Wi-Fi® Device Metrics

v1.0

www.wi-fi.org

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1 Overview

1.1 Scope and purpose

This document provides the Wi-Fi industry with a set of test cases that measure performance of common use cases that a residential end customer might experience.

One premise of this document is that an end customer will use the Wi-Fi device received out of the box and thus testing is performed on the device as-is. This approach aligns with industry trends where, particularly for Access Points and Mesh systems, devices are either pre-configured or self-configuring when installed.

The second premise of this document is statistical representation of results. Wi-Fi 6 is especially aimed at improving the overall experience for a large number of users sharing the channel. This means that one simple performance number for a test is no longer useful since there is a wide/temporal variation in results as the population of Wi-Fi devices contest for the channel. This document recommends how results can be collected and presented in a statistical manner to give the test engineer a clearer view of the spread of these results to gain a better understanding of the likely overall user experience.

Thirdly, this document emphasizes key specific components essential to building a repeatable and reproducible test bed. Repeatable means multiple tests on the same test bed give the same results as previous runs. Reproducible means the same test conditions on a similar test bed, perhaps in a different location, also provides the same results.

1.2 Definition of a Device Under Test

The program procedures are applicable to Access Point (APUT) and Station (STAUT) whether sourcing or sinking data.

2 References

[1] RFC 7679 A One-Way Delay Metric for IP Performance Metrics (IPPM), 2016

[2] RFC 3393 IP Packet Delay Variation Metric for IP Performance Metrics (IPPM)

[3] IPerf2 A tool to measure network performance of TCP/UDP including latency

2.1 Definitions, acronyms, and abbreviations

2.1.1 Definitions

The following definitions are applicable to this document.

Table 1. Definitions

Term	Definition
Jitter	Inter packet delay variation.
One Way Delay	Time required to convey a packet of information from the source to the destination on the Wi-Fi link.
Roaming	Describes the action of a device that moves from one wireless network area to another wireless network area.
Throughput	The maximum rate at which none of the offered frames are dropped by the device.

2.1.2 Acronyms and abbreviations

This section defines the acronyms and abbreviations used throughout this document. Some acronyms and abbreviations are commonly used in publications and standards defining the operation of wireless local area networks, while others have been generated by Wi-Fi Alliance. Refer to the Wi-Fi Alliance Acronyms Terms Definitions document for a complete list of approved acronyms and abbreviations.

Table 2. Acronyms and Abbreviations

Acronyms	Definition
AP	Access Point
AR	Augmented reality
CCDF	Complementary Cumulative Distributive Function
CDF	Cumulative Distributive Function
DFS	Dynamic Frequency Selection
DL	Downlink
DUT	Device Under Test
FTP	File Transfer Protocol
HD	High Definition
HTTP	Hypertext Transfer Protocol
MIMO	Multiple-Input Multiple-Output
OBSS	Overlapping BSS
OWD	One Way Delay

Acronyms	Definition
PDF	Probability Density Function
QoS	Quality of Service
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
STA	Station
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UL	Uplink
VR	Virtual Reality
VSWR	Voltage Standing Wave Ratio
XR	Extended Reality

3 Test bed setup and calibration

This section provides an overview of the test method and guidelines for test bed set up and calibration.

3.1 Test methodology

The two most common methods for testing Wi-Fi devices are:

- Over the Air (OTA)
- Conducted (Cabled)

Both methods have their benefits and tradeoffs. For either approach, a stable and calibrated test bed is a critical prerequisite. This document uses the OTA test methodology.

In the OTA test methodology, there is no direct physical connection between STAs and APs as communication is purely through the wireless medium or OTA. There are many forms of OTA testing, but this document focuses on OTA testing within an RF chamber. OTA is a commonly used test methodology and is simple to get started. OTA testing also works well for many types of devices especially when antennas are embedded within the device.

Getting accurate and repeatable results can be a challenge in OTA testing because the wireless channel is constantly changing, and external sources of interference can impact performance. RF shields should be used to isolate the test activity from external interference sources. RF shields range from small benchtop units to large walk-in chambers. Regardless which form factor is used, isolation chambers are key to stable and repeatable Wi-Fi tests. It is also recommended that baseline calibration testing should be done for each device in the test bed. This ensures the device is working to vendor specifications, unless using a testing platform that comes pre-calibrated.

Calibrating the OTA test bed involves calibrating each of the component to ensure the performance expected is delivered. The test bed performance should always be greater than the stated performance of the DUT to ensure the maximum potential of the DUT can be reached. Each device and accessory must be verified independently to a known calibrated reference.

3.2 Test bed requirements

The following sections detail the requirements of the test bed to achieve repeatable and reproduceable test results for any of the above setups.

3.2.1 Shielded test chamber requirements

Good RF shielding is required to enable repeatable tests. Several tests will make use of shielded chambers to isolate the devices from one another and from the outside world.

The two most common OTA setups for Wi-Fi testing are small semi-anechoic chambers or large walk-in chambers.

Chambers should be anechoic to limit reflections and standing waves. Within the chamber, the ambient noise and signals from the outside shall be less than -100 dBm measured in an 80 MHz channel bandwidth. This measurement shall be performed using a spectrum analyzer with sufficient sensitivity in this channel bandwidth. All cable ingress and egress points should provide filtering to maintain the isolation requirement.

Using multiple small semi-anechoic chamber OTA testing, APs and STAs are placed in different chambers connected to each other using RF cables. An example of a three-chamber setup is shown in Figure 1.

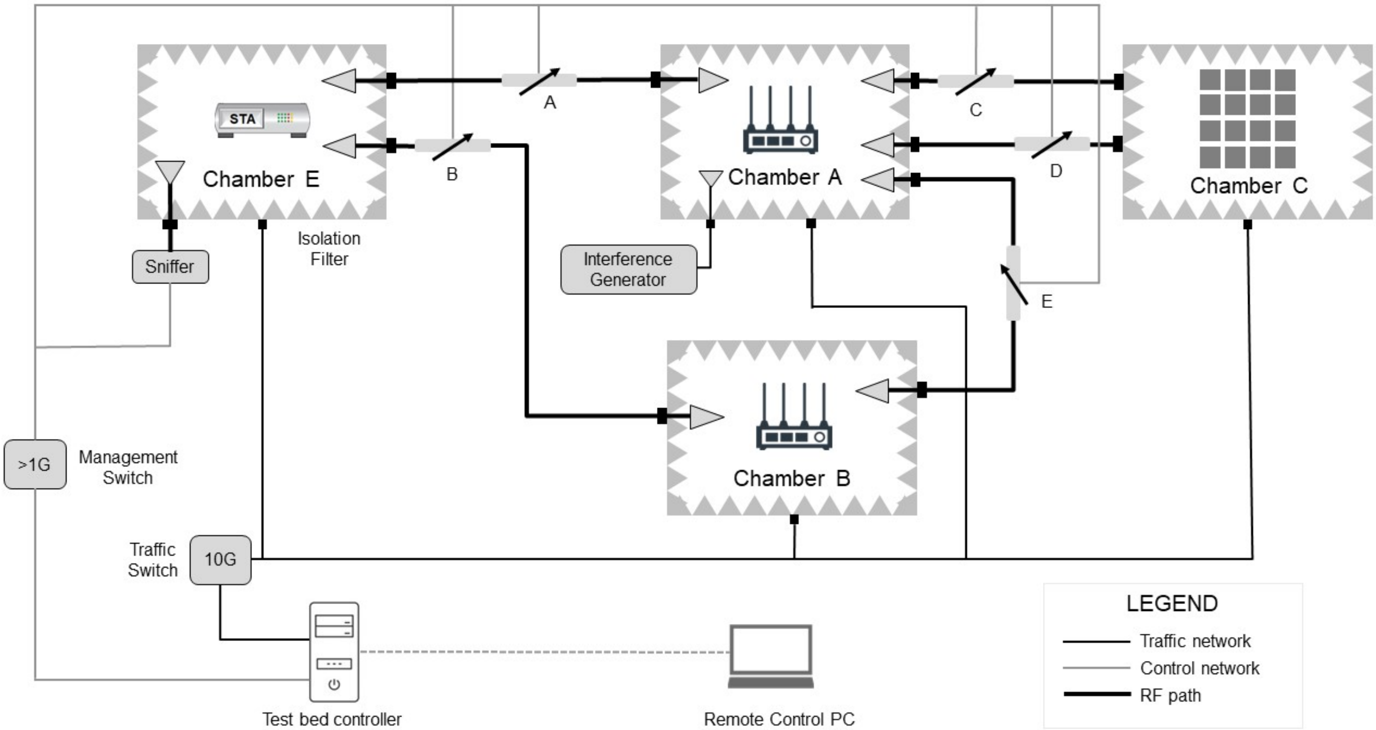


Figure 1. Three-Chamber test bed example

In this example, these multiple chambers serve to isolate the devices and to control the channel path characteristics between them. In these cases, separation is determined by path loss introduced by attenuators.

It is important that all components, cables, ingress/egress points, and outside devices preserve the integrity of the key RF isolation requirements. Ethernet cables should be chosen appropriately according to the traffic generation data rate (see section 3.2.4).

Alternatively, a large walk-in chamber accommodates both STAs and APs in the same chamber. If using this form factor, variability in signal strength at the client devices is a key concern and care must be taken to optimize placement of STAs relative to APs. Path loss is introduced by physical separation of devices. While not ideal for performance testing, a large walk-in chamber can be effective provided it is properly configured.

3.2.2 Test Channel requirements

To enable repeatable testing, the wireless channel between the devices shall be well controlled. A test configuration is defined by the following key channel attributes.

3.2.2.1 Path loss

Separation between devices shall be modelled by either physically distancing devices, or by introducing attenuation that models free space isotropic loss as expressed in this formula.

$$PathLoss(dB) = 20\ log_{10}\big(Frequency(GHz)\big) + 20\ log_{10}\big(Distance(m)\big) + 32.5$$

If attenuators are used, each attenuator shall be sufficiently RF isolated as to maintain the requirements in 3.2.1

3.2.2.2 Multipath

A channel emulator may be used as part of the test equipment to implement the wireless channel. If a channel emulator is used, the channel emulator shall be sufficiently RF isolated as to maintain the requirements in 3.2.1.

3.2.2.3 Number of spatial streams

If the wireless channel is created using a channel emulator or attenuators, the setup shall support at least the same number of independent channels as the number of spatial streams being tested.

3.2.3 Test bed devices and DUT requirements

Typically, test bed devices assume two different roles, either as:

- A device being tested (DUT), or
- A test bed device(s)

For example, a simple roaming test case uses two APs, and one STA. The STA will be made to roam between the APs. If the STA is the DUT (STAUT), the two APs shall be test bed APs. If the DUT is an AP (APUT), the STA and the other AP shall be test bed devices.

3.2.3.1 Test bed device requirements

Test bed APs shall have at least the same, or better, Wi-Fi physical layer capability as the STAUT. Examples include spatial streams, maximum MCS, and other functionality as appropriate for the test such as OFDMA or MU-MIMO. It is recommended that test bed equipment supports the latest generation of Wi-Fi CERTIFIED technology.

Test bed STAs shall have the same, or better, Wi-Fi physical layer capability as the APUT, except that they may support up to only two antennas and two spatial streams.

Test bed devices may be either real products or dedicated test instruments.

3.2.3.2 DUT requirements

DUTs are expected to be consumer products, either STAs or APs, and shall have no specific physical layer requirements.

DUTs may support the ability to be configured and controlled by either the local test automation, or by some other means, remotely. Some examples for automation control are QuickTrack Control App, Android Debug Bridge (ADB), and others. Various screen mirroring apps could be used for control from outside the test environment.

If a test requires a measurement of throughput, a STAUT shall support traffic generation with configurable parameters. The traffic generation tool utilized must be capable of accurate measurement of throughput. The traffic generation solution should provide measurement of throughput with constant steady state load.

If a test measures One Way Delay, a STAUT shall support the ability to time synchronize with the test bed controller such as using IEEE 1588.

3.2.4 Traffic generation

The traffic generation tool(s) should meet these characteristics:

- Provide reliable traffic generation
- Provide isochronous, variable data rate, traffic
- Control of parameters that remain constant throughout the test
- Configuration of frame size, frame rate and time interval
- Support TCP and UDP traffic generation
- Automated real world traffic applications such as HTTP, video, and voice
- Configurable QoS parameters

In downlink mode, the test bed controller generates the traffic towards the STA through the AP in bridge mode. In uplink mode, the STA generates traffic toward the test bed controller through the AP.

3.2.5 Interference generation

Interference is commonplace in real world Wi-Fi environments and is an important aspect of testing performance. In the context of Wi-Fi, there are two broad categories of interference.

1. Interference from devices that do not respect other users of the channel. A microwave oven is an example.
2. Interference from devices that do respect other users of the channel. Another group of Wi-Fi devices in the same location is an example.

Strictly speaking, the former is true interference, and the latter is just other Wi-Fi devices following the channel contention rules, also termed OBSS. Traditionally the Wi-Fi community has used the term interference to mean the latter, and this method uses the term interference in this context unless specifically stated. Microwave interference is an example.

OBSS interference can be generated in several ways. One example is to set up an independent BSS, have the devices pass normal traffic, and introduce an RF connection of an appropriate level between the OBSS and the devices being tested. Another example could be a Wi-Fi chipset used to broadcast data packets to congest the channel at a certain level while observing the channel contention rules.

3.2.6 Traffic capture and analysis

A sniffer may be required for analysis of OTA Wi-Fi traffic. The sniffer shall have the same, or better, Wi-Fi physical layer capability as the test bed devices.

Figure 2 depicts the basic test bed configuration illustrating separate traffic and control networks.

The traffic network shall support 10G Ethernet. The Control network shall support 1G Ethernet or higher.

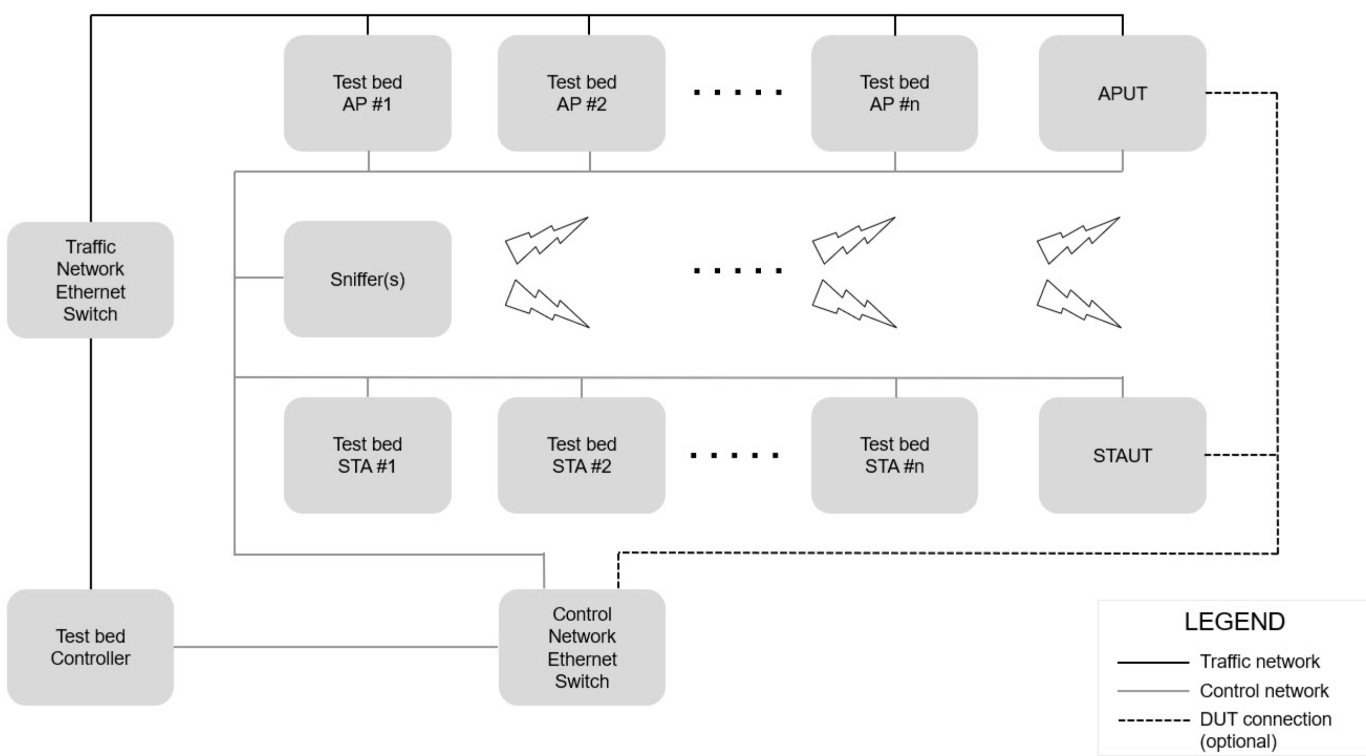


Figure 2. Standard Wi-Fi Alliance test bed network schematic

3.3 Test bed calibration

The final step in setting up the test bed is calibration. This is done to understand the test bed's overall performance, especially limitations with respect to traffic generation or measurement. This is a critical foundational step to achieving a stable test bed. Calibrating a test bed involved verifying performance of the key individual components of the test bed. Whenever there is a change in the test bed, it is a good practice to recalibrate. This step can be skipped if test equipment already comes calibrated.

3.3.1 Calibrating the RF components and accessories

The RF properties of the components of the test bed such as RF shields, cables, attenuators, splitters/combiners will impact the performance of the test bed. As part of the test bed calibration, it is recommended that the test engineer analyzes the quality of the RF components by looking at performance metrics such as insertion loss, return loss, bandwidth, port isolation, and VSWR.

3.3.2 Calibrating STA, traffic generation and measurement

The goal is to verify the limits of STA and traffic generator to generate and sustain high throughput and accuracy of the measurement system with regards to latency, throughput, and packet loss.

1. Calibration will be done for one STA at a time.
2. Start with a reference AP that has already been proven to provide acceptable performance.
3. Set up the test bed per the guidelines provided above.
4. Set attenuators to 0 dB.
5. Run UDP downlink traffic at maximum rate.
6. Run UDP uplink traffic at maximum rate.
7. Evaluate results to make sure that the maximum expected performance is achieved and that the highest MCS is achievable.

4 Statistical analysis of Wi-Fi performance

Wi-Fi technology constantly evolves to improve the capacity and efficiency in delivering data to multiple STAs. Wi-Fi CERTIFIED 6 features, such as OFDMA/MU-MIMO, can efficiently serve multiple simultaneous STAs with multimedia use cases such as gaming, video conferencing, and online streaming. Traditionally, a Wi-Fi network's performance is assessed by measuring the mean throughput, latency, packet loss, and jitter.

As Wi-Fi was initially developed as a replacement to ethernet, deterministic testing methods such as RFC2544 are sometimes used. However, they give limited information on Wi-Fi performance because wireless signals propagate using principles of reflection, refraction, diffraction, and channel contention which are non-deterministic in nature. As a result, it is necessary to use statistical methods to effectively evaluate Wi-Fi performance.

By using statistical methods such as Probability Density Functions (PDF), Cumulative Distribution Functions (CDF), and Complementary Cumulative Distribution Functions (CCDF), Wi-Fi performance can be analyzed in a way that is meaningful for a Wi-Fi system with multiple simultaneous users.

4.1 Analytical methods

4.1.1 Data representation

PDF: A PDF shows the distribution of Wi-Fi performance measured over a period. It helps in discovering the outliers, skewness, and range of the measured throughput/latency dataset. An example PDF is shown in Figure 3.

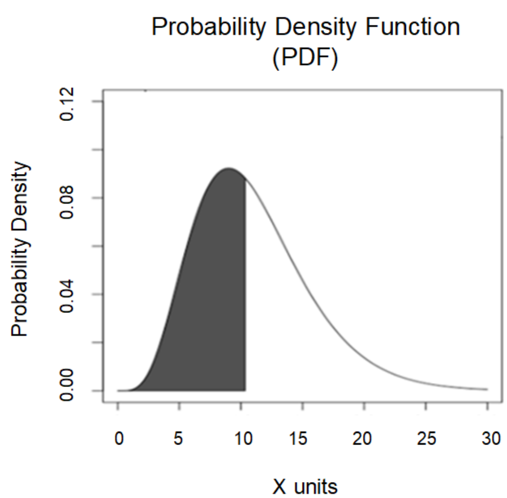


Figure 3. PDF example

CDF: Useful for analysis where one is interested in the probability that the measurement samples are less than or equal to certain value. For example, in latency measurements, a test engineer may want to know the delay value where 97% of all measured values are less than 22 msec as a requirement for voice quality. An example is shown in Figure 4.

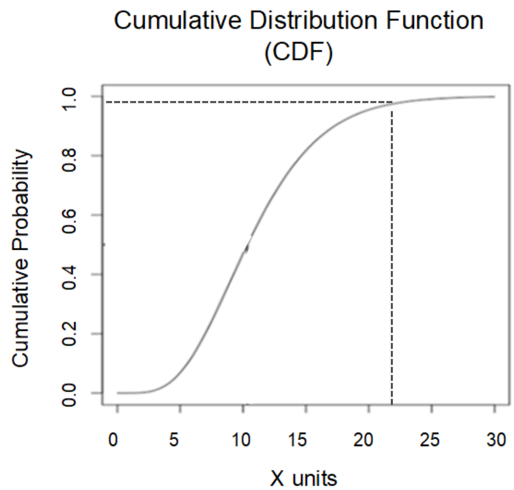


Figure 4. CDF example

CCDF: Useful for analysis where one is interested in the probability that the measurement samples are greater than or equal to certain value. For example, in throughput measurements, a test engineer may want to know the value of throughput where 97% of all measured values are greater than 5 Mbps as a requirement for video quality. An example is shown in Figure 5.

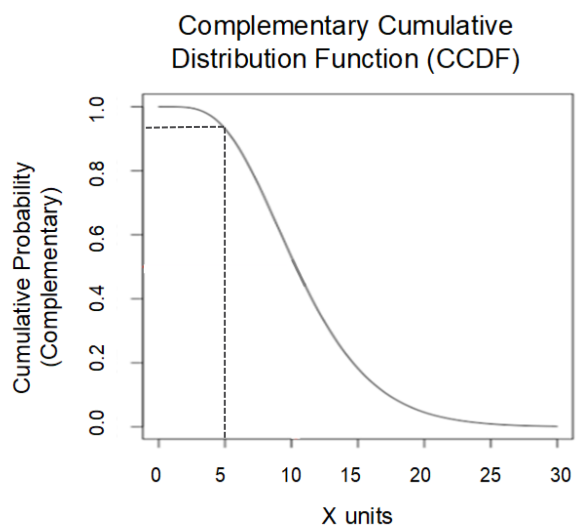


Figure 5. CCDF example

4.1.2 Computing statistics

Graphs are useful to visualize the data, but test reports generally require numbers that can be compared with a threshold of some acceptable performance or compared against measurements of different DUTs. Three common examples include:

1. Mean, or expectation E, usually calculated from a time series $t(n)$ as

$$E = \frac{\sum_{1}^{num\_samples} t(n)}{num\_samples}$$

Where *num_samples* is the number of samples in the time series. E can also be calculated from the PDF or histogram as follows where x is the spacing between bins of the histogram.

$$E = \frac{\sum_{1}^{num\_bins} xf(x)}{\sum f(x)}$$

2. Variance, S, can calculated as follows

$$S = \frac{\sum_{1}^{num\_bins} x^2 f(x)}{\sum f(x) - E^2}$$

3. Standard deviation $D = \sqrt{S}$

4. Coefficient of variation, CV, is defined as

$$CV = \frac{S}{E}$$

Appendix C provides an application of these three statistical methods of a Wi-Fi throughput/latency dataset.

5 Test configuration parameters

Typically test plans have two groups of configuration parameters:

- **External:** Parameters such as the topology being tested, stimulus such as traffic types, levels of interference, and attenuation are examples. In this case, these external parameters are derived from exemplary real world use cases
- **Internal:** Parameters for items such as channels, security, packet sizes, spatial streams, and RF channel bandwidth are examples

Traditionally, external parameters were relatively simple and test plans focused on testing with a variety of different internal parameters.

As Wi-Fi has evolved, so have the number of internal configuration parameters. This makes thorough testing of all internal combinations nearly impossible. And how meaningful these tests are is questionable since most of these combinations are invisible or unused by most end customer's devices. The Wi-Fi industry has been working for some time developing methods to automatically configure devices in the most appropriate way for the use case scenario. This automatic configuration can often be quite sophisticated and dynamic as the situation changes, and indeed there is a growing trend, for consumer equipment, where direct control of many internal parameters is no longer provided. This is the basis of the out of box testing premise.

At the same time topologies have evolved to include multiple Wi-Fi devices in the test architecture, more diverse types of traffic generation, and various types of interference or OBSS loading. Since the average customer is more interested in how a Wi-Fi device performs in a whole system, this approach places greater emphasis on the external parameters and less emphasis on internal parameters.

The method is built to emulate end customer uses cases. To this extent, the approach will specify only aspects of the test setup that are pertinent to emulating a use case in the test bed. For example, the Latency test case specifies appropriate external parameters such as traffic profiles, number of devices, and background interference which are fundamental to the use case. It is silent on the internal parameters such as channel, channel bandwidth, NSS, MCS, packet size, security type etc.

Typically, this means testing out of box where devices are pre-configured or have the ability to self-configure.

For devices that require manual configuration the test engineer should configure the internal parameters based upon the specification of the device, or in line with other appropriate guidance. This test methodology is designed to be robust enough that if a test engineer is interested in performance with a specific set, or variations of certain internal parameters, these could be introduced without changes to the test method[1].

The test engineer may choose to change the external parameters. However, this would be deemed as a new and different test case that is not part of this document.

[1] Scenarios such as this often exist as part of a debug exercise where performance in a specific set of circumstances.

6 Test Cases

6.1 Rate vs Range test

6.1.1 Objective

Measuring the throughput rate of a device at different distances from the AP is an important test which exercises several aspects of the wireless device including the interplay of RX sensitivity, TX power, and data rate adaption. Data rate adaption incorporates adaption of other parameters such as MCS, number of spatial streams (NSS), and channel bandwidth which are influenced by signal strength and Packet Error Rate.

Distance can be effectively simulated by controlling the path loss between the devices with attenuators.

Most Wi-Fi devices exhibit some degree of directionality, so it is important to check out performance in different orientations to cover the cases where users in the house are in different places.

It is important to note that measurement versus orientation is not an attempt to measure a radiation pattern, rather it is used to determine an average throughput for all orientations for each path loss attenuation and improve the repeatability and reproducibility of the test result.

6.1.2 Topology

The same test bed topology as described in section 3 with the addition of a turntable.

6.1.3 Configuration

Configure the devices according to the default configuration described in section 5.

6.1.4 Procedure

1. Mount the DUT on the turntable.
2. Configure the AP and STA to the desired configuration.
3. Set the attenuators to 0 dB.
4. Set the turntable to 0 degrees.
5. For attenuation ρ = 0 in steps of 3 dB to 90 (or until the link fails).
    a. For turntable orientation θ = 0 in steps of 15 degrees to 360-15
    b. Run traffic for 30 seconds and record the throughput each interval t

6.1.5 Analysis

Use the notation $t_{\theta,\rho}(n)$ to denote a collection of throughput time series, sampled at n, usually 1 second intervals, according to the orientation θ and attenuation ρ.

Compute an average value for each time series to populate the center of the summary results table as seen in the example Table 10.

$$\bar{T}_{\theta,\rho} = \frac{\sum_n t_{\theta,\rho}(n)}{num\_n\_samples}$$

Compute the mean throughput for each value of attenuation ρ as,

$$E_\rho = \frac{\sum_\theta \bar{T}_{\theta,\rho}}{num\_\theta\_samples}$$

and the standard deviation as,

$$S_\rho = \sqrt{\frac{\sum_\theta (\bar{T}_{\theta,\rho} - E_\rho)^2}{num\_\theta\_samples}}$$

Calculate a coefficient of variation (CV) in the following way

$$C_\rho = \frac{S_\rho}{E_\rho}$$

The above is used to populate the summary results table, an example of which is shown in Table 10.

In keeping with section 4, calculate a Probability Density function (PDF), and Complementary Cumulative Distribution Function (CCDF).

Create a concatenated time series of $H_\rho(t)$ using the smaller time series by assembling a time series of throughput data $t_{\theta,\rho}(t)$ over each orientation θ for each attenuation ρ.

$$H_\rho(t) = \bigvee_\theta t_{\theta,\rho}(n)$$

These time series for each attenuation are used by the methods in section 4 to calculate PDFs and CCDFs for each attenuation.

6.2 AP Latency test

6.2.1 Objective

Use cases such as gaming, video conferencing, and online streaming demand real-time transfer of data from a Wi-Fi AP. The real-time performance of an AP depends on the number of STAs to be serviced and interference due to neighboring Wi-Fi devices. Latency is a measure of the real-time performance of an AP which is found by measuring the delay between frames being sent and its reception on the other end of the Wi-Fi link.

Latency can be measured as a Round Trip Time (RTT) or One Way Delay (OWD). RTT is a bidirectional latency measurement, which includes latency contributions due to various components of a network, such as IP stack, operating system, etc. In OWD, latency is measured on a unidirectional Wi-Fi data stream by measuring the delay in arrival of Wi-Fi frames at the AP (uplink), or STA (downlink).

For accurately measuring latency of a Wi-Fi system, OWD measurement is preferred. OWD is a key performance indicator in any network, measuring and optimizing the latency performance of last hop (Wi-Fi) is critical to ensuring positive user experiences. This test benchmarks latency performance of AP by measuring OWD on traffic types generated by common use cases.

6.2.2 Topology

The test topology is shown in Figure 6 with the following equipment:

- APUT
- STAs with independent PHY layer and network stack
- Traffic emulator capable of generating isochronous, variable bit rate traffic at multiple throughout levels
- Interference generator to create OBSS traffic

The test setup measuring OWD must be time synchronized. When adding interference, ensure that the interference signal at the APUT resembles near interference scenario with APUT RSSI of approximately -40 dBm.

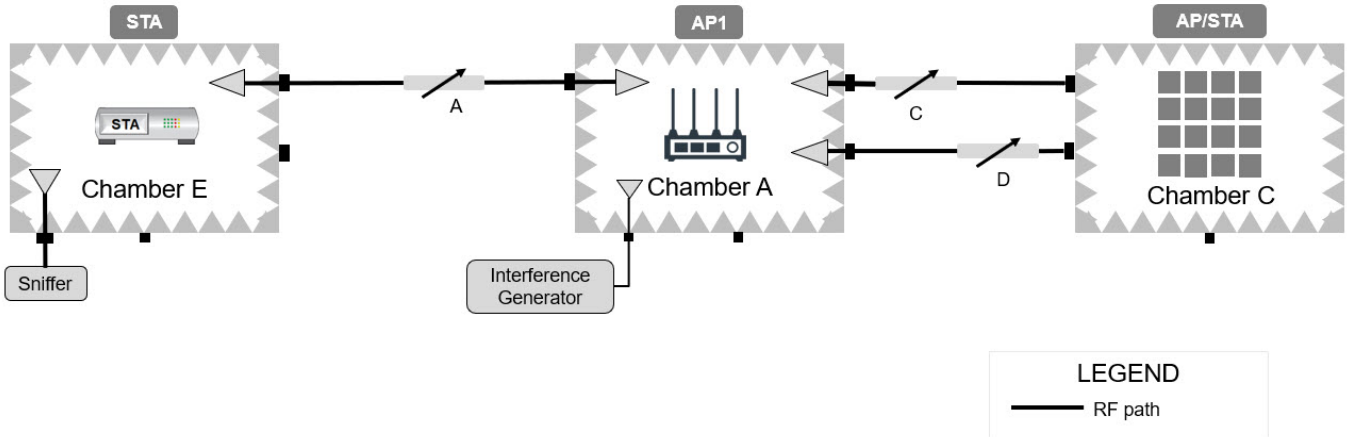


Figure 6. Latency testing topology

6.2.3 Configuration

OWD should be measured for traffic types which are isochronous and have a log-normal distributed variable data rate (see Appendix B) at a throughput load which represents the use case under test (see Table 3). Refer to section 5 for guidance.

Table 3. OWD throughput load

Use case	Traffic rate (Mbps)	Variance (Mbps)
UHD Video Streaming	35 Mbps TCP/UDP	10
FHD video streaming	20 Mbps TCP/UDP	7
HD video streaming	10 Mbps TCP/UDP	5
Cloud UHD AR/VR	100 Mbps TCP/UDP	10
VOIP telephony	1 Mbps UDP	0.2
IOT	2 Mbps UDP	0

6.2.4 Procedure

1. Set up the test bed and turn on the APUT.
2. Configure the APUT to initial configuration.
3. Associate the STA to APUT. Start the traffic emulator and configure it for the use case under test.
    - Traffic Duration: At least 10 secs
    - Traffic direction: Downlink
4. Begin with 1 STA for baseline and repeat the test with increasing number of STAs.
5. Repeat steps 1 through 4 for uplink traffic.

6.2.5 Analysis

Use the statistical methods as discussed in Section 4 and Appendix B for analyzing latency measurements.

6.3 Channel Switching

6.3.1 Objective

An AP typically uses an automatic or dynamic channel selection mechanism to select an operating channel which has the least amount of interference. It can also measure the deterioration of the performance of its connected STAs on the current operating channel due to interference. Based on these measurements, the AP may select another operating channel and communicate a channel switch request to its connected STAs using Wi-Fi Agile Multiband.

Most common sources of interference that may trigger a channel switch are:

- Neighbor effect caused by an OBSS operating on the same channel
- A 2.4 GHz energy source such as Microwave, baby monitor, or Bluetooth activity
- When a radar pulse is detected in a 5 GHz DFS channel

6.3.2 Topology

The STA is placed in chamber E, and the AP in chamber A. A second AP is placed in chamber B to communicate with the test bed STA to generate OBSS traffic as shown in Figure 7. The link quality between E and A is controlled using the attenuator between the two chambers. The attenuator between chamber A and A is used to control the level at which AP1 hears the OBSS traffic. The attenuator between Chambers E and B controls the level at which the STA hears the OBSS traffic. The level of interference is controlled directly within the interference generator.[2]

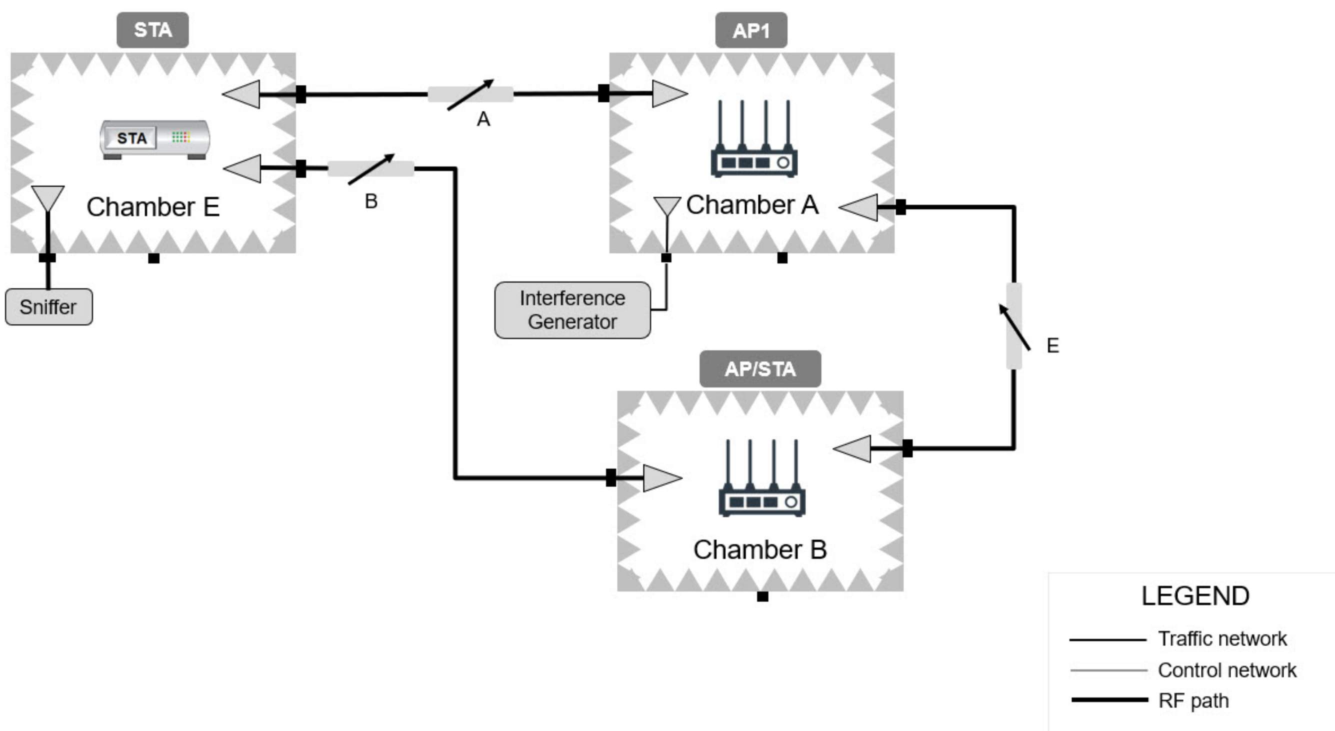


Figure 7. Channel switching topology

[2] Control and traffic network not shown for clarity

6.3.3 Procedure for Channel Switching for OBSS activity

1. Set up test bed as shown in Figure 7.
2. Power on APUT and record channel chosen for operation.
3. Start 1 Mbps of uplink UDP traffic.
4. Start packet capture on same channel.
5. Power on OBSS AP and OBSS STA. Set up OBSS AP on same channel as APUT.
6. Use a Wi-Fi interference generator to simulate the presence of OBSS. Configure to occupy 40% airtime of the channel. Use Channel Utilization tool to measure loading.
7. Observe and record time when APUT changes channel and observe time when the STA Switches over.
   a. For APUT: Tune the sniffer on the APUT channel and track the Beacon frames until the last one where the CSA count (Chanel Switch Count) IE is 1, and
   b. The APUT should not transmit any Beacon frames after the last Beacon frame containing CSA count set to 1 is sent out on the previous working channel
8. The test engineer may choose to test with different OBSS levels of 50, 60, 80, or 100%.

6.3.4 Procedure for Channel Switching on interference

1. Set up test bed as shown in Figure 7.
2. Power on APUT and record channel chosen for operation.
3. Start 1 Mbps of uplink UDP traffic.
4. Start packet capture on same channel.
5. Set up interference to simulate Microwave Oven Interference on AP channel.
6. The power level of the interference should be set for -50 dBm.
7. Observe and record time when APUT changes channel and observe time when the STA switches over from the captures. This is the same as used in section 6.3.3.

6.3.5 Procedure for Channel Switching because of DFS

1. Set up test bed as shown in Figure 7.
2. Power on APUT and ensure that APUT selects a DFS channel for operation.
3. Start 1 Mbps of uplink UDP traffic.
4. Start packet capture on same channel.
5. Set a suitable DFS interference level at DUT.
6. Cause the interference generator to transmit the geographically appropriate DFS interference profiles and check if APUT has changed channel.
7. Through sniffer logs, observe the duration since APUT sends Channel Switch Announcement (CSA) and time when STA switches over.

6.3.6 Analysis

Table 4. Channel switching expected results

	APUT expected result	STA expected result	Traffic resuming expectation
Channel Switching for OBSS activity	AP sends CSA and switches channel	STA receives CSA and reassociates to AP on new channel	Traffic should resume after 5 seconds maximum
Channel Switching for Interference	AP sends CSA and switches channel	STA receives CSA and reassociates to AP on new channel	Traffic should resume after 5 seconds maximum
Channel Switching for DFS	AP sends CSA as soon as the Radar is detected and moves to the new best selected channel (preferably non-DFS to avoid ISM state of 60 sec quiet duration before transmitting)	STA receives CSA and reassociates to AP on new channel	Traffic should resume after 5 seconds maximum

6.4 Band Steering

6.4.1 Objective

APs often use band steering functionality to automatically steer a STA connecting to a wireless network to the best band/channel available, thereby optimizing performance for the STA. Band steering can intelligently move devices between the available bands/channels based on parameters such as usage, speed, or coverage. For band steering to work, the SSID and credentials of the network on each of the bands must be the same.

6.4.2 Topology

The test topology is shown in Figure 8 with the following equipment:

- Traffic Generation server
- Programmable attenuator bank
- Three Medium sized chambers
- RF Connectivity: cabling
- Multiple Wi-Fi STAs which support Wi-Fi Agile Multiband BSS-Transition Management

The STA is placed in chamber E and the AP in chamber A. The link quality is controlled by the attenuator between them. Chamber C contains multiple real STAs and the ability to emulate many virtual STAs for channel loading purposes.[3]

[3] Management and traffic networks not shown for clarity

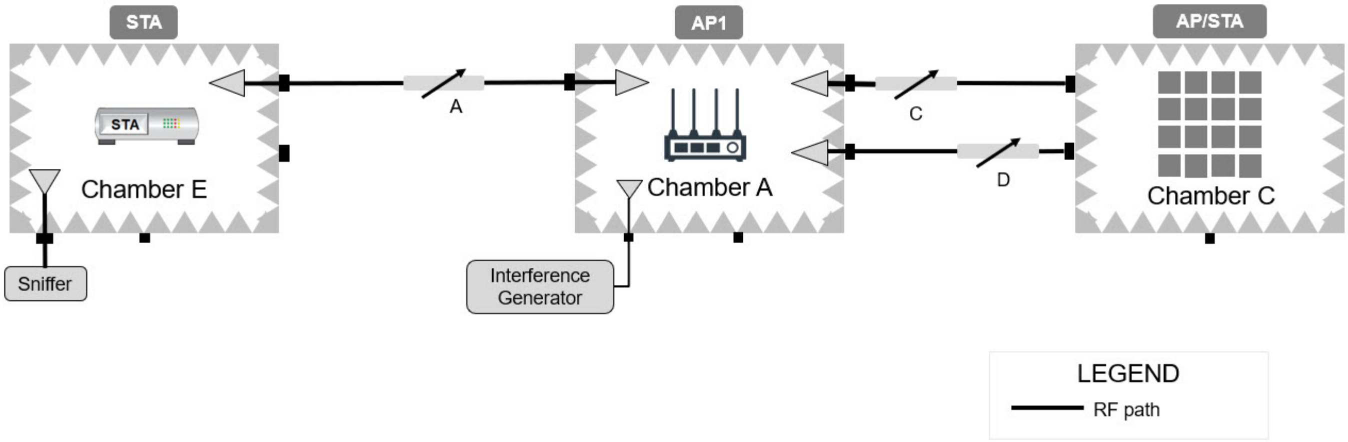


Figure 8. Band steering test bed topology

6.4.3 Procedure for RSSI based band preference

1. Set up test bed as shown in Figure 8.
2. Power on APUT and record channels chosen for operation.
3. Start packet capture on APUT's operating channel on both 2.4 GHz and 5 GHz band.
4. Attenuate the link between APUT and STA using the programmable attenuator such that the RSSI measured by STA is -50 dBm.
5. Associate the STA and observe the band selected. The STA should select 5 GHz band.
6. Check STA capabilities for Wi-Fi Agile Multiband support as shown in Figure 9.

```
> Tag: HT Capabilities (802.11n D1.10)
v Tag: Extended Capabilities (8 octets)
    Tag Number: Extended Capabilities (127)
    Tag length: 8
  > Extended Capabilities: 0x00 (octet 1)
  > Extended Capabilities: 0x00 (octet 2)
  v Extended Capabilities: 0x08 (octet 3)
      .... ...0 = TFS: Not supported
      .... ..0. = WNM Sleep Mode: Not supported
      .... .0.. = TIM Broadcast: Not supported
      .... 1... = BSS Transition: Supported
      ...0 .... = QoS Traffic Capability: Not supported
```

Figure 9. Wi-Fi Agile Multiband steering support

7. Start 1 Mbps of UDP uplink traffic.
8. Increase attenuation and measure corresponding RSSI until the STA changes to 2.4 GHz band.
9. Measure the data outage time during the band steering event from the sniffer logs. Use statistical methods as described in section 4 to perform data outage analysis.

6.4.4 Procedure for band preference due to AP loading

1. Set up test bed as shown in Figure 8.

2. Power on APUT and record channel chosen for operation.
3. Start packet capture on APUT's operating channel on both 2.4 GHz and 5 GHz band.
4. Attenuate the link between APUT and STA in chamber E using the programmable attenuator such that the RSSI measured by STA is -80 dBm.
5. Associate the STA in chamber E to the APUT. The STA should associate on the 2.4 GHz band.
6. Start 1 Mbps of UDP uplink traffic between the AP and the STA in chamber E.
7. Configure and associate multiple STAs in chamber C to the APUT on the 2.4 GHz band. All STAs should not roam and have Wi-Fi Agile Multiband BSS Transition Management disabled.
8. Start 10 Mbps of UDP uplink traffic with each STA.
9. Increase the traffic load by adding multiple STAs in steps and observe if the APUT triggers band steering to the 5 GHz band.
10. Measure the data outage time during the band steering event from the sniffer logs. Use statistical methods as described in section 4 to perform data outage analysis.

6.4.5 Analysis

The following table contains band steering expected results.

Table 5. Band steering expected results

Test case	APUT	STA
RSSI based band preference	At high RSSI, the STA connects to the APUT on the 5 GHz band. At low RSSI, the APUT steers the STA to the 2.4 GHz band.	Traffic should resume after 5 seconds maximum.
Band preference due to AP loading	For light traffic loading, the STA could remain in the 2.4 GHz band. For heavy traffic loading, the APUT should steer the STA to the 5 GHz band.	Traffic should resume after 5 seconds maximum.

6.5 Roaming

6.5.1 Objective

With the advent of Wi-Fi CERTIFIED EasyMesh, more homes have multiple APs to extend coverage. This means that as a user moves about the home his device may move out of coverage of one AP and into the coverage of another. In the simplest case, the STA will drop the first link and scan around for another AP and attempt to associate to it. This may take some time and the user will experience a data outage, but there are many mechanisms available to make this transition smoother and faster. The degree to which these mechanisms are employed by the APs differs between manufacturers.

This test measures only the roaming performance and makes no assumptions about what the mechanism is that causes the roam. This may be initiated by the STA, or it may be initiated by the AP.

Three scenarios regarding the DUT exist:

1. The STA is the DUT, roaming between two test bed APs.
2. The AP is the DUT, being tested against a test bed AP and a test bed STA.

3. AP1 and AP2 could be pairs, possibly from the same manufacturer, and can be tested against a test bed STA.

The description of this test focusses upon AP1, AP2, and the STA regardless of which one is the DUT.

6.5.2 Methodology

Movement of a device between the APs is often simulated by controlling the path loss between the STA and the respective APs. The preferred method of doing this is to set up two APs in a home and simultaneously measuring the RSSI that the STA observes from each AP as it is moved around the house.

This recording is then used to play back the walk through the attenuators creating a highly repeatable, lifelike test. The approach is versatile because the test engineer can choose the type of home to simulate and make the appropriate recordings, or the test engineer could use a channel model such as free space path loss to calculate his own movement.

Two test cases are described. Firstly, the maximum throughput that can be achieved is recorded in one second intervals over the length of the run using the procedure in section 6.5.5 and analysis in section 6.5.6. This test is useful to gauge user experience as the test engineer moves around the house, possibly watching a video. The second test is done at a low data rate to limit the sniffer capture that runs the length of the test using the procedure in section 6.5.7 and analysis in section 6.5.8. Once complete, the sniffer trace can be analyzed for KPIs such as data outage time in a roam, Wi-Fi Agile Multiband request/response timing, etc.

6.5.3 Topology

AP1 and AP2 are placed in chambers A and B, respectively as shown in Figure 10. The STA is placed in Chamber E. The STA hears the APs at levels determined by the respective attenuators. The inputs of the two sniffer probes are combined and connected to chamber E. Each probe will be set to the appropriate channel/band being tested.[4]

[4] Management and traffic networks not shown for clarity.

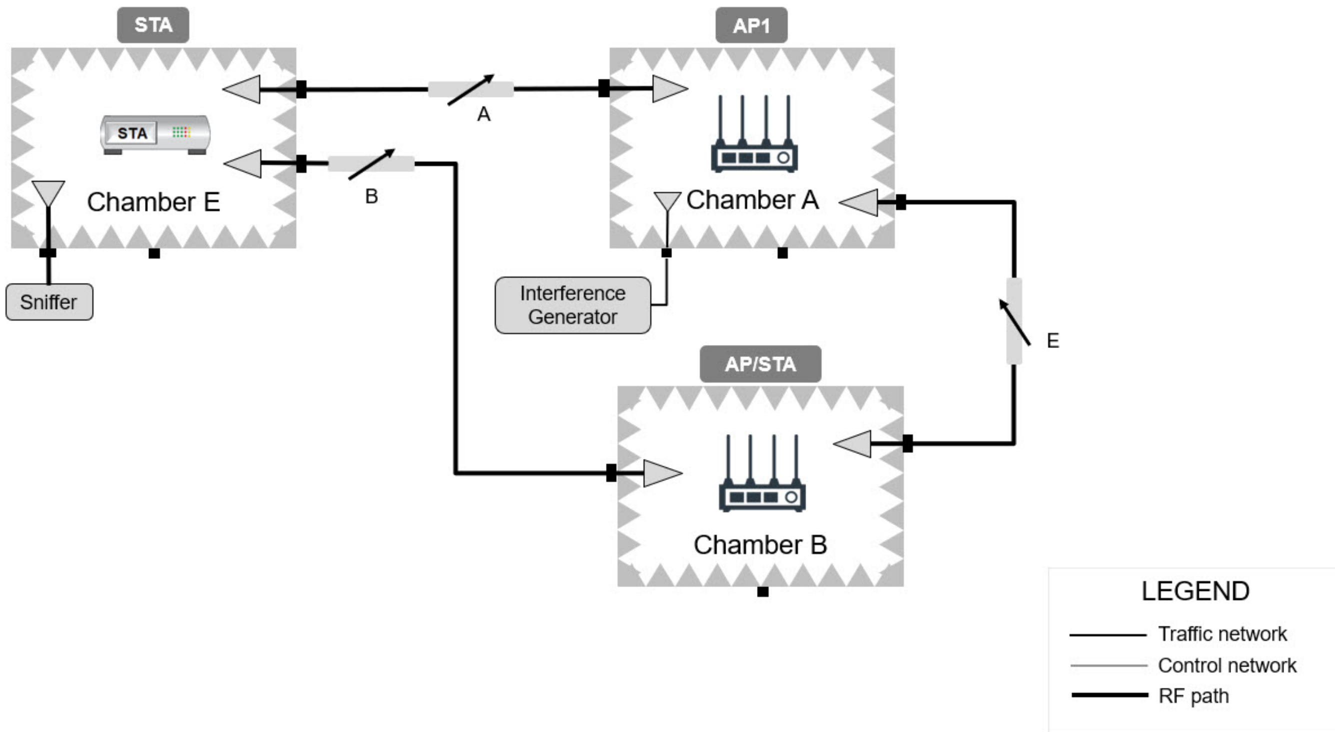


Figure 10. Roaming test bed topology

6.5.4 Calibration procedure

6.5.4.1 Signal strength calibration

The test engineer uses two RSSI recordings measured simultaneously in an appropriate environment, which could be inside a home, outdoors, or some other venue. The recordings are made on the device as it is moved along a prescribed route through the environment of choice. $R_A(t)$ is the RSSI received at the recording device from AP A. Similarly, $R_B(t)$ is the RSSI received from AP B. Usually, t is 100 msec.

The calibration section seeks to determine the correct attenuations to replicate the respective RSSIs in the test bed.

1. Set the attenuation between box B and box E to maximum.
2. Set the attenuation between box A and box E to minimum.
3. Configure the devices and associate the STA to AP A.
4. Select n points on $R_A(t)$ to get $R_{As}(n)$. For each n, iteratively adjust the attenuator value $Att_A(n)$ between box A and box B until the STA reports the desired RSSI, $R_{As}(n)$. Calculate the offset $O_A(n)$. Finally calculate the average of $O_A(n)$ to smooth out any measurement error to arrive at $\overline{Att_A}$. This allows us to calculate the appropriate Attenuator value to ensure the correct RSSI at the STA.

$$Att_A(t) = \overline{Att_A} - R_A(t)$$

5. Set the attenuation between box A and box E to maximum.
6. Set the attenuation between box B and box E to minimum.
7. Associate the STA to AP B.
8. Repeat the above for $R_B(t)$ to get $\overline{Att_B}$ so that:

$$Att_B(t) = \overline{Att_B} - R_B(t)$$

Table 6. Roaming signal strength calibration

n	Desired test bed RSSI $R_{As}(n)$	Attenuation value to achieve desired RSSI $At_A(n)$	Offset $O_A(n)$
1	-35	12	-23
2	-50	30	-20
3	-64	34	-30
4	-78	52	-26
5	-82	58	-24
		Average offset $\bar{Q}_A$	-24

6.5.4.2 Throughput calibration

This calibration seeks to determine the maximum theoretical throughput $T(n)$ that can be achieved as the STA is subjected to the variation of signal strength $R_A(\tau)$, and $R_B(\tau)$, from each AP. Usually, τ is in increments of 100 msec, and n is in increments of 1 second.

1. Set the attenuation between box B and box E to maximum.
2. Set the attenuation between box A and box E to minimum.
3. Configure the devices and associate the STA to AP A.
4. Repeat the following k times:
    a. Start downlink traffic and simultaneously start the playback of $Att_A(n)$ and record the throughput $T_{Ak}(n)$
    b. Calculate $T_A(n)$ by averaging the k values of each $T_{Ak}(n)$
5. Set the attenuation between box A and box E to maximum.
6. Set the attenuation between Box B and box E to minimum.
7. Configure the devices and associate the STA to AP B.
8. Repeat the following k times:
    a. Start downlink traffic and simultaneously start the playback of $Att_B(n)$ and record the throughput $T_{Bk}(n)$
    b. Calculate $T_B(n)$ by averaging the k values of each $T_{Bn}(n)$
9. Calculate the maximum theoretical throughput as $T_0(n) = \max(T_A(n), T_B(n))$.

6.5.5 Procedure for Max Throughput

1. Set the attenuators between box A and box E to maximum.
2. Set the attenuators between box B and box E to maximum.
3. If RSSI values are available from the APs, set the attenuator between box A and box B to achieve an RSSI of ~ -50 dBm. If RSSI is not available a simple link budget calculation can be made. This is to facilitate backhaul communication if this exists.
4. Set the attenuators to the first value of $Att_A(n)$ and $Att_B(n)$ respectively.
5. Configure the devices and let the STA associate to its preferred AP.

6. Repeat the following N times where r denotes each run from 1 to N:
    a. Start downlink traffic and simultaneously start the playback of $Att_A(n)$ and $Att_A(n)$ previous calculated above, and
    b. Record the throughput $T_r(n)$ for each run

6.5.6 Analysis of Max Throughput

The results may be analyzed using the procedure described below.

6.5.6.1 Visualization

Visualizing the difference in throughput by plotting the theoretical maximum $T_0(n)$ in bold, together with the respective $T_r(n)$'s, for each run r, on the same graph. An example is shown in Figure 11.

This provides the reader with a quick way to determine any anomalies if they exist.

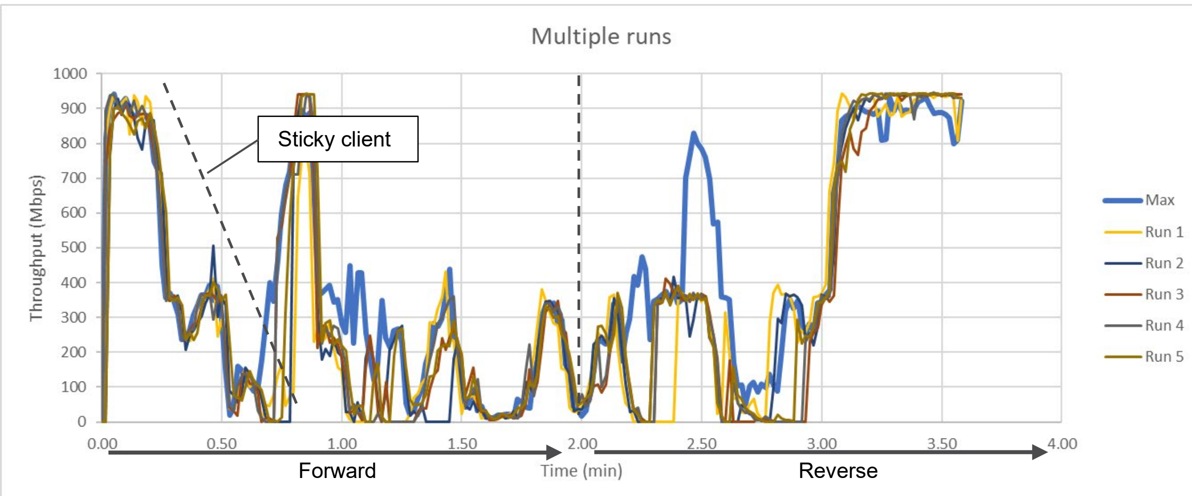


Figure 11. Throughput visualization

6.5.6.2 Top level statistics

Compute the mean throughput for each complete run r as:

$$E_r = \frac{\sum_n T_r(n)}{num\_n\_samples}$$

and the standard deviation as:

$$S_r = \sqrt{\frac{\sum_n (T_r(n) - E_r)^2}{num\_n\_samples}}$$

The test engineer may also calculate a coefficient of variation (CV) in the following way:

$$CV_r = \frac{S_r}{E_r}$$

An example of the results in tabular form shown in Table 7.

Table 7. Roaming example results

Run r	Mean (Mbps) E_r	Std Dev (Mbps) S_r	CV (%) CV_r
T_0	389	132	34
1	332	164	49
2	292	158	54
3	249	164	66
4	314	164	52
5	262	183	70
6	340	176	52
7	290	170	59
8	280	173	62
9	236	160	68

6.5.6.3 Further Statistics

Create a set of all measured values $t_{\theta,\rho}(n)$ for each attenuation $\rho = R$ such that a PDF can be created across all measured times *n* and all orientations θ for that value of $\rho = R$. Refer to section 4 to plot the PDF and CDF of each of the runs $T_r(n)$.

6.5.7 Procedure for Roaming KPIs

1. Set the attenuators between box A and box E to maximum.
2. Set the attenuators between box B and box E to maximum.
3. If RSSI values are available from the APs, set the attenuator between box A and box B to achieve an RSSI of ~-50 dBm. If RSSI is not available a simple link budget calculation can be made. This is to facilitate backhaul communication if this exists.
4. Set the attenuators to the first value of $Att_A(t)$ and $Att_B(t)$ respectively.
5. Configure the devices and let the STA associate to its preferred AP.
6. Repeat the following n times:
    a. Start a (new) Wireshark capture
    b. Start 1 Mbps of uplink UDP traffic and simultaneously start the playback of $Att_A(t)$ and $Att_B(t)$ previously calculated above
    c. Save the Wireshark capture for later analysis

6.5.8 Analysis of Roaming KPIs

6.5.8.1 Data Outage

Process the Wireshark capture file to extract:

- Time $t\_full_n(f)$
- Time difference between successive UDP packets $O\_full_n(f)$
- Transmitter MAC address of each packet, $wlan.ta\_full_n(f)$
- Receiver MAC address of each packet, $wlan.ra\_full_n(f)$

Even at low data rates the capture files can become very large, and it is necessary to retain only information that is of interest, to limit the size. The test engineer assumes packets that are spaced by more than some threshold O, for example 100 msec, are considered outages and the test engineer creates new arrays

$$t_n(i),\ O_n(i),\ wlan.ta_n(i),\ wlan.ra_n(i)$$

containing information related only to the outages where $O_{full}(f) > 100\ ms$.

Concatenate all $O_{1..n}(i)$ to plot a PDF and CDF of data outage times as detailed in section 4.

6.5.8.2 Roam time

Process $wlan.ta_n(i)$ to determine the indices at which the transmitter MA address has changed. This indicates that a roam has occurred. Create a roam time array $R_n(j)$ containing the outage times $O_n(i)$ where the roam occurs.

Concatenate all $R_{1..n}(i)$ to plot a PDF and CDF of roam times as detailed in section 4.

6.5.8.3 Fast BSS transition time

Process the Wireshark capture to determine the time difference between the Wi-Fi Agile Multiband reassociation request from the STA and the association response from the AP. Save these results in an array $A_n(k)$.

6.6 Testing Wi-Fi performance of AR/VR devices

6.6.1 Objective

Augmented reality (AR), virtual reality (VR) and mixed reality (MR) enabled devices collectively contribute to the extended reality (XR) experience in consumer, enterprise, and industrial space. These devices are intended to render a high quality, real time, spatially aware video/audio immersive experience by transmitting and receiving various types of data (e.g., video, audio, haptics, pose) with various latency requirements over a Wi-Fi network.

For example, a VR connection may utilize approximately 100 Mb/s and with a desired end-to-end latency of less than 20 msec and OWD of less than 10 msec on a single hop Wi-Fi link. Some AR/VR experiences may have to meet the performance KPIs in presence of multiple AR/VR devices on the same Wi-Fi network.

6.6.2 Topology

The test topology is shown in Figure 12 with the following equipment characteristics:

1. Time synchronized server and endpoints.
2. Traffic emulator capable of generating isochronous, variable bit rate traffic.
3. Packet capture and analysis.
4. Programmable attenuator bank.
5. Three medium sized chambers.
6. Multiple STAs which support Wi-Fi Agile Multiband BSS Transition Management.

The STAUT, which can be AR/VR device or a STA, is placed in Chamber E and the test bed AP in Chamber A. Chamber C contains multiple real STAs and may have the ability to emulate many virtual STAs for network loading. If the STAUT is an AR/VR device, it should be capable of generating networked traffic.

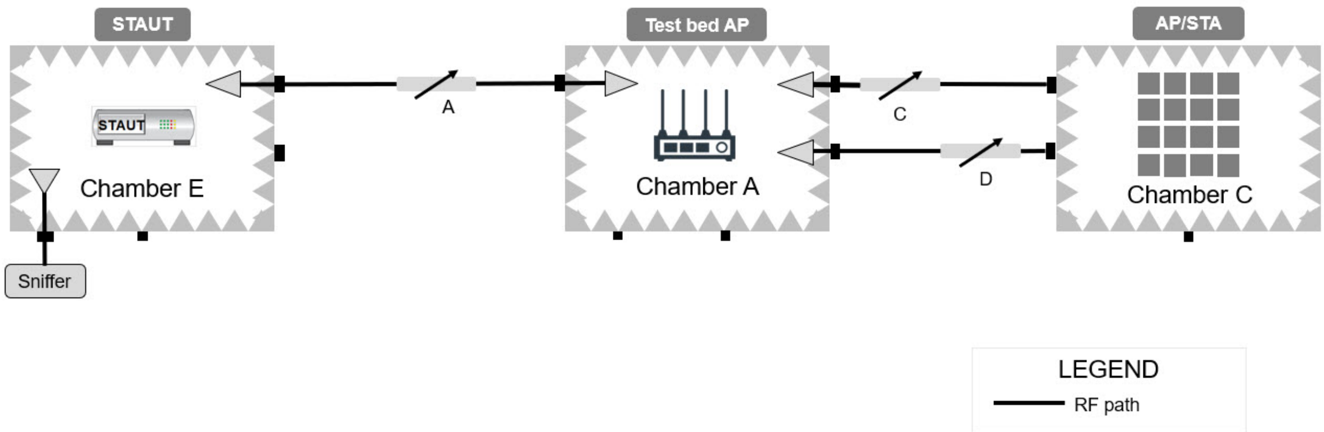


Figure 12. AR/VR test bed topology

6.6.3 Configuration

AR/VR devices can be tested at different traffic loads, RSSI levels (measured for Wi-Fi Beacon frames) and the network loads.

AR/VR traffic load

- Refer to Table 3 for AR/VR traffic load configuration

RSSI level

- Optimal: -40 to -50 dBm
- Acceptable: -50 to -60 dBm
- Marginal: -60 to -70 dBm

Network load

- No load: Only STAUT device is active
- Light: 4 AR/VR devices are active
- Medium: 12 AR/VR devices are active
- Heavy: 20 AR/VR devices are active

6.6.4 Procedure

1. Set up test bed as shown in Figure 12.
2. Power on test bed AP and record channel chosen for operation.
3. Associate the STAUT to test bed AP at a desired RSSI level as discussed in section 6.6.3.
4. Start downlink AR/VR traffic on STAUT.
5. Configure the desired network load and RSSI level as discussed in section 6.6.3.
6. Apply statistical methods as discussed in section 4 to analyze the throughput and OWD latency measurements on STAUT.
7. Repeat Step 1-6 for uplink AR/VR traffic on STAUT.
8. Repeat Step 1-6 for bi-directional AR/VR traffic on STAUT.

6.6.5 Analysis

For an optimal VR/AR user experience in presence of selected network loading and RSSI level, following KPIs are exemplary performance benchmarks for use with the statistical analysis described in section 4.

- Average throughput: 100 Mbps
- Wi-Fi OWD: 10 msec or lower
- Jitter variance: 2.5 msec or lower
- Packet Loss: 0.001%

Appendix A Document Revision History

Table 8. Document Revision History

Version	Date dd/mm/yy	Remarks
1.0	16/09/22	Initial release

Appendix B Applying statistical analysis

B.1 Video streaming use case

A popular multimedia application is video streaming which has following characteristics:

Log-normal variable data rate: Distribution is right skewed, i.e., there are measurements which are larger than the mean but are less frequent as shown in Figure 13.

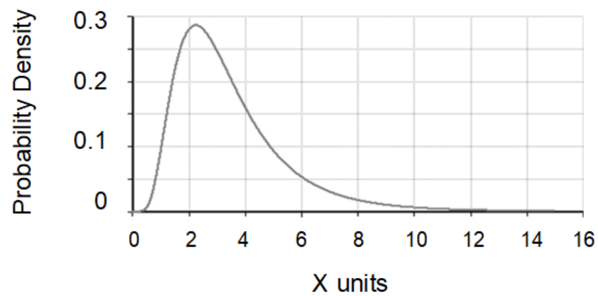


Figure 13. Log-normal variable data rate

Isochronous packets: Uniform in time, recurring at regular intervals as in real-time transfer of audio/video data as shown in Figure 14.

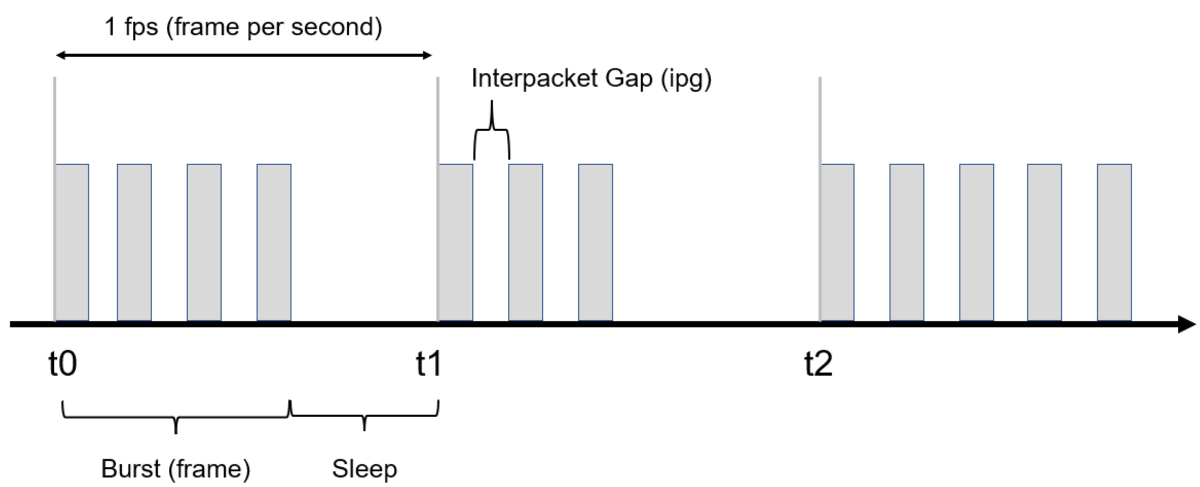


Figure 14. Video streaming traffic pattern

Low bitrate: Table 9 is a list of bitrates of common video encoding schemes.

Table 9. Video encoding scheme bitrates

Video Quality	Bitrate
720p	5-10 Mbps
1080p	20 Mbps
4K	30-35 Mbps

Latency sensitive: Delays in arrival of video/audio packets causes audio stutters and video artifacts.

B.2 Throughput Measurements

Throughput was measured using a throughput measurement tool taking measurements every 0.5 seconds as shown in Figure 15.

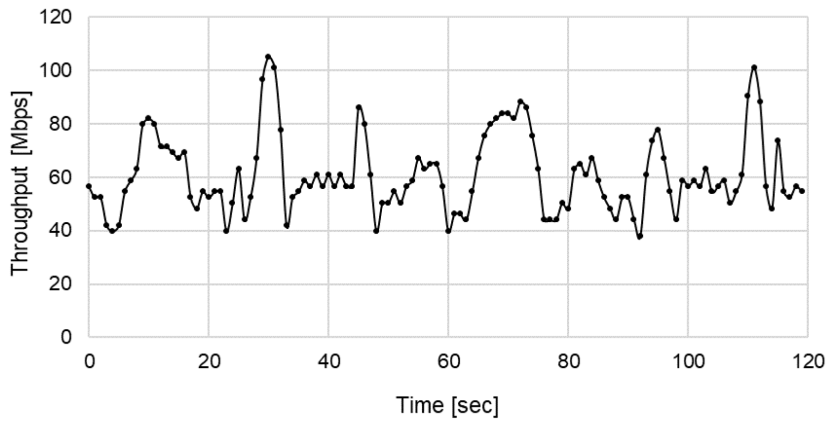


Figure 15. Throughput plot example

Figure 16 and Figure 17 show the PDF and the corresponding CCDF. The PDF shows a log normal distribution with mean throughput of 59 Mbps.

The CCDF, also sometimes called as confidence curves, show the minimum available throughput with respect to the availability. For example, this dataset shows 90% availability of throughput better than 42 Mbps.

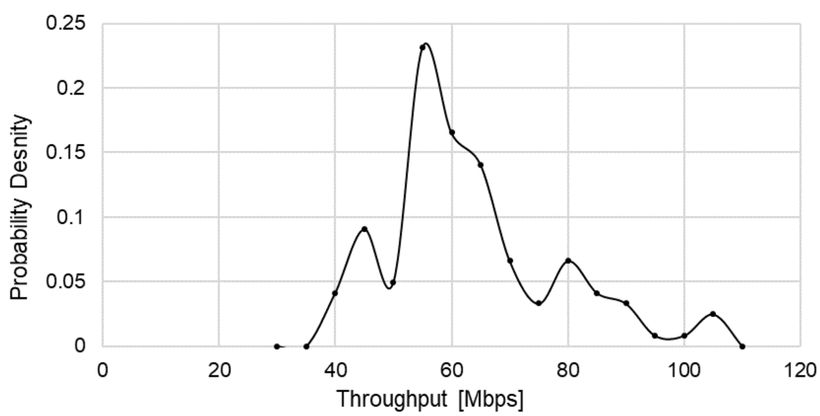


Figure 16. Example of a throughput measurements PDF

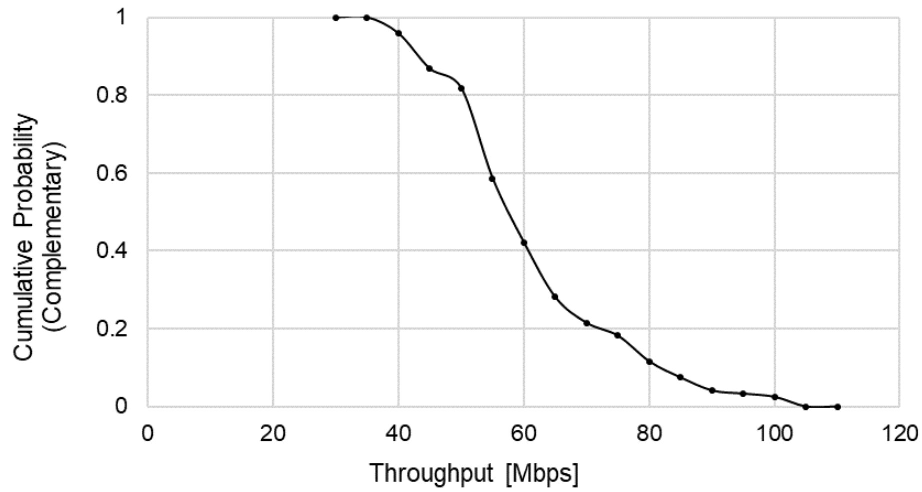


Figure 17. Example of a throughput measurements CCDF

B.3 Latency Measurements

Figure 18 and Figure 19 show the histogram and CDF of One-Way Delay (OWD) latency measurements using isochronous, variable bit rate traffic. The PDF and CDF plot helps in visualization of the deviation or spread of the measurements. From the CDF plot, one can infer that latency of the Wi-Fi system is 1.5 msec or better for 90% of the collected samples.

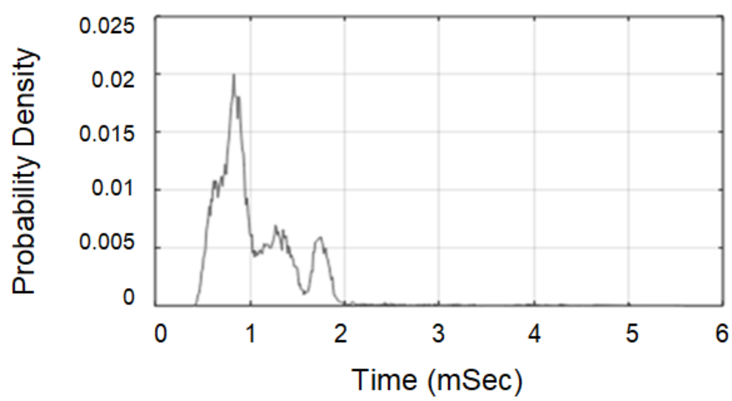


Figure 18. Example of a OWD PDF

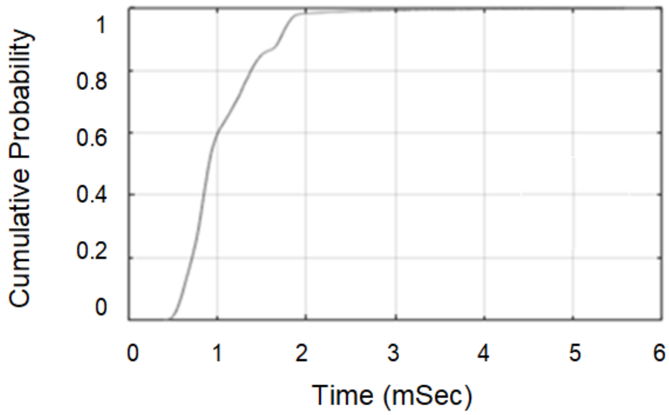


Figure 19. OWD CDF example

B.4 Computing statistics

Using the code snippet below in Figure 20, the expectation or mean for the throughput dataset is 58.5 Mbps. It has a variance of 89.1 Mbps and standard deviation of 9.5 Mbps.

```
% Calculate the mean
% E = integral(x * f(x))
expectation = sum((time_weight.*final_PDF))/sum(final_PDF);
% Calculate the variance
% variance = integral(x^2 * f(x)) - E^2
variance = sum((time_weight.*time_weight.*final_PDF))/sum(final_PDF) - expectation^2;
std_dev = sqrt(variance);
```

Figure 20. Computing statistics example

Appendix C Rate vs Range (RvR) example results

An example results table is shown in Table 10.

Table 10. RvR results table example

Attenuation ρ	Orientation θ													Mean E_ρ	Std Dev S_ρ	CV C_ρ
dB	0	30	60	90	120	150	180	210	240	270	300	330	360	Mbps	Mbps	%
0	948	957	954	870	894	956	953	954	922	957	954	946	954	940	27	3
3	921	957	957	941	831	840	955	951	957	945	956	951	947	931	42	5
6	955	914	954	957	883	743	716	938	957	931	942	952	952	907	79	9
9	945	953	925	918	935	875	765	668	837	932	832	916	926	879	81	9
12	936	944	953	957	849	883	777	629	578	799	835	753	812	823	115	14
15	829	887	924	929	953	743	809	731	635	379	639	747	669	759	152	20
18	728	797	835	831	840	922	676	730	635	570	376	624	639	708	139	20
21	578	613	645	708	806	758	836	581	627	568	378	251	490	603	157	26
24	576	490	580	628	637	640	638	754	519	603	382	378	195	540	142	26
27	378	459	407	447	523	584	630	578	639	437	499	378	253	478	108	23
30	161	244	345	306	301	378	383	511	412	552	361	379	251	353	102	29
33	187	131	200	243	225	201	258	379	379	378	377	305	252	270	82	30
36	188	128	76	102	153	168	133	183	251	252	252	328	273	191	72	38
39	188	124	72	62	68	94	111	65	118	187	205	192	222	131	57	43
42	161	124	68	32	28	36	46	50	44	81	120	123	124	80	43	54
45	162	134	71	46	25	21	20	29	29	29	44	57	63	56	43	76
48	63	94	90	36	25	10	6	12	13	14	14	25	33	34	29	86
51	36	33	39	52	18	17	7	5	5	1	5	4	7	18	16	92

Figure 21 provides an example of rate versus range results.

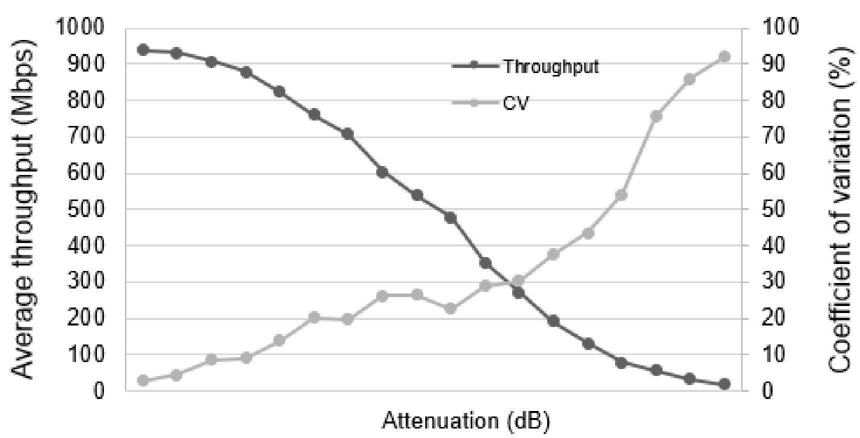


Figure 21. Example of Rate vs Range results

Figure 22 indicates how throughput spread increases as attenuation is increased.

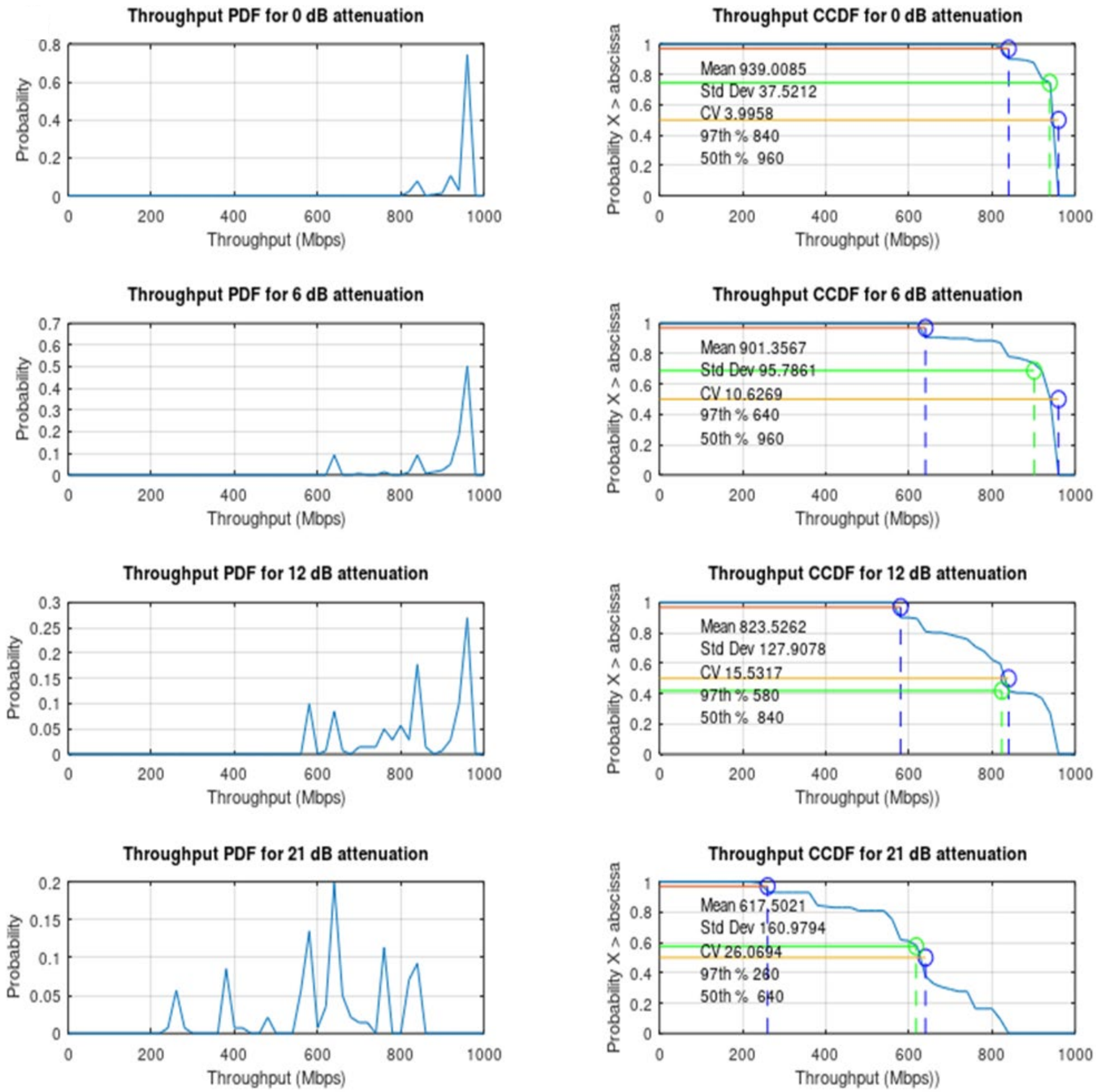


Figure 22. Throughput PDF (left) and CCDF (right) at various attenuations

Appendix D Roaming example results

Table 11 provides roaming example results.

Table 11. Roaming example results

Run r	Mean (Mbps) E_r	Std Dev (Mbps) S_r	CV (%) C_r
T_0	389	132	34
1	332	164	49
2	292	158	54
3	249	164	66
4	314	164	52
5	262	183	70
6	340	176	52
7	290	170	59
8	280	173	62
9	236	160	68

Figure 23 provides an example of throughput PDF and CCDF for all roaming runs.

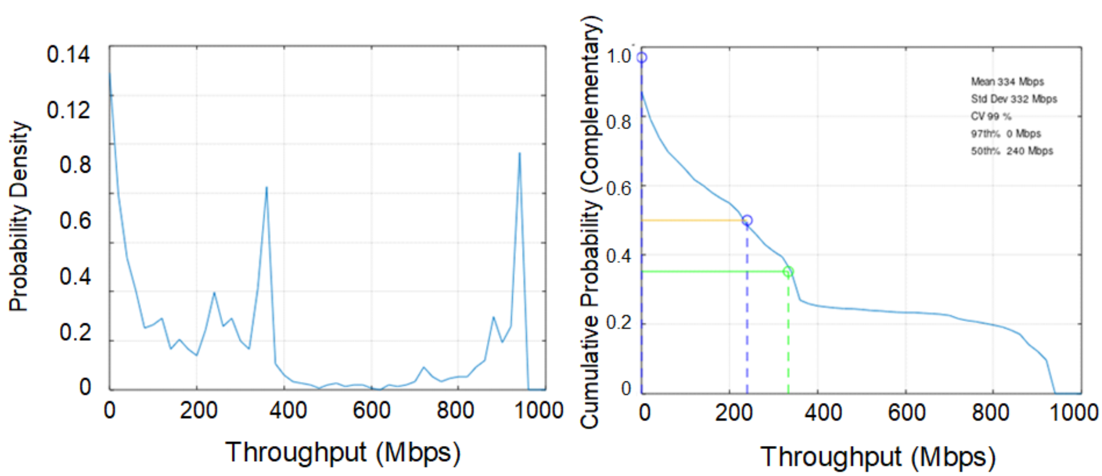
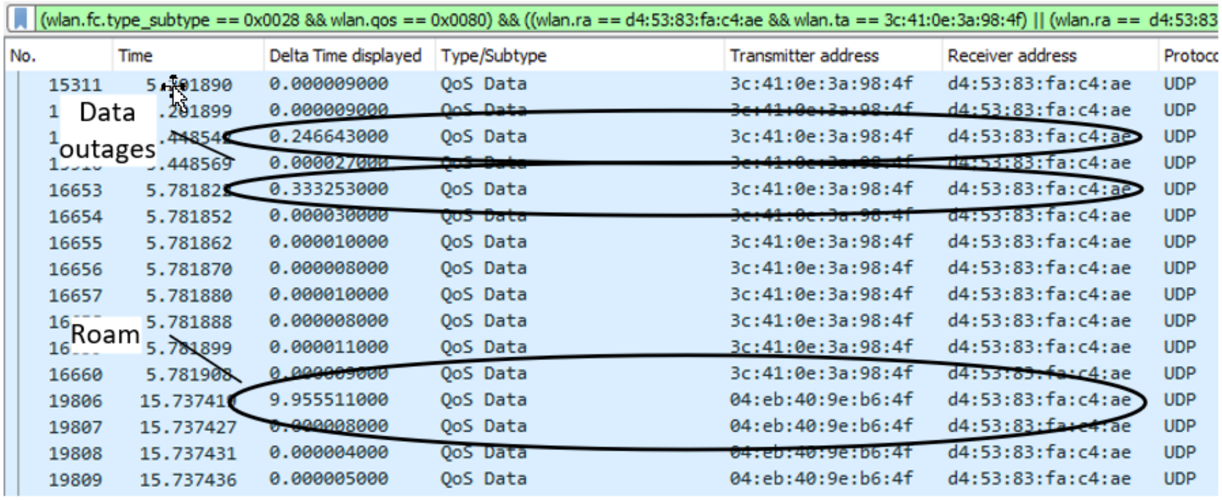


Figure 23. Throughput PDF and CCDF for all roaming runs

Figure 24 provides an example of data outage detection.


(wlan.fc.type_subtype == 0x0028 && wlan.qos == 0x0080) && ((wlan.ra == d4:53:83:fa:c4:ae && wlan.ta == 3c:41:0e:3a:98:4f) || (wlan.ra == d4:53:83

No.	Time	Delta Time displayed	Type/Subtype	Transmitter address	Receiver address	Protocol
15311	5.[illegible]1890	0.000009000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
1[illegible]	[illegible].281899	0.000009000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
1[illegible]	[illegible].448546	0.246643000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
1[illegible]	[illegible].448569	0.000027000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16653	5.781825	0.333253000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16654	5.781852	0.000030000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16655	5.781862	0.000010000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16656	5.781870	0.000008000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16657	5.781880	0.000010000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16[illegible]	5.781888	0.000008000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16[illegible]	5.781899	0.000011000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
16660	5.781908	0.000009000	QoS Data	3c:41:0e:3a:98:4f	d4:53:83:fa:c4:ae	UDP
19806	15.73741[illegible]	9.955511000	QoS Data	04:eb:40:9e:b6:4f	d4:53:83:fa:c4:ae	UDP
19807	15.737427	0.000008000	QoS Data	04:eb:40:9e:b6:4f	d4:53:83:fa:c4:ae	UDP
19808	15.737431	0.000004000	QoS Data	04:eb:40:9e:b6:4f	d4:53:83:fa:c4:ae	UDP
19809	15.737436	0.000005000	QoS Data	04:eb:40:9e:b6:4f	d4:53:83:fa:c4:ae	UDP

Figure 24. Data outage detection

Figure 25 provides an example histogram of data outage over time.

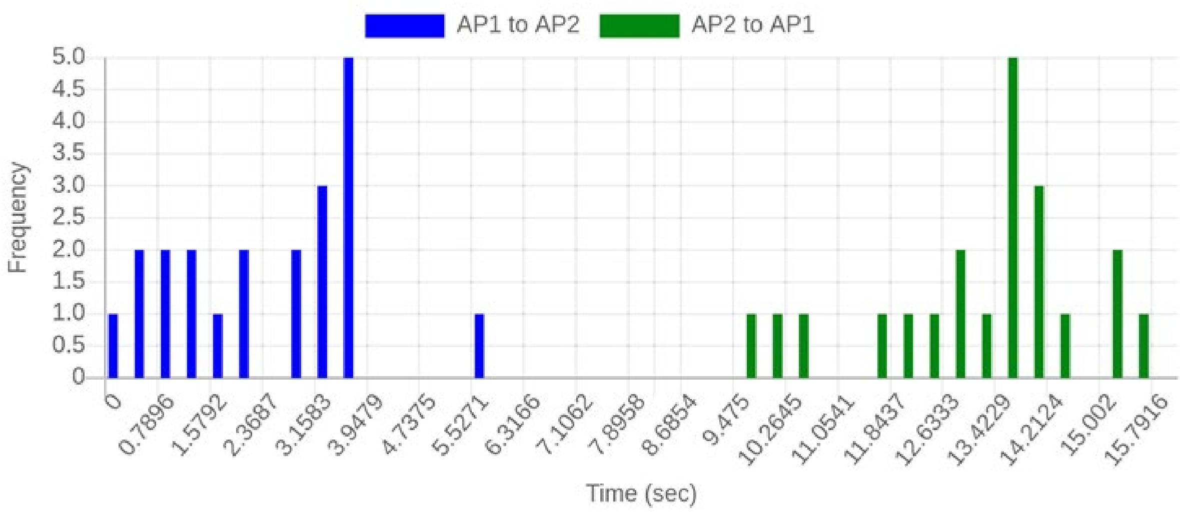
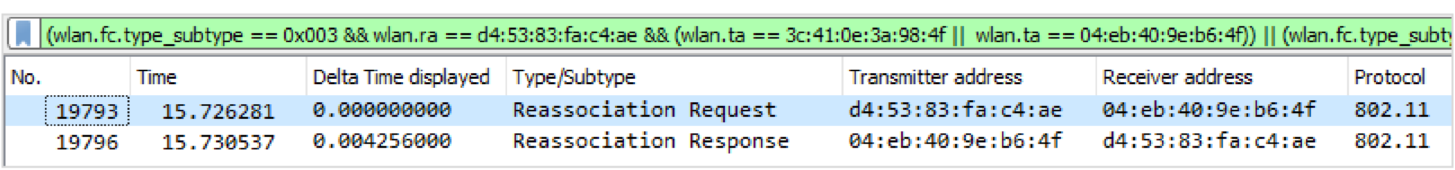


Figure 25. Histogram of data outage time

Figure 26 provides a fast BSS transition example.


(wlan.fc.type_subtype == 0x003 && wlan.ra == d4:53:83:fa:c4:ae && (wlan.ta == 3c:41:0e:3a:98:4f || wlan.ta == 04:eb:40:9e:b6:4f)) || (wlan.fc.type_subty

No.	Time	Delta Time displayed	Type/Subtype	Transmitter address	Receiver address	Protocol
19793	15.726281	0.000000000	Reassociation Request	d4:53:83:fa:c4:ae	04:eb:40:9e:b6:4f	802.11
19796	15.730537	0.004256000	Reassociation Response	04:eb:40:9e:b6:4f	d4:53:83:fa:c4:ae	802.11

Figure 26. Fast BSS transition example

Concatenate all $A_{1..n}(i)$ to plot a PDF and CDF of reassociation times as detailed in section 4.

Figure 27 provides an example histogram of fast BSS reassociation time.

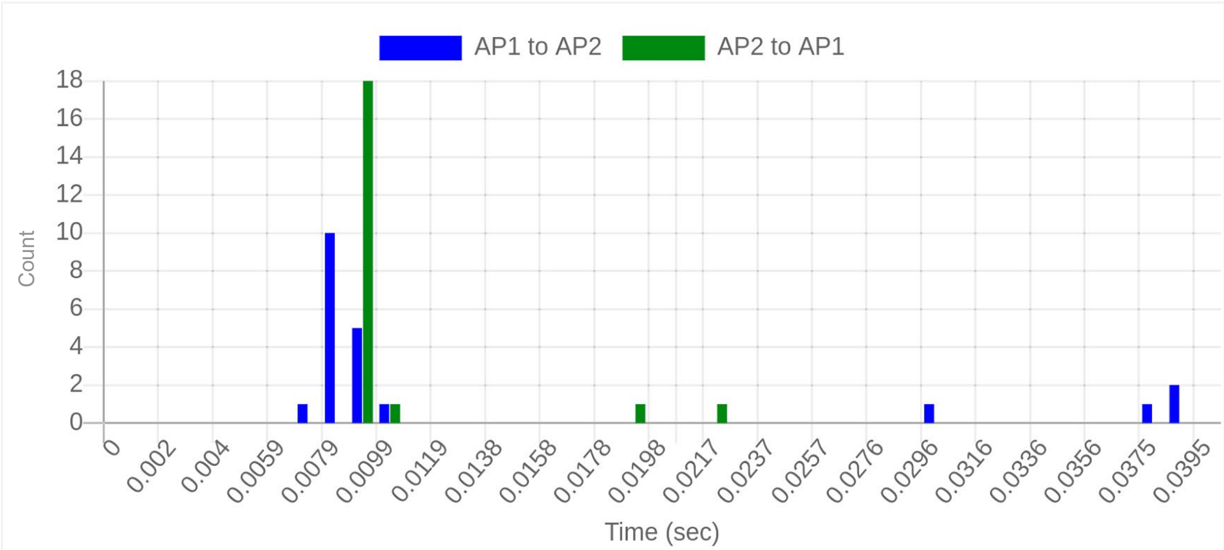


Figure 27. Histogram of fast BSS reassociation time