Measuring Network Quality for End-Users, 2021

An Internet Architecture Board virtual workshop
Day 2
Agenda

Metrics 2
14:00 Chairs’ Intro
14:10 Jonathan Foulkes. Metrics helpful in assessing Internet Quality
14:17 Vijay Sivaraman, Sharat Madanapalli, Himal Kumar. Measuring Network Experience Meaningfully, Accurately, and Scalably
14:31 Discussion

Metrics 3
15:00 Kyle MacMillian, Nick Feamster. Beyond Speed Test: Measuring Latency Under Load Across Different Speed Tiers
15:07 Gregory Mirsky, Xiao Min, Gyan Mishra, Liuyan Han. Error Performance Measurement in Packet-Switched Networks
15:14 Gino Dion. Focusing on latency, not throughput, to provide better internet experience and network quality
15:21 Praveen Balasubramanian. Transport Layer Statistics for Network Quality
15:28 Discussion
16:00 Break

Cross-Layer 1
16:10 Jari Arkko, Mirja Kuehlewind. Observability is needed to improve network quality
16:24 Rajat Ghai. Measuring & Improving QoE on the Xfinity Wi-Fi Network
16:31 Discussion

Cross-Layer 2
17:00 Koen De Schepper, Olivier Tilmans, Gino Dion. Challenges and opportunities of hardware support for Low Queuing Latency without Packet Loss
17:07 Ken Kerpez, Jinous Shafiei, John Cioffi, Pete Chow, Djamel Bousaber. State of Wi-Fi Reporting
17:14 Mikhail Liubogoshchev. Cross-layer Cooperation for Better Network Service
17:21 Francois Michel, Olivier Bonaventure. Packet delivery time as a tie-breaker for assessing Wi-Fi access points
17:28 Discussion
18:00 End of Day 2
Metrics helpful in assessing Internet Quality

Jonathan Foulkes
Helpful Internet Quality Metrics

• Line capacity and latency under working loads
  • Capacity variability - 36% of lines vary by more than 10% over time
  • Accounting for ALL capacity usage on the link is important
  • Reporting capacity usage and latency statistics over time
• Dynamic variability
Line stability metrics

• Link loss
  • Date time & duration
  • Segment local vs link losses
• Line instability events
  • 27% have this
  • 16% have >50 events

Unstable line definition:

An increase in latencies with little to no load

Typical causes:
- Link errors due to modem or local loop
- Backhaul congestion
Missing – Local metrics

• Quantify local link performance
  • Capacity and latencies under load

• Contrast to external link metrics
  • Understand where loss of quality happens

• Local network service
  • Router hosted or App on wired system
Measuring Network Experience Meaningfully, Accurately, and Scalably

Vijay Sivaraman
Measuring Network Experience Meaningfully, Accurately, and Scalably

Vijay Sivaraman, Sharat Madanapalli, Himal Kumar

15 Sep 2021
**Meaningfully: What and Why?**

- Speed has diminishing returns for consumers
  - … and the gap across ISPs is narrowing
  - … while racing ISP economics to the bottom

- Latency, loss, etc. may not be directly perceived
  - Applications can absorb these

- Let’s measure what the consumer perceives:
  - Streaming video (on-demand or live):
    - Is video at best resolution? Is it freezing?
  - Gaming:
    - Is latency low and consistent (i.e. low jitter)?
  - Conferencing:
    - Are there stutters and dropouts?
Accurately and Scalably: How?

- Terabit speed Programmable Network chip
  - Scalable to multi-Tbps

- Push telemetry to “pulse” each flow
  - Accurate to sub-100msec (tunable)

- AI behavioral models for application experience
  - Video: chunk fetch patterns for resolution & buffer state
  - Games: latency (TCP), jitter spikes (UDP)
  - Methods are engineered to application dynamics
  - … and agnostic to data (& header) encryption

- Commercial trials underway with Telcos
Measuring ISP Performance in Broadband America: a Study of Latency Under Load

David Reed
MEASURING ISP PERFORMANCE IN BROADBAND AMERICA
A Study of Latency Under Load

Dr. David P. Reed & Dr. Levi Perigo
Computer Science Department
University of Colorado Boulder
FCC’s Downstream Latency Under Load Data By Technology (Average RTT, 2020)
FCC’s Downstream Latency Under Load Data By Technology (Maximum RTT, 2020)
FCC’s Historical Latency Under Load Data Over Cable (Longitudinal Average RTT, Comcast, 2020)
FCC’s Historical Latency Under Load Data Over Cable (Comcast, 2020)

Distribution of Downstream Latency Under Load Before (July) and After (November) Use of New AQM

- July RTT_Avg: 81.3%
  - 0-149 MS: 8.2%
  - 150-249 MS: 10.5%
  - 250+ MS: 1%
- Nov. RTT_Avg: 96.8%
  - 0-149 MS: 2.2%
  - 150-249 MS: 1%
  - 250+ MS: 1%
- July RTT_Max: 69.3%
  - 0-149 MS: 11%
  - 150-249 MS: 19.7%
  - 250+ MS: 1%
- Nov. RTT_Max: 85%
  - 0-149 MS: 10%
  - 150-249 MS: 5%
  - 250+ MS: 5%
Findings

• LUL data shows network performance changes under increased traffic loads – *useful additional information for future FCC MBA Reports*

• Substantial difference downstream and upstream LUL for all technologies – due to *lower upstream speed, multiple access to shared upstream bandwidth*

• Substantial variation in downstream and upstream LUL by technology type – *due to varying service speeds, cable/FTTH latency much lower than DSL*

• Max RTT shows upper bound on latency experienced by users – *enough for users to experience notable degradation of real-time applications*

• LUL performance by cable ISP (Comcast) improved average of ~10% per year – *due to increasing service speeds and IP protocol/device improvements*
  • New AQM immediately improved average LUL performance by 48% in 2020

• LUL data shows relationship between latency and service speed – *forecasts improved latency performance as trend continues to higher speeds*
Discussion

To be enqueued, please write ‘+q’ in the chat

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The duration of each comment is limited by 60 seconds
Beyond Speed Test: Measuring Latency Under Load Across Different Speed Tiers

Kyle MacMillan
Measuring Latency Under Load Across Different Speed Tiers

- Preliminary results from latency under load tests conducted across tens of homes across Chicago.
- Latency under load is given by the RTT of an ICMP packet to a given destination when either uplink or downlink is saturated.
- Link is saturated using iPerf3 TCP speed test.
- Tests are conducted every 2 hours.
- Data collected from at least 30 days of tests.

Figure 1: Measurement collection setup. A raspberry pi on a wired connection runs our measurement suite in each participant’s home.
Observation #1: Latency Under Load Related to Speed Tier

- Users subscribed to internet service plans with lower throughput generally experience higher latency under load than those on higher speed plans.

Figure 2: Mean latency under upstream load over time, aggregated by subscriber plan and ISP, with 95% confidence intervals.
Observation #2:
Same Service Plan + Same ISP ≠ Same Latency Under Load

- Users subscribed to the same service plan on the same ISP experience different latency under load.
- While the differences are clear, the causes are challenging to uncover.

Figure 3: Latency Under Load for two subscribers to ISP A's 1 Gbps service plan, in two different Chicago neighborhoods.
Error Performance Measurement in Packet-Switched Networks

Gregory Mirsky
Error Performance Measurement in Packet-switched Networks

Greg Mirsky (Ericsson)
Xiao Min (ZTE)
Gyan Mishra (Verizon)
Liuyan Han (China Mobile)
What is Error Performance?

- OAM toolset includes methods to detect defects and measure performance
- Defect is an inability to communicate. Defect in PSN is Loss of path continuity, i.e., there's no path through the network to get a packet from the source node to the destination node
- Defect state is the state of 100% packet loss – bridge Fault Management and Performance Monitoring OAM
- Packet Loss is an infinite delay of a packet
- Error Performance – quantitative characterization of the network condition between endpoints
EPM is Active OAM

- EPM is well-known in constant bit-rate, e.g., TDM, communication technologies (ITU-T G.826 and G.827)
  - based on the guaranteed presence of data, several EPM states and metrics defined, including state of path availability and unavailability
- A packet-switched network is based on the principle of statistical multiplexing and does not provide a predictable, guaranteed rate of receiving packets in the specified flow
- Without predictable flow, the operational state of a PSN cannot be characterized with certainty. If the state to be determined using only data traffic, how to differentiate pause in receiving data packets caused by the nature of the application from caused by the network failure?
- Only active OAM can create a sub-flow with a predictable rate of packets that EPM OAM can use
EPM Apparatus

• Consider using G.826/G.827 EPM parameters:
  – Errored Interval (second)
  – Severely Errored Interval (second)
  – Error-free Interval (second)

• Consecutive intervals form a period of:
  – Availability
  – Unavailability

• To make it stable, the definition of a period includes hysteresis. For example:
  – Ten consecutive Severely Errored intervals determine that a path is in an unavailable period that started at the beginning of the first Severe Errored interval.
  – A sequence of Errored and Error-free intervals shorter than ten does not change the state of the path, i.e., it is still in unavailable period.

• Other metrics:
  – Errored Interval Ratio = Errored Intervals / Total Number of Intervals
  – Severely Errored Interval Ratio = Severely Errored Intervals / Total Number of Intervals
Focusing on latency, not throughput, to provide better internet experience and network quality

Gino Dion
Low Latency vs Consistent Latency
Cloud Gaming Latency Budget Example

<table>
<thead>
<tr>
<th></th>
<th>Median Latency</th>
<th>Jitter Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Home Ethernet</td>
<td>1-2 ms</td>
<td>&lt;1 ms</td>
</tr>
<tr>
<td>In-Home Wi-Fi (sub 100 Mb/s traffic load, without AQM)</td>
<td>~10-20 ms</td>
<td>~10-4000 ms</td>
</tr>
<tr>
<td>xDSL</td>
<td>~20-50 ms</td>
<td>~5 ms</td>
</tr>
<tr>
<td>DOCSIS (3.0 under load, with buffer control)</td>
<td>~10 ms</td>
<td>~10-200 ms</td>
</tr>
<tr>
<td>LLD DOCSIS (estimated)</td>
<td>~1 ms</td>
<td>~1-5 ms</td>
</tr>
<tr>
<td>Access - FTTH</td>
<td>&lt;1 ms</td>
<td>~1-2 ms</td>
</tr>
<tr>
<td>4G/5G (RAN latency, non-URLLC based profile, QCI 9)</td>
<td>~15-35 ms</td>
<td>~10-500 ms</td>
</tr>
<tr>
<td>IP Transport &amp; Peering</td>
<td>~40 ms (near-edge)</td>
<td>~5-10 ms</td>
</tr>
<tr>
<td>Applications &amp; platform</td>
<td>~15-40 ms</td>
<td>~10-500 ms</td>
</tr>
</tbody>
</table>

“How many of the attendees are competitive gamers? Operate your own Twitch stream? If not, can you really relate to application outcomes and benefits?”

“You can’t easily fix low latency consistency with just better peering and edge compute, or better gaming “netcode”, or more efficient video codecs; you need an end-or to-end latency strategy.”

“Instead of application(s) as unique entities, think of use cases and services. CSP don’t sell better application packages, they sell better class of services”
Cloud Gaming Real-World Results – PI2 AQM and L4S

FTTH in a dense residential area, over WIFI, 80Mb/s of sustained Internet traffic

- First graph is a residential gateway (integrated WIFI) on FTTH, without any advanced form of AQM.
- The second graph is a CPE with PI2 and L4S enabled, under traditional home network load. You are looking at 30% improvement in the average latency, but more importantly the latency is very consistent with very little jitter above 100ms.
- Some of the jitter spikes observed do not originate from the in-home network itself, but from the general internet and gaming service platform.

Real-world metrics need to be based on real-world benefits

My personal K/D ratio improved by 0.5 in less than 4 weeks!

If I see a “lag spike” as a gamer, it’s already too late, but please tell me where it came from!

Source: Measurement and results for video-conferencing courtesy of DOMOS, 2021
Last-Mile & CPE Latency Video-Conferencing Benchmarking Results
4G Fixed-Wireless-Access with in-home WIFI

<table>
<thead>
<tr>
<th>KPIs</th>
<th>Default</th>
<th>Domos + PI2</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latency:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>647</td>
<td>203</td>
<td>+69%</td>
</tr>
<tr>
<td>99 percentile</td>
<td>266</td>
<td>96</td>
<td>+64%</td>
</tr>
<tr>
<td>90 percentile</td>
<td>165</td>
<td>56</td>
<td>+66%</td>
</tr>
<tr>
<td>Median</td>
<td>60</td>
<td>14</td>
<td>+77%</td>
</tr>
<tr>
<td>Mean</td>
<td>78</td>
<td>23</td>
<td>+71%</td>
</tr>
</tbody>
</table>

Packet loss: Rate: 0.00019 0.00019 0%

Source: Measurement and results for video-conferencing courtesy of DOMOS, 2021
Cooperative approach to latency improvements

*It’s no longer about agreement, but about alignment*

- Focus on tangible, real-world benefits and results from the consumer point-of-view. Consumers don’t care about CDF curves, they care about K/D, FPS, etc. Measurements, comparisons and improvements of TCP stacks and queuing algorithms are important but will not drive consumer demand and service provider adoption. Focus should be placed on high-value use cases: Working-from-home, gaming, Enterprise services in a residential context, video/content streaming, etc.

- Ping times are often misleading, and the “speedtest” has reached its end-game, we already provide nearly 300x more peak capacity in the last mile than the average sustained usage from broadband subs. You can’t easily sell more bandwidth since it doesn’t solve existing latency issues, nor can the consumer actually put it to any good use. Speedtest should be redefined as a function of what latency can be sustained under a given speedtest. Give latency a context.

- Applications and network elements need to have the same access and visibility to congestion markers so they can adapt natively, instead of probing the network and trying to outsmart it. We are at the point of diminishing returns if we continue the silo based approach to solving latency. L4S provides a proven means to deliver this today.

- The reality is that the latency consistency issues aren’t from the overall internet, they are largely confined to the last mile and in-home. Providing better tools to the end-users and the service providers than “ping” times for latency monitoring are required, there is little value in highlighting a lab spike if we can’t pinpoint the root cause.

- Platform and webscale providers such as Apple, Google, Netflix, etc. have been trying to tackle and solve latency issues for years (for their own services), without implicit support or help from the networks. But today’s networks and consumer CPEs are capable and ready to support this (ie. L4S).
**Is the consumer market ready? Yes**

<table>
<thead>
<tr>
<th>Price</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0/month</td>
<td>22.20%</td>
</tr>
<tr>
<td>$5/month</td>
<td>37.00%</td>
</tr>
<tr>
<td>$10/month</td>
<td>27.80%</td>
</tr>
<tr>
<td>$15/month</td>
<td>5.60%</td>
</tr>
<tr>
<td>$20/month</td>
<td>7.40%</td>
</tr>
</tbody>
</table>

**Poll Question**
Would you rather have the service provider offer a custom broadband package tailored for certain latency needs (e.g., Gaming, working-from-home, etc.), or should they provide the end-user the ability to self-manage this capability?

- Service provider controlled latency: 35%
- End-user managed latency: 65%

Source: Nokia sponsored LightReading webinar, April 2021

**Will CSP see value, and will the consumer?**

- Average NPS score increase:
  - Enterprise sub: 10
  - Pilot participant: 20
- 100% of pilot participant retention rate
- How much would you miss feature (0 - 5):
  1. Prioritisation video conferences: 4.4
  2. Prioritisation specific device: 4.4
  3. Troubleshooting: 4.0
  4. Information about Wi-Fi issues: 3.6
  5. Recommendations for Wi-Fi issues: 4.6

Survey results from Enterprise customers, live field trial, EU FWA provider, 2021. Offering at $10 Euro more per month "extra"
There isn’t a day that goes by that I don’t get a Tier1/2 CSP from around the world asking how they can offer a better latency service (gaming, working, from home, enterprise services in a residential content with SLA, etc)

Cooperative approach to latency improvements

*It’s no longer about agreement, but about alignment*

I’m putting it out there, just ask, and we can connect the dots and make this happen!
Transport Layer Statistics for Network Quality

Praveen Balasubramanian
Transport Layer Metrics for Network Quality

• Transport layer metrics
  • RTT, Loss, Reordering, Bandwidth
  • Estats / TCP_INFO
  • Push model?
  • QUIC has additional complexity

• Correlation with application layer metrics
  • Time to first byte, Response time, Delivery rate, Jitter
  • Connection reuse problems
  • Multi-stream problems
  • Support for stats diff @ request start/end?
Challenges and Research Ideas

• Challenges
  • Multi-platform world
  • Different administrative domains
  • Application intent
    • Not expressed today
    • Difficult to infer
  • User intent
    • Low versus high priority
  • Receive side transport has less visibility

• Research Ideas
  • Design application layer mechanisms to exchange transport metrics
    • Privacy preserving
  • API improvements for expressing application intent
  • Mechanisms for inferring user intent
  • Passive and active measurements
Discussion

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Observability is needed to improve network quality

Jari Arkko
Session: Cross Layer Topic: Observability
Arkko & Kühlewind, 2021

The problem:
- Limited observability
- Problem isolation and debugging is difficult
- Many aspects of desirable behaviour are not directly visible
- Dynamically changing situation is not shared to others

Direction for solutions:
- Better collaboration among parties
- Observability, explicit identification of the situation

Constraints:
- Only for mutually beneficial cases (RFC 8558)
- Needs standards
- Avoid data with privacy, filtering, etc. impacts

Examples
- Network assist for measurements
- Endpoint assist for measurements
- Probing
- Capability discovery
- Security indications
Merge Those Metrics: Towards Holistic (Protocol) Logging

Robin Marx
Merge Those Metrics: Towards Holistic (Protocol) Logging

Measuring Network Quality for End-Users. IAB Workshop 2021

Robin Marx
Joris Herbots

robin.marx@kuleuven.be
joris.herbots@uhasselt.be
Cross-Layer and Cross-Endpoint log aggregation

Challenges aplenty:

- Store, aggregate and synchronize post-hoc
- Analyze and correlate with tooling
- Network emulation / (partial) trace playback
Share That Data (Please)!

Especially for low-layer-encrypted future, endpoint logging is the only thing (?) that scales + deals with privacy

Observability
- Share metrics with (privileged) network operators?

Industry vs Academia: datasets
- Real loss? Real MTUs? Real geographical metric distributions? ...
- Privacy? Intellectual Property/Competitive Edge? Afraid we might laugh?
Measuring & Improving QoE on the Xfinity Wi-Fi Network

Rajat Ghai
Using TCP Connect Latency for measuring CX and Network Optimization

Network Quality workshop
Comcast
QoE KPI

TCP conn: 150 msec

TCP | UDP
---|---
IP

WiFi | DOCSIS | Fiber

BER

~10^-5 | ~10^-11 | ~10^-13

WiFi connection quality can be observed at Layer 4 by observing TCP connect latency
CX KPI Predictors

• **TCP connect Latency**: This is our Primary Latency predictor KPI. It is measures from SACK→ACK, as round trip from network to client and back.

• **TCP Retransmission**: This is our secondary KPI that we are evaluating as a predictor of characterizing good/bad sessions. This is measured for the **entire lifetime** of tcp connection NOT just the start. This marker at 4% is candidate for the CX predictor (specially for mobility / nomadic scenarios where wireless channel quality variability due to motion creates excessive L2 delays which in turn creates retransmissions at TCP layer.

• **Throughput**: Throughput is measured as actual consumed in octets on a 1 second interval granularity. {Not to be confused with a synthetic speedtest that tests the max capacity capability of a connection}

“We collect, store, and use all data in accordance with our privacy disclosures to users and applicable laws”. 
“We collect, store, and use all data in accordance with our privacy disclosures to users and applicable laws.”
TCP Retransmissions

We collect, store, and use all data in accordance with our privacy disclosures to users and applicable laws.
**CX / Latency improvement methodology**

- Conduct Network A/B tests for network optimization
  - Pick A & B sites of very similar traffic and usage profiles.
  - Site A is the Control site
  - Site B is the Test site
  - Baseline and trend KPIs on both sites for fixed duration of time (usually 2 weeks)
  - Make the CX based Network Optimization change only on the Test site
  - Let the Test site (site B) soak the change for a fixed duration of time (usually 1-2 weeks)
  - Start trending KPIs on both control and test sites during post baseline and soak phase for a fixed duration of time (usually 2 weeks)
  - Analyze the network optimization KPI outcome on test site as compared to control site.
  - If KPI trends are favorable on various KPI statistical models, then deploy the change nationwide.

- Wash, rinse, repeat.
Discussion

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Challenges and opportunities of hardware support for Low Queuing Latency without Packet Loss

Koen De Schepper
Challenges and opportunities of hardware support for Low Queuing Latency without Packet Loss

Koen De Schepper, Olivier Tilmans, Gino Dion

IAB Workshop on Measuring Network Quality for End-Users

15 September 2021
Low latency **with** rate priority  ❖ Low latency **without** rate priority

**Just priority**
Give apps all BW they need

**Only latency priority**
Control rate of all flows equally
Low latency with rate priority  \( \Rightarrow \) Low latency without rate priority

New mindset for lower layers:

- Low Latency \# priority \( \Rightarrow \) Low Latency = priority + rate control
- Priority NEEDS rate coupling
- Bigger Queue \( \neq \) needs more bandwidth

Just priority
Give apps all BW they need

Only latency priority
Control rate of all flows equally

L4S ECN
QoS DSCP
Design reorientation needed from speed towards latency

Lower packet aggregation

Throughput

Latency

> 10 ms

< 1 ms

Lower layer queues and staged pipelines

AQM / IP packets

PHY packets
Design reorientation needed from speed towards latency

Optimize ECN usage:
Access ECN in IP headers
Support ECN in lower layers
…
Measuring latencies

L4S: Peak 15ms latency
L4S min latency of 2ms
L4S: Avg 6.5ms latency

Only 1% of the time less than 45ms latency
50% of the time 97ms latency
Peak 116ms latency

Bufferbloat MUST be avoided
1 Extra Packet aggregation time due to multistage pipelining can be avoided
Packet aggregation / serialization time can be reduced
Base processing time

Latency no AQM CUBIC [ms]
Latency L4S Prague [ms]
Latency Ping on Idle NW [ms]
Latency MAC under load [ms]
Should Network report latency per application?

App1  App2
State of Wi-Fi Reporting

Ken Kerpez
ASSIA collects and anonymizes many data parameters
- Millions of lines in both *North America* and *Europe*
- Performance metrics, Diagnostic parameters, Network status & test

Wi-Fi Customer Premises Equipment (CPE)

Broadband Fixed-Line Router Equipment

Wi-Fi and Broadband Data

Wi-Fi Data

<table>
<thead>
<tr>
<th>Wi-Fi Throughput (speed)</th>
<th>Daily, 2.4 and 5 GHz bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi Transmit Rate</td>
<td>Daily, 2.4 and 5 GHz bands</td>
</tr>
<tr>
<td>Wi-Fi Throughput to transmit rate ratio</td>
<td>Daily, 2.4 and 5 GHz bands</td>
</tr>
<tr>
<td>Wi-Fi Congestion</td>
<td>Daily and max hour, 2.4 and 5 GHz bands</td>
</tr>
<tr>
<td>Wi-Fi Interference</td>
<td>Daily and hourly, 2.4 and 5 GHz bands</td>
</tr>
<tr>
<td>Wi-Fi Traffic</td>
<td>Daily and hourly, upstream and downstream, 2.4 and 5 GHz bands</td>
</tr>
<tr>
<td>Wi-Fi Latency</td>
<td>Daily, 2.4 and 5 GHz bands</td>
</tr>
</tbody>
</table>

Broadband Data

<table>
<thead>
<tr>
<th>Broadband Traffic</th>
<th>Daily and hourly, upstream and downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadband Throughput (speed)</td>
<td>Daily, upstream and downstream</td>
</tr>
<tr>
<td>Broadband Latency (round-trip)</td>
<td>Daily</td>
</tr>
</tbody>
</table>
Wi-Fi Traffic increases & Wi-Fi limiting internet access

Wi-Fi traffic doubles about every 3 years, in both 5 GHz and 2.4 GHz

Lines with Wi-Fi slower than broadband access, North America

Percent of lines with Wi-Fi speed < Downstream Broadband speed, North America

<table>
<thead>
<tr>
<th>Wi-Fi slower than broadband</th>
<th>Annual increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 GHz Wi-Fi</td>
<td>13.0%</td>
</tr>
<tr>
<td>5 GHz Wi-Fi</td>
<td>14.4%</td>
</tr>
</tbody>
</table>

Internet access is increasingly limited by Wi-Fi
**Annualized Percent Change in Wi-Fi Data, found by linear regression**

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

**Overall Wi-Fi trend**

\[
\text{Spectrum-need score} = 0.2 \times \text{ds traffic} + 0.2 \times \text{us traffic} + 0.2 \times \text{interference} + 0.2 \times \text{latency} - 0.2 \times \text{tput/tx rate}
\]

<table>
<thead>
<tr>
<th>Continent, Wi-Fi Band</th>
<th>% Annual increase in spectrum-need score (linear regression)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America, 2.4 GHz</td>
<td>13.2%</td>
</tr>
<tr>
<td>North America, 5 GHz</td>
<td>37.1%</td>
</tr>
<tr>
<td>Europe, 2.4 GHz</td>
<td>24.8%</td>
</tr>
<tr>
<td>Europe, 5 GHz</td>
<td>25.3%</td>
</tr>
</tbody>
</table>

**Overall, Wi-Fi spectrum need rises about 25% annually**

Wi-Fi **growth is rapid**

Maintenance of good QoE is increasingly challenging

- Need more spectrum
- 6 GHz will help

Full report: [ASSIA-DSA-Summit-Presentation-v7.8.pdf](dynamicspectrumalliance.org)
Cross-layer Cooperation for Better Network Service

Mikhail Liubogoshchev
Cross-layer Cooperation for Better Network Service

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Application-side Challenges

Hard to perform fine-grained measurements required for latency sensitive applications: audio/videoconferencing, AR/VR, cloud gaming, etc.

“Single packet” measurements:
- Random protocol-induced delays in wireless networks
  - HARQ retransmission timeout in LTE (approx. 8 ms), channel access procedure in Wi-Fi
  - Present at any load
  - Non-linearly depend on load

“Multiple packets” measurements
- High wireless throughput requires high aggregation:
  - 1 ms scheduling/transmission period in LTE (0.5ms in current 5G deployments)
  - Dozens of kB transmissions in Wi-Fi
- High probability of an unsuccessful packet decoding:
  - Target PER=10%
  - For a dozen of packets in a single transmission, the retransmission is required with >70% probability
  - Retransmission of a single packet prevents all the following packets from forwarding up
  - Packets often arrive at the receiver “simultaneously”
Need for Cross-Layer Communication

- End-nodes know “what they want”:
  - Traffic type
  - Current session state (e.g., video buffering)
  - QoS requirements (incl. the requirements “at the moment”)
- Network devices know “what they can offer”:
  - The number and capabilities of clients
  - The state of (wireless) medium: channel throughput, PER, etc.
  - The applied policy and the typical processing delays
  - If some client will soon enter low-coverage area
- We can make the Internet much more efficient by exchanging this information:
  - Intelligent QoE-aware L2 management: provide service as much as and when it is required
  - Accurate and robust L7 (and probably L4) rate adaptation: do not send more data than the network can process
  - Enhanced end-user privacy: applications reveal metadata vs. ISPs deploy DPI
- Examples of such communication protocols:
  - 3GPP TS 26.348 Northbound Application Programming Interface (API) for Multimedia Broadcast/Multicast Service (MBMS) at the xMB reference point; (Release 16). 3GPP, 2020
Packet delivery time as a tie-breaker for assessing Wi-Fi access points

Francois Michel
Packet delivery time as a tie-breaker for Wi-Fi access points

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Diverse devices, diverse use-cases

- File transfer
- Video on demand
- Live streaming
- Audio/video conference
- Online gaming
- Cloud gaming

2.4GHz/5GHz, private APs, campus APs, ...
Diverse needs

Throughput

max(latency)

File transfer
Video on demand
Live streaming
Audio/video conferencing
Online gaming
Cloud gaming
Sometimes several access points are available.
How to choose the AP?

We have signal and theoretical BW informations but no information about the latency/jitter.
Latency can vary even at the same distance to the AP

Same AP
Same distance
Same selected bitrate
(144Mb/s)
Different channels
Help the user selecting the AP for their needs
Help the user selecting the AP for their needs

- **UCLouvain**: Connected
- **eduroam**: Registered
- **wifi-pquic-fec**: Could be cached by the device (or Apple/Google’s servers?) or announced by the AP

Determined while using the channel
Adapt the application to the current conditions

Start the game with a playback buffer of >25ms for less latency sensitive games. Discourage the use of other games.
Exposing Wi-Fi frame delivery time statistics

Applications, users and maintainers may benefit from having information on the AP latency. Avg or percentiles of Wi-Fi frames delivery time could be exposed

- Help the user selecting the correct AP for their needs
- Identify the origin of the latency/jitter
- Adapt the application to the current conditions (use of playback buffers if needed)
- Help the application to choose the correct interface for initiating the transfer
- Help network maintainers reducing latency
Discussion

To be enqueued, please write ‘+q’ in the chat

To cancel being enqueued, please write ‘-q’ in the chat

The duration of each comment is limited by 60 seconds