State of Wi-Fi Reporting

DSA 2021 Global Summit

June 8, 2021

ASSIA®

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Reliably Fast Broadband & Wi-Fi for the Home

Outline

- Introduction
  - ASSIA
  - Data Aggregation
- State of Wi-Fi Report Results: Parameters Evolution Over Time
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  - Wi-Fi Latency
  - Wi-Fi Interference
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- Overall Spectrum-Need Score
- Wi-Fi, Broadband, and infrastructure investment
- Conclusions

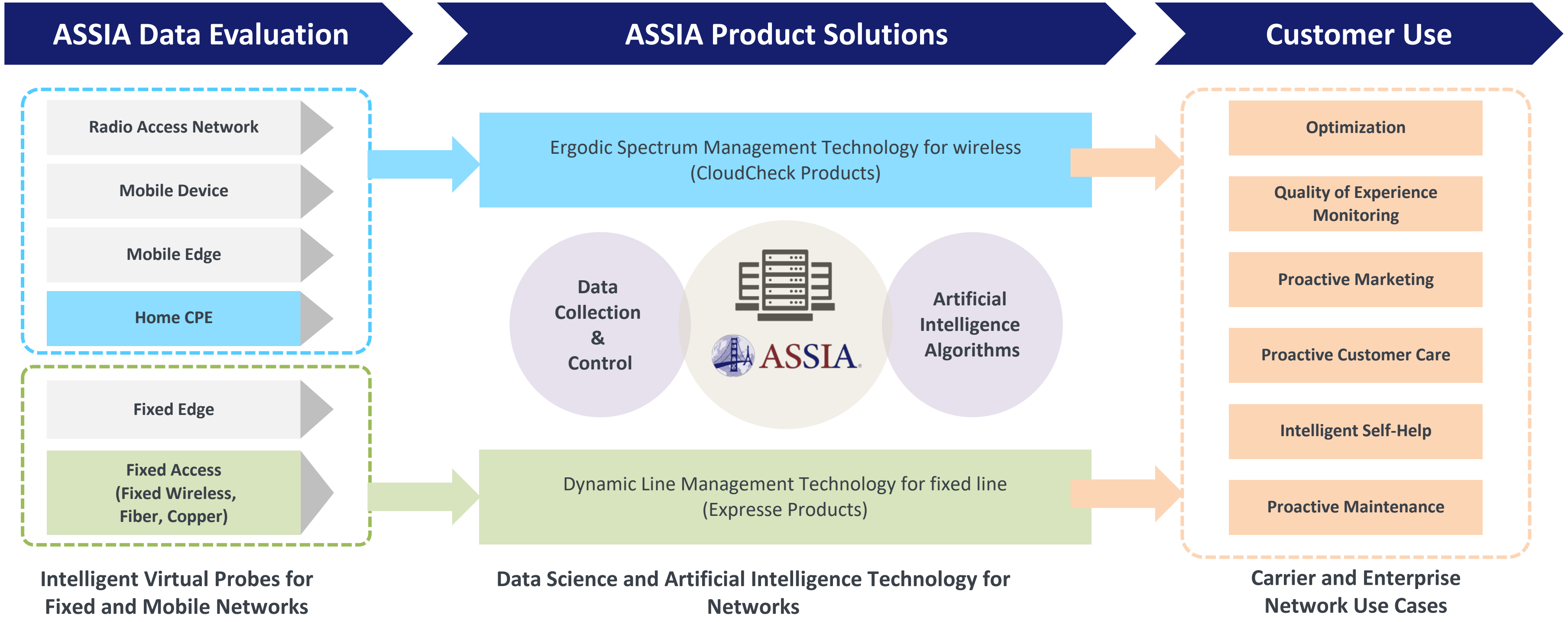
Introduction

ASSIA

Wi-Fi and Broadband Data Aggregation

Reliably Fast Broadband & Wi-Fi for the Home

ASSIA AI-PLATFORM FOR CONNECTIVITY

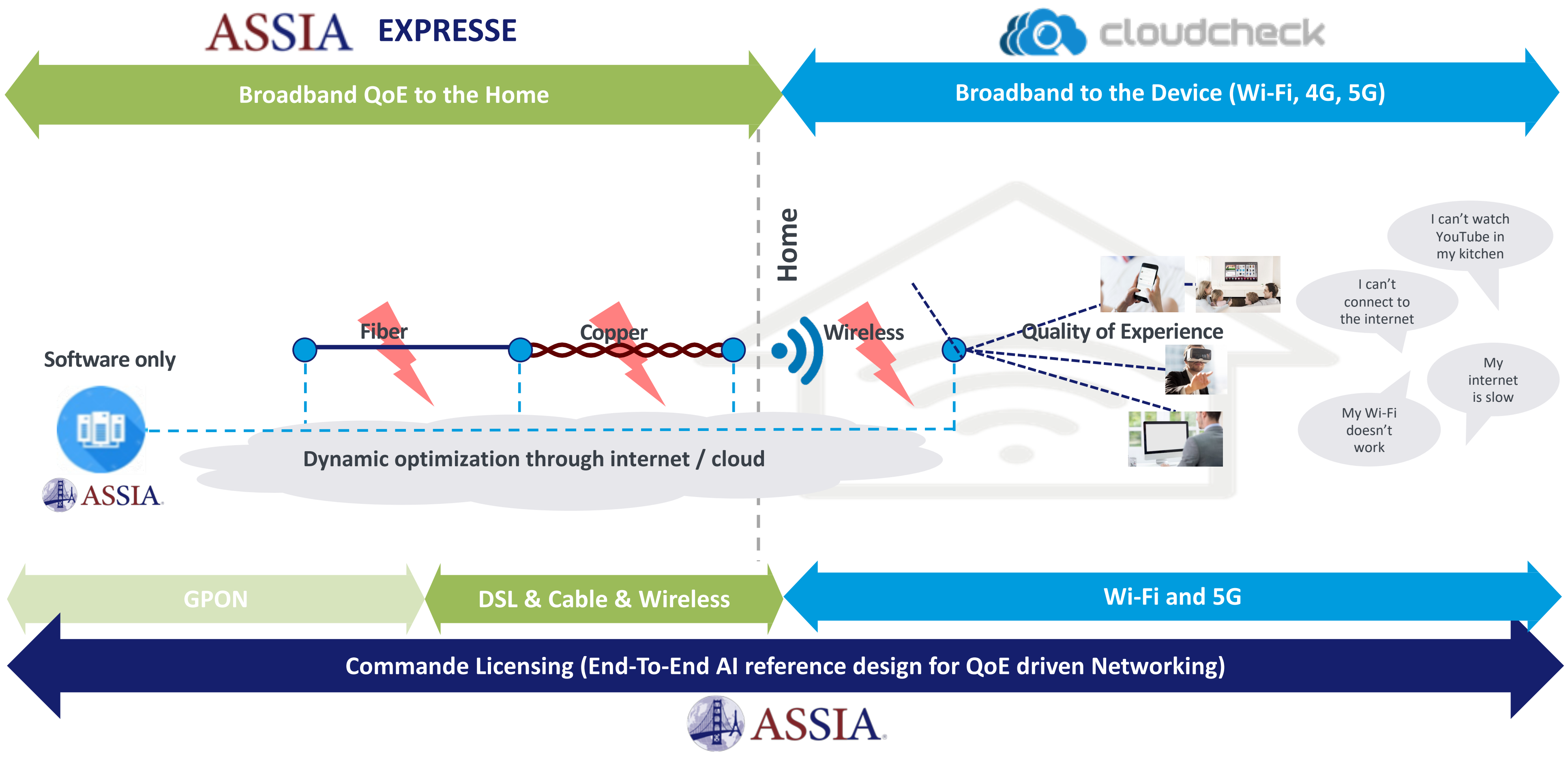


ASSIA's AI optimizes fixed/wireless connections Quality of Experience through data-collection/analysis, all devices, equipment, middleware, and networks

per-customer, neighborhood or network-wide basis

reduces operating expenses related to service calls, dispatches, hardware replacements, or related to customer churn

ASSIA and Software Products



Sold to ISPs Globally (5 continents)

Data Aggregation

ASSIA footprint for collection globally > 50M access connections
Serving 100's of millions of Wi-Fi –Connected Devices

Reliably Fast Broadband & Wi-Fi for the Home

ASSIA Data Collection and Aggregation

ASSIA Data Collection

- Performance metrics
- Diagnostic parameters
- Network status & test

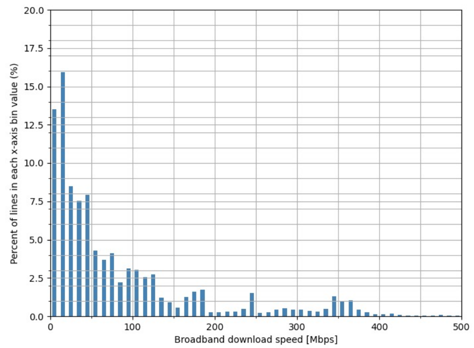
Wi-Fi Customer Premises Equipment (CPE)

Broadband Fixed-Line Router Equipment

Wi-Fi and Broadband Data

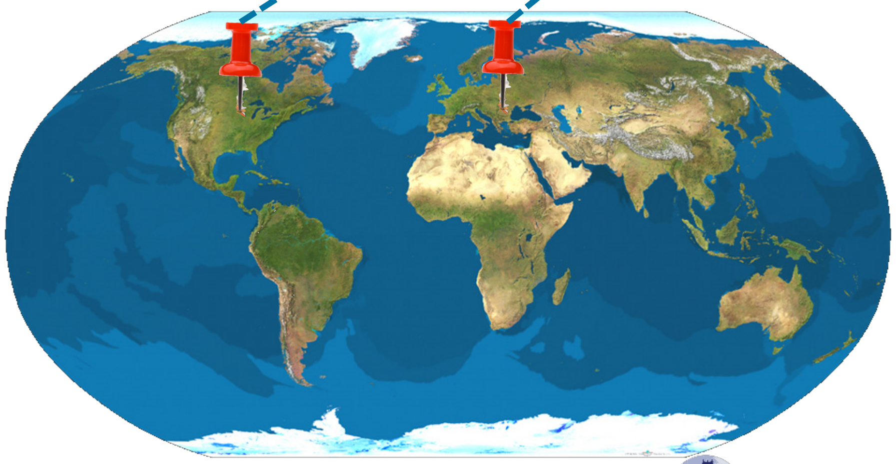
Statistical Analysis

Anonymized Histogram Data



North America (USA, Canada)

Europe



- Millions of lines in North America and Europe
  - ~40 Global ISP's (most have >1M links)
  - ISP operational-expense reduction is main use

ISPs invest in Wi-Fi because their customers' QoE is significantly impacted. Consumers fault the ISP for poor Wi-Fi!

Some metrics that ASSIA's customers desire

All correlate well to field QoE for Wi-Fi in live ISP service & cost ISPs and Application Providers $ when poor

- **Wi-Fi Traffic**

  Wi-Fi traffic at each Wi-Fi router, sum of all stations' traffic, daily and hourly

- **Wi-Fi Latency**

  Average daily round-trip delay (ms) between the Wi-Fi router and all its clients

  This is not the server to client delay measured, e.g., by Opensignal (it is less)

- **Interference**

  Time percentage that a channel is unavailable because **other routers** (and unassociated stations) occupy that same channel

- **Congestion**

  QoE-extrapolated measure of end-customer frustration as a function connection-bandwidth use by **stations associated to this router;** i.e., how active is the router?

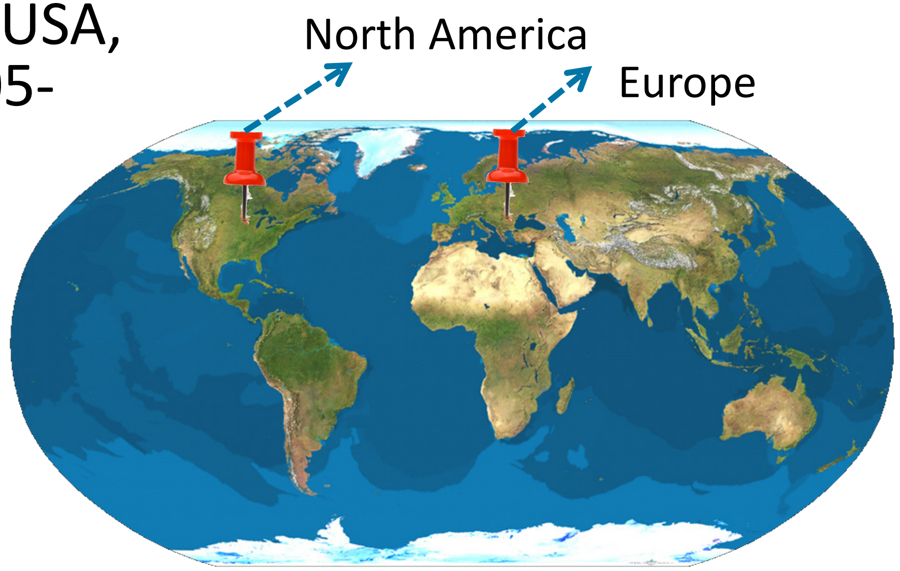
- **Wi-Fi throughput to transmit rate ratio**

  Router's available throughput divided by the maximum transmit rate (MCS data rate)

  Interference and congestion *decrease* this measure and so indicate spectrum need

More Specifics on ASSIA's Wi-Fi and Broadband Collections

- ASSIA collects and anonymizes many data parameters
  - Currently, across millions of lines in North America (USA, Canada excluding Mexico) and Europe, All data 28-05-2020 to 28-02-2021
- This report currently aggregates & analyzes:



Wi-Fi Data

Wi-Fi Throughput (speed)	Daily, 2.4 and 5 GHz bands
Wi-Fi Transmit Rate	Daily, 2.4 and 5 GHz bands
Wi-Fi throughput to transmit rate ratio	Daily, 2.4 and 5 GHz bands
Wi-Fi Congestion	Daily and max hour, 2.4 and 5 GHz bands
Wi-Fi Interference	Daily and hourly, 2.4 and 5 GHz bands
Wi-Fi Traffic	Daily and hourly, upstream and downstream, 2.4 and 5 GHz bands
Wi-Fi Latency	Daily, 2.4 and 5 GHz bands

Broadband Data

Broadband Traffic	Daily and hourly, upstream and downstream
Broadband Throughput (speed)	Daily, upstream and downstream
Broadband Latency	Daily

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State of Wi-Fi Report

ASSIA's business depends profits from the ISP's commercial value attributable to Wi-Fi.

ASSIA realizes regulators and application providers also care (or soon will) about Wi-Fi QoE

This DSA Report thus provides unique insights about Wi-Fi spectrum, its use, its limitations.

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Wi-Fi already needs the 6 GHz spectrum in North America

- **to avoid QoE limitations on:**
  - **Video for work from home**
  - **Remote health care**
  - **Video entertainment**
- **to justify any fiber-to-home infrastructure investment**

Europe follows roughly 6 to 12 months later

State of Wi-Fi Report

- Report Objectives
  - Track Wi-Fi traffic evolution
  - Monitor & analyze spectrum use
  - Improve spectrum use to reduce interference & congestion
- Wi-Fi QoE degrades from spectrum limitations
  - Steady Wi-Fi-use growth (with pandemic bump, of course)
  - Clear shift from 2.4 GHz to 5 GHz, occurred first in North American, now Europe
  - Track periodically (quarterly to annually)
- Relate to Market trends to leverage best Wi-Fi bands
  - Very little 6 GHz data yet (expect in 18 months, annual Wi-Fi replacement 10%)
- Report Link: http://dynamicspectrumalliance.org/global-summit/

Annualized Percent Change in Wi-Fi Data: Summary

	2.4 GHz	5 GHz
North America		
Wi-Fi traffic, downstream	4.4%	30.2%
Wi-Fi traffic, upstream	5.5%	22.5%
Wi-Fi interference*	7.1%	18.3%
Wi-Fi congestion in busy hour	-3.6%	760.9%
Wi-Fi latency	13.4%	21.7%
Wi-Fi throughput / transmit rate	-7.3%	-18.8%
Europe		
Wi-Fi traffic, downstream	42.0%	42.0%
Wi-Fi traffic, upstream	14.4%	21.8%
Wi-Fi interference	3.7%	5.4%
Wi-Fi congestion in busy hour	64.0%	28.6%
Wi-Fi latency**	29.9%	5.7%
Wi-Fi throughput / transmit rate	-8.7%	-8.4%

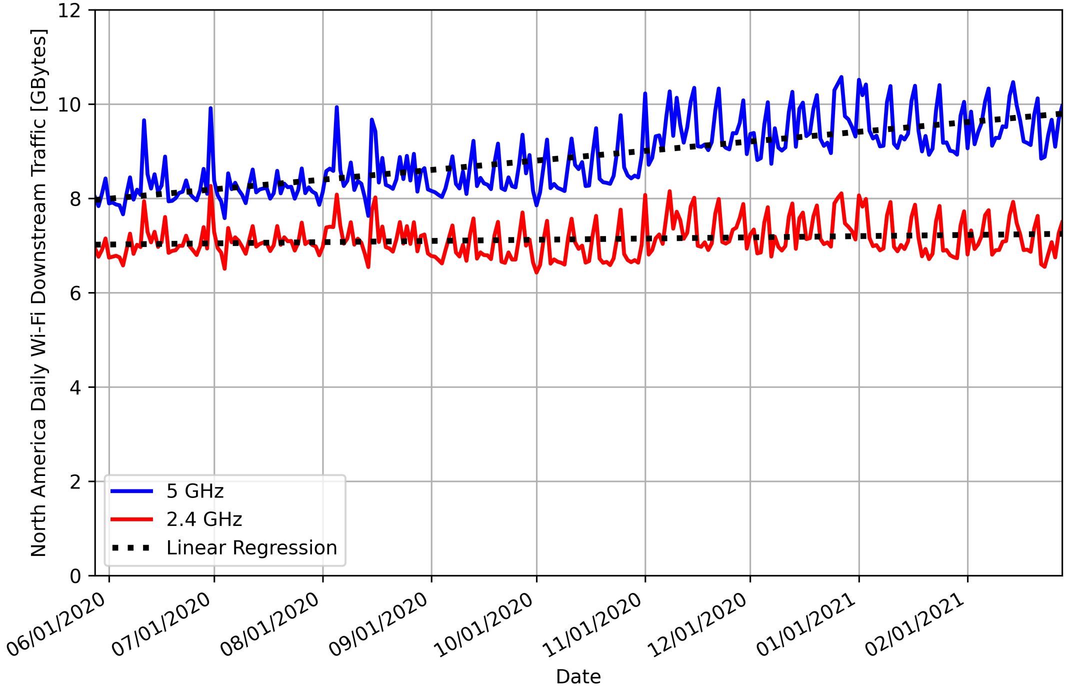
Wi-Fi **growth is rapid**,
Maintenance of good QoE
is increasingly challenging

Let's investigate further some of these …

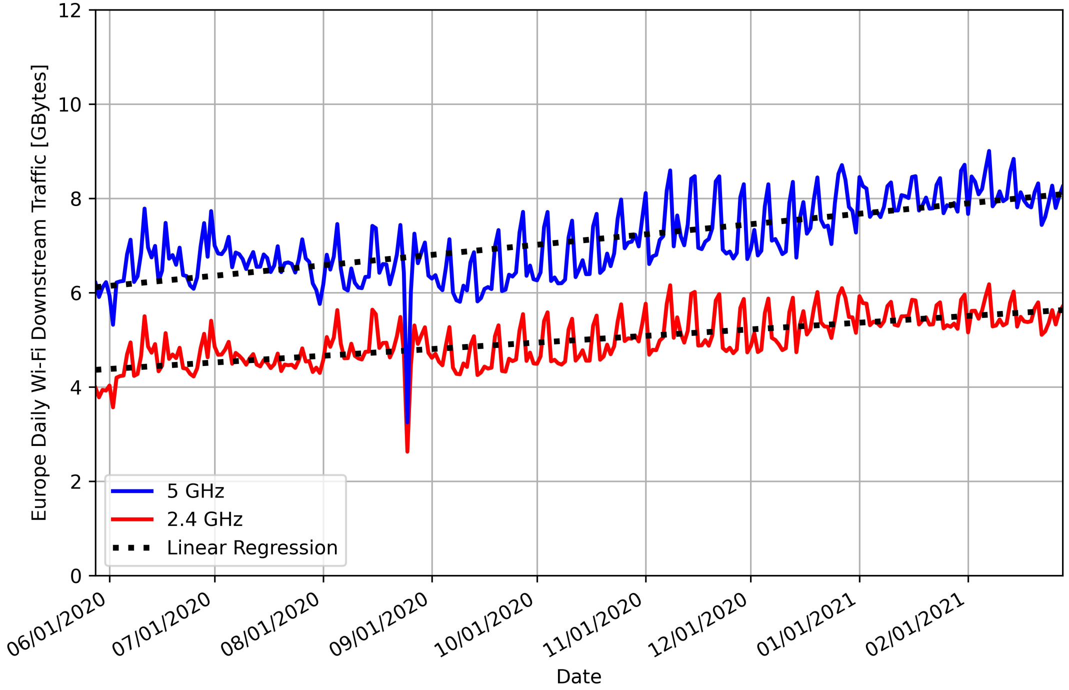
Wi-Fi Traffic

- Wi-Fi traffic **doubles every 3 years.**

NORTH AMERICA



EUROPE



2.4 GHz | 5 GHz
4 | 30 %

Wi-Fi traffic is growing in both 5 GHz and 2.4 GHz

2.4 GHz | 5 GHz
42 | 42 %

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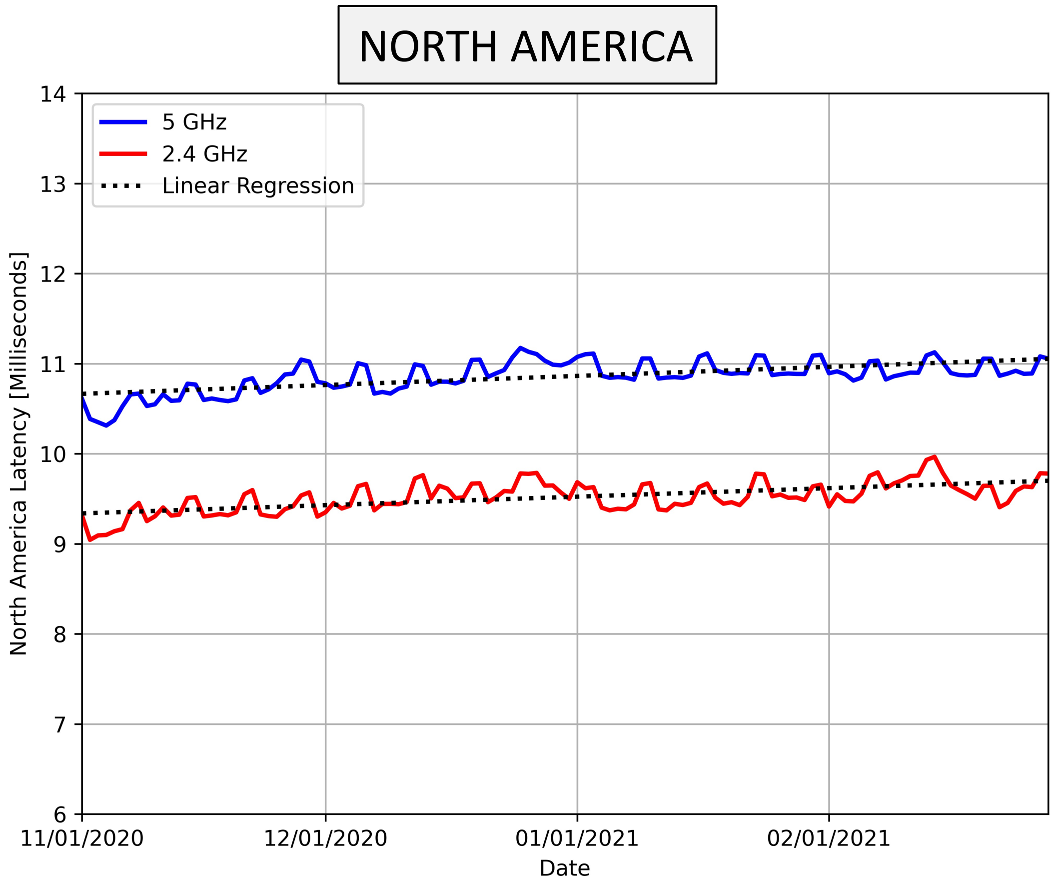
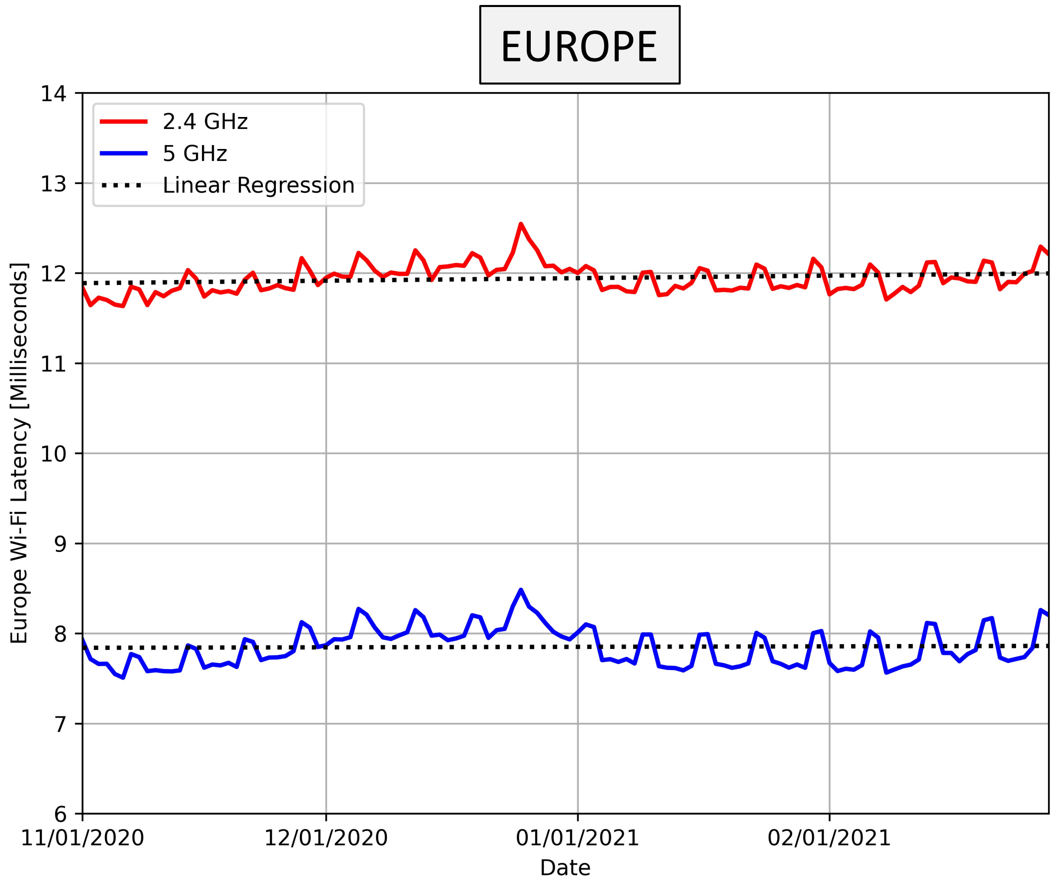
Wi-Fi Latency evolution (ms)



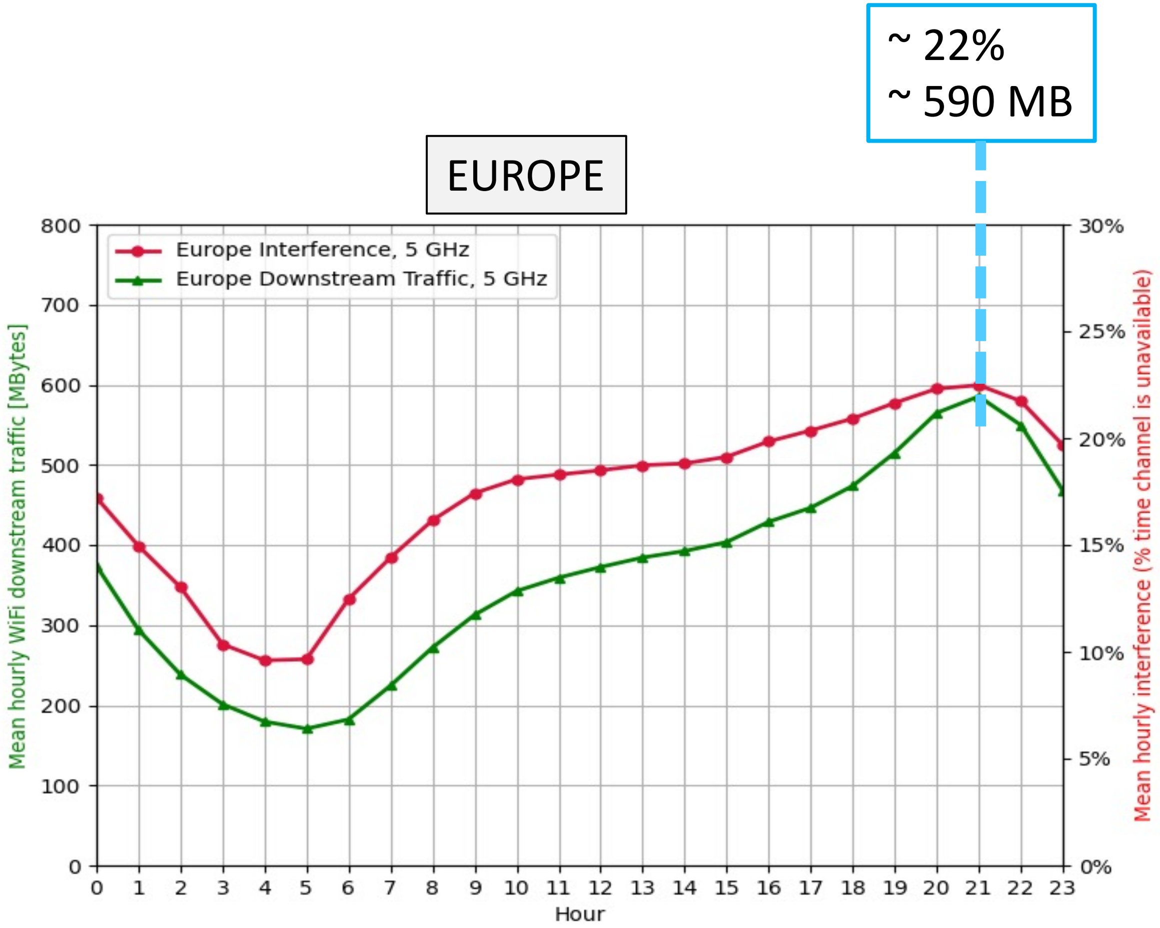


2.4 GHz | 5 GHz
13 | 22 %

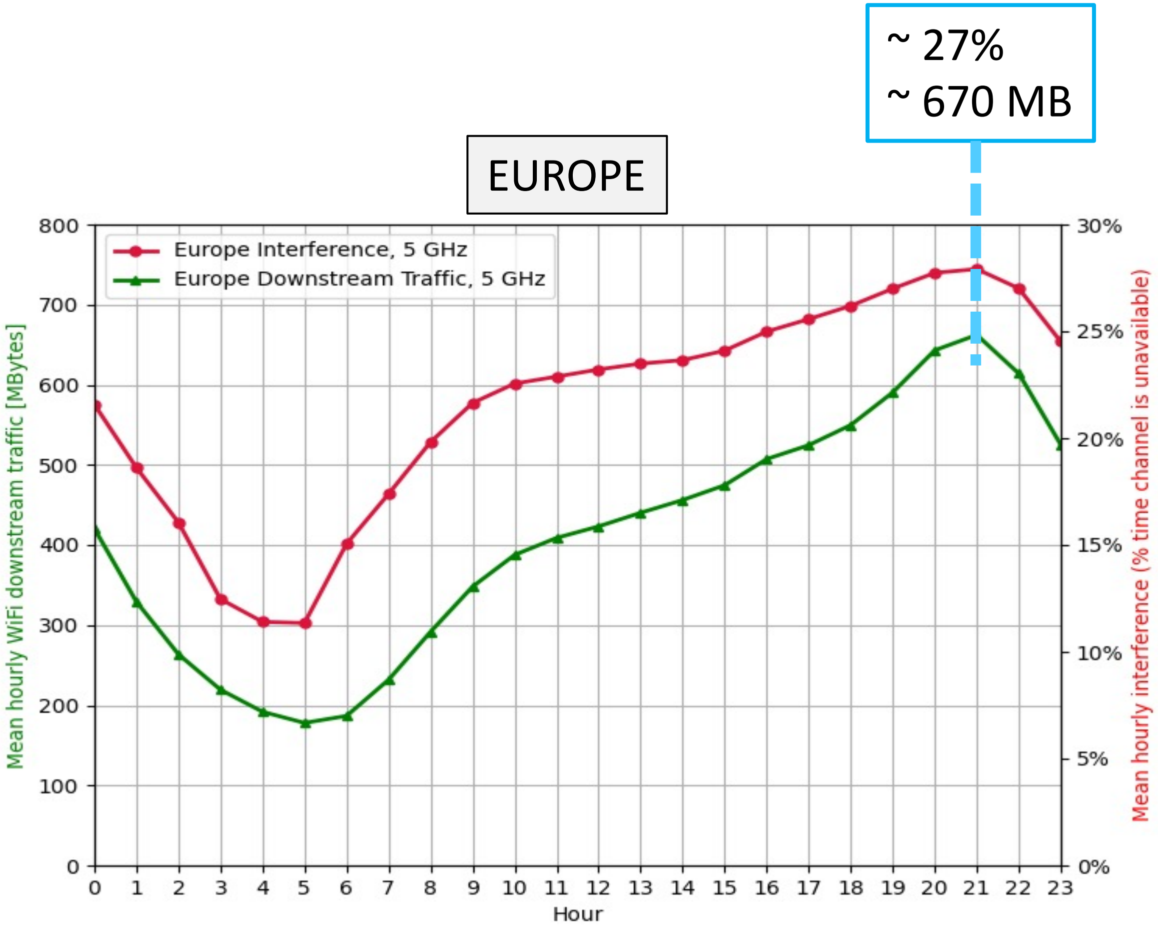
Latency is degrading over time as traffic increases

2.4 GHz | 5 GHz
30 | 6 %

European Hourly Wi-Fi Interference



5/28/20 to 11/27/20



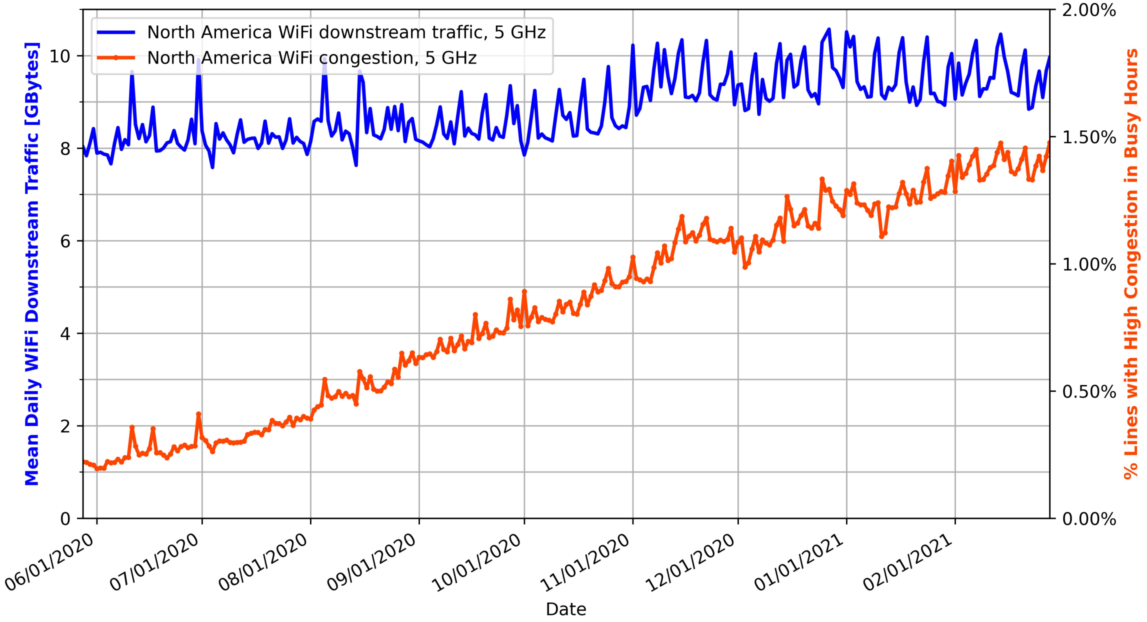
5/28/20 to 2/28/21

Interference growing as traffic grows
Interference increased 5% in 3 months

Wi-Fi Congestion vs Traffic

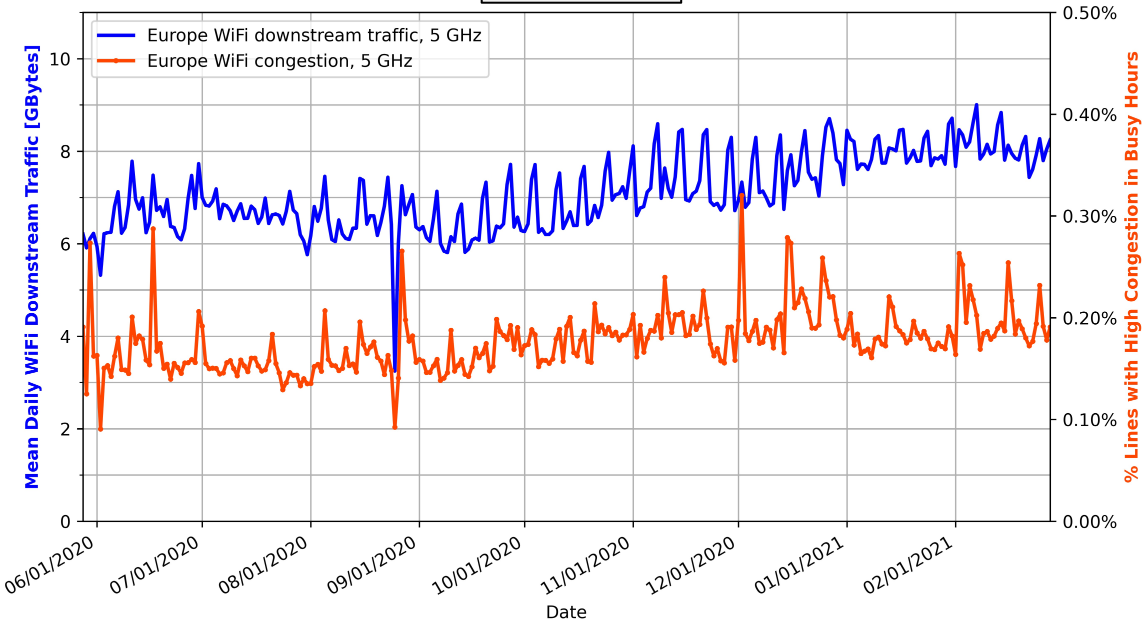
- Congestion grows much faster than traffic

NORTH AMERICA



- Congestion still grows linearly with traffic

EUROPE



1% congestion typically means
users complain because QoE is unacceptable

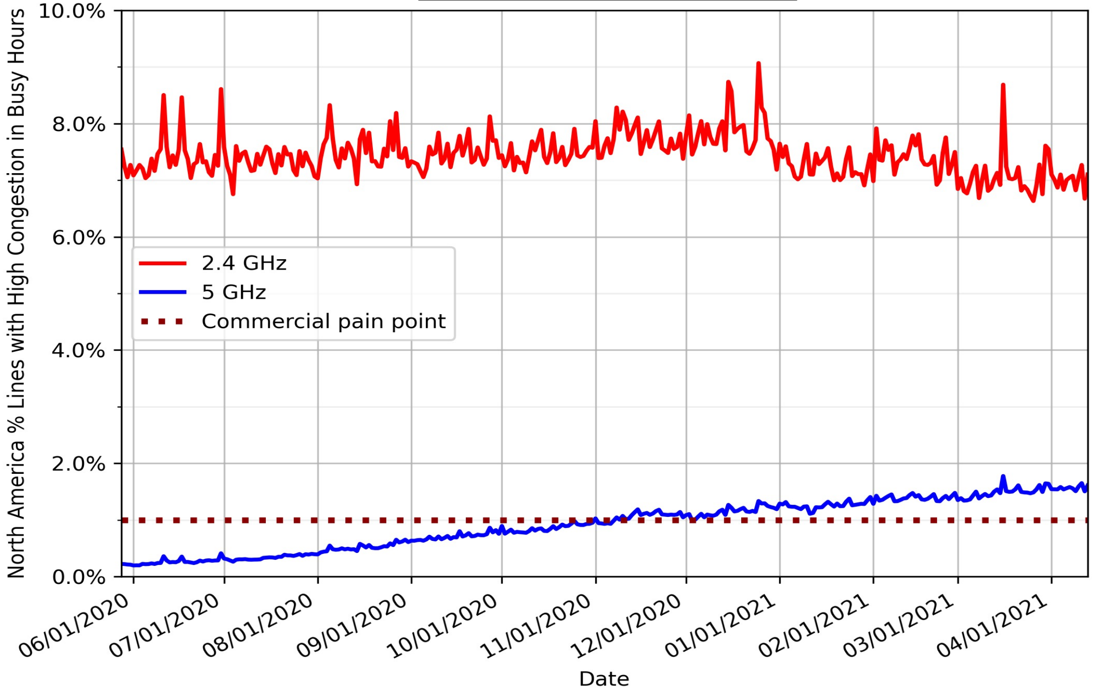
Operational costs become unacceptable

Wi-Fi congestion growing nonlinearly as Wi-Fi traffic grows
North America already faces congestion issues
Europe will in 6 months

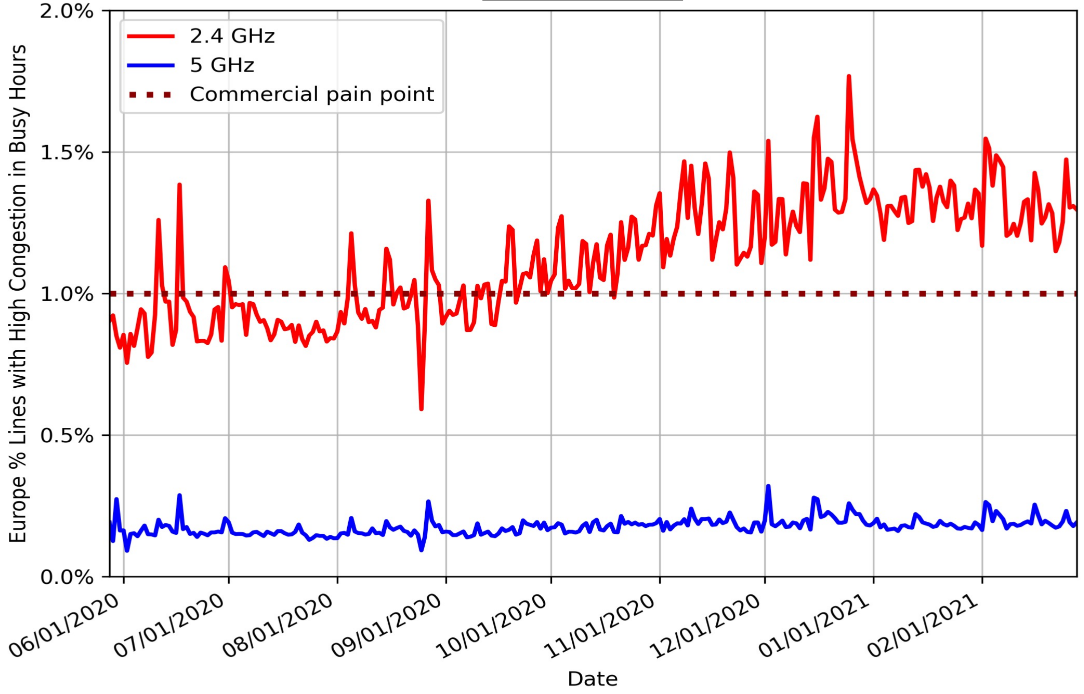
Busy Hour Wi-Fi Congestion

- busy hour has the maximum congestion over 24 hours for each service (% of links)

NORTH AMERICA



EUROPE



The problem is even more acute during busy hour
Users are reaching the limits of Wi-Fi @ 5GHz.
Wi-Fi 6E additional channels are designed to address this issue

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Overall Spectrum-Need Score (SNS)

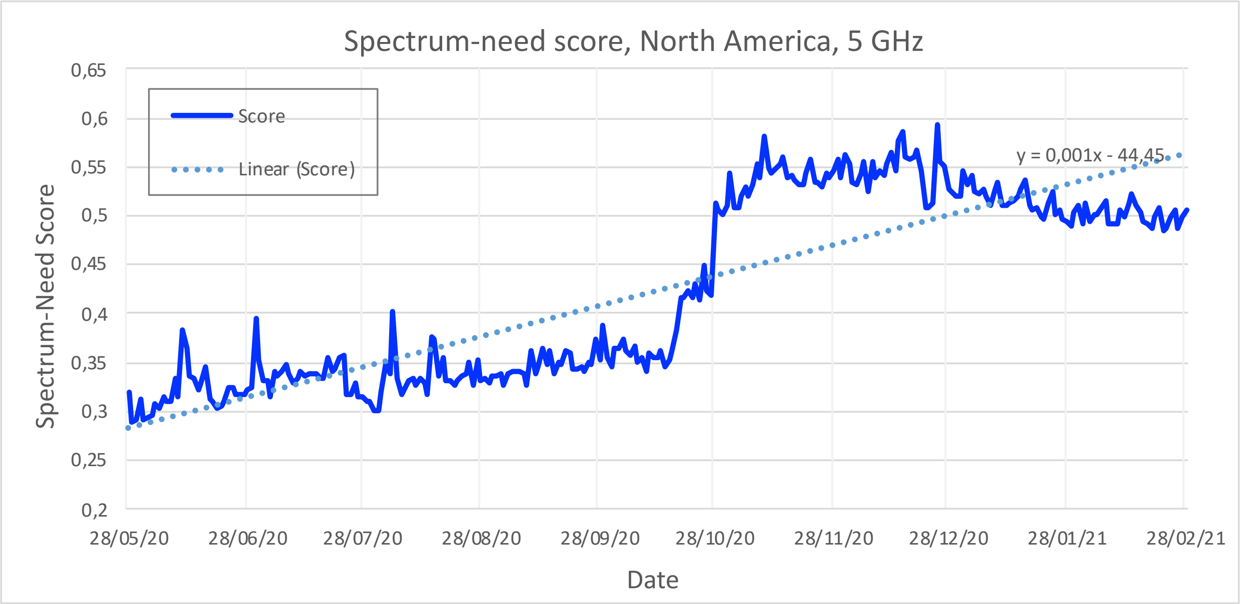
- ***Why***
  - ISPs care about all P's (traffic, latency, etc)
  - Regulator and consumers need simpler metric
  - **Great 0** < SNS < **1 Awful - need it now.**
  - Single agreed measure to measure spectrum scarcity

- ***Spectrum-need score*** combines salient Wi-Fi parameters (P's)
- Predicts spectrum need using:
  - *Wi-Fi traffic, downstream and upstream (P1,P2):* Traffic *increase* → more spectrum.
  - *Wi-Fi interference (P3):* Interference increase → more spectrum.
  - *Wi-Fi latency (P4):* Latency increase → more spectrum.
  - *Throughput to transmit rate ratio (P5):* This parameter's decrease (so subtract) → more spectrum

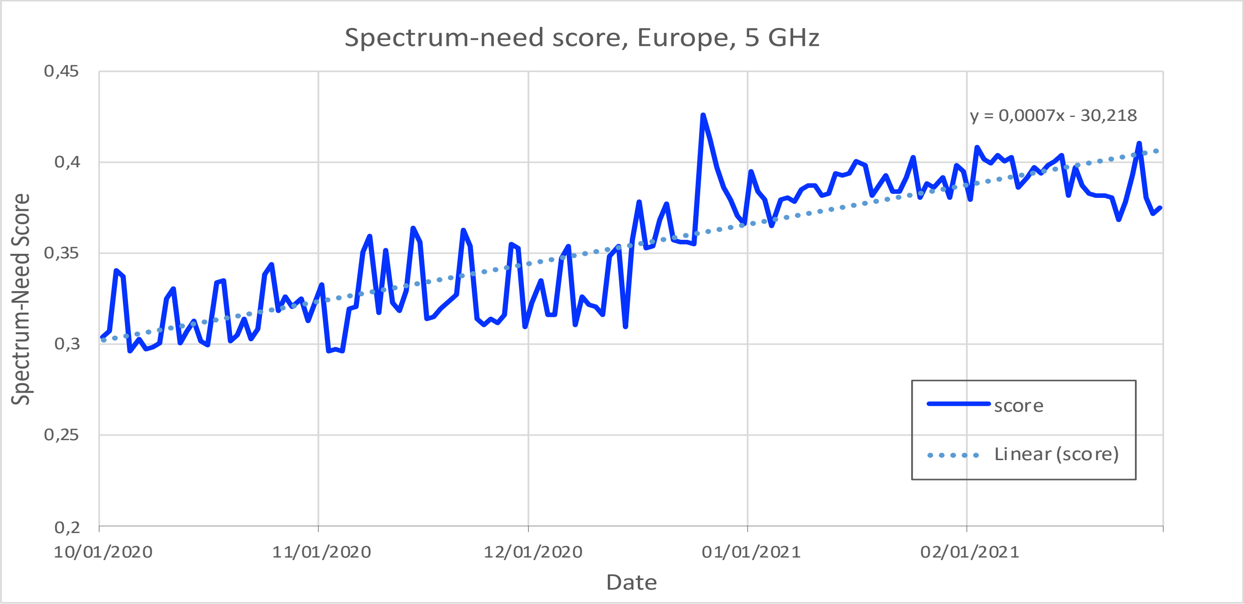
- Each parameter uses a 5% worst-case threshold, because the stress points are of interest.
  - SNS linearly combines the 5 P's with equal weight.

Overall SNS (Spectrum-Need Score)

NORTH AMERICA



EUROPE



Spectrum-need score = 0.2 P1 + 0.2 P2 + 0.2 P3 + 0.2 P4 - 0.2 P5

Wi-Fi-related productivity negatively impacted in 1 year
(SNS rises 25-40% annually)
→ 6 GHz will help

Continent, Wi-Fi Band	% Annual increase in spectrum-need score (linear regression)
North America, 2.4 GHz	13.2%
North America, 5 GHz	37.1%
Europe, 2.4 GHz	24.8%
Europe, 5 GHz	25.3%

Wi-Fi versus Broadband Access Connection

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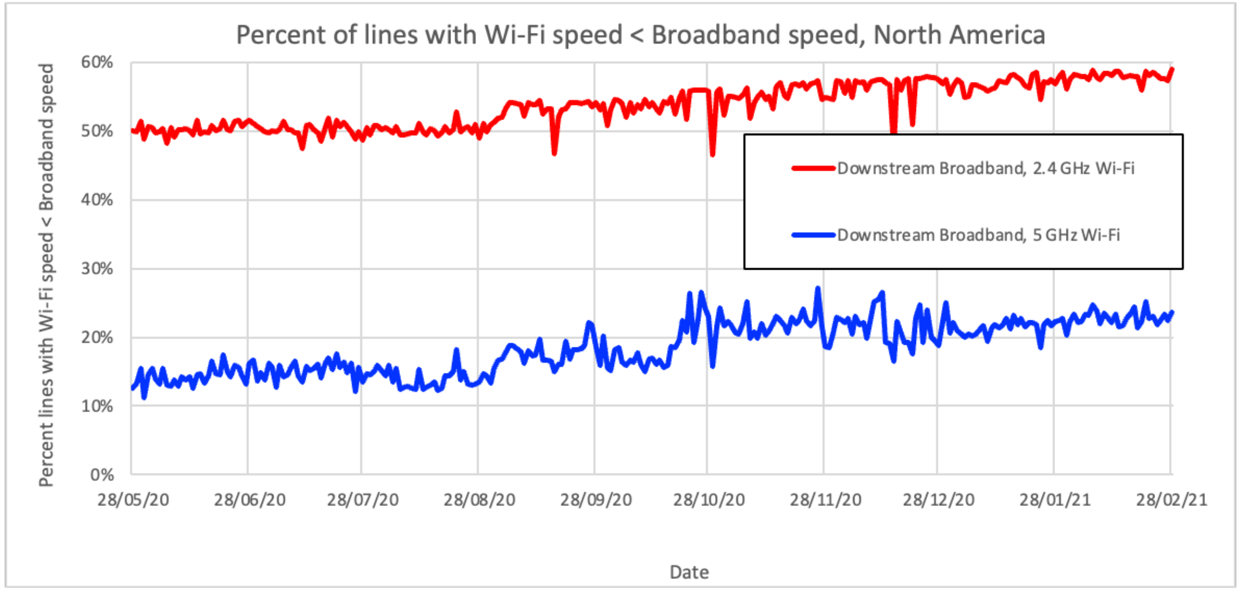
Wi-Fi vs Broadband Access Throughput

The **connectivity QoS is increasingly limited by Wi-Fi** rather than broadband

ISP investment might better be to Wi-Fi than FTTH, or FTTH investment return reduces



This is already a big problem in the US, and the problem is becoming more acute.

Wi-Fi slower than broadband (North Am)	Increase over one year
Downstream Broadband, 2.4 GHz Wi-Fi	13.0%
Downstream Broadband, 5 GHz Wi-Fi	14.4%

The curves tend to be higher in the plot as broadband speed increases or Wi-Fi speed decreases, i.e., Pr (Wi-Fi speed < Broadband speed) increases.

User-perceived performance is yet worse with increasing stations on same router.

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State of Wi-Fi Report Conclusions

- Both 2.4 GHz and 5 GHz bands at or headed to saturation
  - annual increase in 5 GHz band is higher than 2.4 GHz band in North America (USA, Canada) and Europe.
- Increasing traffic exacerbates this trend (more work-at-home, remote anything).

- Wider Wi-Fi channels also encourage more traffic, so then
  - Wider channels → more congestion
  - Wider channels → more interference
  - Higher SNS

- The next generation of applications will require very low latency, which is sensitive to spectrum "quality".

Thank You

End of Presentation

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Reliably Fast Broadband & Wi-Fi for the Home

Wi-Fi and Broadband Data

June 2021

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1 TABLE OF CONTENTS

2 INTRODUCTION

ASSIA collects many performance, status test, and diagnostics parameters from Wi-Fi customer premises equipment (CPE) and broadband fixed-line router equipment worldwide, and this report provides a view into that data. This report describes and presents a multitude of broadband and Wi-Fi parameters that show trends over time and relations between parameters. No single Wi-Fi parameter can show the entire network status, and so many parameters appear here. This document further describes the process for creating this data, and for each data category a description of what the data represents.

Data appears separately for North America and Europe. This report presents data from North America and for Europe for a nine-month period from May 28, 2020, to February 28, 2021, where data for North America includes the USA and Canada, but does not include Mexico. Linear regression was performed on daily data, finding the minimum mean squared error (MMSE) straight-line fit to the data, and the resulting trends appear in Table 1 and Table 2 below:

Table 1. Annualized Percent Change in Wi-Fi Data.

	2.4 GHz	**5 GHz**
North America		
Wi-Fi traffic, downstream	4.4%	30.2%
Wi-Fi traffic, upstream	5.5%	22.5%
Wi-Fi interference*	7.1%	18.3%
Wi-Fi congestion in busy hour	-3.6%	760.9%
Wi-Fi latency	13.4%	21.7%
Wi-Fi throughput / transmit rate	-7.3%	-18.8%
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Wi-Fi congestion in busy hour	64.0%	28.6%
Wi-Fi latency**	29.9%	5.7%
Wi-Fi throughput / transmit rate	-8.7%	-8.4%

* North American Wi-Fi interference is the trend up until the discontinuity on November 27.

** Europe Wi-Fi latency is the trend until November 27

The *increases* in Wi-Fi traffic, interference, and latency indicate a scarcity of available spectrum.

Wi-Fi throughput / transmit rate is the throughput available to an individual AP divided by the maximum transmit rate on that channel. The *decreases* in throughput / transmit rate also indicate a scarcity of available spectrum.

Table 2. Annualized Percent Change in Broadband Data.

Broadband	Downstream	Upstream
North America		
Broadband traffic	31.6%	40.6%
Broadband throughput	49.8%	65.8%
Europe		
Broadband traffic	39.0%	23.5%
Broadband throughput	-2.2%	116.7%

2.1 ANONYMIZED HISTOGRAM DATA

Per-connection datum x_A measures a line analytic (like Broadband or Wi-Fi traffic) for internet service provider (ISP) A on a particular continent (e.g., North America, Europe) for a particular parameter *x*. A histogram vector H_{xA} of values for x_A represents an array of estimates of the probability density function corresponding to an array of histogram bin start and stop values. Histogram vectors H_{xA} are constructed separately for each day or hour over the connections to each subscriber (line) in ISP *A*'s network. Each histogram-vector element equals the number of lines that have the parameter *x* between the histogram bin start and stop values, divided by the total number of lines, where each line represents a single user's Wi-Fi network.

Histograms are merged across multiple ISPs for each continent, and these merged histograms are provided to DSA. ASSIA uses a confidential continental weighting among ISP's *A, B, C, ...* , which is $w_A, w_B, w_C, ...$ where $w_A + w_B + w_C + ... = 1$. The list of ISPs and associated weighting on a particular continent cannot be disclosed. An overall histogram for the set of ISPs on each continent $C_i = \{A, B, C, ...\}$ is available to DSA as

$$H_x^i = w_A H_{xA} + w_B H_{xB} + w_C H_{xC} + \cdots = \sum_{j \in C_i} w_j H_{xj}$$

This histogram permits calculation of quantities such as average values, means, medians, quartiles, 90% worst-case for the continent. The weighted final histogram anonymizes fully the original per-line and ISP-identity data so that this data derived across multiple ISPs no longer belongs to any of them and is anonymized.

2.2 HISTOGRAM EXAMPLE

Here is an example to illustrate the meaning of the histogram plots. Figure 1 considers the daily Wi-Fi downlink traffic for 5 GHz with a simplified plot. This plot shows a histogram. The x-axis shows traffic in GigaBytes (GBytes) per day. Each histogram bin is 20 GBytes wide, so the first bin is from 0 to 20 GBytes, the second bin is from 20 to 40 GBytes, etc. There are five histogram bins, spanning from 1 to 100 GBytes in total. Each bin is labeled on the x-axis by the value in the center of the bin; for example, the first bin from 0 to 20 GBytes is labeled as 10. The y-axis shows the percent of all the lines which have data within each bin. For example, 87% of all the lines have data in the first bin; meaning that 87% of all lines have downstream Wi-Fi traffic between 0 and 20 GBytes/day.

The second bin shows that 9% of the lines have traffic between 20 and 40 GBytes per day. Here a "line" represents a single broadband subscriber.

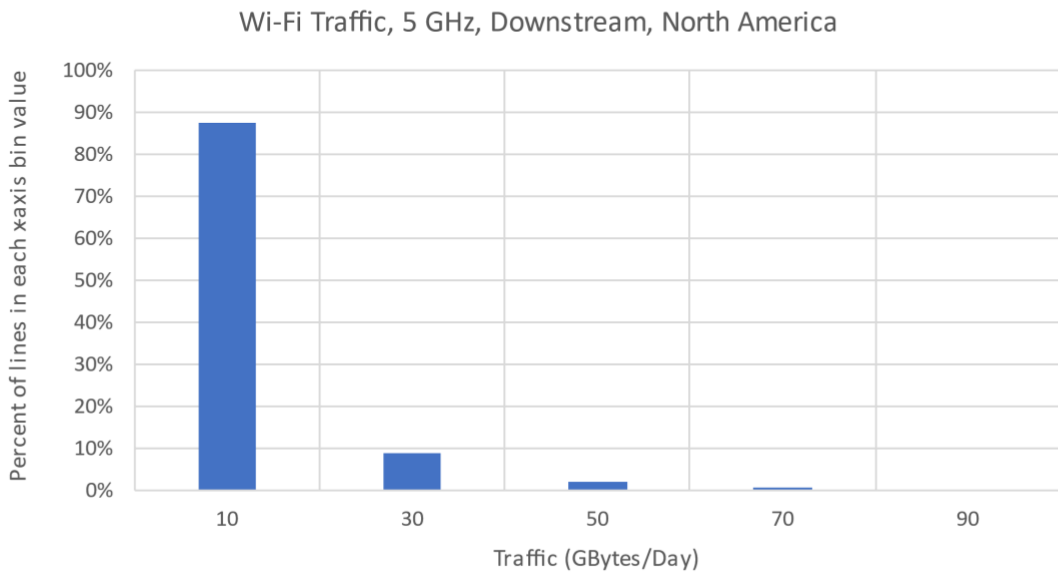

Figure 1. North America, Wi-Fi traffic 5 GHz Downstream 5 bins.

Next, Figure 2 shows the same data as Figure 1 above, but with 50 bins instead of five. Now each bin spans 2 GBytes instead of 20.

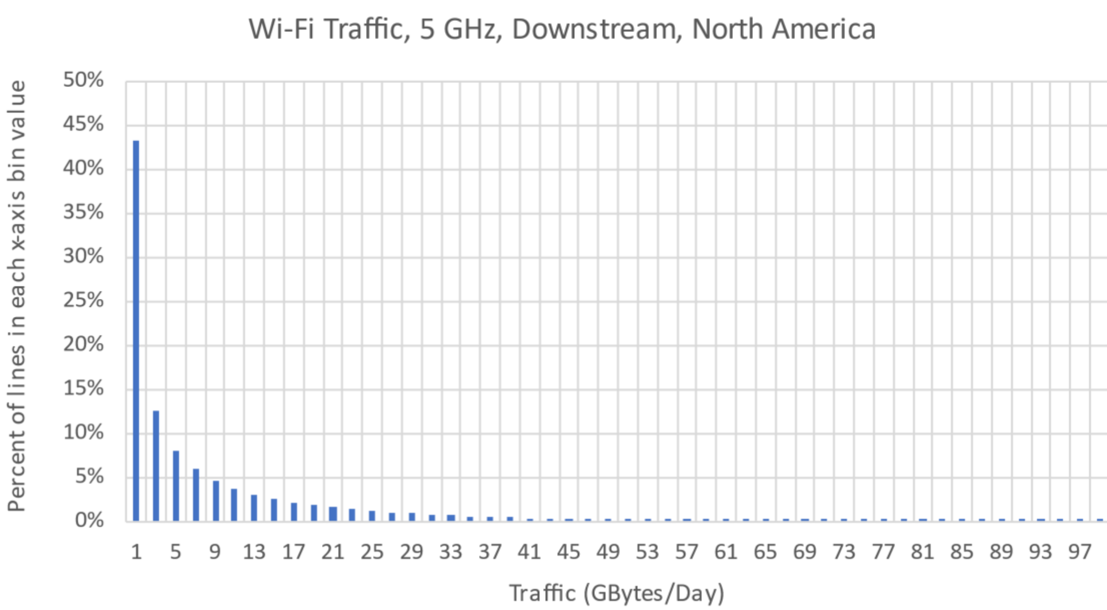

Figure 2. North America, Wi-Fi traffic 5 GHz Downstream, 50 Bins.

The histograms here generally have 100 bins. This is a large number, for accuracy, but it can be down-sampled for plotting. Plots presented further in this report simply show curves across the top of all bins instead of all the columns as shown above; this is easier to read and allows multiple curves on a single figure. Data was recorded every day, and the histograms presented here generally show the average across all the recorded days.

Data can equivalently be plotted as a Cumulative Distribution Function (CDF), as shown in Figure 3. At a given x-axis value in the CDF plot, the y-axis shows the total percent of lines at or below that x-axis value. The y-axis of the CDF also equals the sum of all histogram bins at or below that x-axis value.

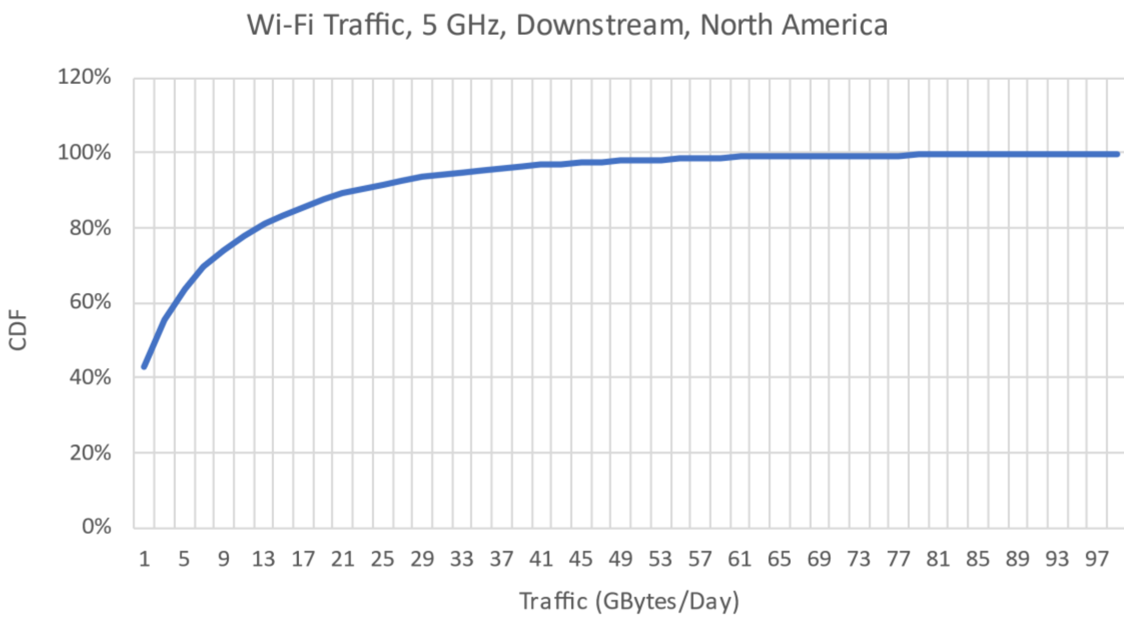

Figure 3. North America, Wi-Fi traffic 5 GHz, Downstream, Cumulative Distribution Function (CDF)

Histograms are recorded for each day and in some cases for each hour each day. Currently the plots run across nine months; over time more data will accumulate across a longer time-scale. Some figures show visible discontinuities, which may be due to the particular equipment reporting the parameter values, or due to the quantization of the originally recorded data.

The reader may ask why we recorded histograms instead of a simpler parameter such as the average or median. The answer is simple: the histograms contain a wealth of data. Data is accumulated from well over a million samples for each continent; this allows us to accurately represent the underlying probability density function. The histogram can thus be used to provide many statistics: CDF, mean, median, standard deviation, higher-order moments, correlations between times or between different parameters, etc. Some plots of these are shown in later sections.

3 Wi-Fi Data Parameters and Plots

Histograms are recorded both for North America and for Europe, for the Wi-Fi parameters shown in Table 3. The histograms have data for a nine-month period from May 28, 2020, to February 28, 2021. Parameters with hourly data contain data for each of the 24 hours in each of these days. All Wi-Fi data is collected and split into 2.4 GHz and 5 GHz collections. The data is collected over millions of lines.

Table 3. Wi-Fi Parameters

Wi-Fi Throughput (speed)	Daily, 2.4 and 5 GHz bands
Wi-Fi Transmit Rate	Daily, 2.4 and 5 GHz bands
Wi-Fi Throughput / transmit rate	Daily, 2.4 and 5 GHz bands
Wi-Fi Congestion	Daily and max hour, 2.4 and 5 GHz bands
Wi-Fi Interference	Daily and hourly, 2.4 and 5 GHz bands
Wi-Fi Traffic	Daily and hourly, upstream and downstream, 2.4 and 5 GHz bands
Wi-Fi Latency	Daily, 2.4 and 5 GHz bands

3.1 Wi-Fi Throughput

Wi-Fi throughput is measured periodically, as often as every 15 minutes, by an active probe "speed test" between the Access Point (AP) to each station. The agent on the Wi-Fi Access Point (AP) measures Wi-Fi throughput using active probing to estimate the capacity of a Wi-Fi link by stimulating the network with injected traffic and collecting performance statistics.

The throughput reported here is an aggregate interface measurement over all stations measured. Data is collected at intervals throughout a day, and the median throughput of all measurements is plotted or the particular geographic region over all service provider links.

Wi-Fi throughput is the measured achievable data rate with no congestion but including interference from other Wi-Fi BSSs. Throughput is only measured when the link congestion (see Section 3.3 for congestion definition) is zero so that no station associated to the same BSS is producing traffic. The throughput includes the effects of interference.

The histograms of Wi-Fi throughput with 100 bins have:

- For 2.4 GHz, 2 Megabits per second (Mbps) span per bin with a maximum value of 200 Mbps.
- For 5 GHz, 10 Mbps span per bin with a maximum value of 1000 Mbps.

3.1.1 North America Throughput

Figure 4. presents the CDF of throughput in North America, averaged across all days for the recorded time period. It shows separate curves for 5 GHz and 2.4 GHz bands.

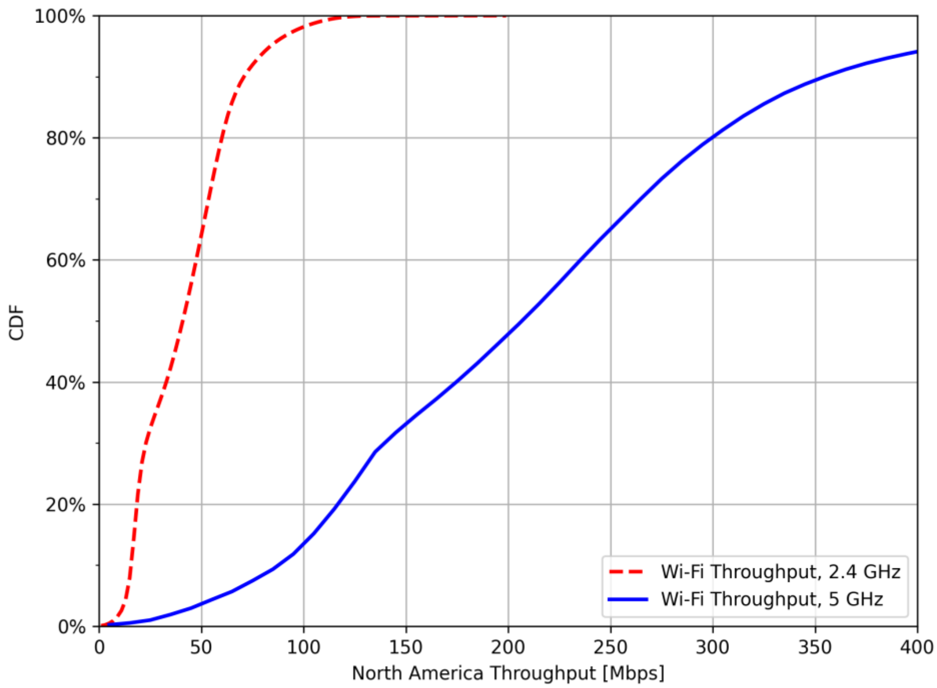

Figure 4. North America, Wi-Fi Throughput CDF for 5 GHz and 2.4 GHz.

3.1.2 Europe Throughput

Figure 5 presents the CDF of throughput in Europe for the recorded time period. It shows separate curves for 5 GHz and 2.4 GHz bands .

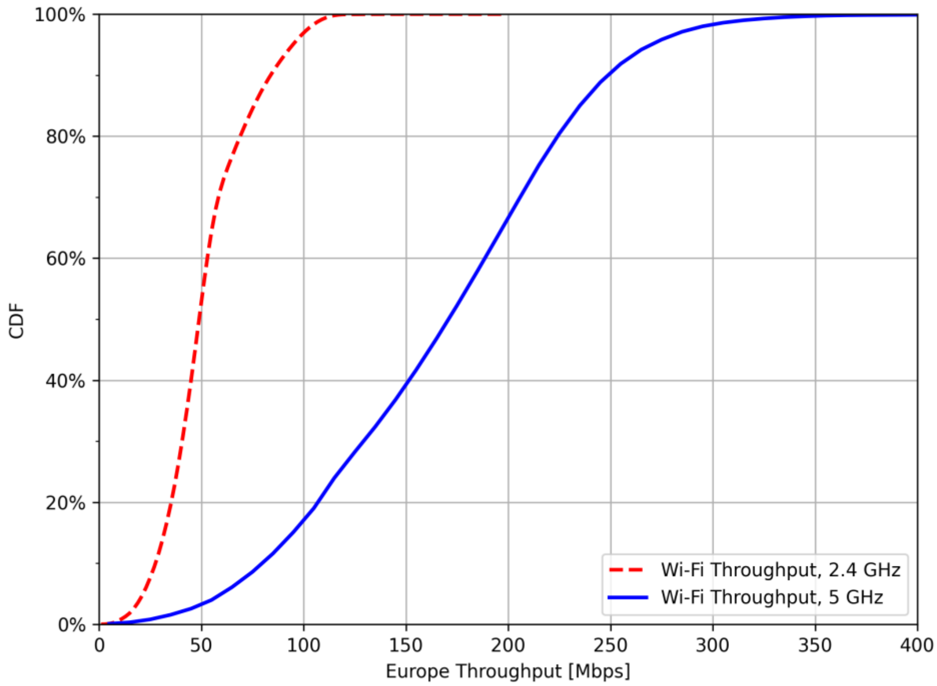

Figure 5. Europe, Wi-Fi Throughput CDF for 5 GHz and 2.4 GHz.

Figure 6 shows the daily trend in the 5% worst case or busy-hour throughput in Europe, for 5 GHz and 2.4 GHz bands.

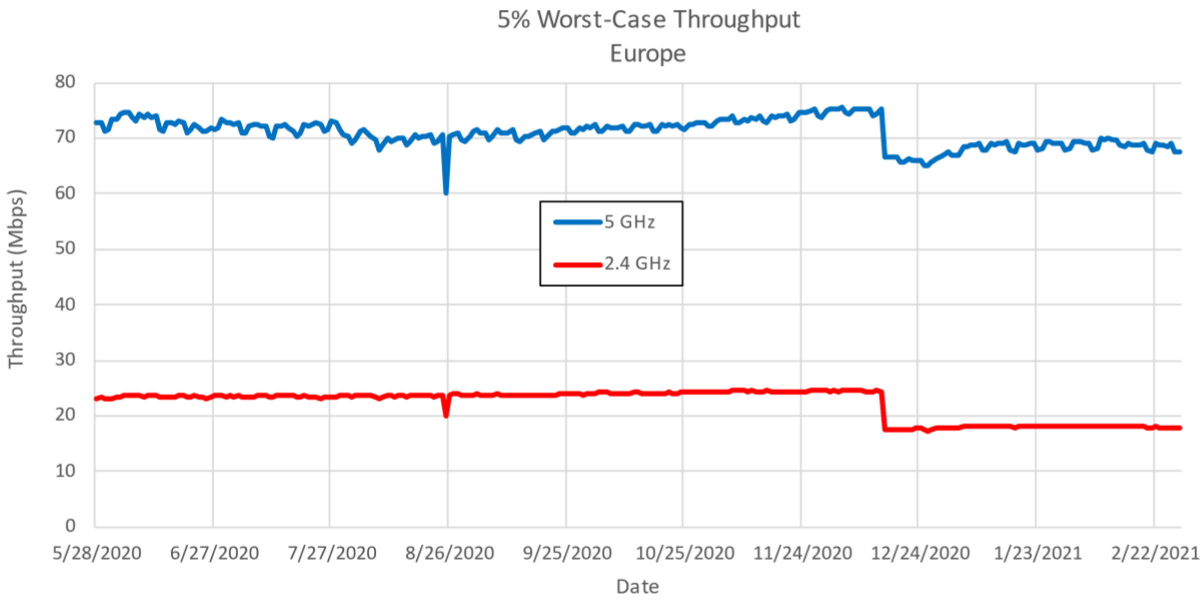

Figure 6. Europe, 5% Worst-Case Wi-Fi Daily Throughput for 5 GHz and 2.4 GHz.

3.2 Wi-Fi Transmit Rate and Throughput to Transmit Rate Ratio

Wi-Fi transmit rate is the theoretical maximum data rate, as determined by the Modulation and Coding Scheme (MCS), the channel bandwidth, guard interval, and the number of spatial streams.

The Wi-Fi transmit rate is typically collected at each station every 5 seconds. Every 15 minutes an average of the samples from all stations is uploaded and collected.

Each day the transmit rate samples are used to build a transmit rate average, in Megabits per second (Mbps) for the day. Transmit rate can be low if the stations do not have traffic.

The histograms of Wi-Fi transmit rate with 100 bins have:

- For 2.4 GHz, 4 Mbps span per bin with a maximum value of 400 Mbps.
- For 5 GHz, 20 Mbps span per bin with a maximum value of 2000 Mbps.

Wi-Fi throughput to transmit rate ratio is the average of Wi-Fi throughput divided by the Wi-Fi transmit rate (range from 0 - 100%) calculated and recorded on a daily basis.

Wi-Fi throughput to transmit rate ratio includes the effects spectrum sharing with other APs and other users, as well as other factors such as overhead. For example, if two APs are sharing the same channel equally, then the highest throughput / transmit rate they could both achieve is 50%. Wi-Fi throughput / transmit rate further decreases with increasing congestion, interference and overhead. Throughput / transmit rate relates to what a user now gets relative to having unlimited spectrum.

The histogram values for Wi-Fi Throughput / transmit rate span 1% throughput / transmit rate per bin, for 100 bins with maximum value of 100%.

3.2.1 North America Wi-Fi Throughput to Transmit Rate Ratio Histogram

Figure 7 presents the average throughput / transmit rate percent histogram in North America for the recorded time period. It shows separate curves for 5 GHz and 2.4 GHz bands.

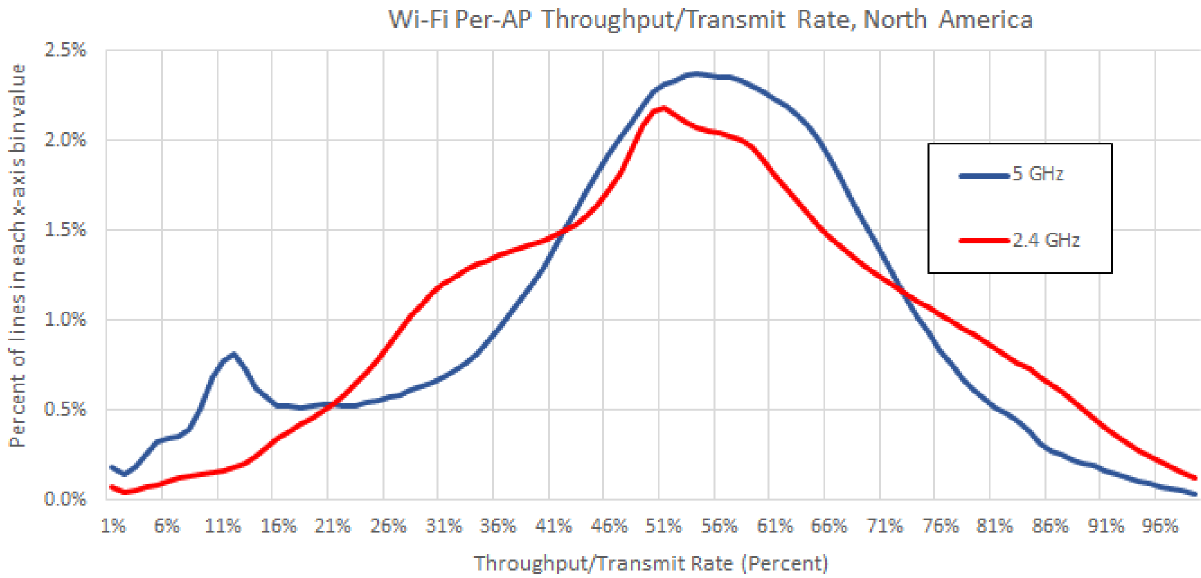

Figure 7. North America, Wi-Fi Throughput / transmit rate Histogram for 5 GHz and 2.4 GHz.

3.2.2 Europe Wi-Fi Throughput to Transmit Rate Ratio Histogram

Figure 8 presents the average throughput / transmit rate percent histogram in Europe for the recorded time period. It shows separate curves for 5 GHz and 2.4 GHz bands.

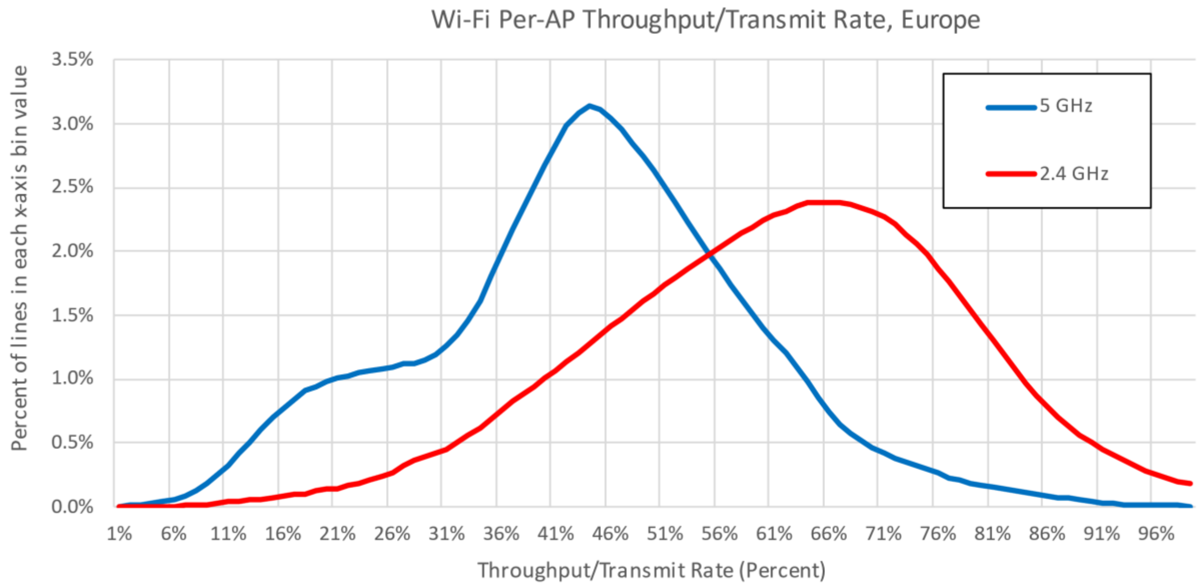

Figure 8. Europe, Wi-Fi Throughput / transmit rate Histogram for 5 GHz and 2.4 GHz.

3.3 Wi-Fi Congestion

Wi-Fi drivers periodically report if there is high congestion at the BSS. These metrics are summarized in a daily congestion detection metric that provides an indicator of the level of congestion. Wi-Fi congestion is an estimate of how much airtime is used by stations associated to this BSS, relative to how much airtime is unused. For a given associated station, congestion occurs due to Wi-Fi frames arriving at the BSS from other stations that are also associated to this BSS; these frames are addressed to the MAC address of this BSS. Congestion for a BSS is then the median across all stations.

The histogram values for this metric have two bins, one is if high congestion that may cause a problem is detected, and the other is no or little congestion detected. Congestion is probed very often in the AP, typically every 5 seconds. High congestion is declared in a 15-minute period if more than 75% of the airtime during the measurement is used by traffic to and from attached stations in at least 10% of the 5-second probe samples. If more than half of the 15-minute periods for that day are declared with high congestion, the link is deemed as highly congested for that day.

Currently the system only presents high levels of congestion, so much so that the customer would call and complain. So, few lines are shown to have high congestion here. Reporting lower levels of congestion is being investigated at this time of writing.

3.3.1 North America Daily Congestion

Figure 9 presents the percent of lines that have experienced high congestion in North America. It shows separate curves for 5 GHz and 2.4 GHz bands.

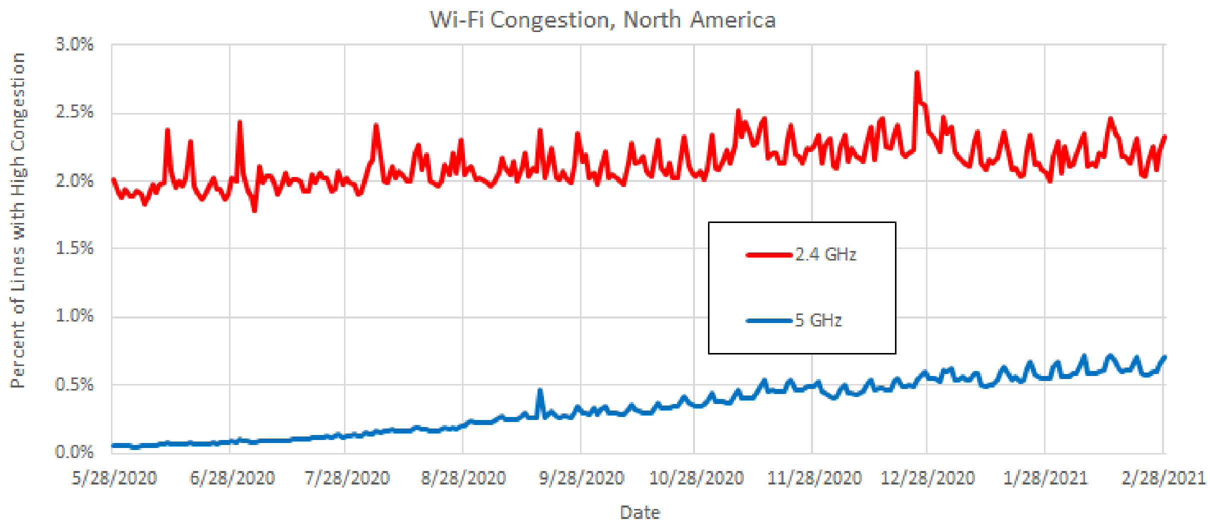

Figure 9. North America, Wi-Fi Daily Congestion for 5 GHz and 2.4 GHz.

3.3.2 Europe Daily Congestion

This figure presents the percent of lines that have experienced high congestion in Europe for the recorded time period. It shows separate curves for 5 GHz and 2.4 GHz bands.

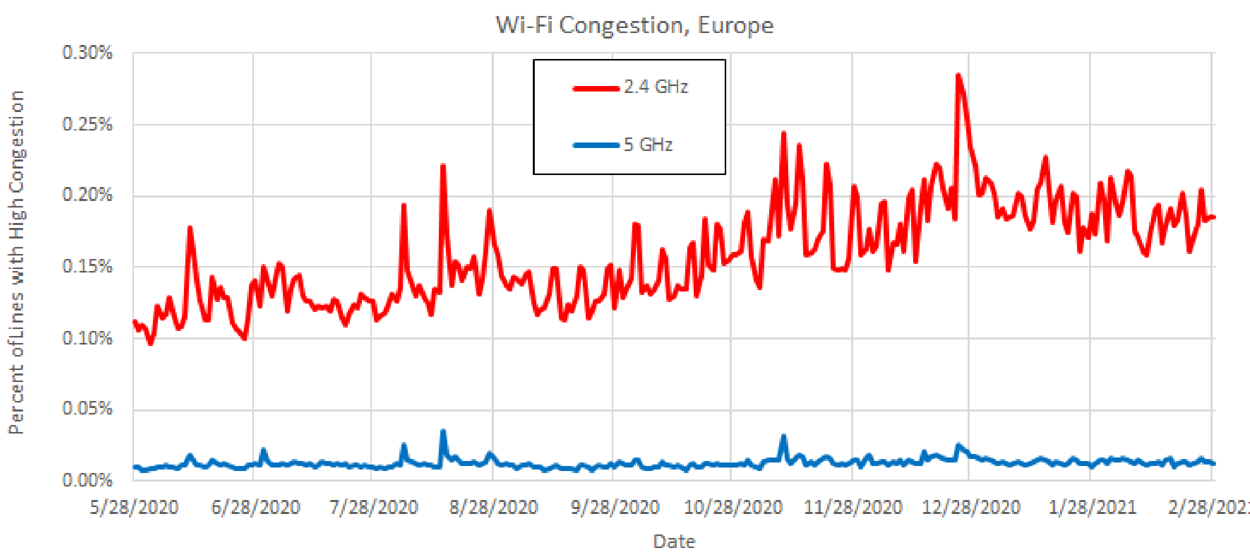

Figure 10. Europe, Wi-Fi Daily Congestion for 5 GHz and 2.4 GHz.

In addition, there is hourly congestion data, and data on CCA Idle which is a measure of the available airtime. At this time of writing, we are still researching the availability and applicability of this data.

3.3.3 Hour with Maximum Congestion

The busy hour has the maximum level of congestion among 24 hours, which can be different for each line. The percent of lines with high congestion in busy hours are plotted in Figure 11 and Figure 12.

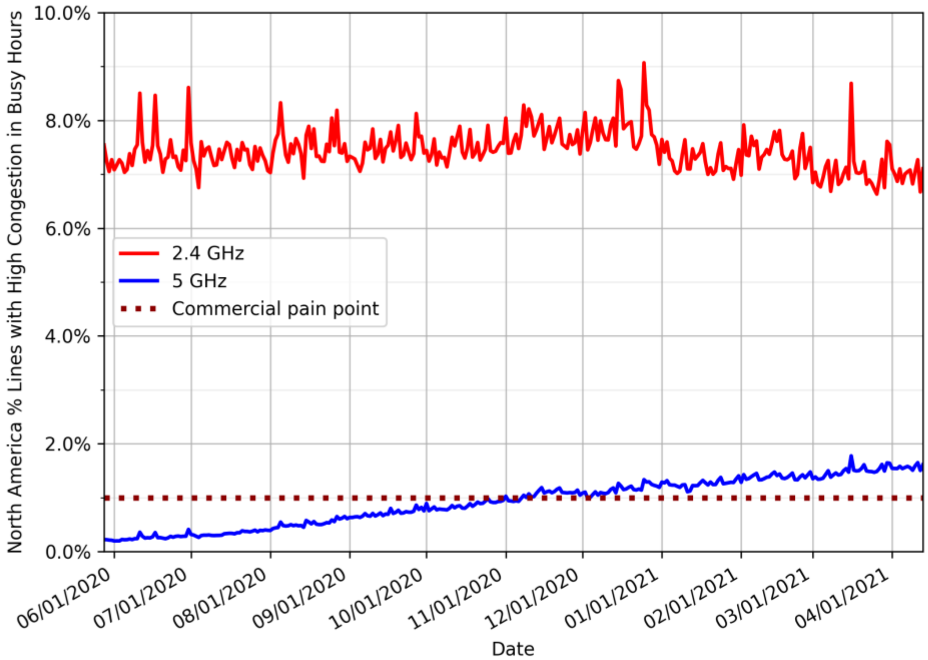

Figure 11. North America, Max Hour Wi-Fi Congestion for 5 GHz and 2.4 GHz.

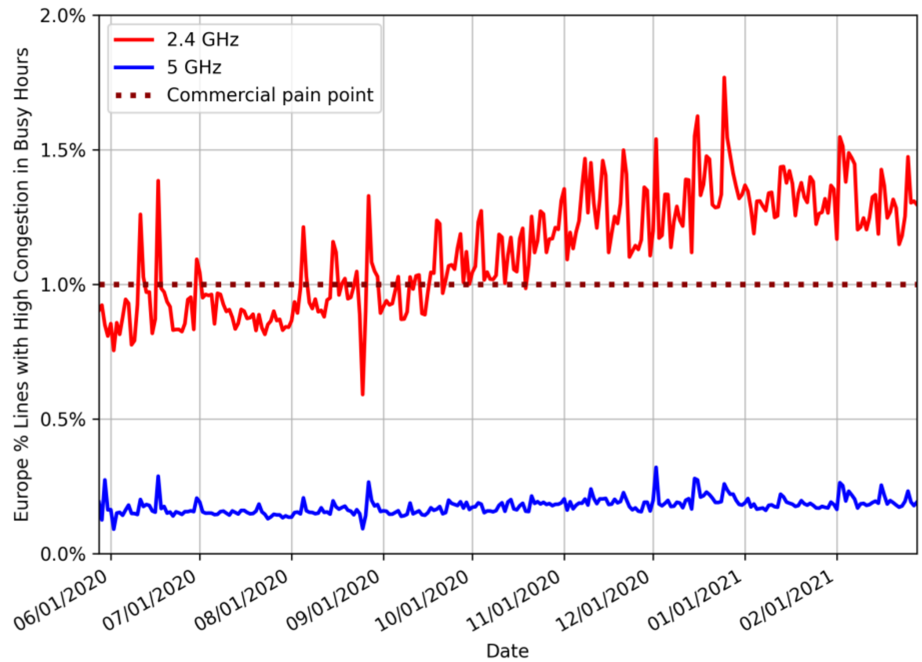

Figure 12. Europe, Max hour Wi-Fi Congestion for 5 GHz and 2.4 GHz.

3.4 Wi-Fi Interference

Wi-Fi interference presents the percent of time that the channel is not available due to interference from other APs and from unassociated stations. Interference is detected if the Clear Channel Assessment (CCA) indicates that the channel is unavailable. Interference can be measured on channels other than the current channel, however this can interrupt the user traffic.

Wi-Fi interference is typically recorded every 5 seconds on a Wi-Fi Access Point, and indicates the percent of time the Wi-Fi Access Point cannot use the channel due to interference from unassociated stations and other APs within each 5 second timeframe as reported by the Wi-Fi driver. Interference data is then aggregated hourly and daily.

The higher the Wi-Fi interference, the more interference seen on the Wi-Fi Access Point.

The histogram values for interference are recorded with histogram bins spanning 1% per bin, for 100 bins with a maximum value of 100%. Daily and hourly histograms are recorded.

3.4.1 North America Daily Interference

Figure 13 presents the CDF of North America daily interference, plotting ten bins, each bin spanning 10% of interference so that bin 1 represents the percent of lines with 0 to 10% interference, bin 2 represents the percent of lines with 0 to 20% interference, etc. Figure 13 shows data from both 5 GHz and 2.4 GHz bands.

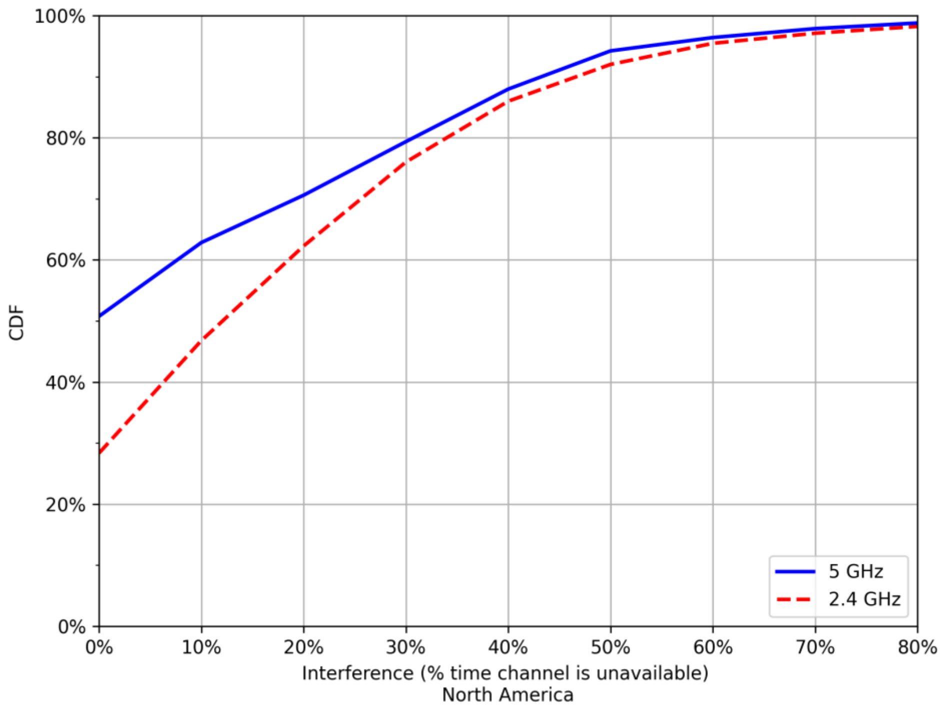

Figure 13. North America, CDF of Wi-Fi Interference for 5 GHz and 2.4 GHz.

3.4.2 Hourly Interference

The mean hourly interference in 5GHz bands in North America and Europe is presented along with mean hourly traffic in Figure 28 and Figure 29 in Section 5.3. The mean is computed as $E[x] = sum\ (x_i\ Pr(x_i))$ where $Pr(x_i)$ is given by the histogram bin values. The means were further averaged across all days in that time period.

3.4.3 Europe Daily Interference

Figure 14 plots the CDF of Wi-Fi interference in Europe in both 5 GHz and 2.4 GHz bands.

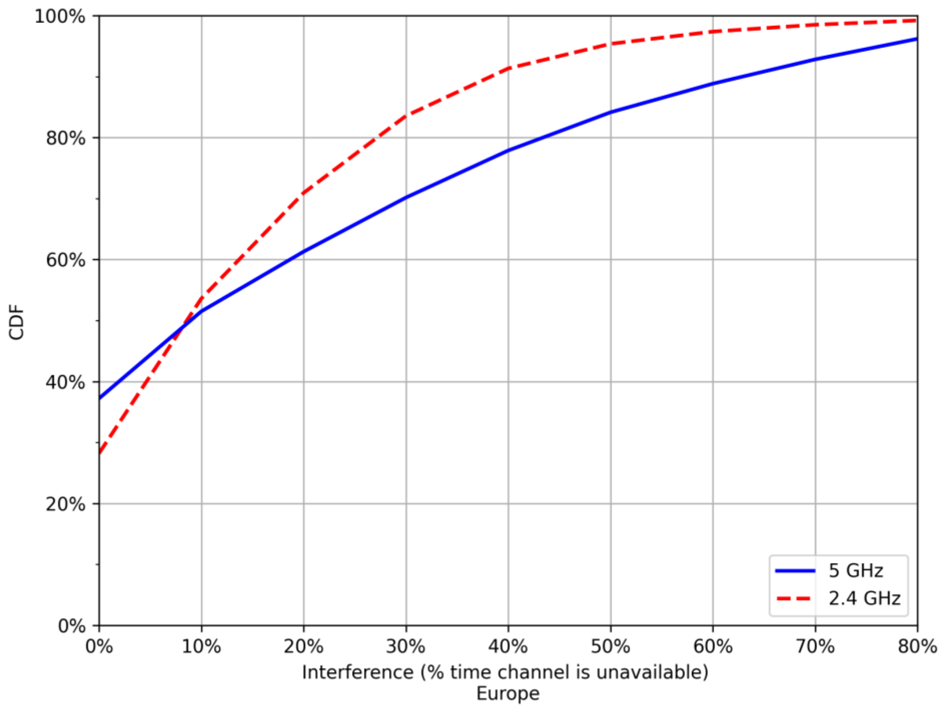

Figure 14. Europe, CDF of Wi-Fi Interference for 5 GHz and 2.4 GHz.

3.5 Wi-Fi Traffic

Wi-Fi traffic is measured in Megabytes (MBytes) of total data over a time period and is measured both for upstream and downstream traffic in 2.4 GHz and 5 GHz bands. Wi-Fi traffic is recorded daily and hourly. The Wi-Fi traffic is measured at each Wi-Fi Access Point as the sum of all the stations traffic within a day or an hour.

The histograms for Wi-Fi traffic have 100 bins, with:

- Daily uplink for 2.4 GHz and 5 GHz are collected in 1 GByte bins with a maximum value 100 GBytes.
- Daily downlink for 2.4 GHz and 5 GHz are collected in 2 GByte bins with a maximum value 200 GBytes.
- Hourly uplink for 2.4 GHz are collected in 50 MBytes bins with a maximum value 5 GBytes.
- Hourly downlink for 2.4 GHz are collected in 100 MBytes bins with a maximum value 10 GBytes.
- Hourly uplink for 5 GHz are collected in 100 MBytes bins with a maximum value 10 GBytes.
- Hourly downlink for 5 GHz are collected in 200 MBytes bins with a maximum value 20 GBytes.

3.5.1 Daily Wi-Fi Traffic

Daily Wi-Fi traffic is plotted along with daily broadband traffic in Figure 20 - Figure 23 in Section 5.1.

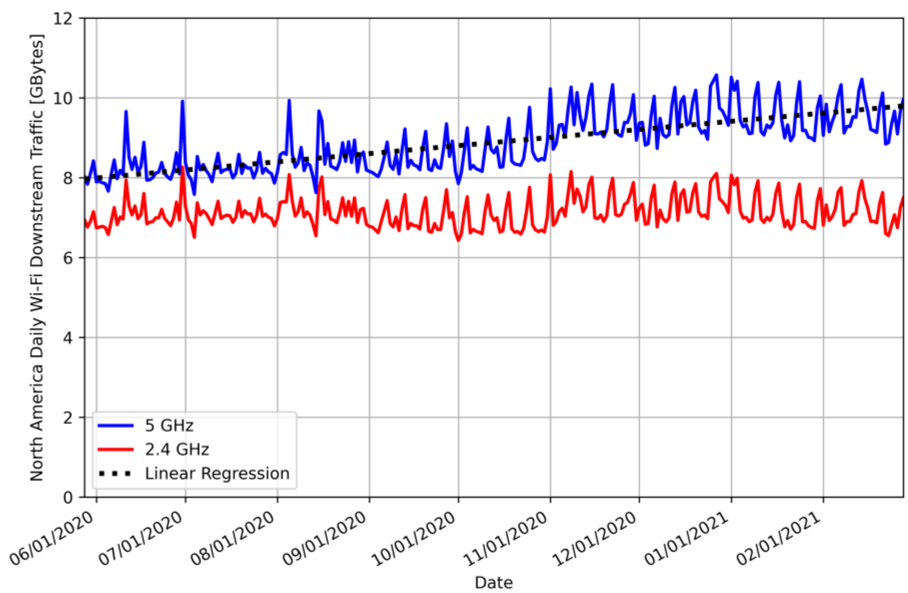

Figure. North America, Average Daily Wi-Fi Traffic.

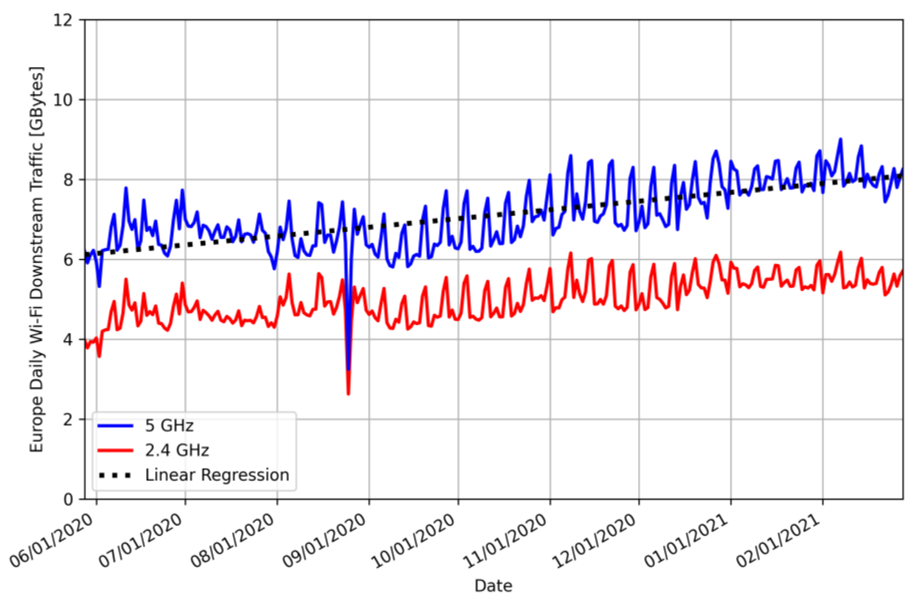

Figure. Europe, Average Daily Wi-Fi Traffic.

3.5.2 Hourly Wi-Fi Traffic

Figure 15 and Figure 16 presents the mean hourly traffic in North America and Europe for the recorded time period. These shows separate curves for 5 GHz and 2.4 GHz bands and for upstream and downstream traffic. On the plot, Hour "0" is midnight, Hour 1 is 1:00 AM, etc.

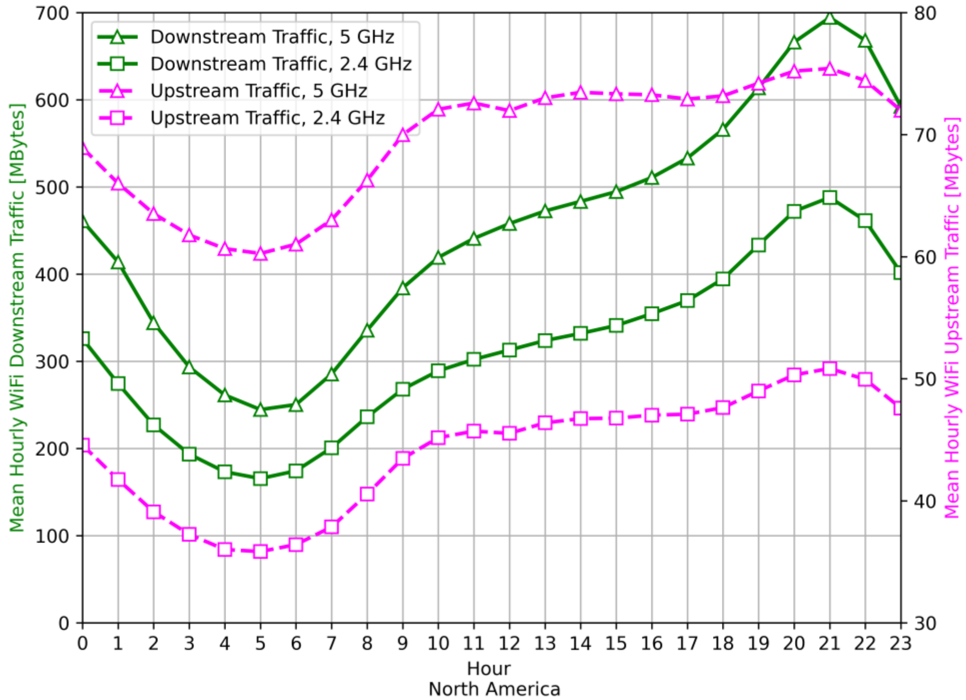

Figure 15. North America, Wi-Fi Hourly Traffic for 5 GHz and 2.4 GHz.

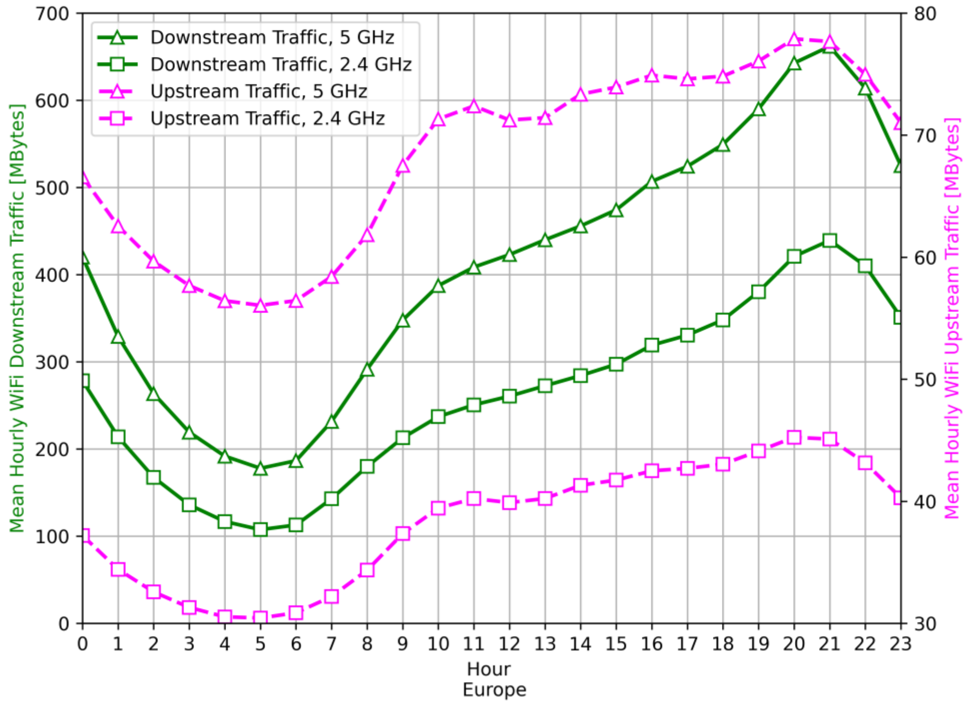

Figure 16. Europe, Wi-Fi Hourly Traffic for 5 GHz and 2.4 GHz.

3.6 Wi-Fi Latency

Wi-Fi latency is measured and recorded as a daily average in milliseconds, using round-trip latency measurements between the Wi-Fi access point and all the associated stations.

Latency histograms have 100 bins, with bin spacing 5 milliseconds, and maximum value of 500 milliseconds.

Wi-Fi Latency in North America and Europe is plotted along with broadband latency in Figure 31 and Figure 32 in Section 5.5.

4 BROADBAND DATA PARAMETERS AND PLOTS

Histograms are recorded both for North America and for Europe, for the broadband parameters shown in Table 4. The histograms have data for each day in a nine-month period from May 28, 2020, to February 28, 2021. Parameters with hourly data contain data for each of the 24 hours in each of these days. The data is collected over millions of lines.

Table 4. Broadband Parameters

Broadband Traffic	Daily and hourly, upstream and downstream
Broadband Throughput (speed)	Daily, upstream and downstream
Broadband Latency	Daily

4.1 BROADBAND TRAFFIC

Broadband traffic is measured daily (average) in Gigabytes (GBytes) for upstream and downstream traffic. The daily traffic is measured with a single metric for the day. The hourly traffic is measured the same but on an hourly basis.

The histograms for broadband traffic are recorded with 100 bins, with:

- Daily upstream in 1 GByte bins with maximum value 100 GBytes.
- Daily downstream in 2 GBytes bins with maximum value 200 GBytes.
- Hourly upstream in 100 MBytes bins with maximum value 10 GBytes.
- Hourly downstream in 200 MBytes bins with maximum value 20 GBytes.

Daily broadband traffic is plotted along with daily Wi-Fi traffic in Figure 20 - Figure 23 in Section 5.1.

Hourly broadband traffic is plotted along with hourly Wi-Fi traffic in Figure 24 - Figure 27 in Section 5.2.

4.2 BROADBAND THROUGHPUT (SPEED)

Broadband throughput (speed) is measured as the average daily throughput for upstream and downstream in Megabits per second (Mbps). The daily traffic is measured by speed tests from the Wi-Fi access point to a network-located test server and is averaged into a single metric for the day.

The histograms for broadband throughput are recorded daily with 100 bins, with:

- Upstream has bins spaced at 5 Mbps with a maximum value of 500 Mbps
- Downstream has bins spaced at 10 Mbps with a maximum value of 1 Gbps

4.2.1 North America Broadband Throughput Histogram

Figure 17 presents the CDF of throughput averaged over all days in the recorded time period in North America. It shows separate curves for upstream and downstream traffic, and Wi-Fi throughput with 2.4 and 5 GHz.

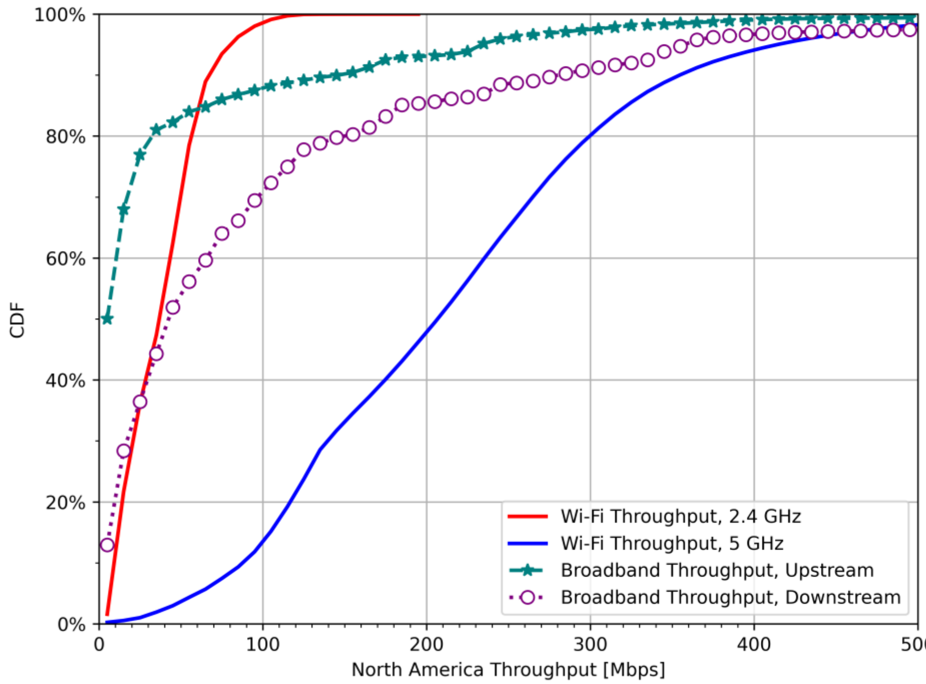

Figure 17. North America. Broadband Throughput CDF, upstream and downstream.

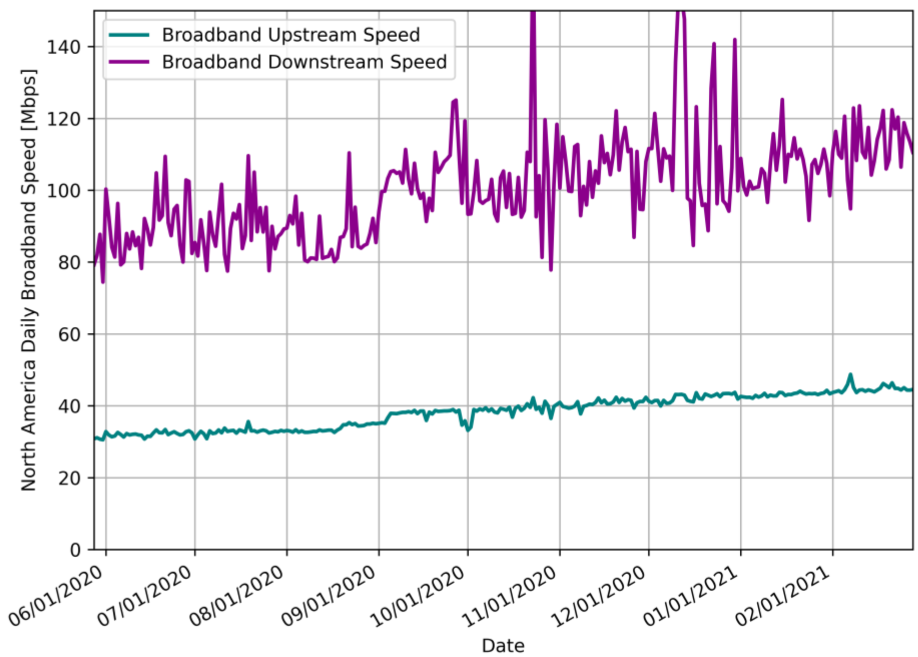

Figure 18. North America, Broadband Throughput (Speed), Upstream and Downstream.

4.2.2 Europe Broadband Throughput

Figure 19 presents the CDF of throughput averaged over all days in the recorded time period in Europe. It shows separate curves for upstream and downstream traffic, and Wi-Fi throughput with 2.4 and 5 GHz. European broadband throughput data currently presents mostly copper connections. More fiber connections are anticipated over the coming year.

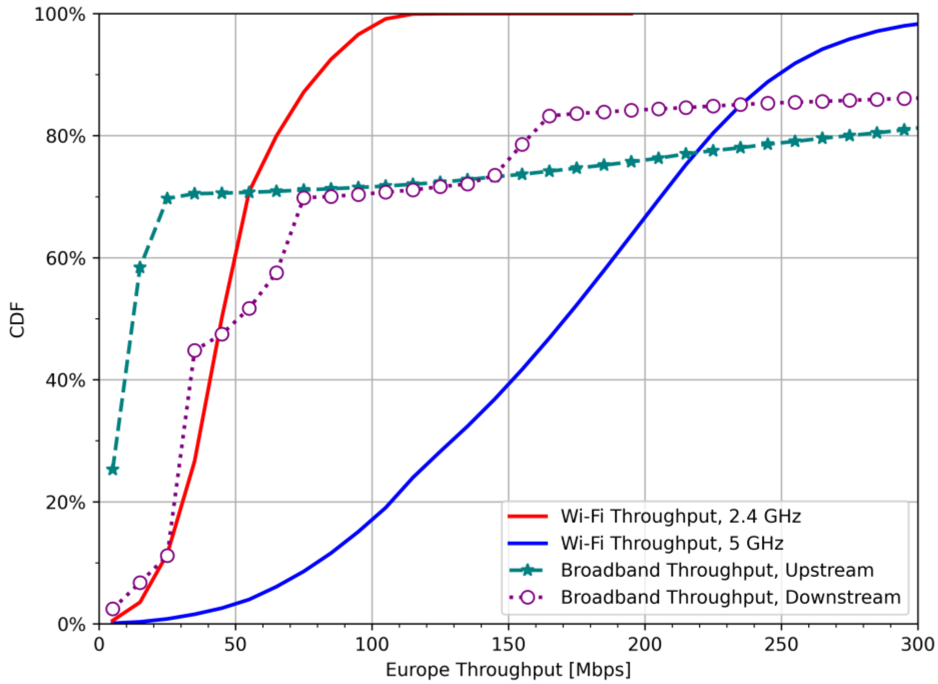

Figure 19. Europe. Broadband Throughput CDF, upstream and downstream.

4.3 Broadband Latency

Broadband latency is measured and recorded as a daily average in milliseconds, using round-trip latency measurements between the Wi-Fi access point and a network-located broadband speed test server.

Latency histograms have 100 bins, with bin spacing 10 milliseconds, and maximum value of 1000 milliseconds.

Broadband Latency in North America and Europe is plotted along with Wi-Fi latency in Figure 31 and Figure 32 in Section 5.5.

5 Combined Plots

This section shows some plots that combine related parameters.

5.1 Wi-Fi and Broadband Daily Traffic

Figure 20 - Figure 23 plot both Wi-Fi and broadband traffic. It can be seen that the average broadband traffic is approximately the sum of the average Wi-Fi traffic in 2.4 plus 5 GHz bands.

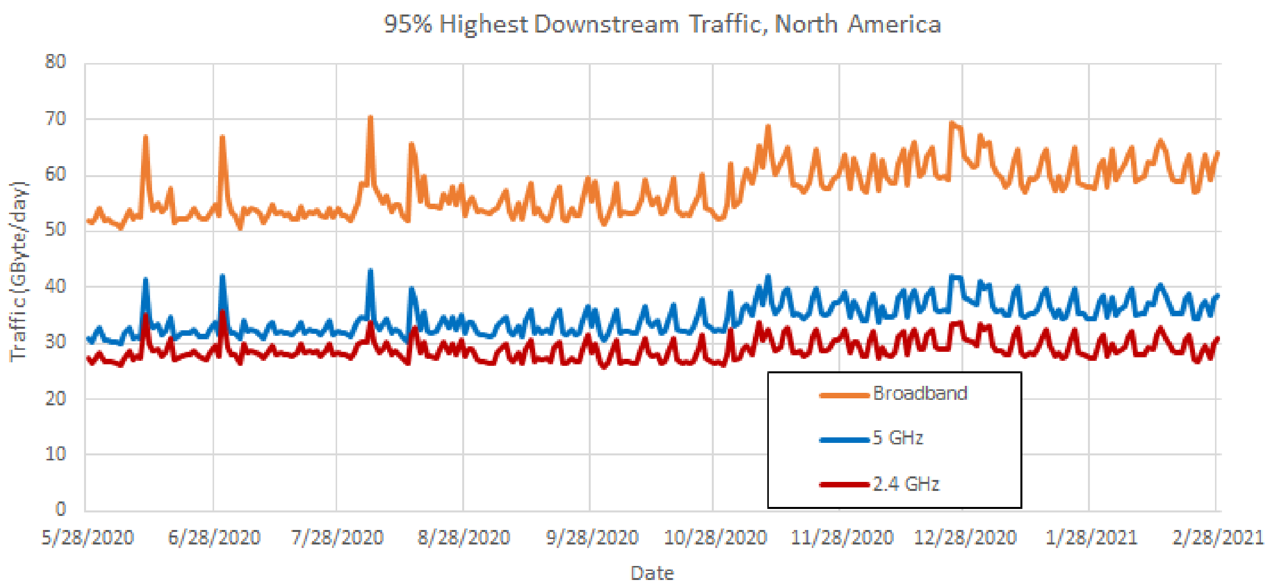

Figure 20. North America, Downstream Daily Broadband and Wi-Fi Traffic.

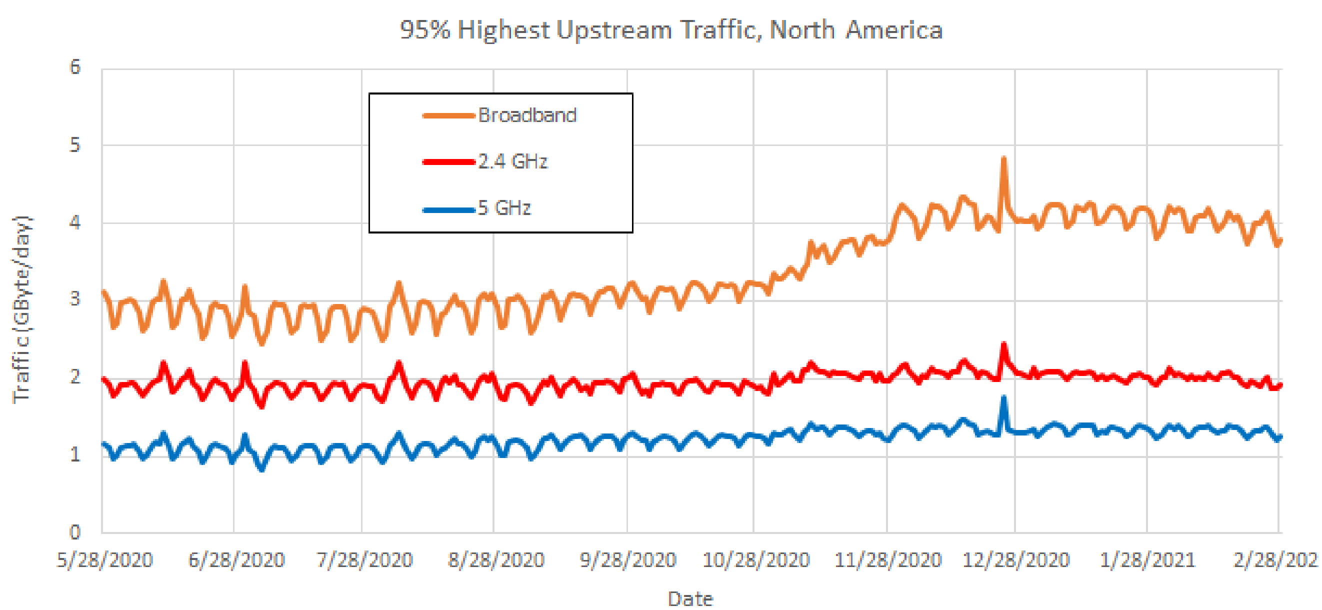

Figure 21. North America, Upstream Daily Broadband and Wi-Fi Traffic.

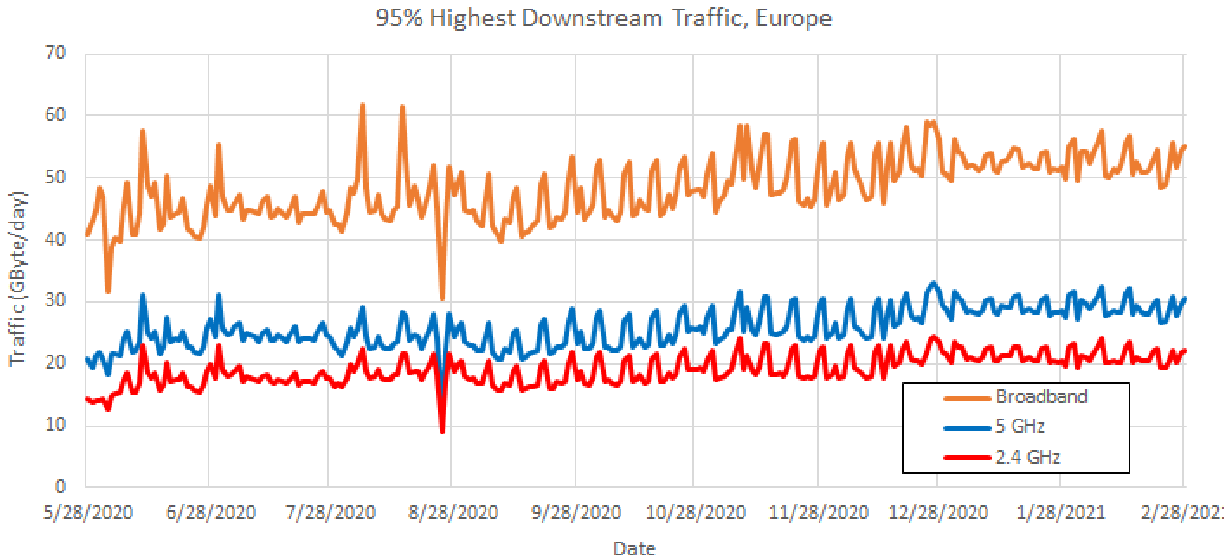

Figure 22. Europe, Downstream Daily Broadband and Wi-Fi Traffic.

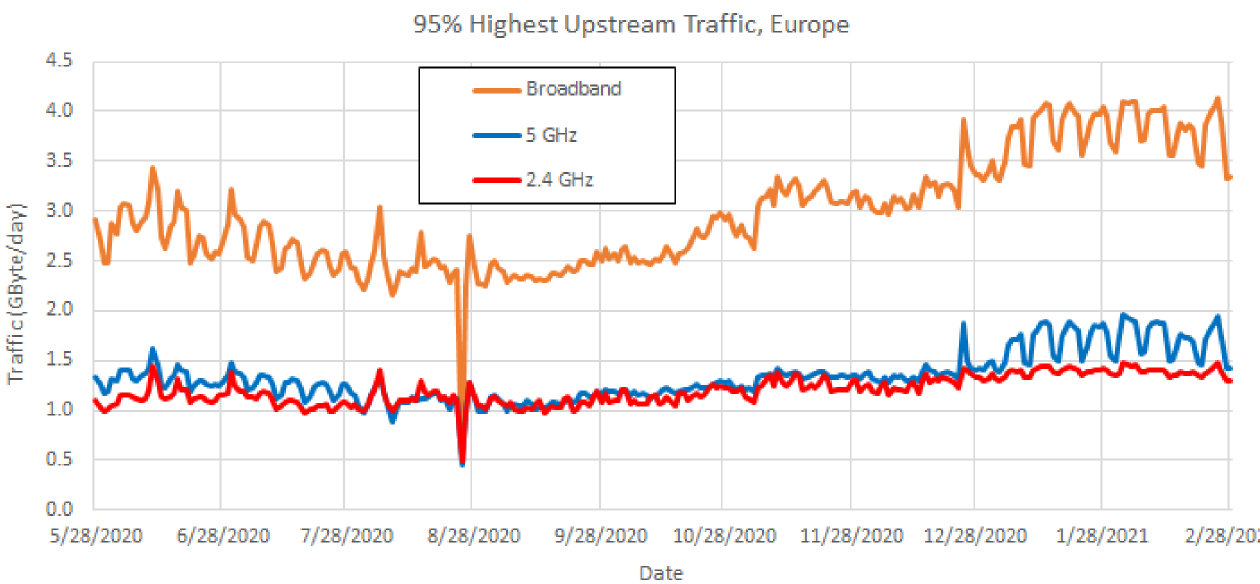

Figure 23. Europe, Upstream Daily Broadband and Wi-Fi Traffic.

5.2 Hourly Broadband and Wi-Fi Traffic

Figure 24 and Figure 25 compare broadband and Wi-Fi hourly traffic in North America by presenting the mean upstream and downstream traffic for each hour, averaged over all days for the recorded time period. These show separate curves for Wi-Fi traffic in 2.4 and 5 GHz bands.

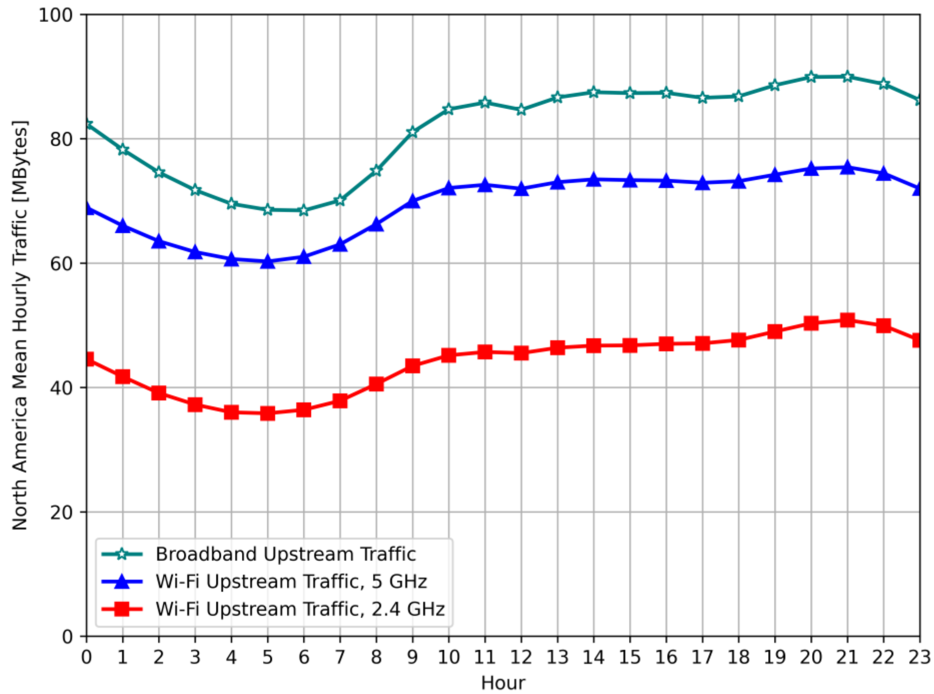

Figure 24. North America, Upstream Hourly Broadband and Wi-Fi Traffic.

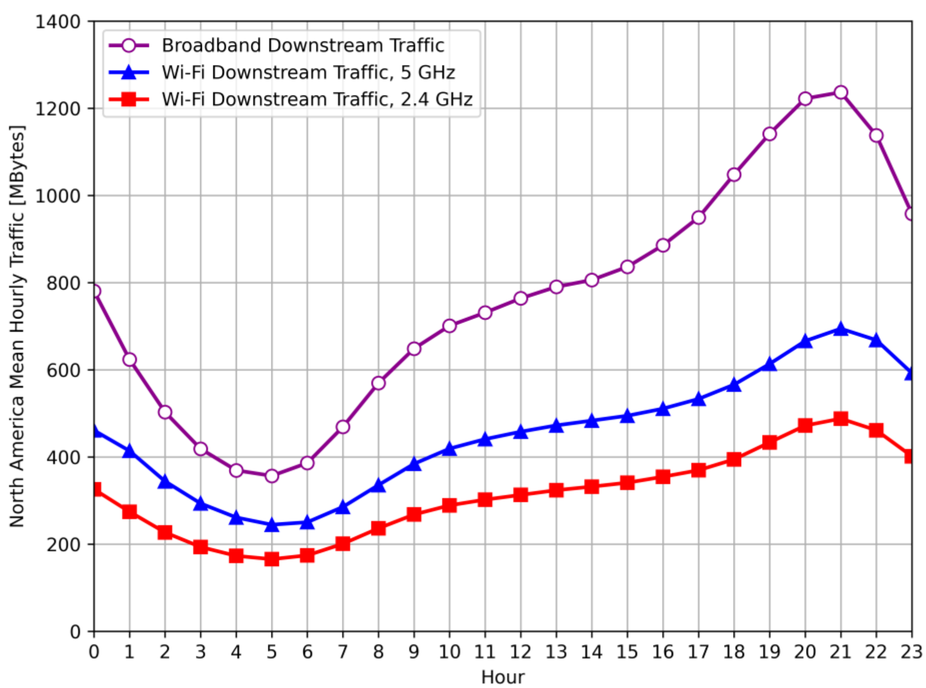

Figure 25. North America, Downstream Hourly Broadband and Wi-Fi Traffic.

Figure 26 and Figure 27 compare broadband and Wi-Fi hourly traffic in Europe by presenting the mean or average hourly upstream and downstream traffic in Europe for each hour, averaged over all days for the recorded time period.

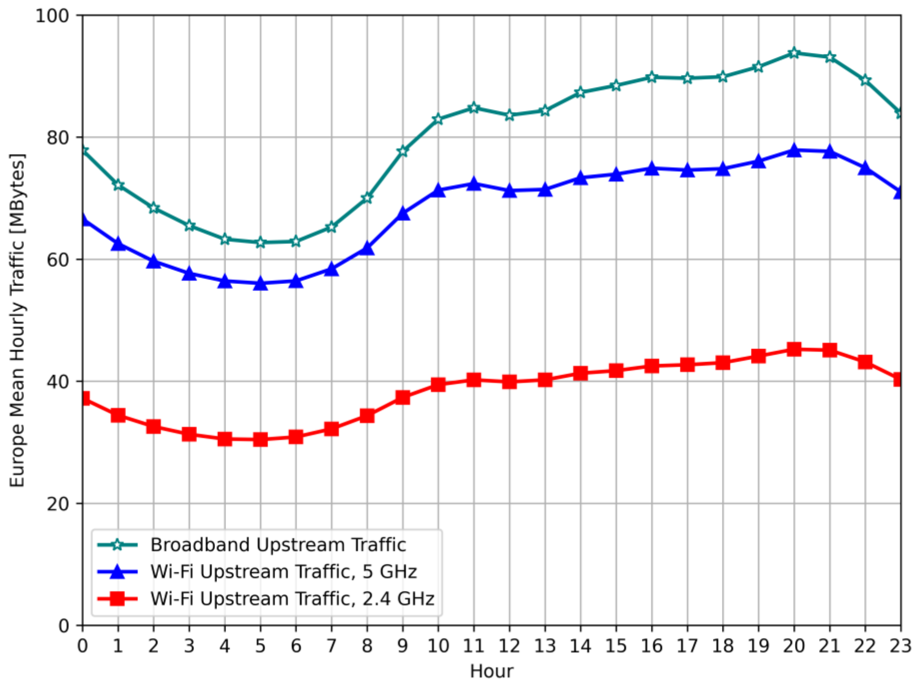

Figure 26. Europe, Hourly Upstream Broadband and Wi-Fi Traffic.

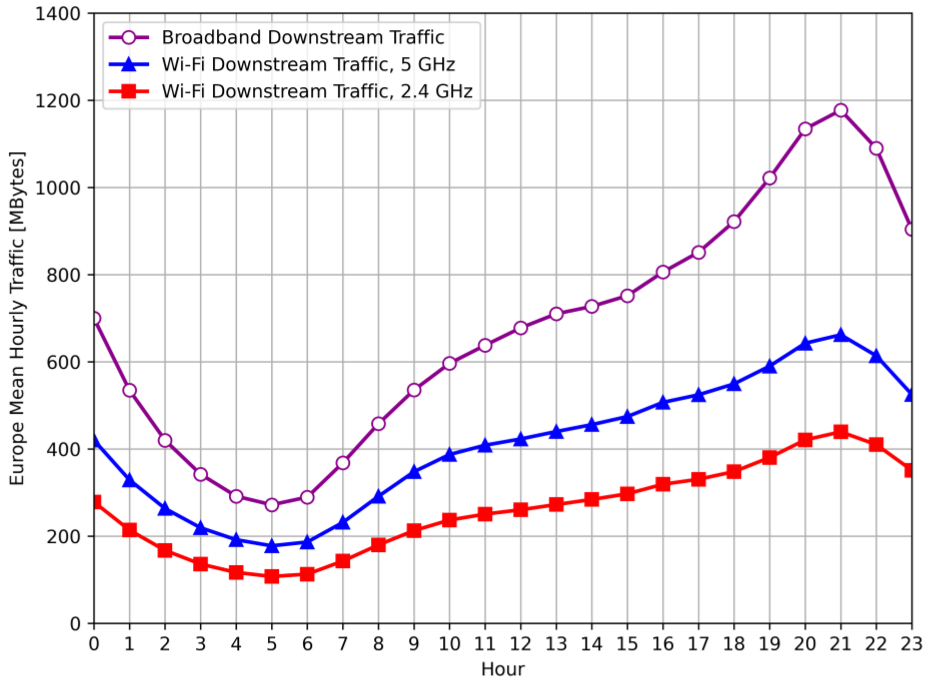

Figure 27. Europe, Hourly Downstream Broadband and Wi-Fi Traffic.

5.3 HOURLY TRAFFIC AND INTERFERENCE

Figure 28 and Figure 29 show hourly traffic and interference in the 5 GHz band in North America and Europe. These shows a positive correlation between downlink traffic and interference score over the time of day (the left and right y-axes correspond to downstream traffic and interference, respectively.). Quantifying correlations between these and other parameters can be the subject of future work.

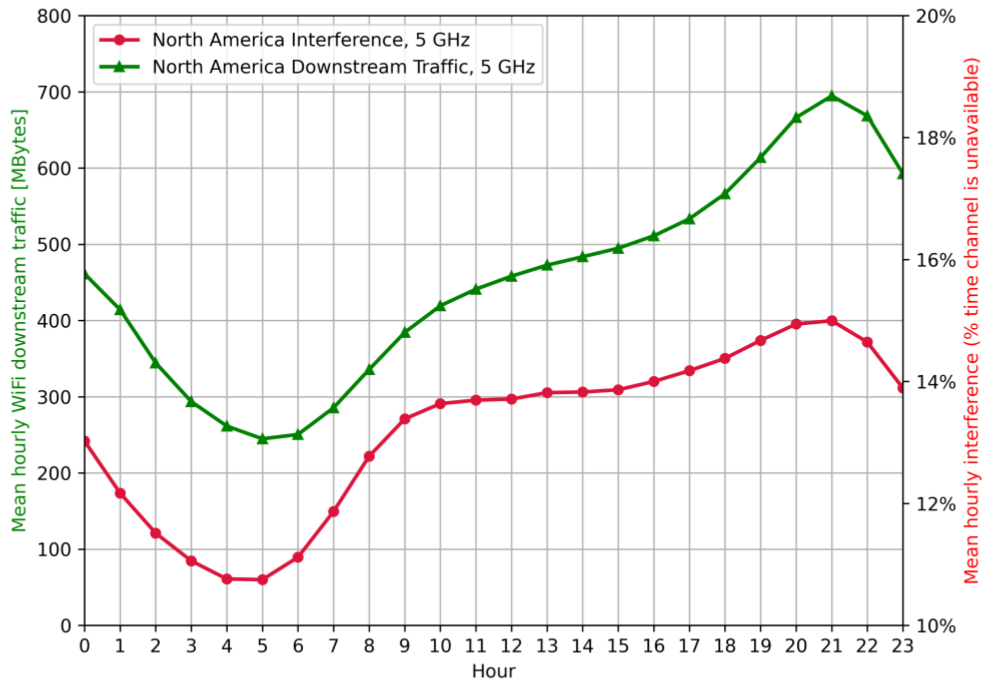

Figure 28. North America, Wi-Fi Hourly Downstream Traffic and Interference.

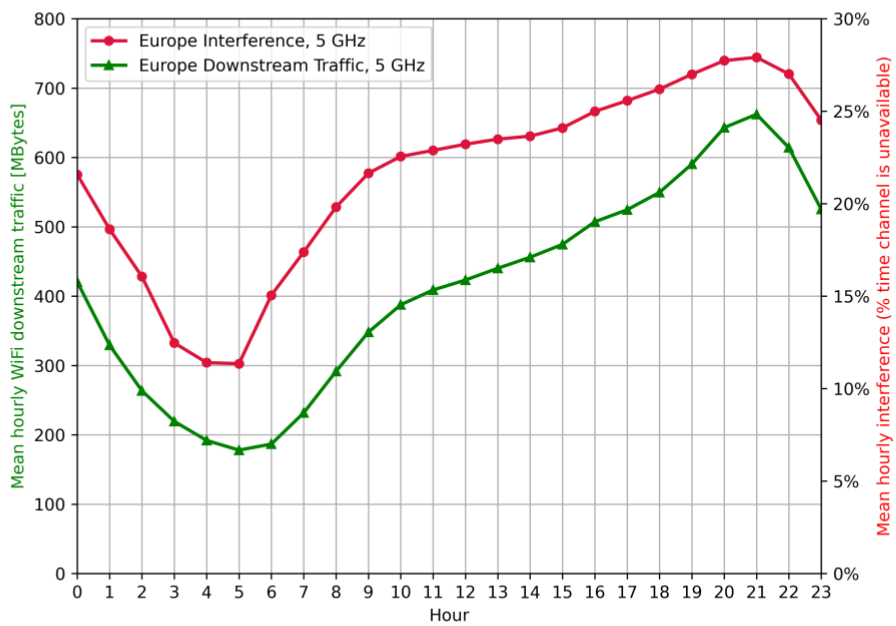

Figure 29. Europe, Wi-Fi Hourly Downstream Traffic and Interference.

5.4 WI-FI TRAFFIC AND CONGESTION

Figure 30 shows North American downstream traffic and congestion in the 5 GHz band. Much of the variation is due to weekly effects. The figure shows that both traffic and congestion are increasing over time.

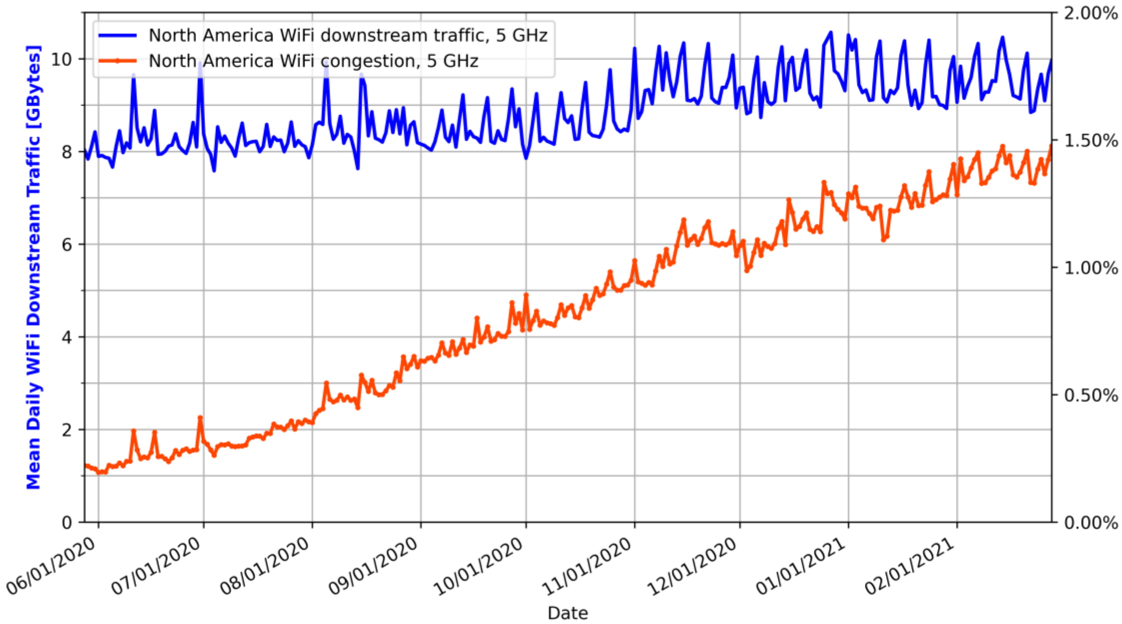

Figure 30. North America Downstream Traffic & Congestion.

5.5 BROADBAND AND WI-FI LATENCY

Figure 31 and Figure 32 show the daily average broadband and Wi-Fi latency on lines in North America and Europe over the time period.

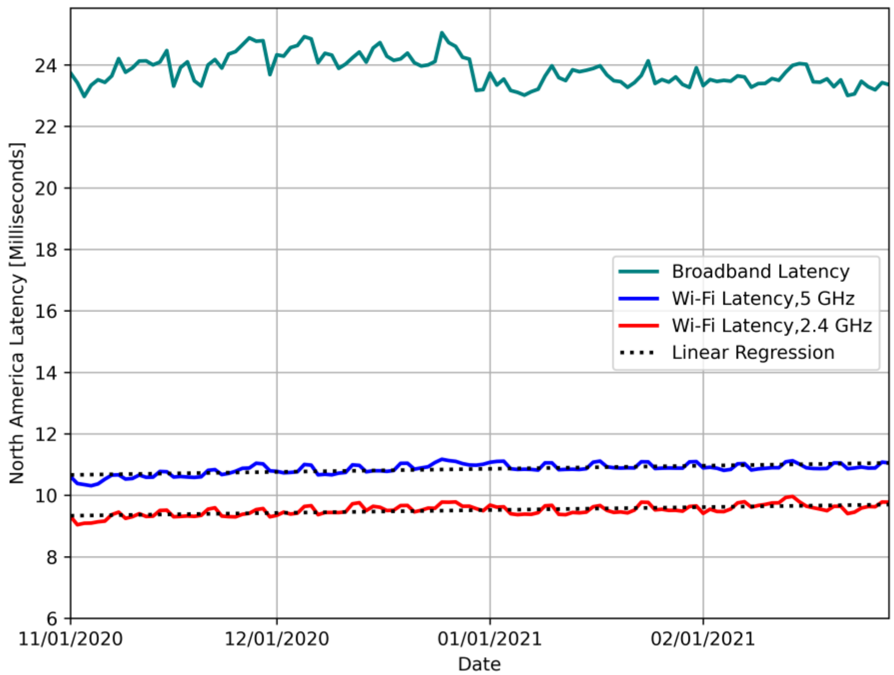

Figure 31. North America, Daily Broadband and Wi-Fi Latency.

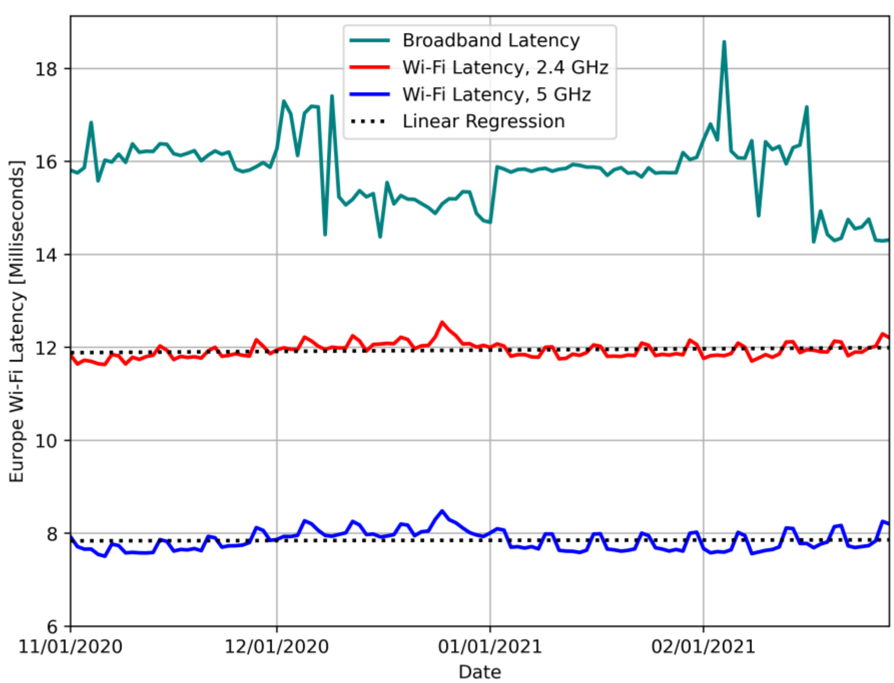

Figure 32. Europe, Daily Broadband and Wi-Fi Latency.

5.6 Interference Statistics

Figure 33 shows the average (or mean) Wi-Fi interference in Europe in the 2.4 GHz and 5 GHz bands. Here, the mean is computed as $E[x] = sum\ (x_i Pr(x_i))$ where $Pr(x_i)$ is given by the histogram bin values.

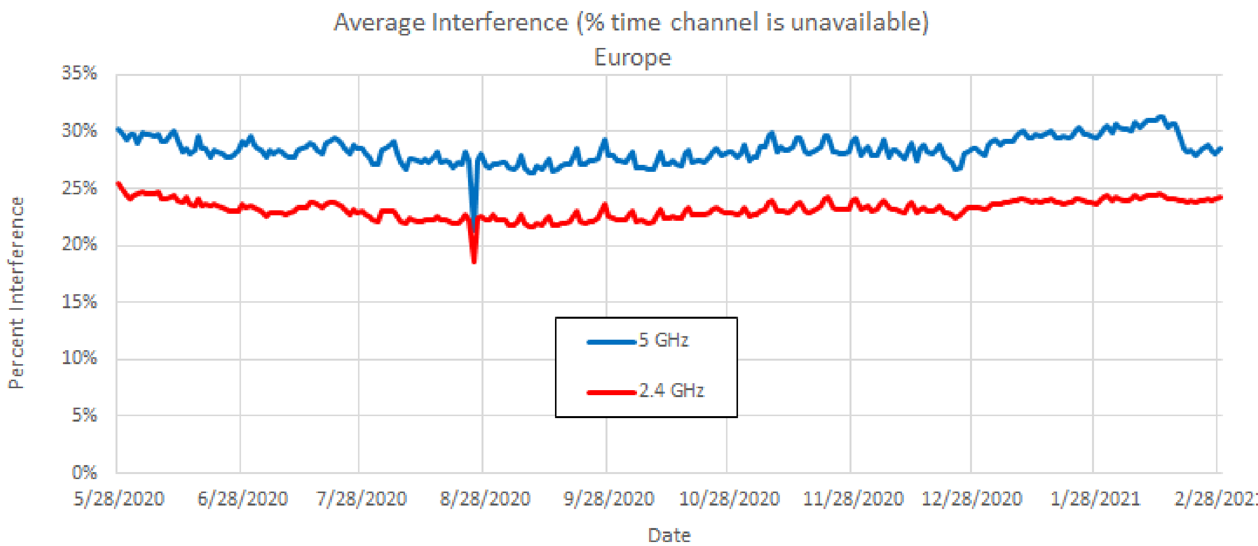

Figure 33. Europe, Average or Mean Wi-Fi Interference, 5 GHz and 2.4 GHz.

Figure 34 shows the median of the Wi-Fi interference in Europe in the 2.4 GHz and 5 GHz bands. The median is the point at which 50% of the interference is below this point, and 50% is above, as computed from the histogram.

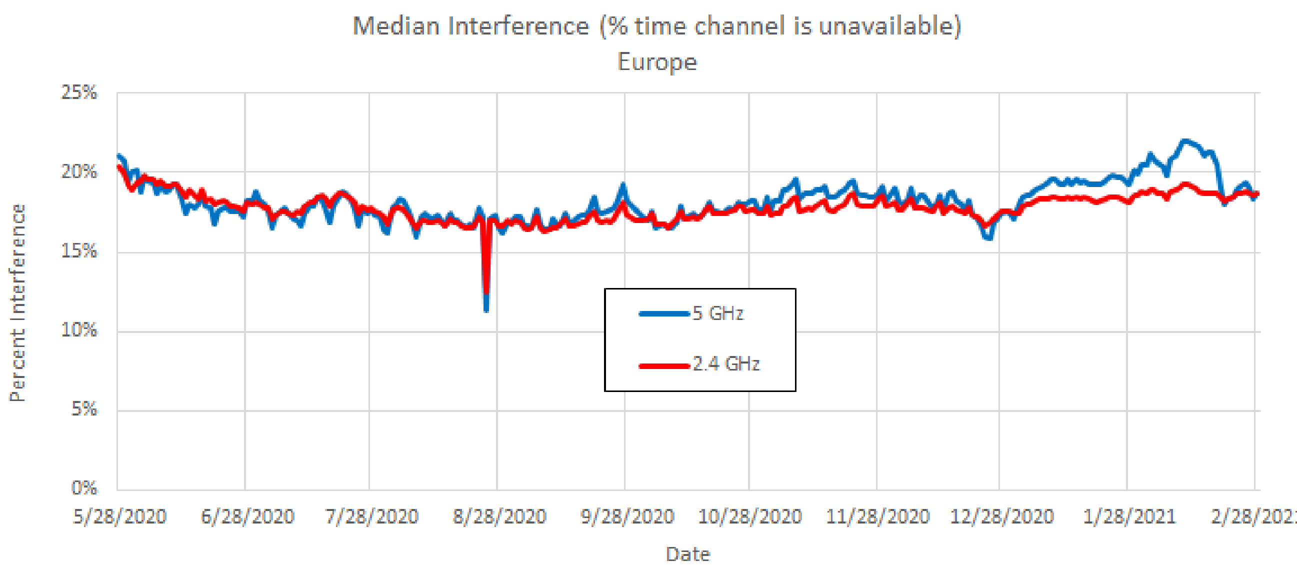

Figure 34. Europe, Wi-Fi Median Interference, 5 GHz and 2.4 GHz.

Figure 35 shows the 95% worst case Wi-Fi interference in Europe in the 2.4 GHz and 5 GHz bands. The 95% worst case is the point at which 95% of the interference is below this point, and 5% is above, as computed from the histogram.

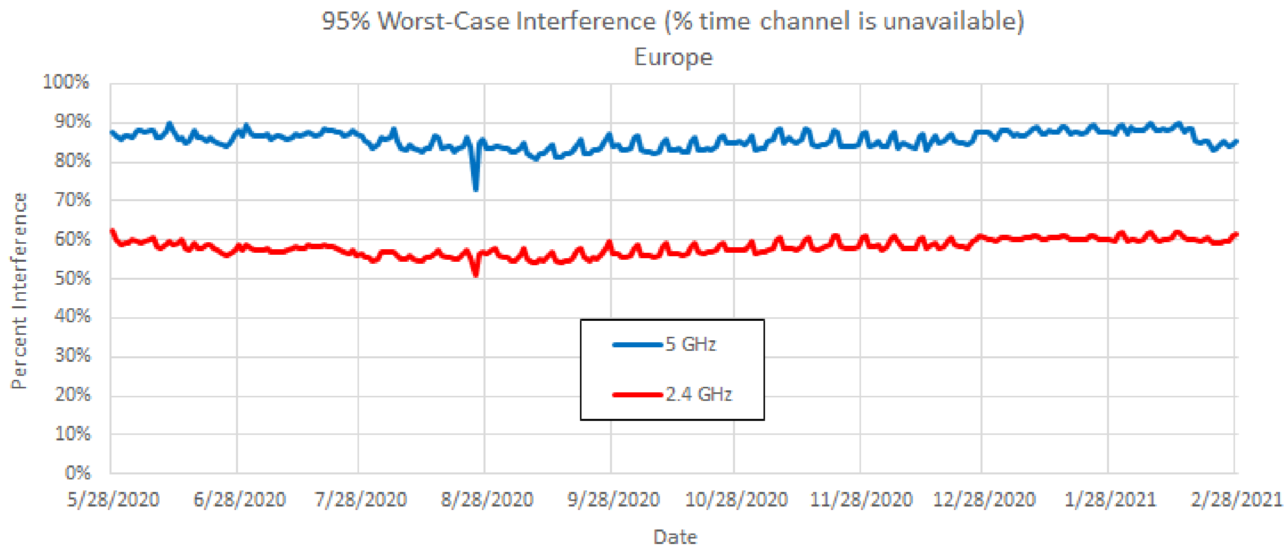

Figure 35. Europe, Wi-Fi 95% Worst Case Interference, 5 GHz and 2.4 GHz.

5.7 5 GHz U-NII Bands

Figure 36 and Figure 37 show Wi-Fi traffic and the number of connections in different 5 GHz sub-bands for North America.

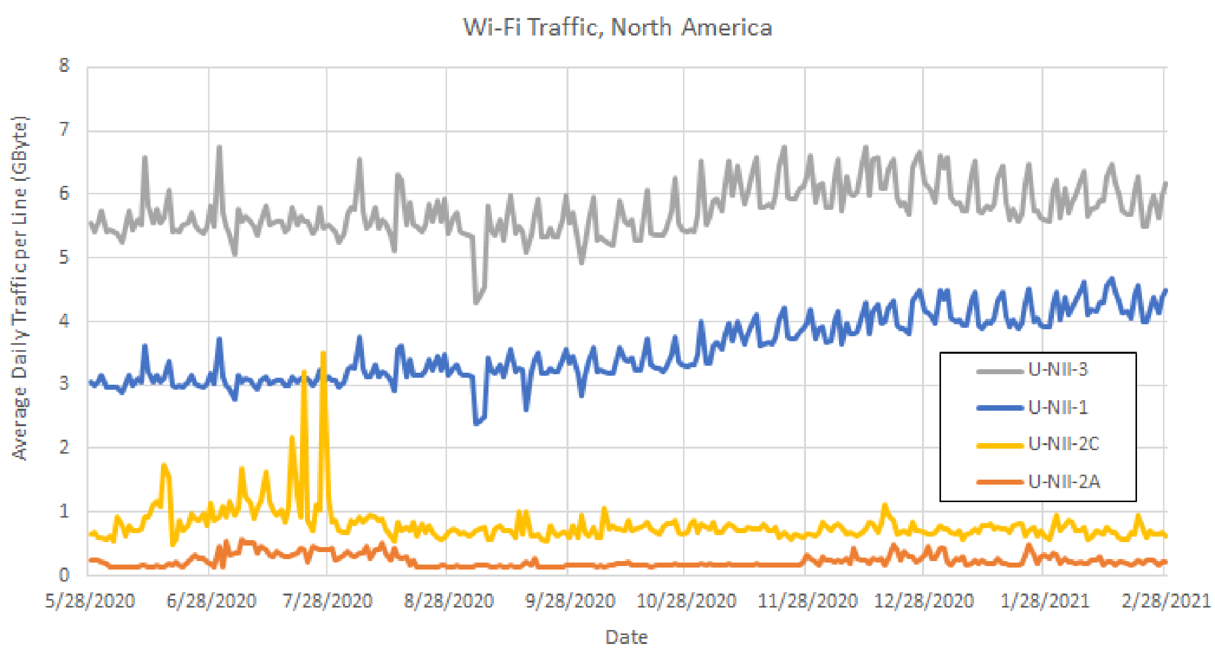

Figure 36. Average downstream Wi-Fi traffic in 5 GHz sub-bands, North America.

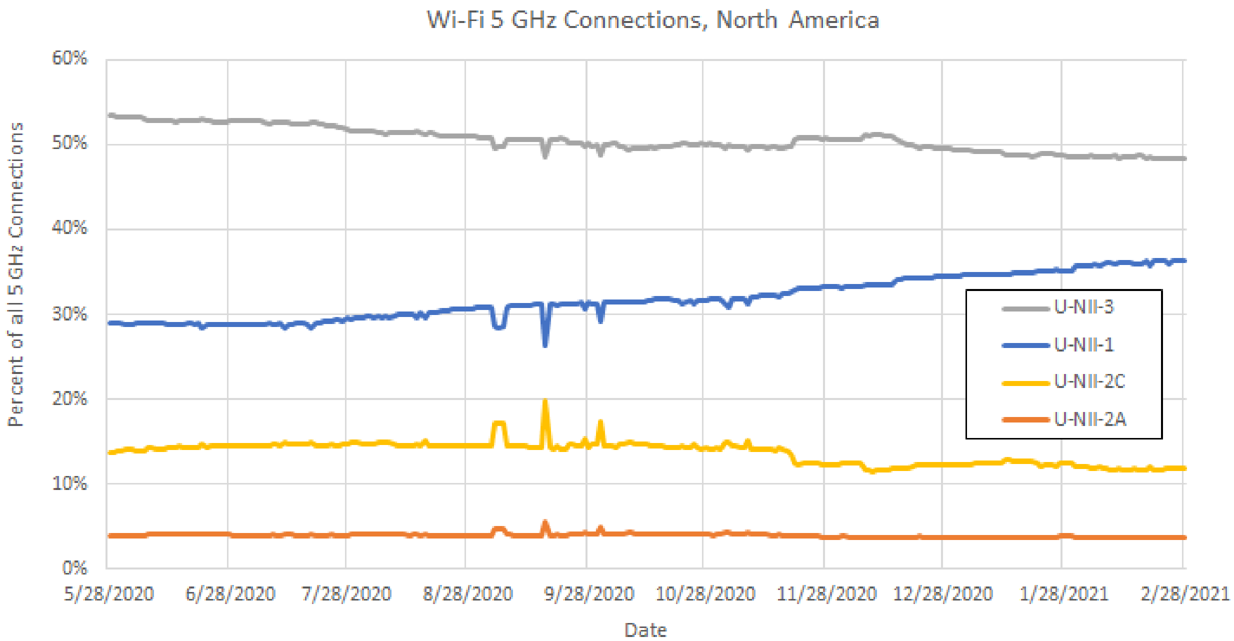

Figure 37. Percent of connections using each 5 GHz sub-band, North America.

5.8 Wi-Fi versus Broadband Access Throughput

Wi-Fi throughput was measured separately in 2.4 and 5 GHz bands via speed tests. Broadband access throughput was measured separately upstream and downstream via speed tests. Assuming that Broadband speed and Wi-Fi speed are independent, their joint histogram was used to determine the probability that Wi-Fi speed is below broadband speed and is shown in Figure 38 for North America. At this time of writing, some additions to the European data are pending which should allow a similar analysis of Wi-Fi versus broadband speed for Europe.

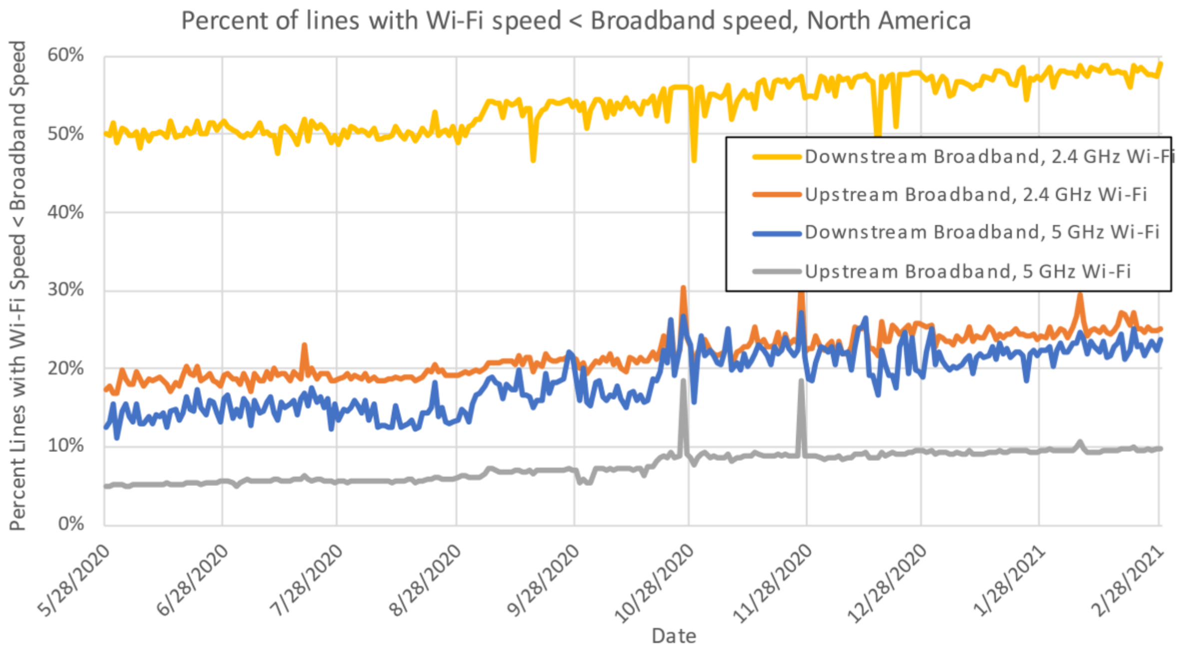

Figure 38. Wi-Fi throughput compared to broadband throughput North America.

Note that often Wi-Fi is slower than broadband, particularly for delivering broadband downstream using 2.4 GHz Wi-Fi. Broadband access often provides slower upstream than downstream, whereas Wi-Fi is roughly symmetric. Therefore, for upstream, Wi-Fi is usually faster than broadband, and so the Pr(Wi-Fi speed < broadband speed) is low in the upstream direction.

The trends over time of the above figure were found by linear regression. As shown in Table 5, the trend of Wi-Fi being slower than broadband is increasing, with the highest increase seen for downstream broadband compared to 5 GHz Wi-Fi.

Table 5. Percent annual increase in the probability that Wi-Fi is slower than broadband.

Broadband vs Wi-Fi throughput	Annual additional percent of lines with Wi-Fi slower than broadband
Upstream Broadband, 2.4 GHz Wi-Fi	10.9%
Upstream Broadband, 5 GHz Wi-Fi	7.4%
Downstream Broadband, 2.4 GHz Wi-Fi	13.0%
Downstream Broadband, 5 GHz Wi-Fi	14.4%

5.9 OVERALL SPECTRUM-NEED SCORE

Salient Wi-Fi performance parameters which indicate how much spectrum is needed for Wi-Fi were amalgamated into a "Spectrum-need score." This score combines the best parameters for predicting the need for more spectrum:

- Wi-Fi traffic, downstream and upstream (Section 3.5.1). Increasing traffic directly indicates increasing usage.
- Wi-Fi interference (Section 3.4). Increasing interference indicates that transmissions from others on the same channel are increasingly crowding the shared spectra.
- Wi-Fi latency (Section 3.6), Increasing latency indicates that the Wi-Fi channel is increasingly occupied and so users must wait to gain access.
- Throughput / transmit rate (Section 3.2). Decreasing throughput / transmit rate indicates that each AP can gain access to a diminishing proportion of the channel time.

These are linearly combined with equal weight. The 5% worst-case point is used for each parameter; 5% of the lines have worse parameter values than this line. Many lines have excess capacity at many times in the day; and it's the stress points which are of interest.

More formally, the following parameters are combined with equal weight:

1. 95% highest downstream Wi-Fi traffic (Section 3.5.1)
2. 95% highest upstream Wi-Fi traffic (Section 3.5.1)
3. 95% highest daily interference (Section 3.4)
4. 95% highest Wi-Fi latency (Section 3.6), and
5. 5% lowest throughput / transmit rate (Section 3.2).

An increase in the first four of these indicates an increasing need for more Wi-Fi spectrum. The last parameter is inversely related; a decrease in the last parameter, the throughput / transmit rate, indicates that capacity is being limited by neighboring APs with interfering channels and so the decrease indicates an increasing need for more Wi-Fi spectrum.

For each day, each of these five parameters is scaled to a variable between 0 and 1 by dividing by its maximum value, resulting in P1, P2, P3, P4, and P5. Then the five parameters are then linearly summed with equal weight:

$$\text{Spectrum-need score} = 0.2\,P1 + 0.2\,P2 + 0.2\,P3 + 0.2\,P4 - 0.2\,P5$$

where the fifth parameter, the throughput / transmit rate, is subtracted since it is inversely related to spectrum need. This spectrum-need score is plotted in Figure 39 and Figure 40.

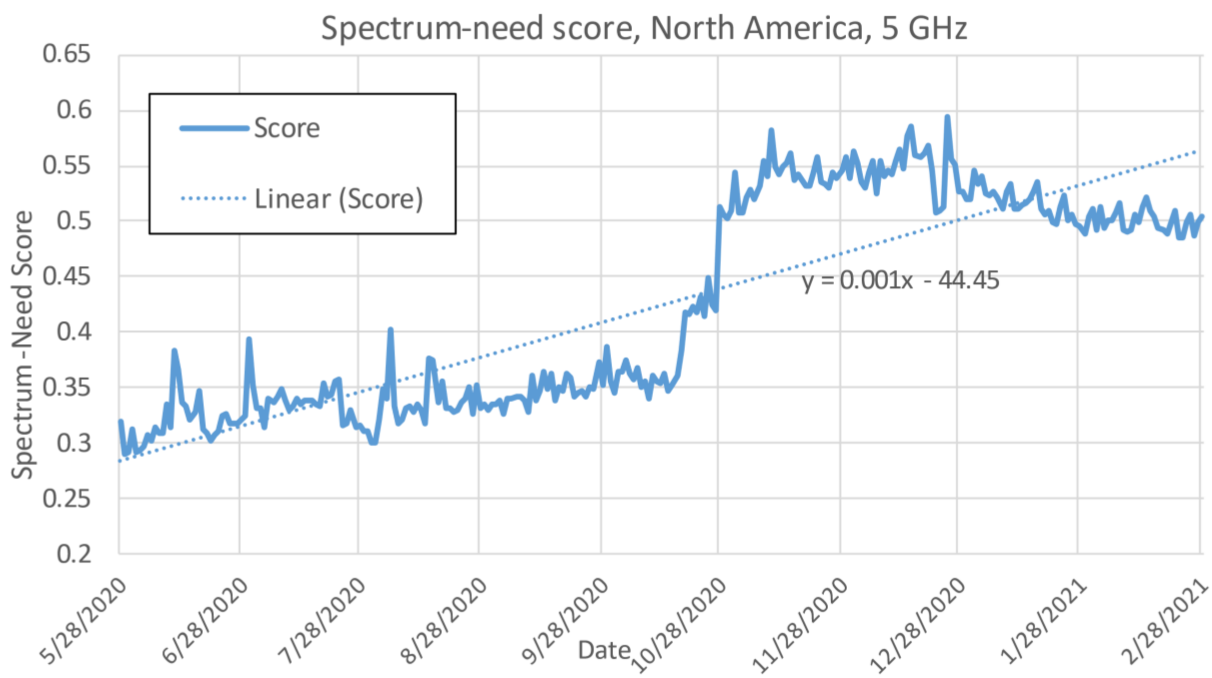

Figure 39. Spectrum-Need Score, 5 GHz Wi-Fi, North America.

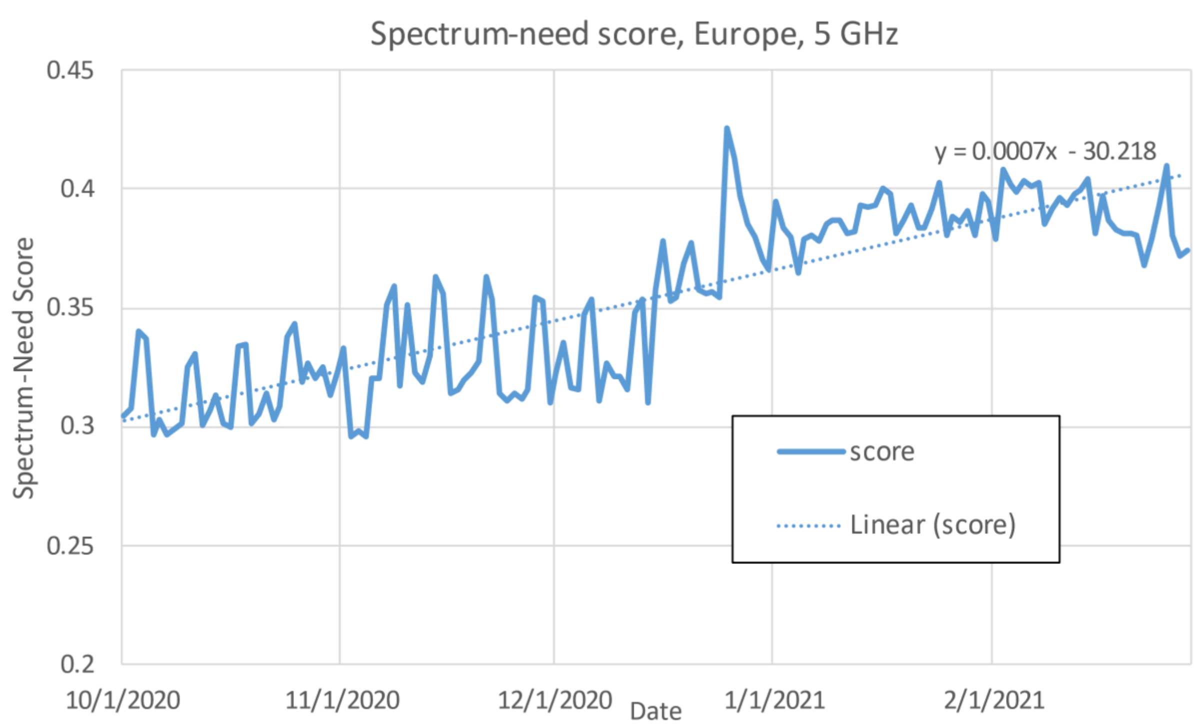

Figure 40. Spectrum-Need Score, 5 GHz Wi-Fi, Europe.

The percent annual increase in spectrum-need score was found by linear regression and is shown in Table 6. These increases are substantial.

Table 6. Percent annual increase in spectrum-need score.

Continent, Wi-Fi Band	% Annual increase
North America, 2.4 GHz	13.2%
North America, 5 GHz	37.1%
Europe, 2.4 GHz	24.8%
Europe, 5 GHz	25.3%

6 CONCLUSIONS

31 different parameters are represented in histograms, both for North America and for Europe. Data for North America includes the USA and Canada, but does not include Mexico. These can be used to compare Wi-Fi in 2.4 GHz and 5 GHz bands. Data shows that 5 GHz currently carries much traffic, and that traffic and interference at 5 GHz is often as high as in 2.4 GHz.
Thus, results indicate that the 5 GHz band is now saturating, and more Wi-Fi spectra is needed. Rapidly growing traffic results in increased congestion and interference, which can be mitigated by wider channels and more channels to reduce congestion and interference, respectively.

Significant increasing trends in spectrum need were found for both 2.4 GHz and 5 GHz bands. The annual increase in 5 GHz band is higher than 2.4 GHz band in North America and Europe.

Table 1 and Table 2 in the introduction show annualized trends in the data as found by linear regression on the data here. The increases in Wi-Fi traffic, interference, congestion and latency indicate a scarcity of available spectrum.

Many other plots, trends, correlations and statistics can be gleaned from this myriad of data. Trends over the limited timespan here (9 months) show some increases in traffic, congestion and interference; however as time progresses and more data is collected these and other trends should become more accurately known and more apparent.

Correlations among parameters across lines could be examined in the future, such as determining the correlation between Wi-Fi interference and throughput per line.

While technology advances and topology evolution can increase the QoE for a given traffic density over a given spectrum, more advanced applications may increase the QoS requirements and therefore lower the acceptable traffic density. This study was conducted in North America (USA, Canada) and Europe, but please take into account that the state of the fixed infrastructure plays a role in how quickly spectrum is required for Wi-Fi. This report indicates that in North America and Europe, Wi-Fi is quickly becoming the dominant QoE weakest link. Depending on the quality of the Fixed Infrastructure, the point in time where the QoE of the Fixed Access surpasses the QoE of the Wi-Fi link may vary from the North America and Europe examples.