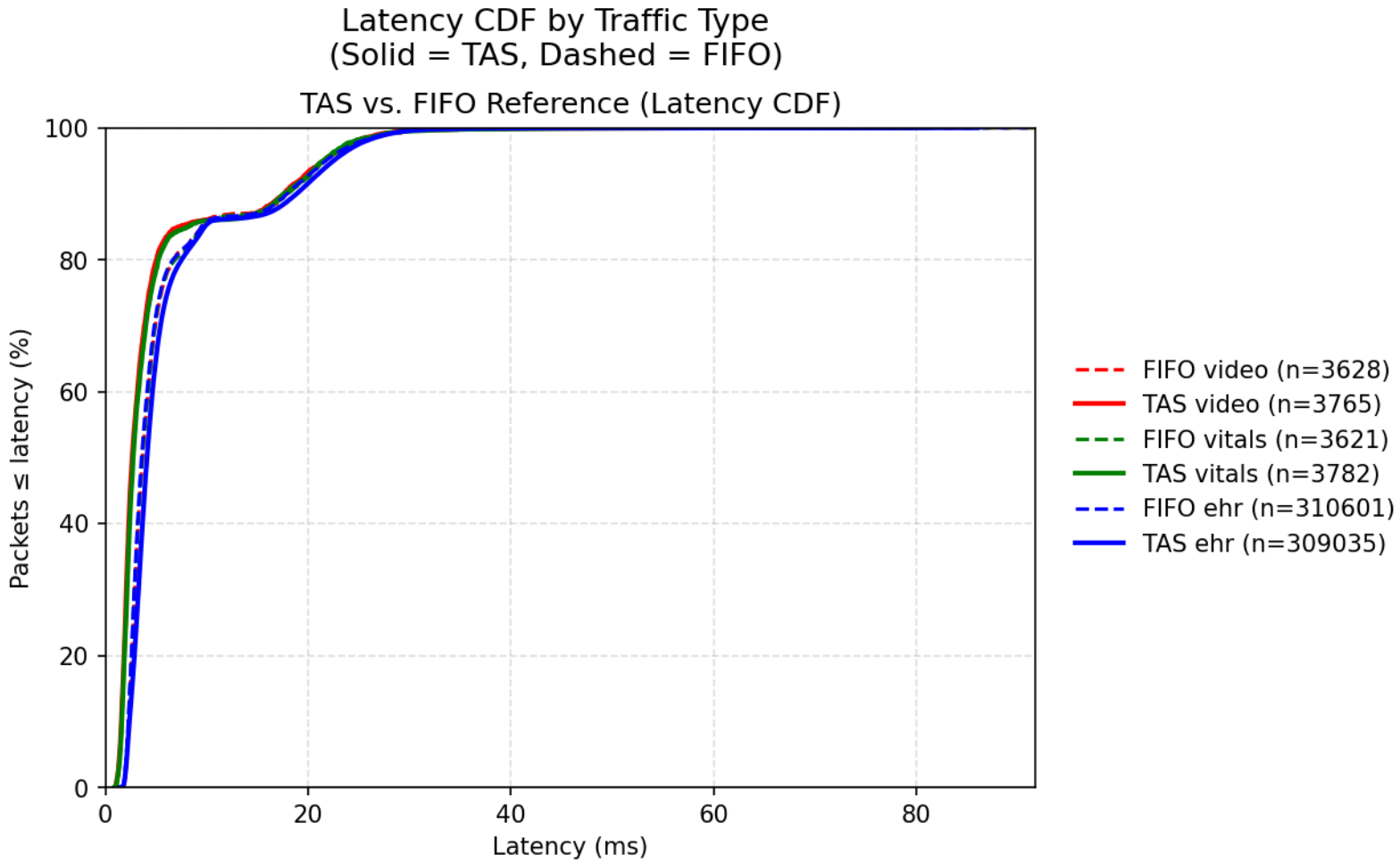
Part 2| *30 Feet – 100Mbps – TAS Run#1*

Where to place the access point is important



Part 2| *30 Feet – 100Mbps – FIFO vs TAS Run#2*

Where to place the access point is important



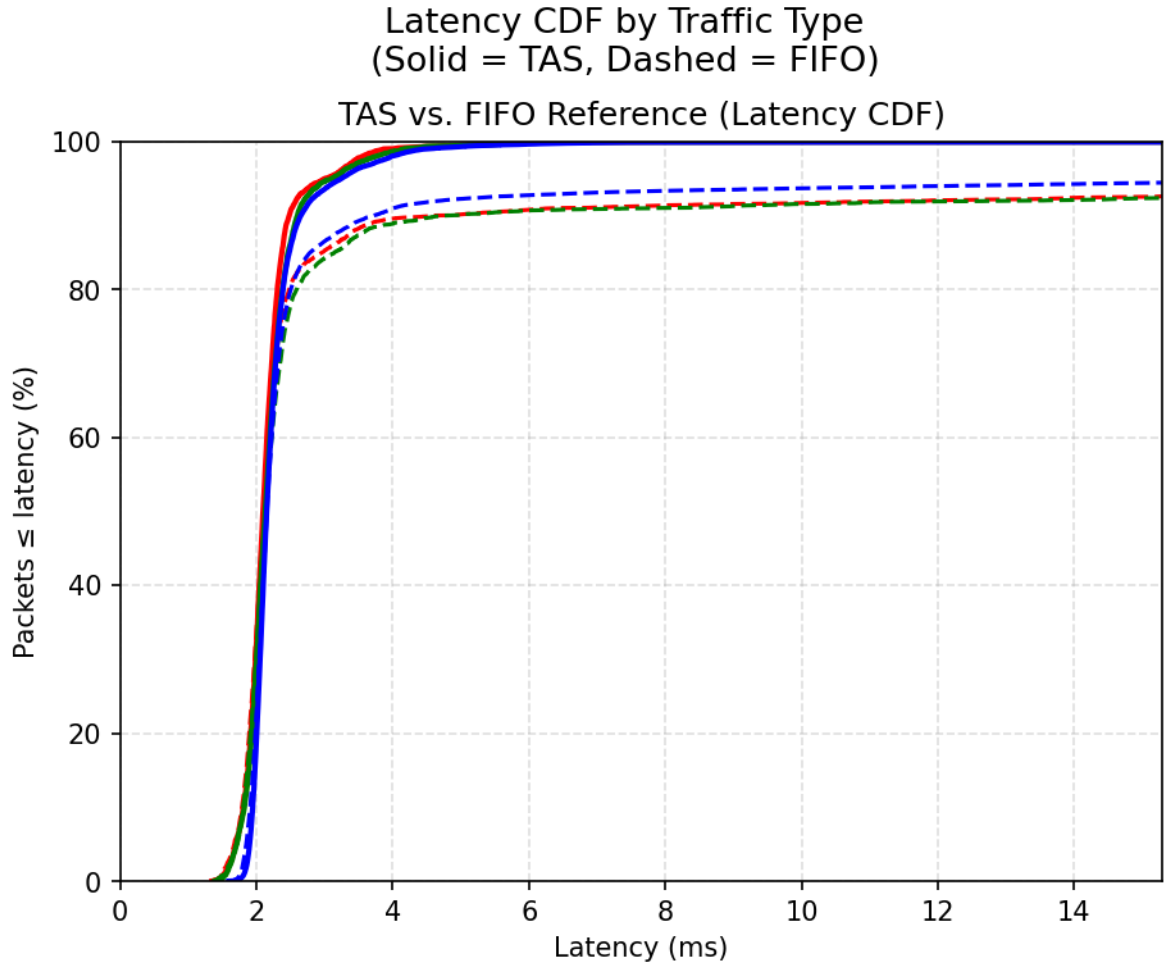
Part 2| *17 Feet - FIFO – base -with Priority (DSCP) vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)

Next Set:
Additional Work done on Priority only without TAS as suggested by Mam

Part 2| *17 Feet - FIFO – base -with Priority (DSCP) vs TAS*

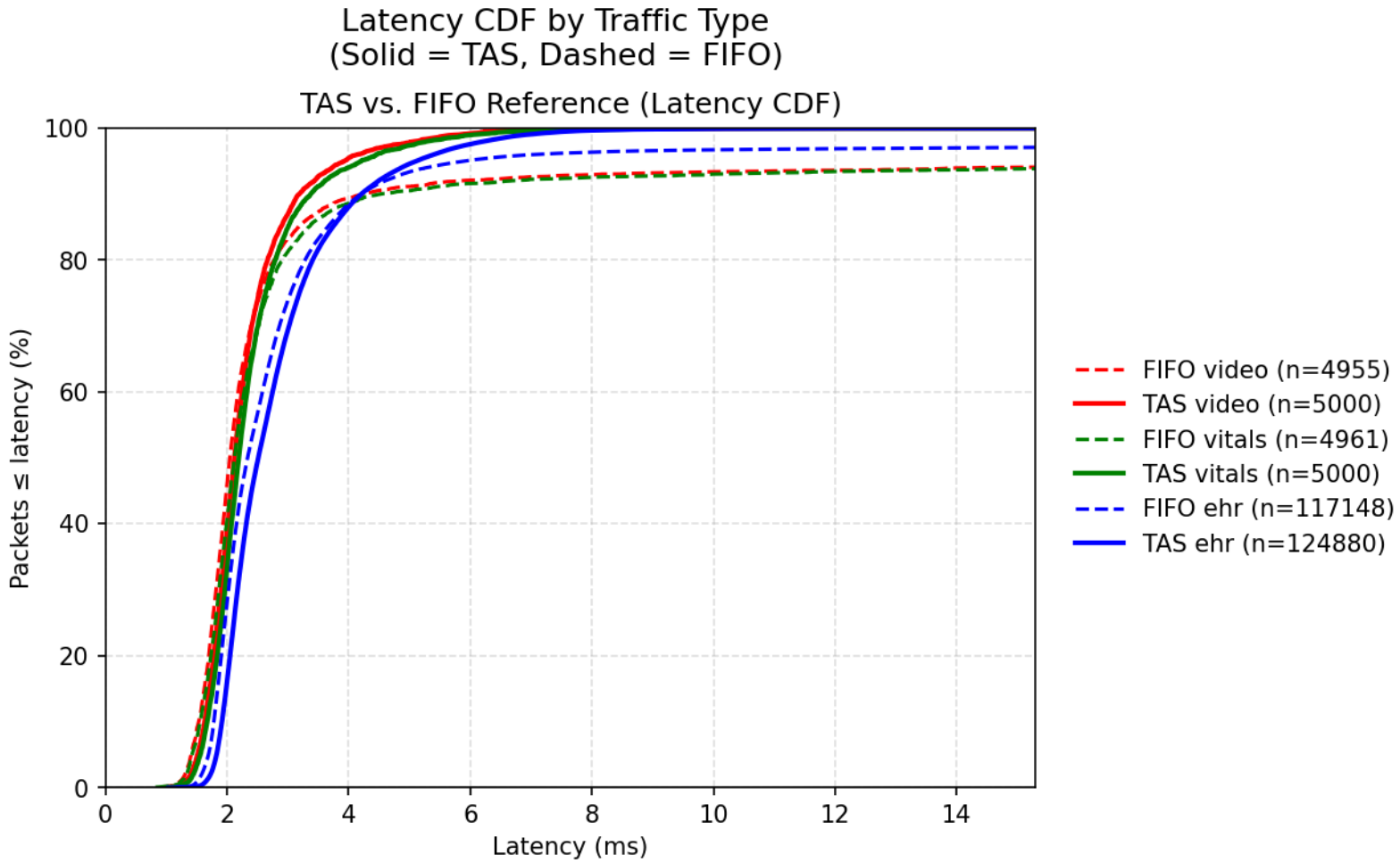
Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



When using DSCP (Case of WiFi Protorities, without TAS) it never stays to be the bound.

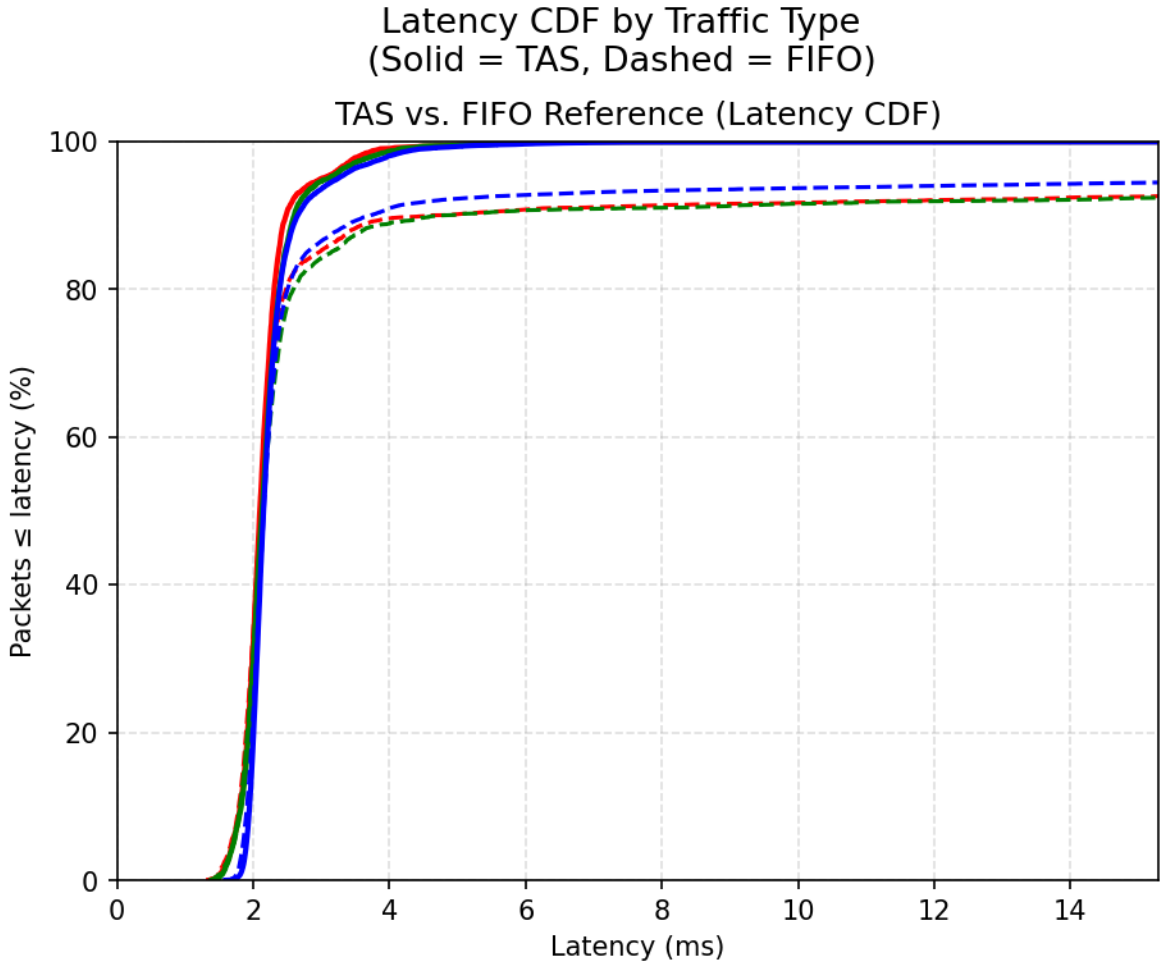
Part 2| *17 Feet - FIFO – 25mbps -with Priority (DSCP) vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



Part 2| *17 Feet - FIFO – 50mbps -with Priority (DSCP) vs TAS*

Comparison – FIFO vs TAS – Using Cumulative Distribution Function (CDF)



TAS is observed to have a steeper ascent showing the low latency. Priority (dscp) with FIFO can be helpful. But that doesn't help latency bounds like shaping does. (Priority packets are still not within latency bounds)

TAS is also observed to reduce the probability of packet loss

Our Work| *Conclusion and Future work*

1. *We could demonstrate that using a Time-aware Shaping over Ethernet before Wi-Fi Access Point is able to meet Class B (<10ms and .1% packet loss) requirements in an integrated wired-wireless scenario (Wi-Fi) with mixed traffic when traffic is within 25Mbps (5% of link speed). This enables video and vitals over tele-surgery and many soft real-time applications in Industrial and IoMT scenarios. Even haptic feedback possible.*

2. *We could demonstrate that Class A (10-50ms and 99-9.9% reliability) requirements can be met in an integrated wired-wireless scenario (Wi-Fi) with mixed traffic in case of traffic till 50Mbps (10% of link speed). This enables many soft real-time applications in Industrial and IoMT scenarios.*

3. *On reaching 100Mbps, it is still able to meet latency requirements of Class A while packet losses are high like >20 percent.*

4. *In case of wireless the coverage analysis and planning in addition to time aware shaping is important.*

END-TO-END DELAY < 10 milliseconds and packet loss <.1%
IEEE RTA CLASS B ✓

END-TO-END DELAY < 50 milliseconds and packet loss <1%
IEEE RTA CLASS A ✓

Work| *References*

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