Basic measurements in IP-based networks

Assoc. Prof. Jan Jerabek, Ph.D.

9.4.2018

BRNO UNIVERSITY OF TECHNOLOGY

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION department of telecommunications

SIX research centre sensor, information and communication systems

Brno University of Technology

University profile

- Located in second biggest city of Czech Republic (Brno)
- Silicon Valley of Czech Republic
- The oldest university in city (founded 1899)
- More than 21.000 students, almost 1.300 academic staff
- Regularly ranked in lists of elite technical and research universities
- Utilize European Credit Transfer and Accumulation System (ECTS)

Structure of university

8 Faculties

- Faculty of Architecture
- Faculty of Business and Management
- Faculty of Chemistry
- Faculty of Civil Engineering
- Faculty of Fine Arts
- Faculty of Information Technology
- Faculty of Mechanical Engineering
- **Faculty of Electrical Engineering and Communication (FEEC)**

BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering and Communication

- Established in 1959
- 12 departments
- ~220 academic staff (FTE)
- Focused also on research and development
- ~3.500 students in full-time and part-time studies
- Bachelor, master and doctoral study programmes and areas

Departments of FEEC

- Dept. of Biomedical Engineering
- Dept. of Control and Instrumentation
- Dept. of Electrical Power Engineering
- Dept. of Electrical and Electronic Technology
- Dept. of Foreign Languages
- Dept. of Mathematics
- Dept. of Microelectronics
- Dept. of Physics
- Dept. of Power Electrical and Electronic Engineering
- Dept. of Radio Electronics
- Dept. of Theoretical and Experimental Electrical Engineering
- **Dept. of Telecommunications**

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

R&D Infrastructures at FEEC

- **Centre for Research and Utilization of Renewable Energy**
  - Electromechanical Energy Conversion
  - Chemical and Photovoltaic Energy
  - Generation, Transmission, Distribution and Utilization of Electrical Energy
- **Centre of Sensor, Information and Communication Systems (SIX)**
  - Base-band layer of communication systems
  - System layer of communication systems
  - Convergence of information and communication technologies
  - Acquisition, processing and representation of communication signals
  - Sensing and detecting chemical and biological substances, and physical quantities

Centre for Research and Utilization of Renewable Energy

SIX research centre sensor, information and communication systems

Department of Telecommunications

- The biggest department at the FEEC
  - >40 academic staff (FTE) and >50 Ph.D. students
  - More than 650 students of bachelor and master studies (Communications and Informatics, Audio-engineering, Information Security)
- The main areas we focus our research on
  - Data communication, cyber security
  - Signal processing, biomedical signal processing
  - Transmission systems, and optical fiber communications
  - Services and technologies for future mobile networks, measurement and maintenance in telecommunications
  - Analog signal processing & IC design

Jan Jerabek: jerabekj@feec.vutbr.cz

- CV
  - Assoc. Prof. at Department of Telecommunications
  - Researcher of SIX research centre
- Recent activities
  - Fundamental research in area of analogue signal processing
  - Lecturing of bachelor- and master-degree courses focusing on computer networks and Internet technologies
  - Interested in internet protocols (IP), routing technologies, cyber security
  - Trained by Cisco (academy instructor) and Huawei (4G network)
  - Supervisor of 3 Ph.D. students, ~50 defended bachelor and master's theses
  - External consultant and evaluator for Czech Telecommunication Office

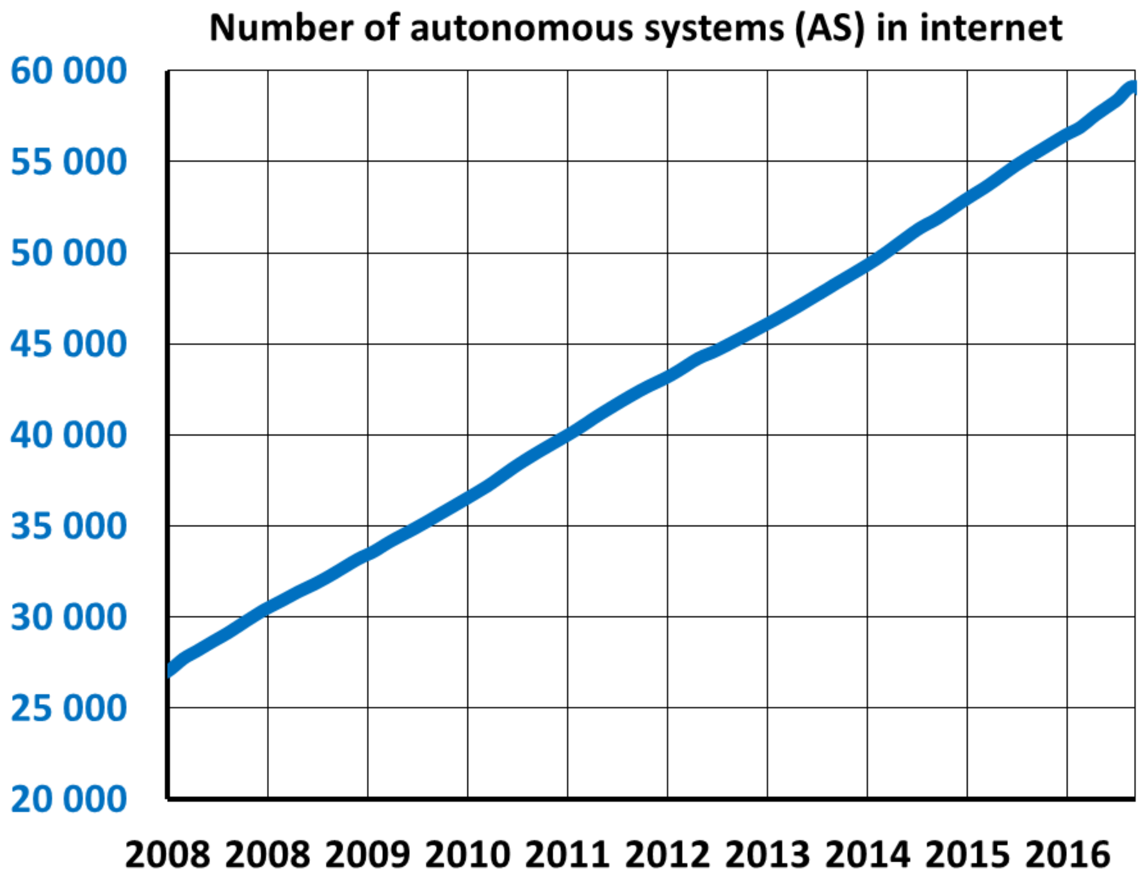
Motivation for basic measurements in IP-based networks

Basic facts about IP-based networks (Internet)

- Autonomous Systems (AS)
  - Internet Service Provider (ISP)
  - Content Provider
  - Content Delivery Network (CDN)
  - Telecom/Transit Operator
  - Big company / university
- Question #1: How many ASes?
- Interconnections of ASes
- Question #2: How many interconnections needed?

Basic facts about IP-based networks (Internet)

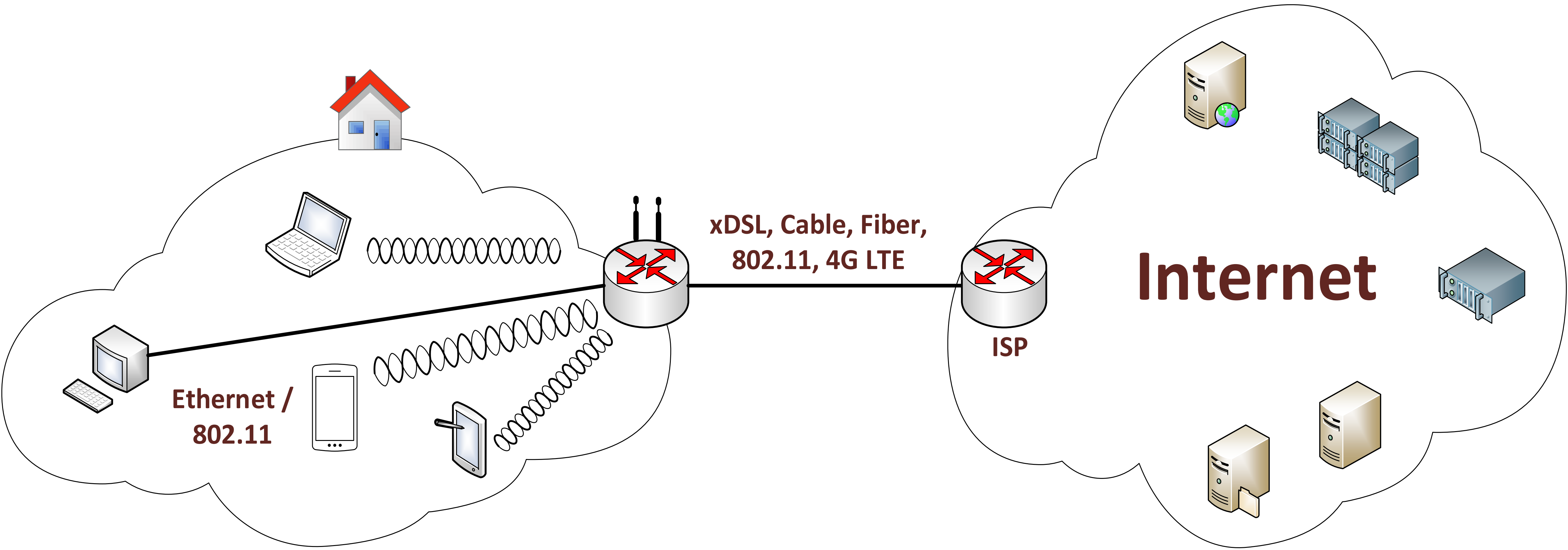
- Question #1: How many ASes?
  - >55.000 of numbered ASes
- Question #2: How many interconnections needed?
  - n = (#ASes(#ASes−1))/2 ≈ 10^9
- Internet Exchange Points (IXP) needed



Basic facts about IP-based networks (internet)

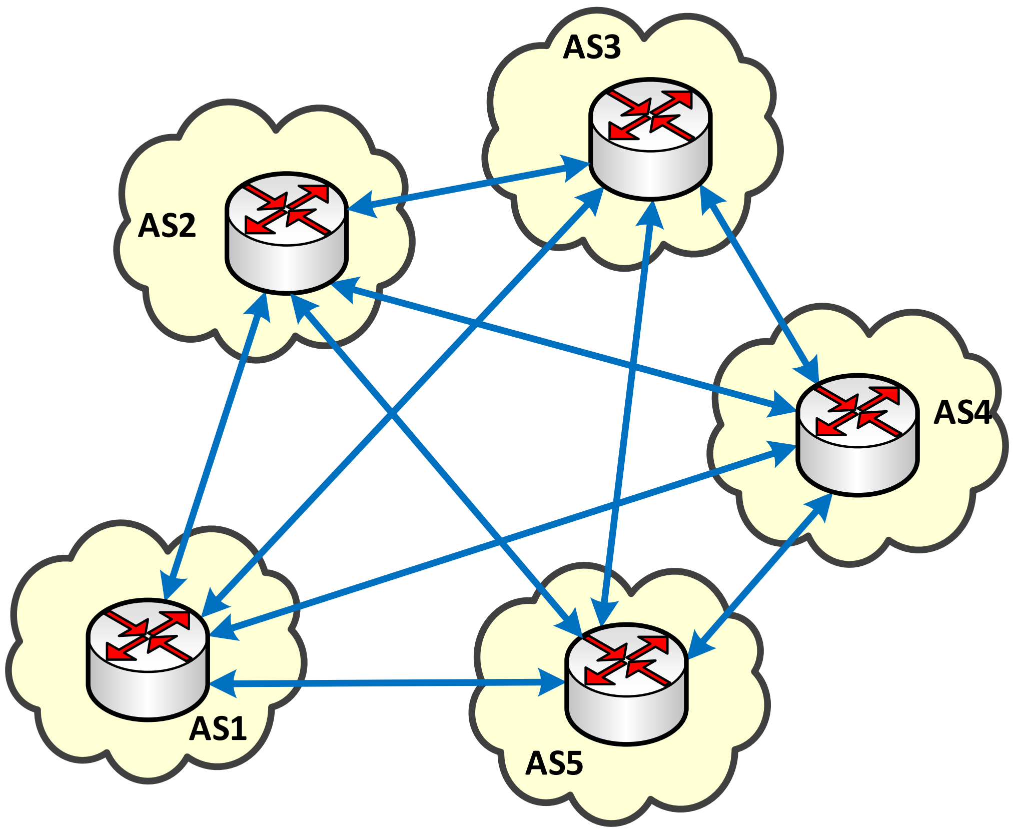
- Network access technologies
  - xDSL, Wi-Fi, Cable, Fiber, 4G LTE, …
- Basic devices
  - End devices
  - Network devices
  - Firewalls and proxies
  - Network Address Translators (NATs), load balancers
- Transmission Control Protocol / Internet Protocol (TCP/IP) stack over *anything*
- HyperText Transfer Protocol (HTTP) *everywhere*

Simple home/local network connected to internet

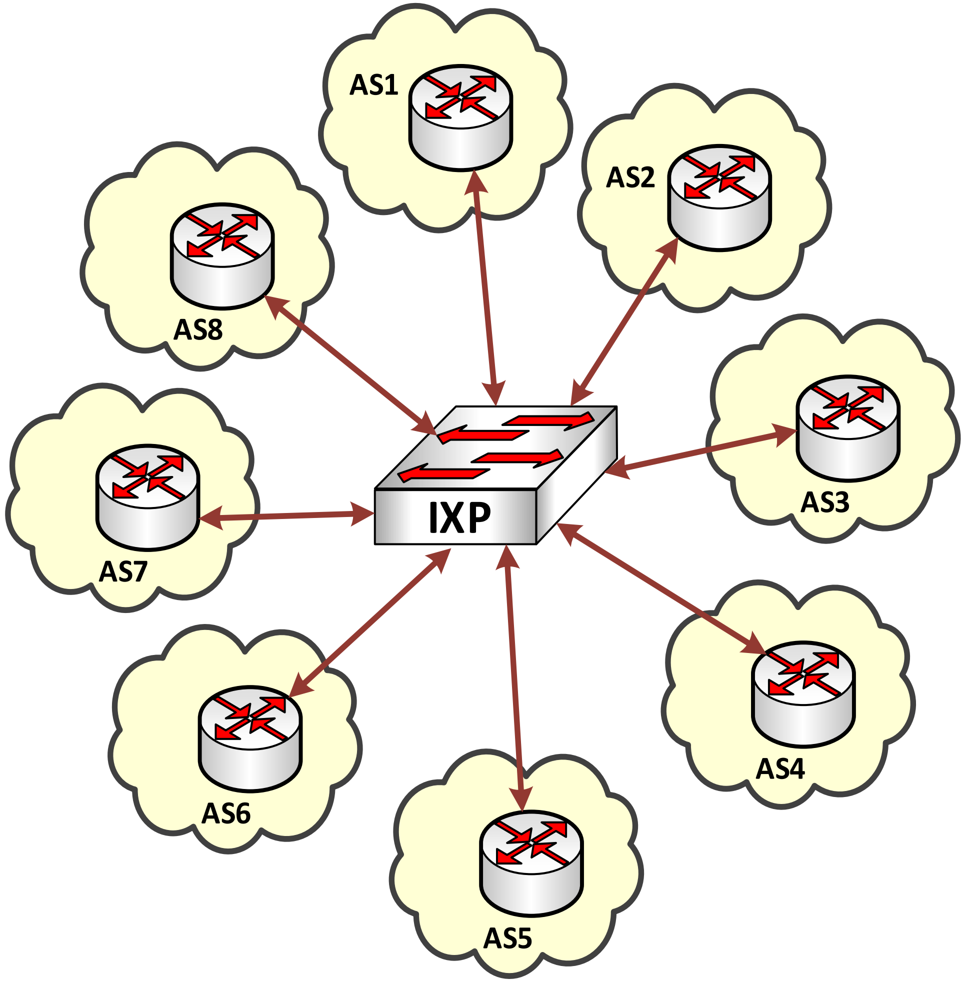


Interconnections of ASes

- Private peering

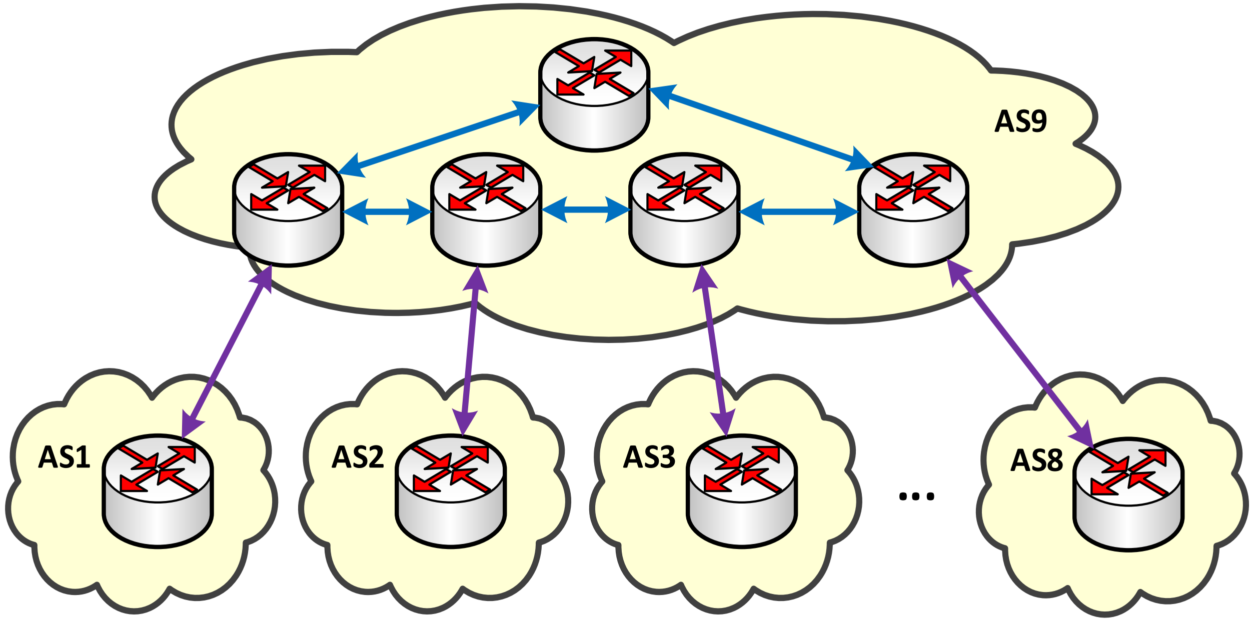


- Public peering

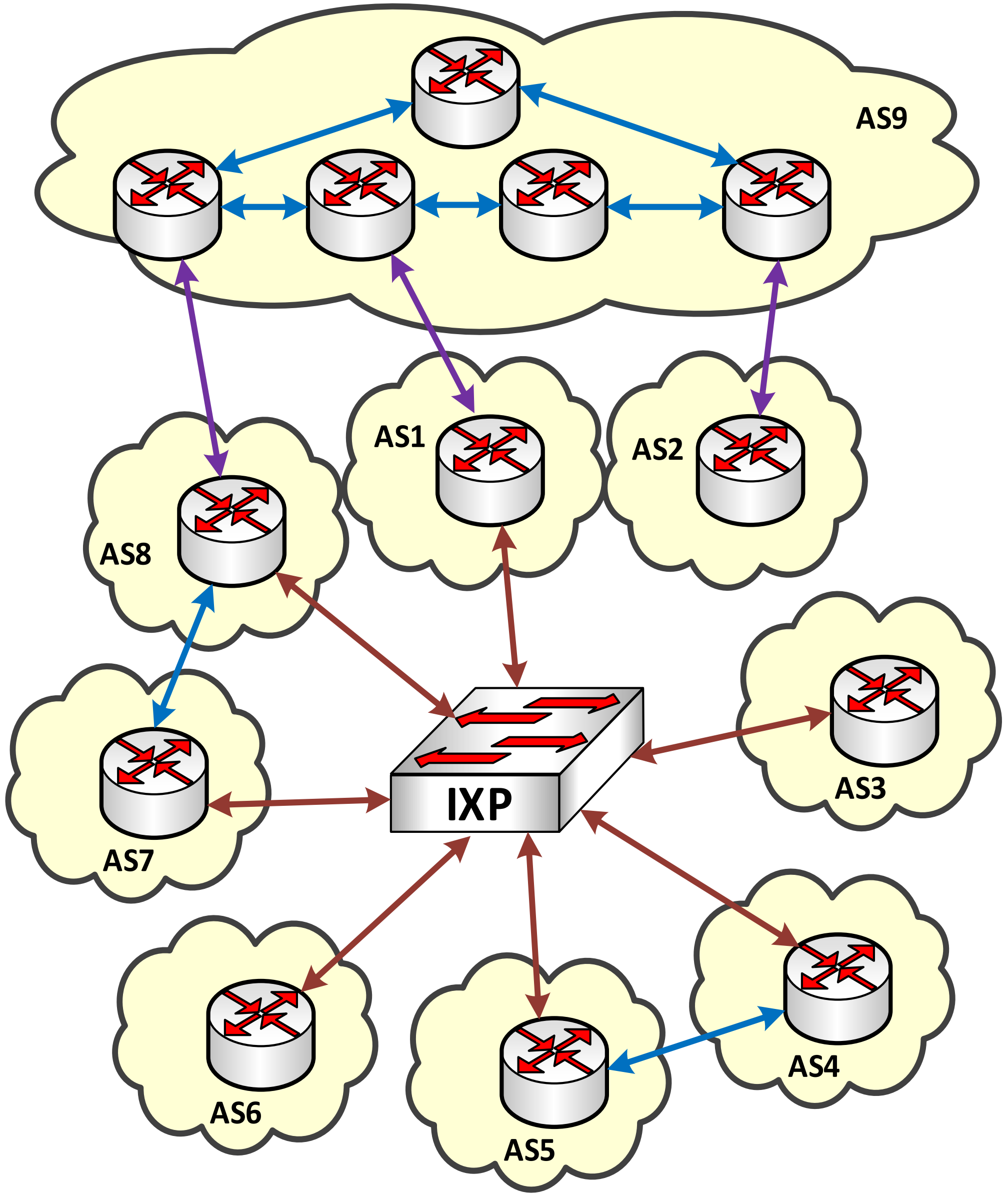


Interconnections of ASes

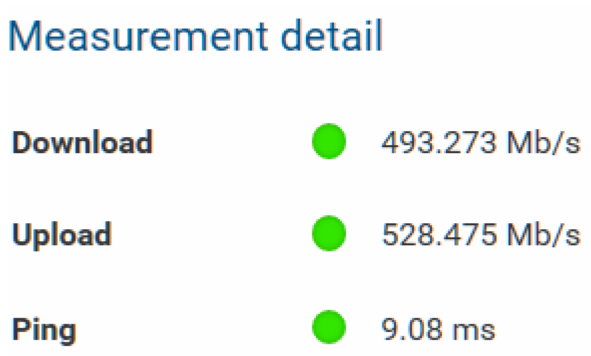
- Transit

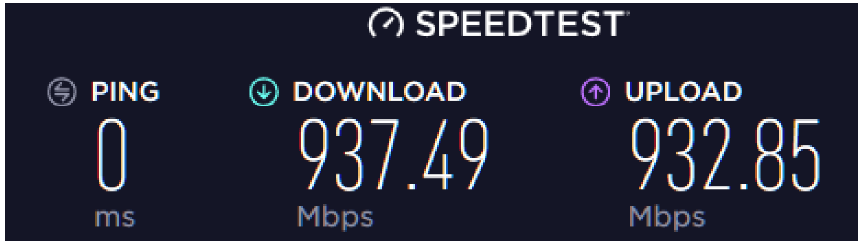


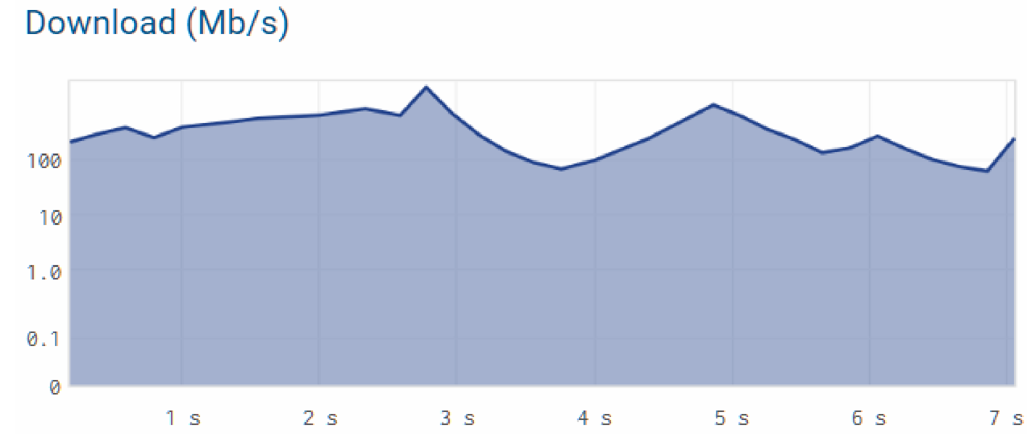
- Combination

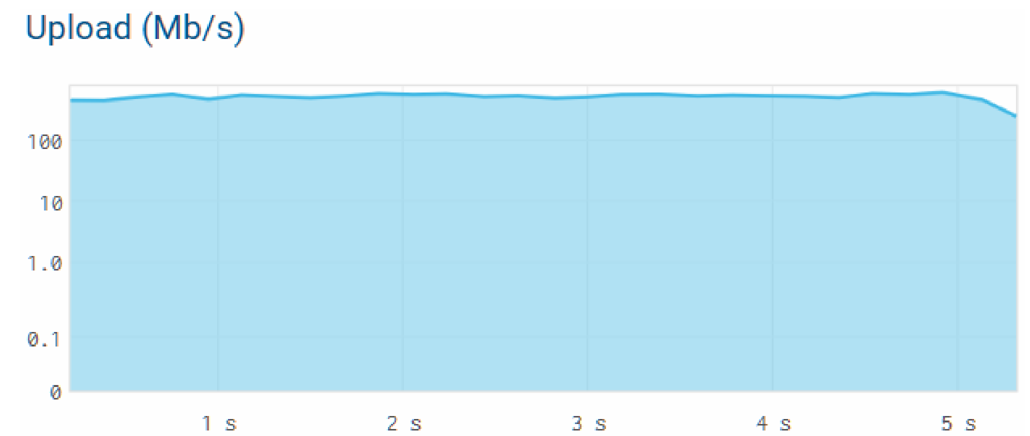


HTTP-initiated measurements



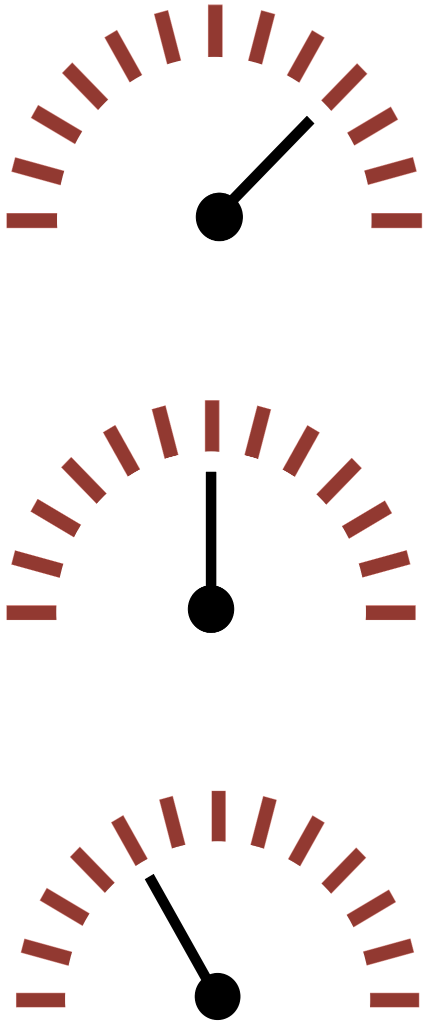




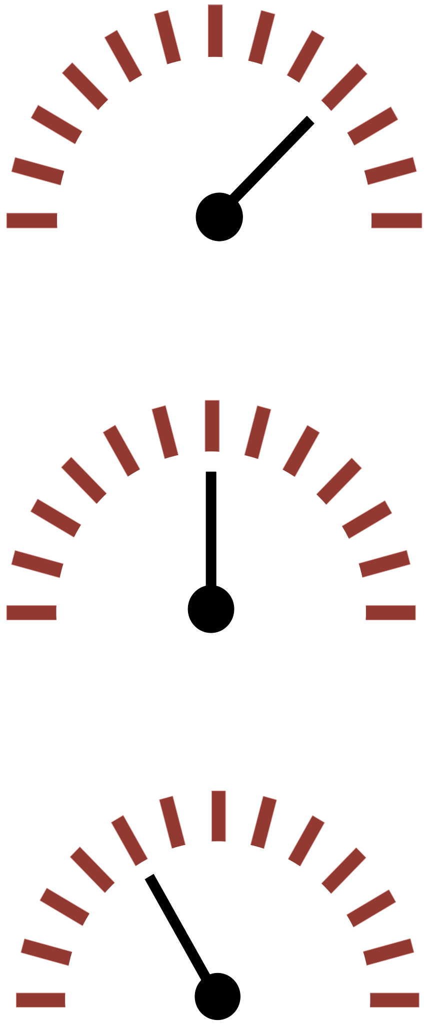


What is the maximum throughput?

- Layer matters
  - L1/L2 (frames)
  - L3 (IP layer)
  - L4 (Transport Layer)
  - L7 (data)
- Example with 100BaseT Ethernet
  - L1/L2: 100.0 Mb/s
  - L3 in Ethernet frame : 97.5 Mb/s
  - L4 in IPv4: 96.2 Mb/s
  - L7 in TCP: 94.9 Mb/s
- Question #3: Reason for decrease?



What is the maximum throughput?



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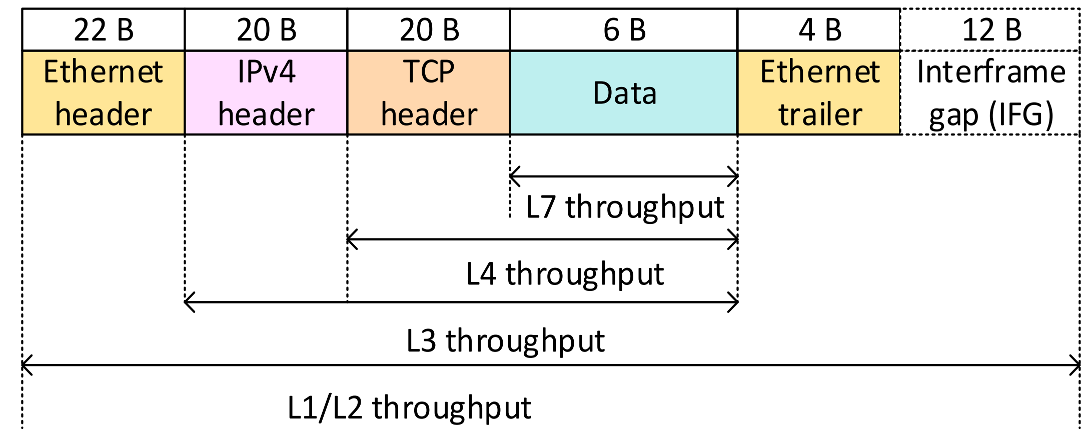
- Question #3: Reason for decrease?
  - Encapsulation at each layer (overhead)

Encapsulation and data size matters

- Data forms certain part of whole frame
  - Minimum
    - 7.1 %
    - 7.1 Mb/s maximum (L7)



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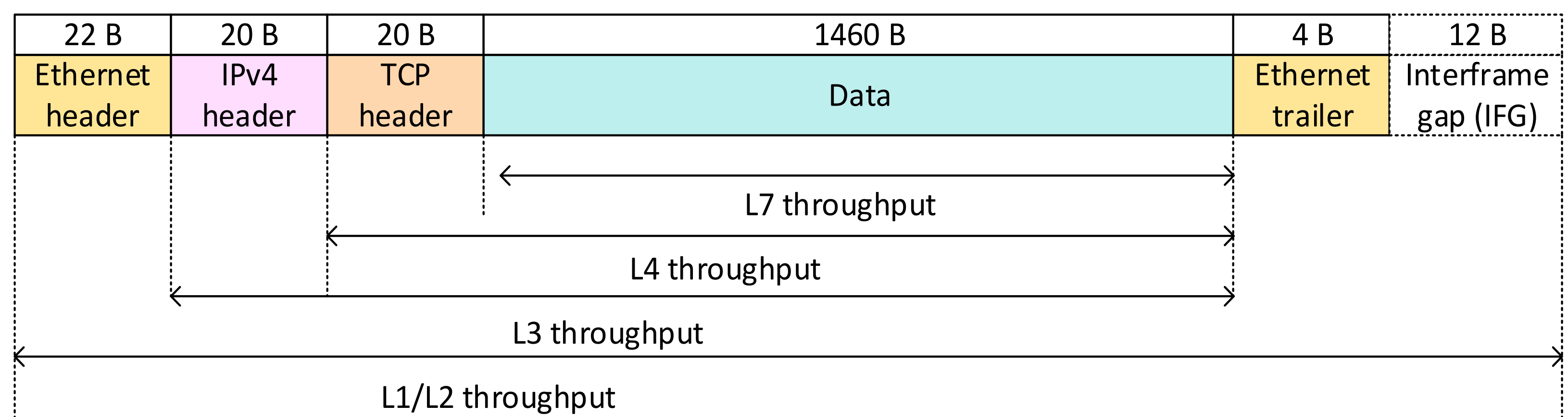
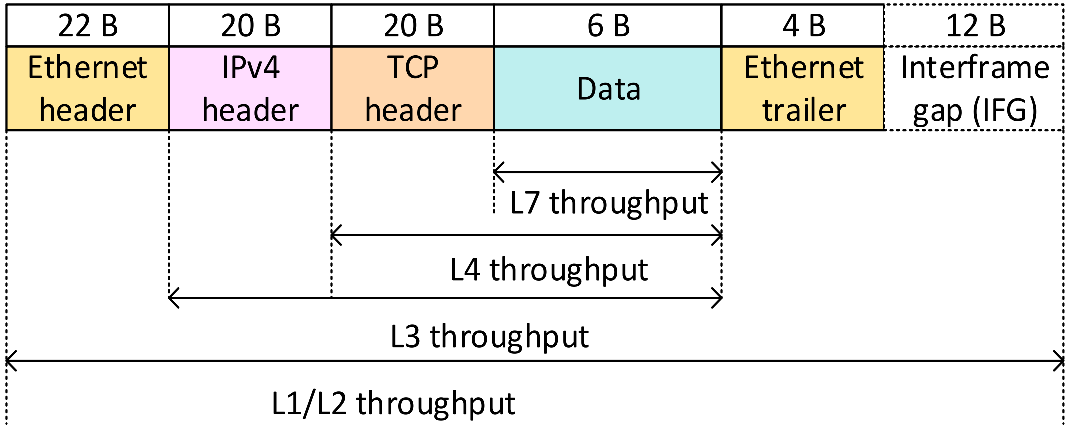


- Question #4: Are there any conditions?

Encapsulation and data size matters

- Data forms certain part of whole frame
  - Minimum
    - 7.1 %
    - 7.1 Mb/s maximum (L7)



  - Maximum
    - 94.9 %
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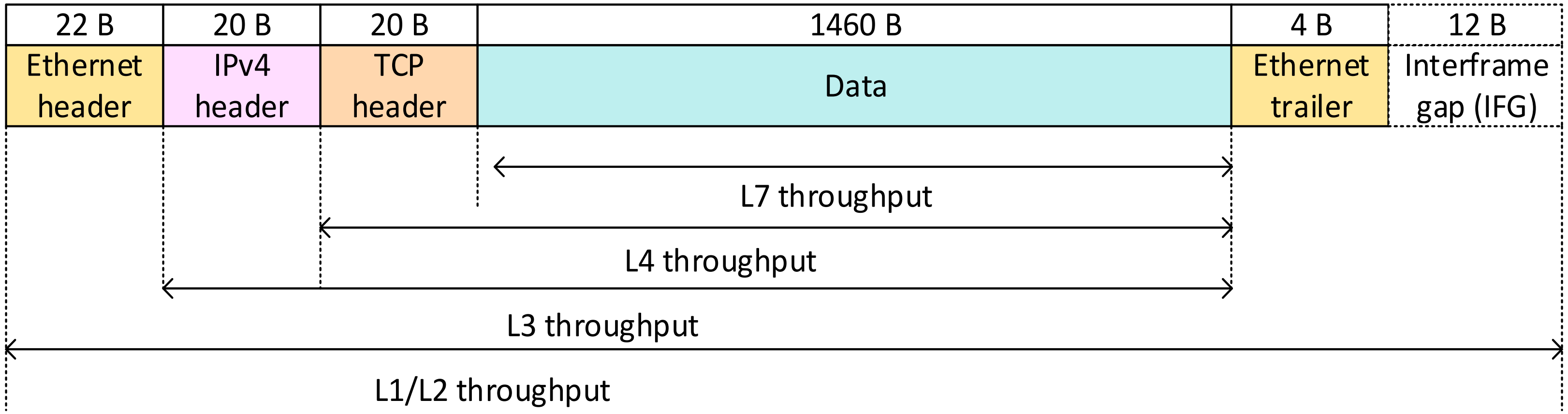
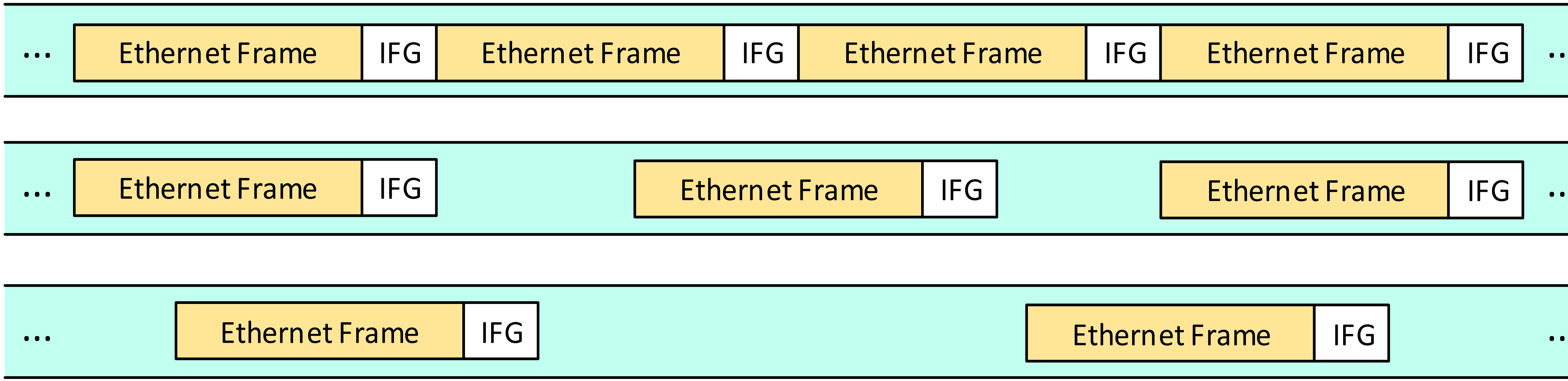


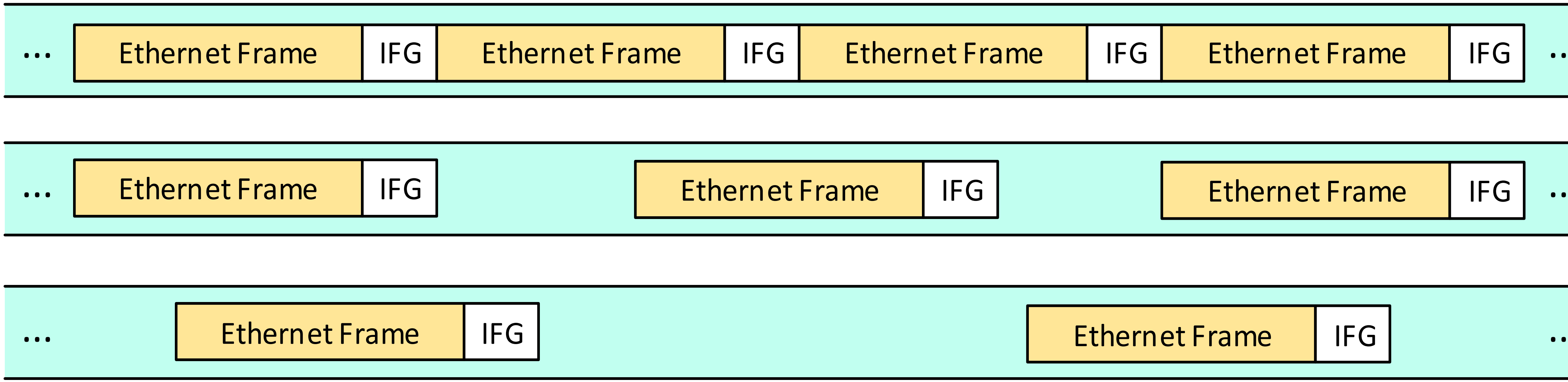
- Question #4: Are there any conditions?
    - No other gaps between frames

Medium utilization matters



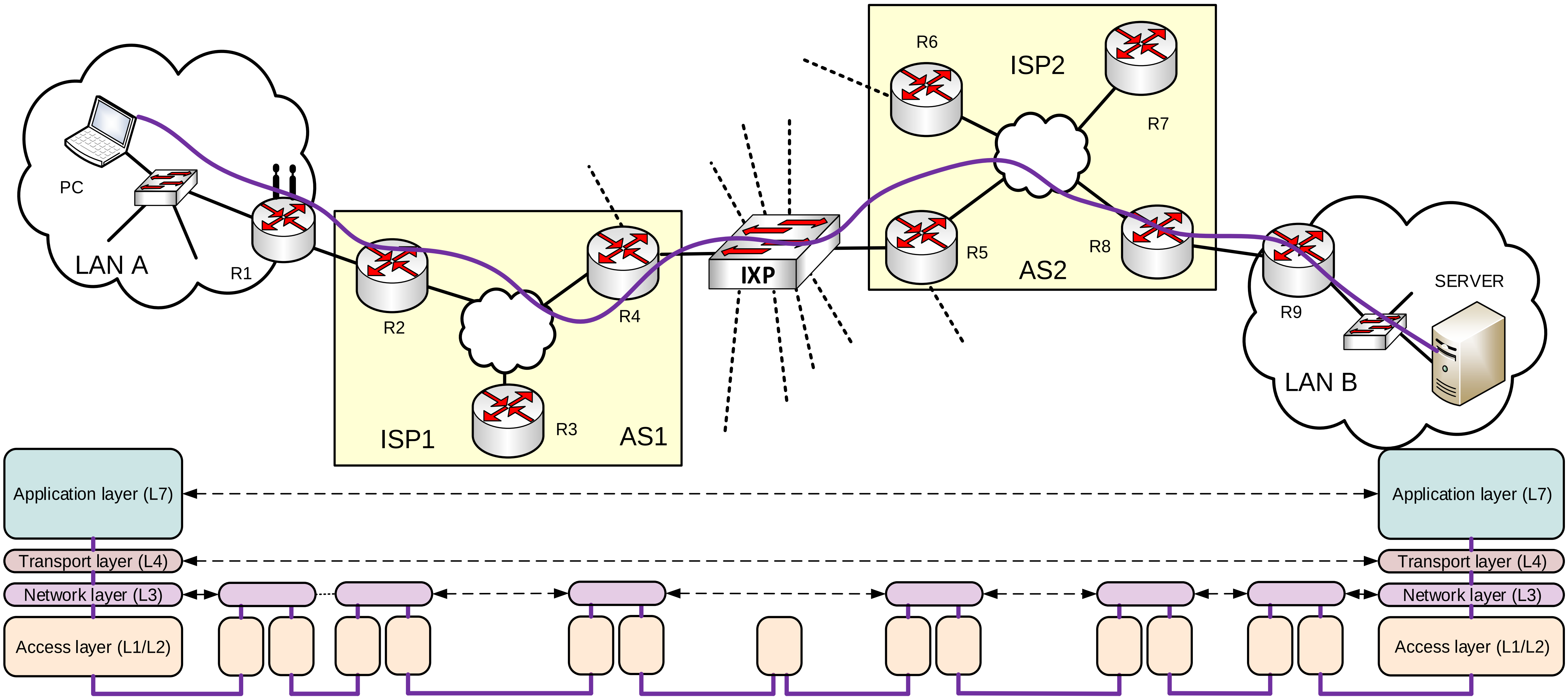
- Question #5: Reasons for gaps?

Medium utilization matters



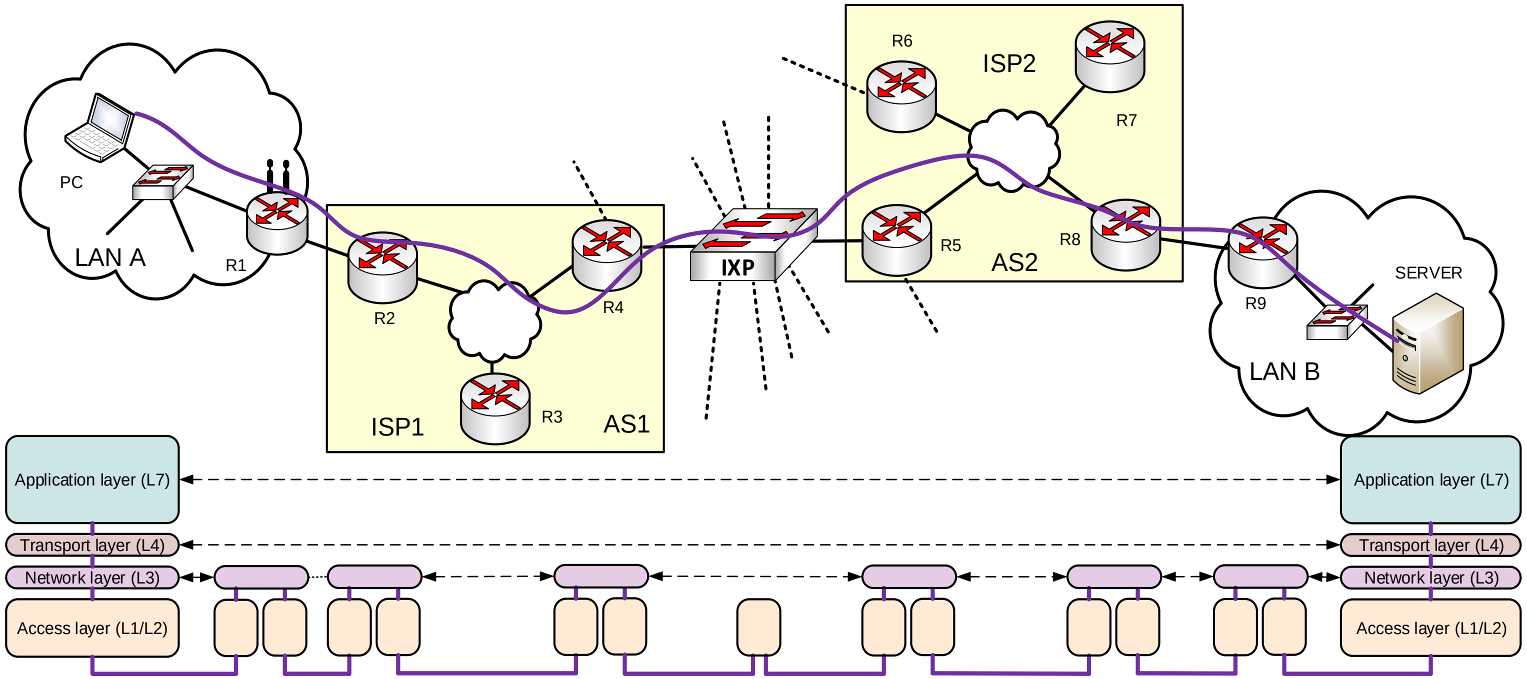
- Question #5: Reasons for gaps?
  - No data to be transferred
  - Data not ready
  - Transmission not allowed
  - Limited somewhere else on the transmission path

Not only single transmission line between hosts



Not only single transmission line between hosts

- L1/L2 useful for hop-by-hop measurements
- L3 can pass the networks
  - IP protocol has no capability of transmission control
- L4 with
  - User Datagram Protocol (UDP)?
  - Transmission Control Protocol (TCP)?
- L7 with HTTP or something else?



UDP vs. TCP protocol in general

- Measurement with UDP
  - No mechanism for control of packet flow
  - No L4 division of data
  - Not able to adapt to current state of the network
  - Measurement or network attack?
  - Additional functions needed at L7 (Chrome and Quick)
- Measurement with TCP
  - Widely used protocol
  - Precise control of transmission of packets
  - Stream of numbered bytes, acknowledged
  - Window size system giving credits to the sender
  - Adaptation

UDP

(8 B)

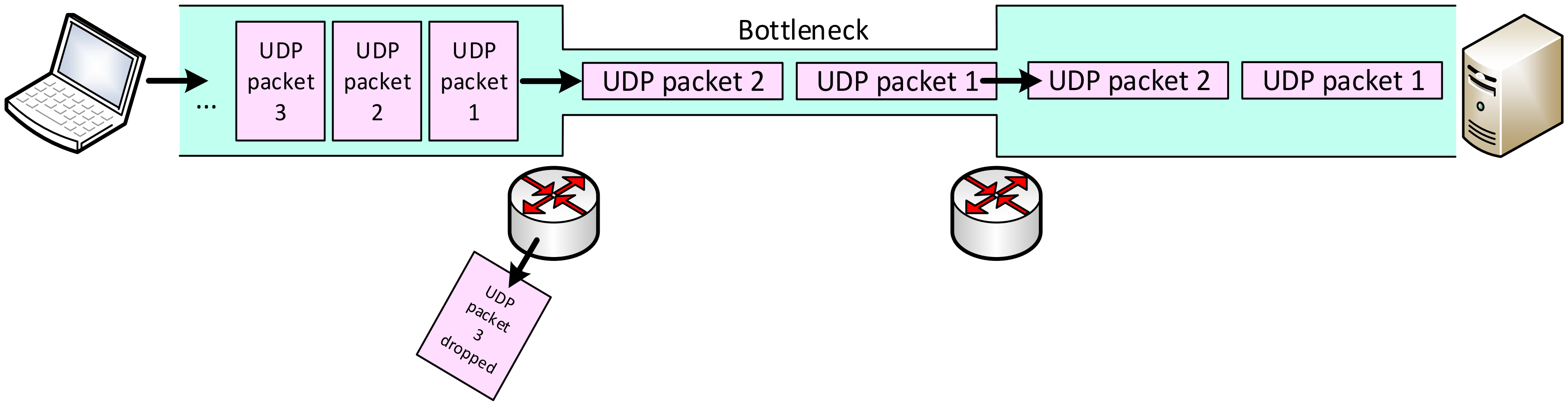
TCP

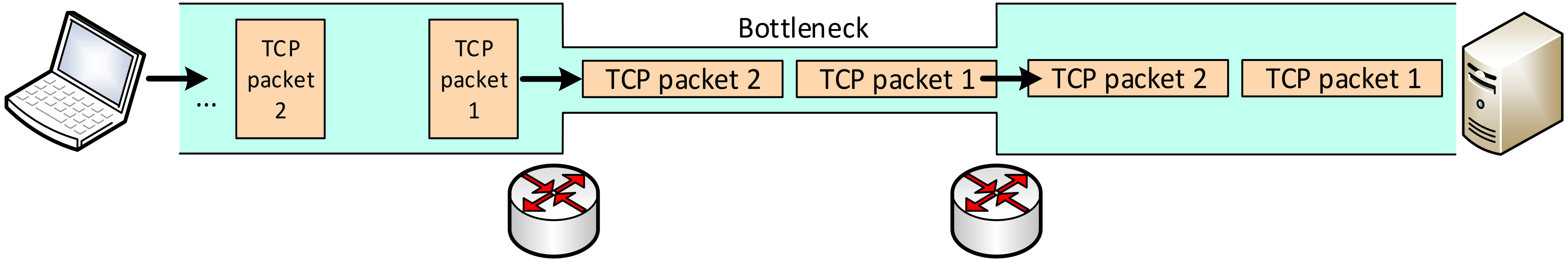
(20 B)

to

(60 B)

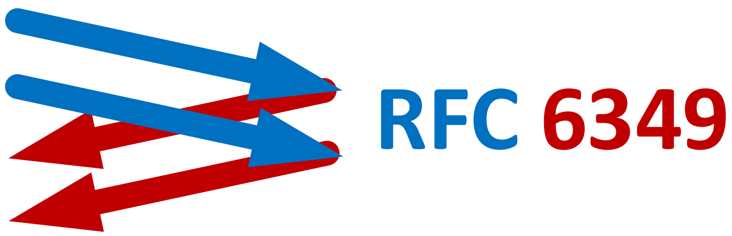
UDP vs. TCP behaviour vs. bottleneck





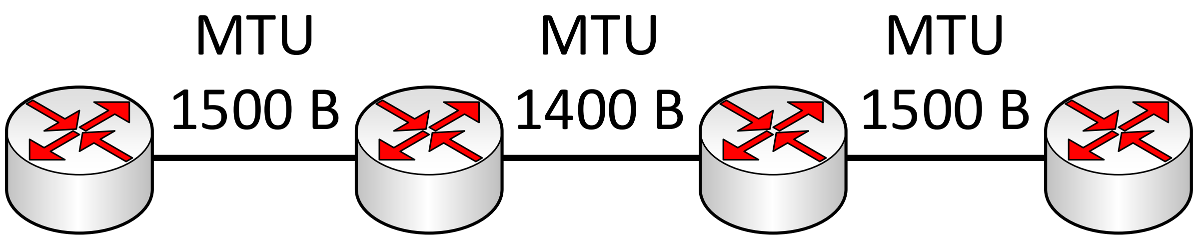
RFC 6349 - Framework for TCP Throughput Testing (*2011)

- Published by Internet Engineering Task Force (IETF)
- Practical methodology for measuring end-to-end TCP Throughput in a managed IP network
- TCP in the equilibrium state should perform very close to the BB (Bottleneck Bandwidth)
- Not suitable for dysfunctional networks / connections
  - >5% packet loss and/or >150 ms of jitter
- Few steps before measurement
  - Identification of Path Maximum Transmission Unit (MTU)
  - Identification of baseline Round-Trip Time (RTT) and expected Bandwidth
  - Configuration of TCP parameters - based on calculation



Path Maximum Transmission Unit (MTU)

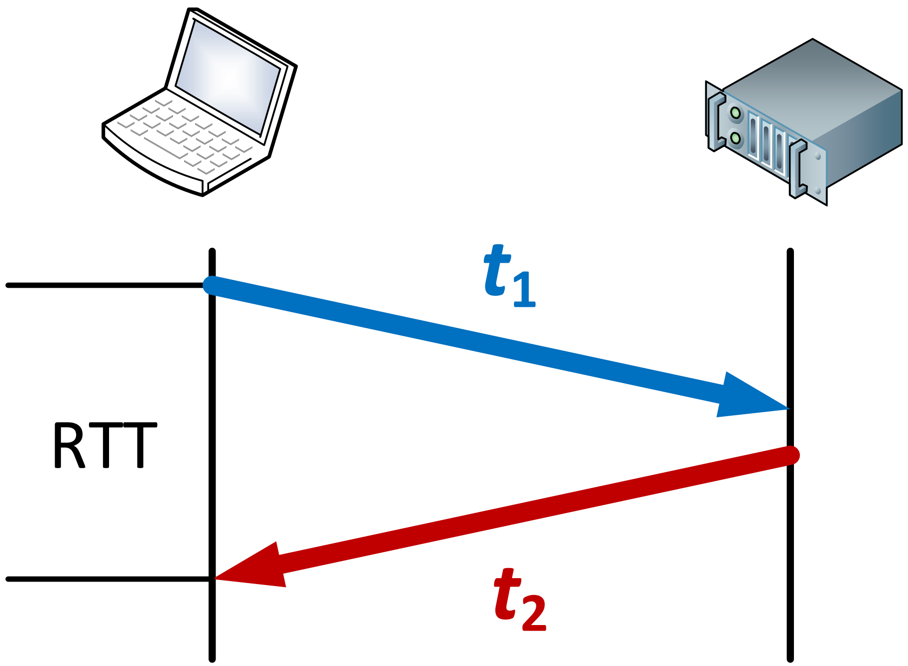
- Why minimum value of MTU matters?
  - Avoid IP fragmentation / drops of packets
  - Fully utilize available bandwidth



- Methods defined by
  - RFC 1191 [*1990] Path MTU Discovery
    - Utilization of IPv4 packets with don’t fragment bit DF = 1
    - Requires Internet Control Message Protocol version 4 (ICMPv4) messaging from network
  - RFC 1981 [*1996] Path MTU Discovery for IP version 6
    - Similar to RFC 1191, adapted for IPv6 environment
    - Requires Internet Control Message Protocol version 6 (ICMPv6) messaging from network
  - RFC 4821 [*2007] Packetization Layer Path MTU Discovery
    - Not dependent on ICMP protocol
    - Considers Path MTU-based problems in communication protocols (TCP)

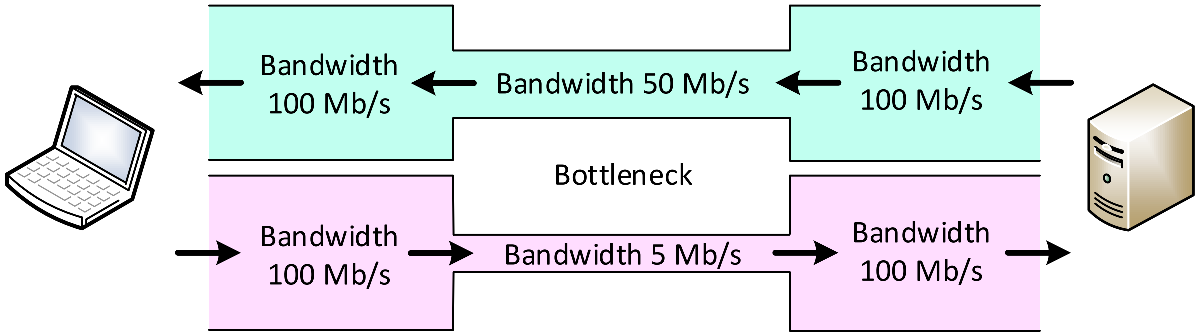
Baseline Round-Trip Time (RTT)

- Response time when load low
- Given by many factors, depends also on
  - Size of packet
  - Security rules
- Basic ways how to estimate it
  - ICMP or ICMPv6 protocol
  - TCP or UDP-based echo protocol
  - Parameters from previous TCP communication (RFC 4898)
  - Packet captures of other tools and protocols (DNS query, HTTP get, …)
  - A Two-Way Active Measurement Protocol (TWAMP) (RFC 5357)



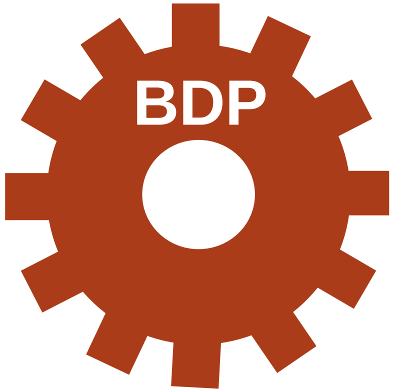
Bottleneck Bandwidth (BB)

- Lowest bandwidth along the path
- Access network
- May by very asymmetric
- Should be estimated by / from
  - Contract with provider
  - Benchmarking Methodology for Network Interconnect Devices (RFC 2544)
    - Laboratory tests
  - Defining Network Capacity (RFC 5136)
    - Defines only particular calculations and methodology for real networks
  - Stateless measurement (UDP)



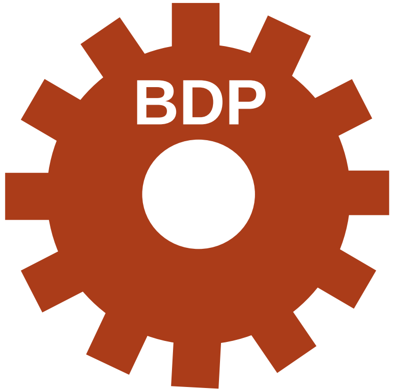
RTT, BB and Bandwidth Delay Product (BDP)

- Question #6
  - What is example value for high/low RTT?



RTT, BB and Bandwidth Delay Product (BDP)

- Question #6
  - What is example value for high/low RTT?
  - 250 ms vs. 50 ms vs. 10 ms

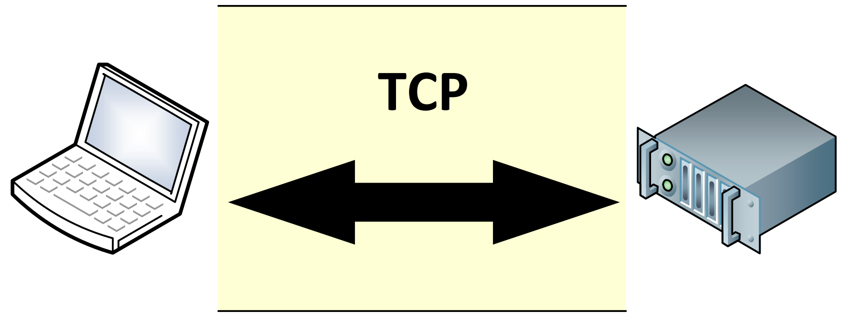


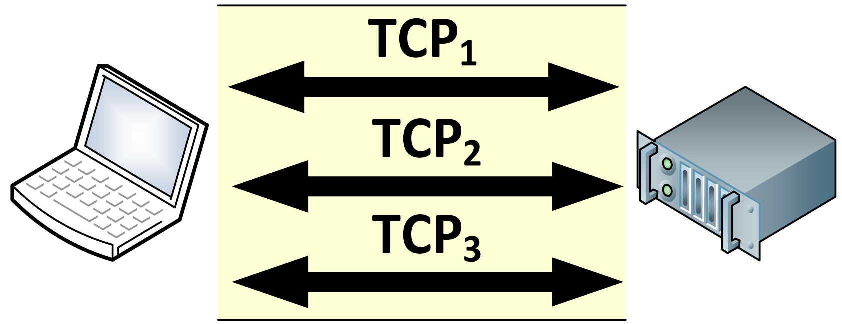
- Bandwidth Delay Product (BDP) is what matters for TCP
  - BDP = RTT * BB
  - Examples

RTT = 250 ms	RTT = 50 ms	RTT = 10 ms
BB = 10 Mb/s	BB = 100 Mb/s	BB = 1 Gb/s
BDP = $2.5 \cdot 10^6$ b = 312.5 kB	BDP = $5 \cdot 10^6$ b = 625 kB	BDP = 10^7 b = 1250 kB

TCP window size and number of connections

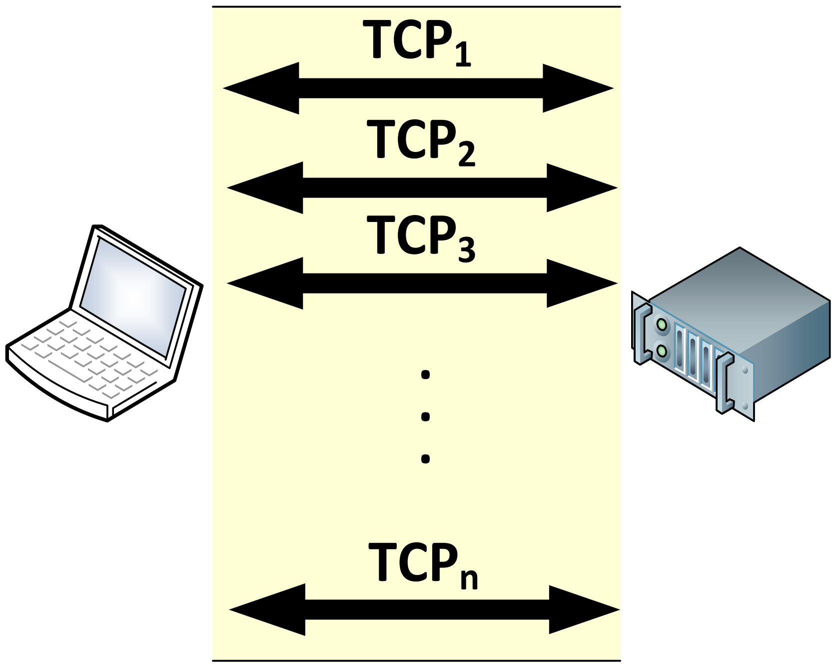
- We need: Receive Window (RWND) ≥ BDP
- Standard TCP RWND size ≤ 64 kB
- TCP Option: Window Scale
  - RWND*2^{SCALE}
  - Where maximum SCALE = 14 (in theory), maximum Scaled RWND = 1 GB
  - In practice, SCALE = 8 is sufficient, maximum Scaled RWND = 16 MB
- What if Scaled RWND is not sufficient or available?
  - Example
    - Required (Scaled) RWND = 160 kB
    - Chosen size of RWND = 64 kB
    - Number of connections required $n \geq 3$





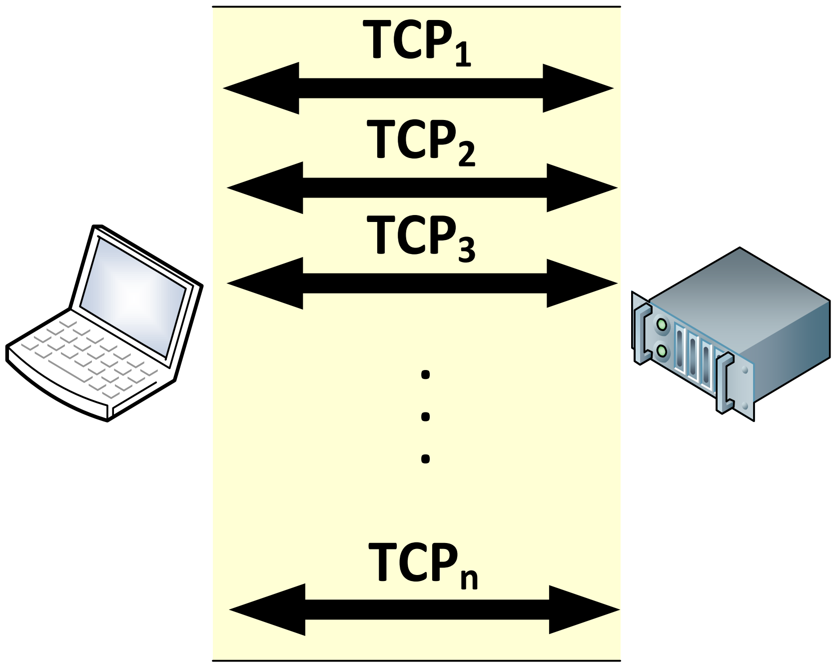
TCP window size and number of connections

- Question #7
  - Is there any limit for total number of concurrent TCP connections?



TCP window size and number of connections

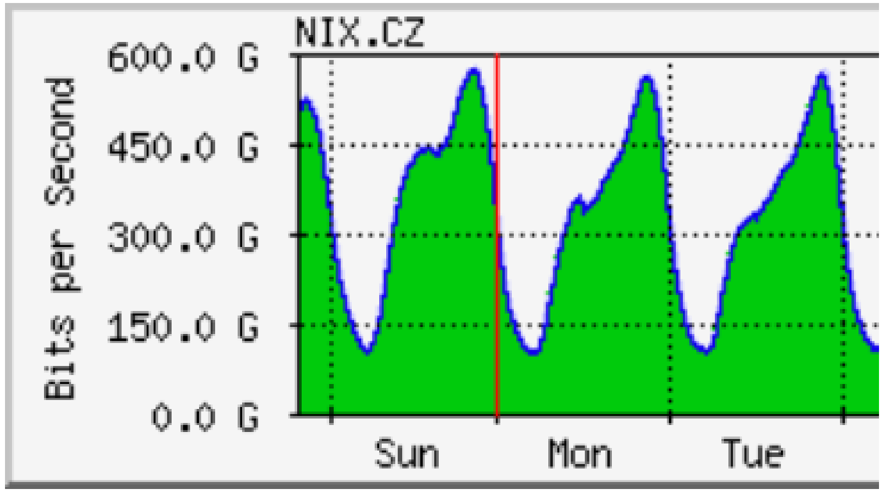
- Question #7
  - Is there any limit for total number of concurrent TCP connections?
  - Always yes, based on
    - Numbers of available ports
    - Software settings or license restrictions
    - Middle-box limits (NAT, firewall, tunnel)
    - Resource consumption



- My recommendation
  - $3 \le n \le 32$
  - *Scaled RWND* ≤ 8 MB

Length of measurement

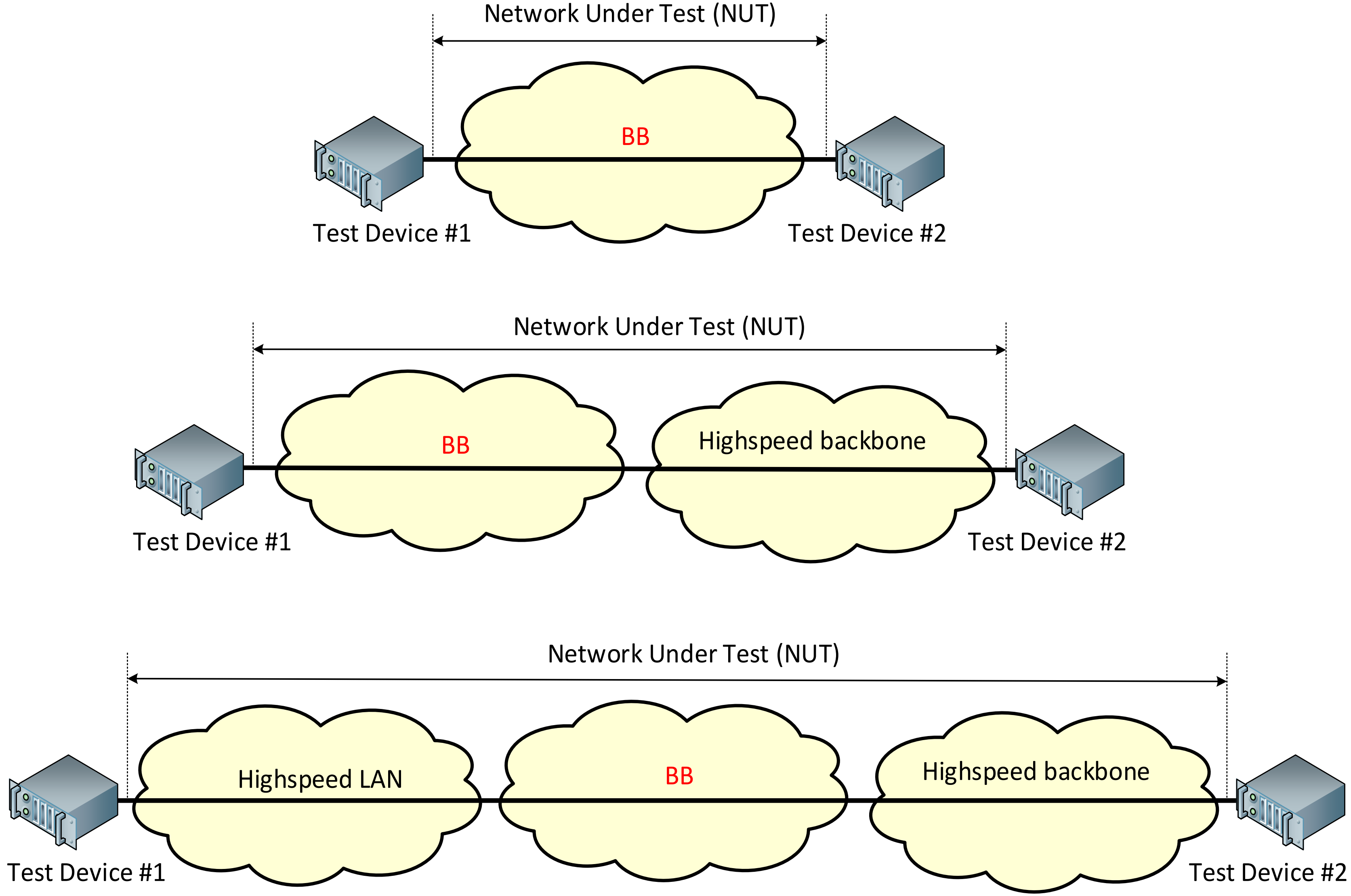
- Problem with accuracy, time demands and total data transferred
- Possible schemes
  - Fixed time of measurement of download and upload throughput
    - Professional measurement (at least 60 s / per direction)
    - Crowdsourced measurements (max 30 s / whole test)
  - Fixed size of data to be transferred
  - Permanently running test
- One test vs. repeated measurements
  - Busy hours
  - Random time during day / hour



Type of measured network (access technology)

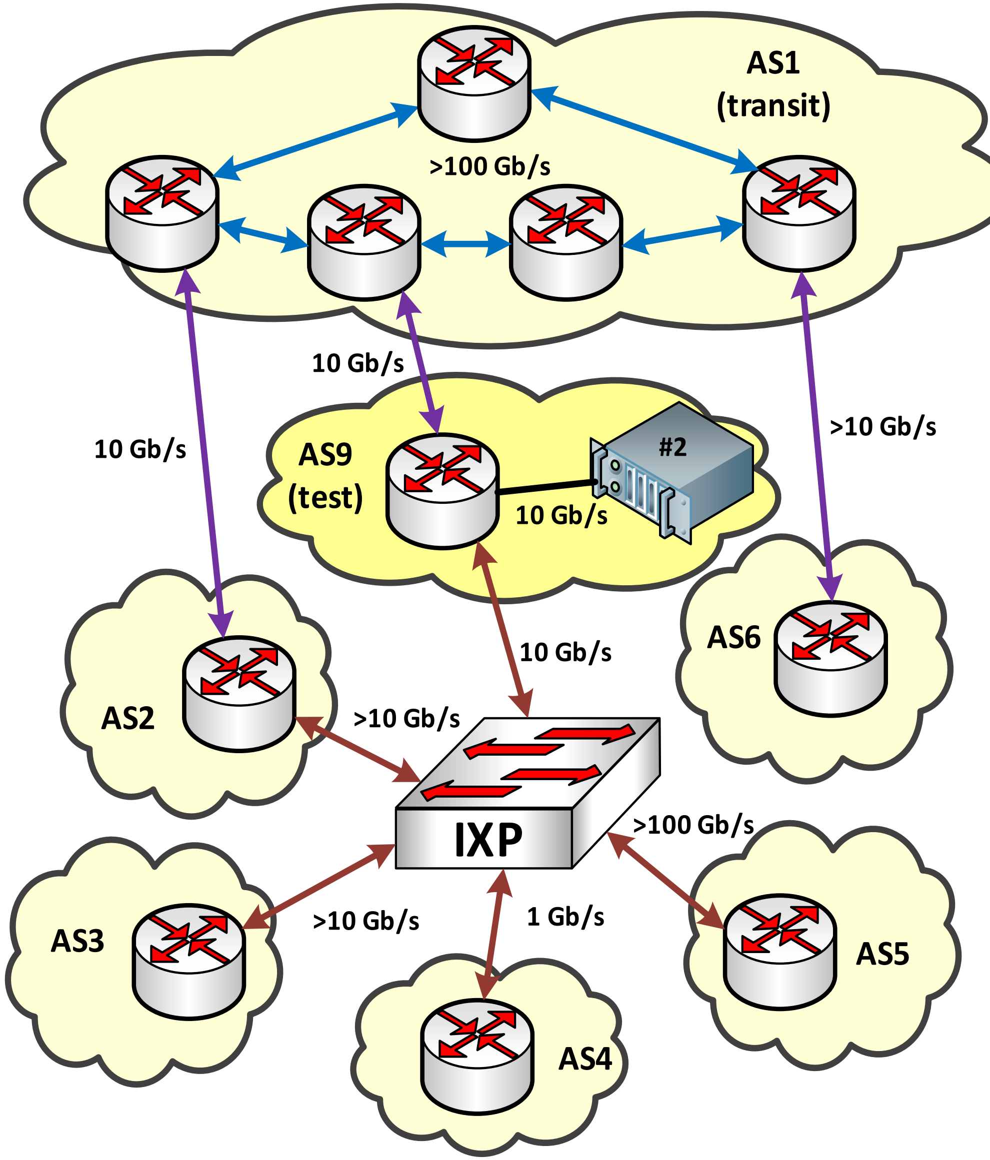
- Wired connections
  - Stable conditions
  - Usually no *visible* transferred data cap in Fair User Policy (FUP)
  - Longer test time acceptable
- Wireless connections
  - Usually with (low) data cap (FUP)
  - Radio parameters change
  - GPS position should be recorded
  - Two types of measurement
    - Fixed position
    - Drivetest

Placement of test devices



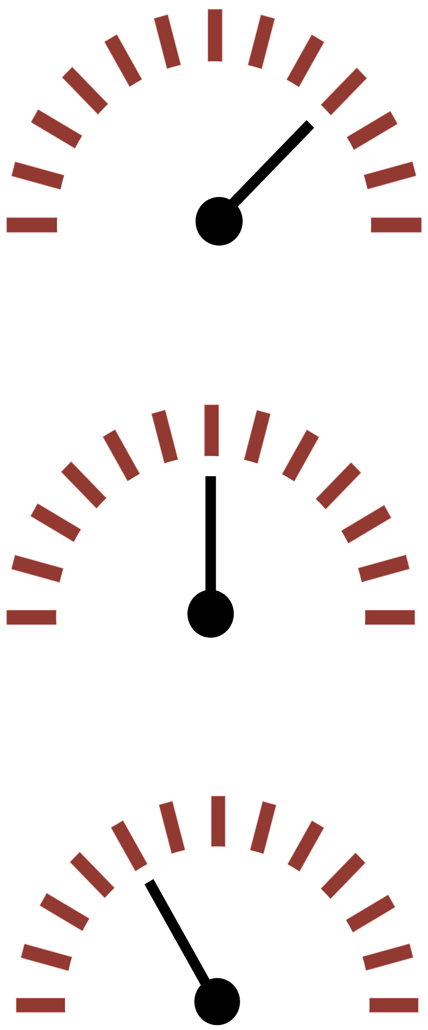
Fixed placement of test device #2

- Special AS created with Test device #2 (measurement server)
- Connected to IXP and transit operator
- Test device #1 in any AS (network)
- Traffic goes through IXP node or transit operator (AS)
- Ready for reliable measurements of throughput up to 1 Gb/s
- BB expected on access part (xDSL, cable, LTE, WiFi)
- Expects any AS to be capable of achieving throughput > BB

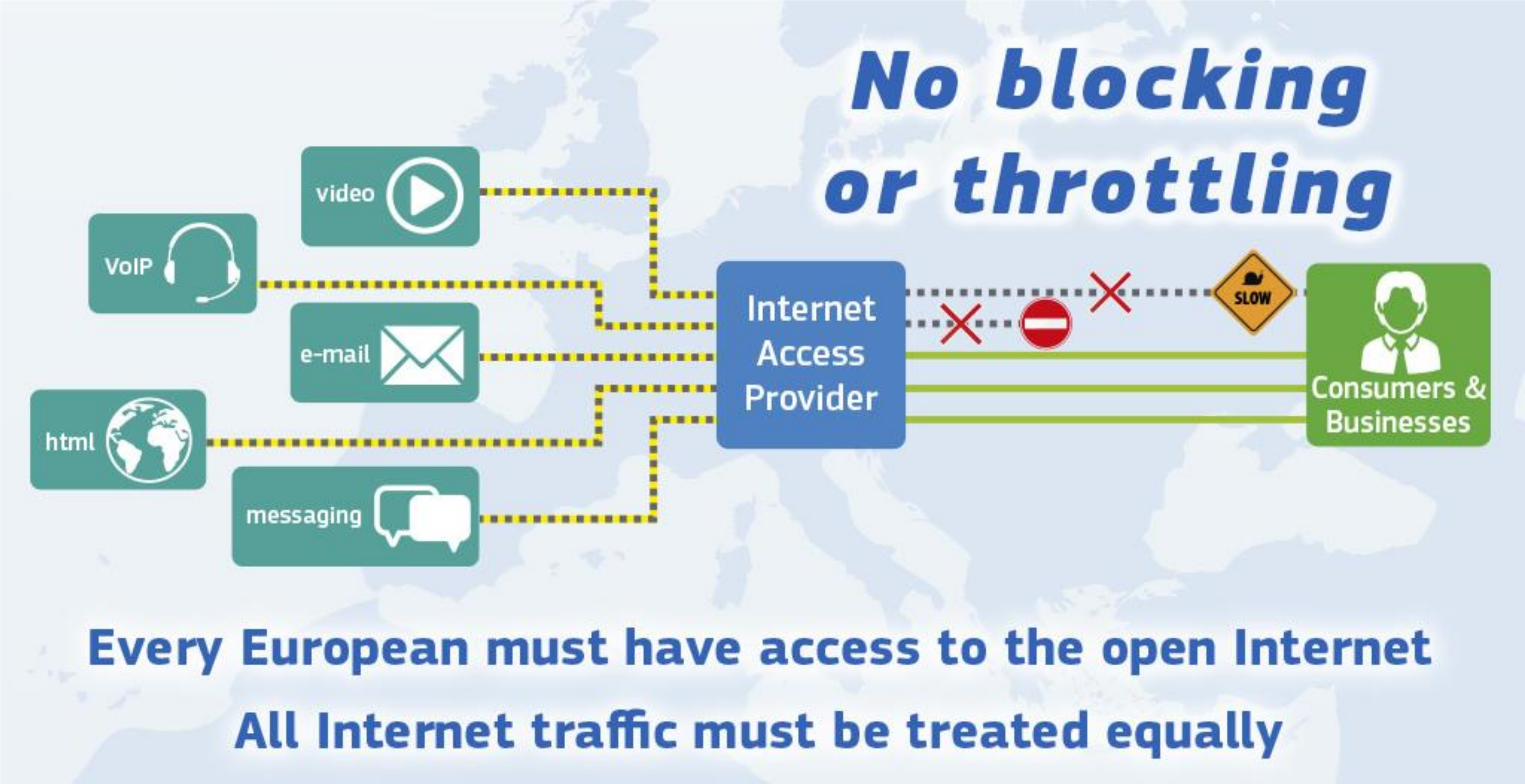


Test device #1

- Smart phones (apps)
  - speedtest.net, FCC speed test
  - HE.net network tools
  - Open Nettest
- Desktop (SW tools)
  - Iperf3
  - Pktgen [19]
- HW probes



Net neutrality in the EU [1]

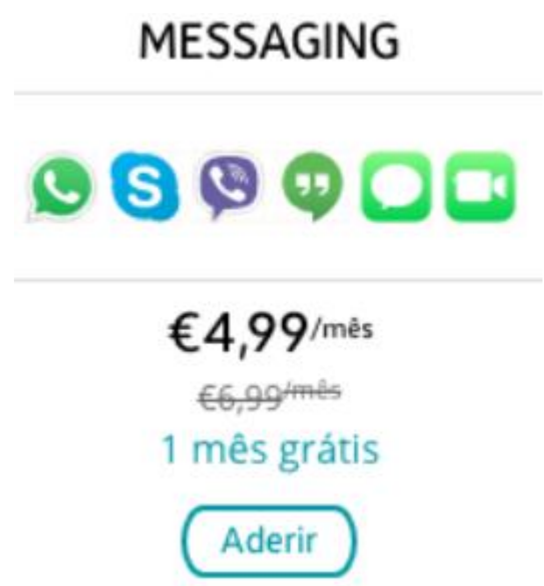


EU regulation 2015/2120 [2]

- Measures concerning area of open internet access
- Equal and non-discriminatory treatment of packets
- End-users should
  - Be free to choose between various types of terminal equipment
  - Have the right to use and provide applications and services without discrimination
- Covers several topics, explained by BEREC = Body of European Regulators for Electronic Communications [16] (group of National Regulatory Authorities (NRAs))
  - 37 member countries, including [8]
  - Portugal (Autoridade Nacional de Comunicações, ANACOM)
  - Czech Republic (Czech Telecommunication Office, CTO)

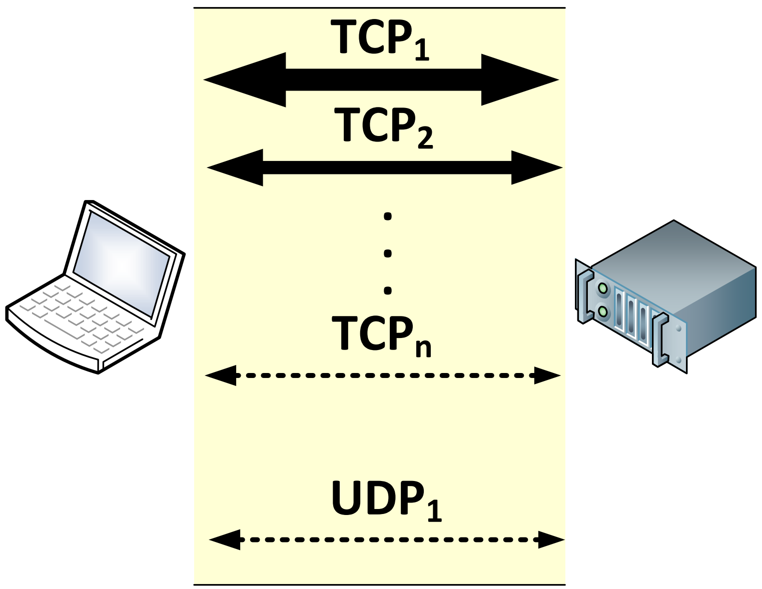
Zero rating [3]

- Price of *zero* to the data traffic associated with a particular application or class of applications
- What is prohibited?
  - When all applications are blocked or slowed down once the data cap is reached except for the zero-rated application(s)
- What is allowed?
  - Not clear
  - Operators are probing the possibilities
  - Depends on judgement of NRA (National Regulatory Authority)



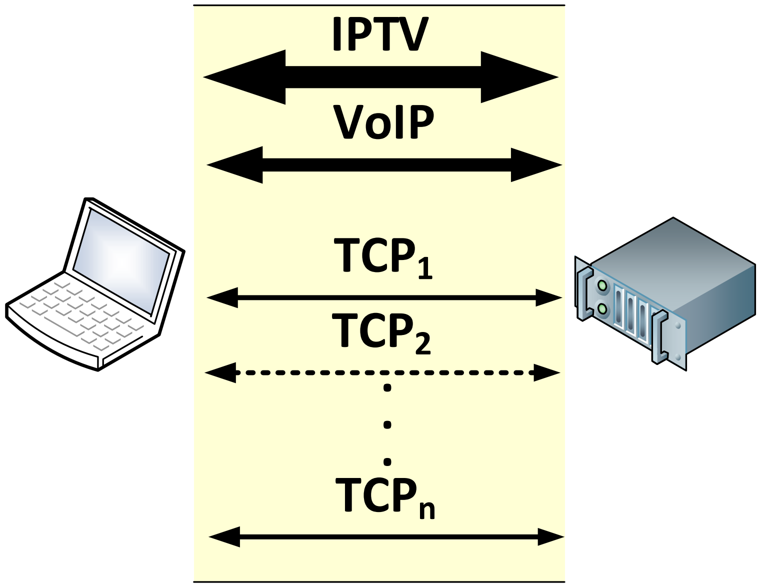
Traffic management [4]

- The traffic is forwarded in the networks several ways
  - First in – first out (FIFO)
  - Reordering of packets (traffic management)
- Treatment of traffic should be done independently of applications, end-users and usage of end-to-end ciphering
- What is allowed?
  - Alternative traffic management under limited circumstances
  - Optimization of the overall transmission quality
  - “Reasonable traffic management” which may be used to differentiate between “categories of traffic” (Quality of Service (QoS) requirements)
  - Preservation of integrity and security, congestion management measures



Specialized services [5]

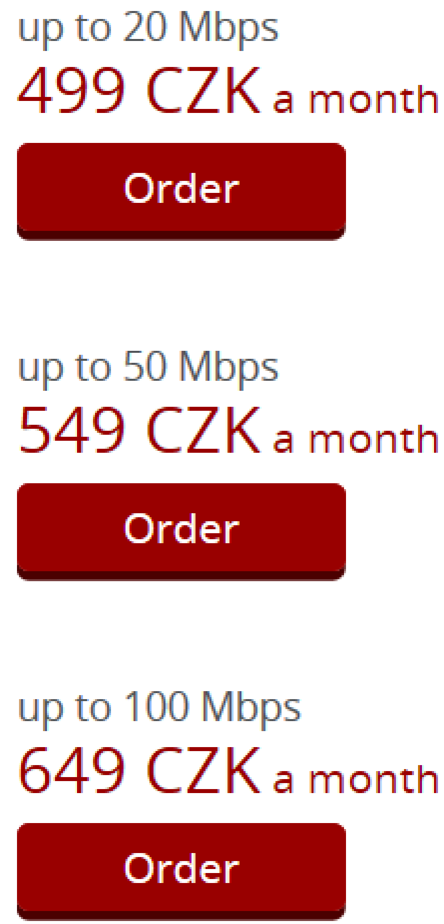
- Other than standard internet access services
- Optimized for specific content, applications or services, where the optimization is necessary
- Examples
  - VoLTE (voice over LTE), IPTV broadcasting, real-time health services
- Can be offered when the network capacity is sufficient that the internet access service is not degraded
- ISP should inform how specialized services might impact standard services



Example:
Company X provides two specialized services, not counting transferred data to data cap, decreasing available speed.

Transparency [6]

- ISP should publish
  - Speeds, data caps, and any traffic management measures
- Speeds for fixed services
  - Minimum – when current speed below, service down
  - Normally available - most of the time – the speed itself and the proportion of time it is available during a given period
  - Maximum - end-user could expect to receive at least some of the time
  - Advertised
  - Maximum ≥ Advertised ≥ (Normally available) ≥ Minimum
- Speeds for mobile services
  - Estimated maximum - realistically available maximum speed in different locations in realistic usage conditions
  - Advertised (Estimated maximum ≥ Advertised)



Example of speeds for mobile data services [11]

Type of technology		Estimated maximum speed		Advertised speed	
		Download	Upload	Download	Upload
2G	Edge	0,2 Mb/s	0,1 Mb/s	0,125 Mb/s	0,04 Mb/s
3G	HSPA	7,2 Mb/s	3,6 Mb/s	5 Mb/s	1 Mb/s
3G	HSPA+	42 Mb/s	5,76 Mb/s	5 Mb/s	1 Mb/s
4G	LTE	150 Mb/s	50 Mb/s	15 Mb/s	5 Mb/s
4G	LTE Advanced	375 Mb/s	50 Mb/s	15 Mb/s	5 Mb/s

Example of speeds for mobile data services [10]

Type of technology		Estimated maximum speed / Advertised speed		Minimum guaranteed speed	
		Download	Upload	Download	Upload
2G	Edge	0,2 Mb/s	0,1 Mb/s	16 kb/s	16 kb/s
2G	CDMA	3,1 Mb/s	1,5 Mb/s	16 kb/s	16 kb/s
3G	HSPA+	42 Mb/s	5,76 Mb/s	16 kb/s	16 kb/s
4G	LTE	150 Mb/s	55 Mb/s	16 kb/s	16 kb/s
4G	LTE Advanced	300 Mb/s	55 Mb/s	16 kb/s	16 kb/s

Example of speeds for mobile data services [9]

Type of technology and band		Estimated maximum speed		Advertised speed*				Minimum guaranteed speed	
		Down load (Mb/s)	Upload (Mb/s)	Download (Mb/s)		Upload (Mb/s)		Down load (Mb/s)	Upload (Mb/s)
				from	to	from	to		
2G	**EDGE**	0,2	0,1	0,02	0,1	0,02	0,04	0,02	0,02
3G	**HSPA+**	42	5,76	1,68	16,8	0,17	3,46	0,02	0,02
4G	**LTE 900**	20	4	0,5	6,5	0,11	2,2	0,02	0,02
4G	**LTE 800**	75	15	2,44	18,75	0,38	7,5	0,02	0,02
4G	**LTE 2100**	112	37	2,8	28	0,93	18,5	0,02	0,02
4G	**LTE 1800**	150	50	2,63	26,25	1,13	22,5	0,02	0,02
4G	**LTE-A**	337	100	6,74	67,4	2	40	0,02	0,02

- * 80% of costumers experiencing speeds within this range

National Regulatory Authority tasks [7]

- Closely monitor activities and ensure compliance with the rules
- Supervision of
  - Commercial practices
  - Traffic management practices
  - Specialized services

BEREC Tool

- Current effort to build a tool for measurement of IP networks [17], [18]
- The following measurements of Internet access Service (IAS) shall be supported
  - Speedtest part
  - Regulation compliance (Quality of Service = QoS) part
- Speedtest part includes
  - Download speed measurements
  - Upload speed measurements
  - Round-trip latency measurements
  - Packet loss and packet jitter measurements
  - Cross-border measurements

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BEREC

BEREC Tool

- The following “application specific” measurement tasks shall be supported (QoS part)
  - Unmodified content
  - Transparent connection
  - TCP ports (blocked) incoming and outgoing
  - UDP ports (blocked) incoming and outgoing
  - Multimedia blocking (e.g. VoIP or streaming test)
  - …
  - Cross-border measurements

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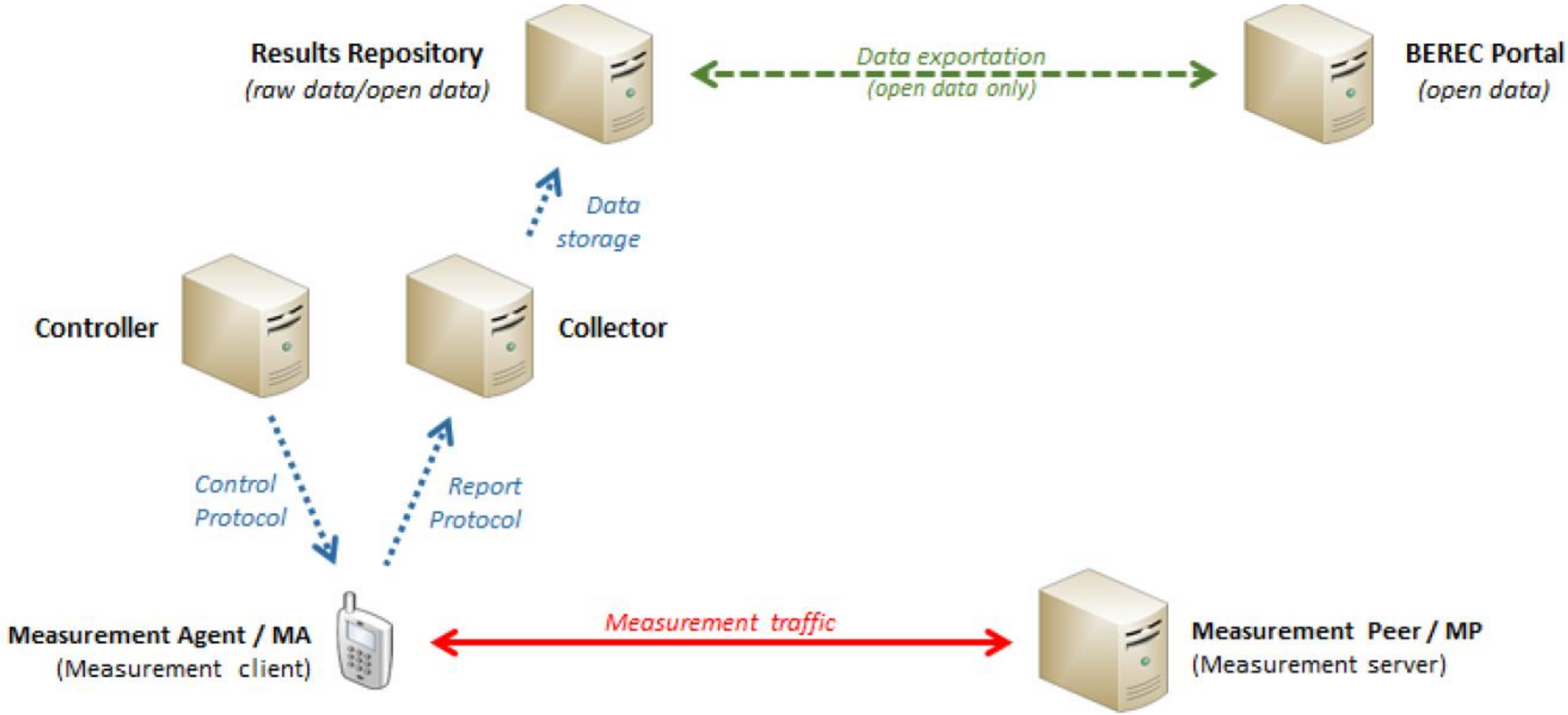
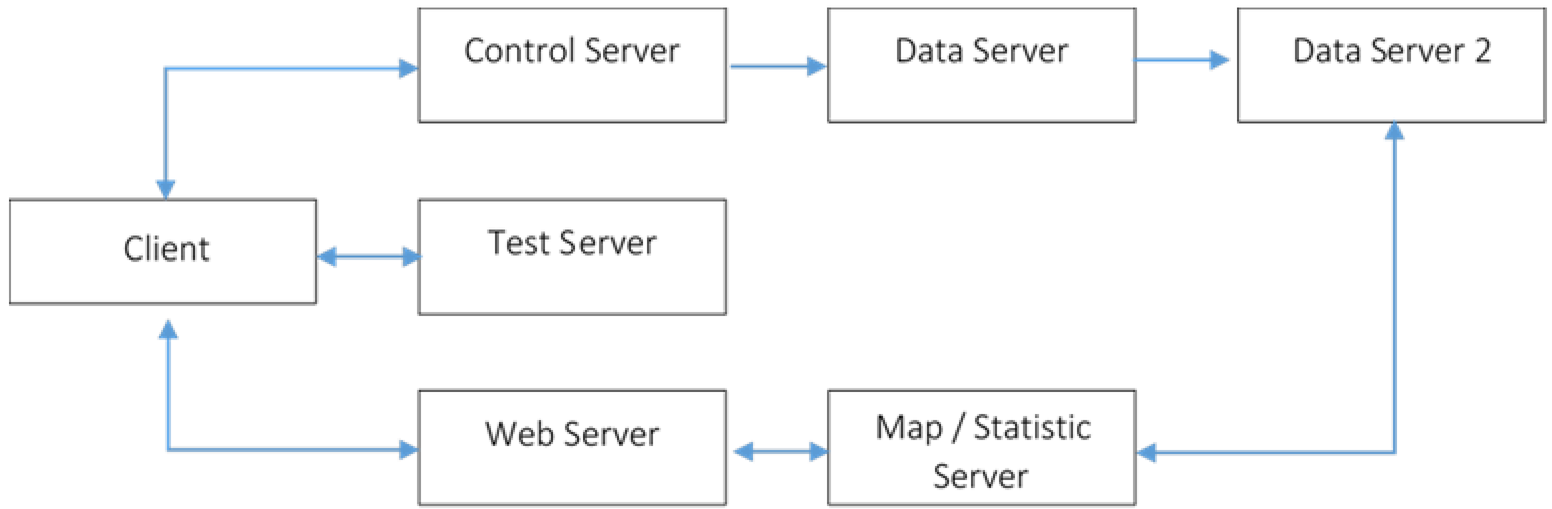
- All these tasks are sample-based probes, no continuous monitoring

Architecture design for BEREC Tool



Example of mobile app (Open Nettest) [12]

- Developed in MoQoS project, open source code
- Useful for crowdsourced measurements
- Probes against servers in CZ, SK, AT, SI, DE, UK, IR, [JP, US]
- Basic speedtests + additional tests (QoS)
- Test Environment:



Speedtest part of Open Nettest [12]

- Steps and tests in sequence:
  - Initialization
  - Download preparation
  - Latency
  - Download
  - Upload preparation
  - Upload
  - Finalization

Speedtest part of Open Nettest [12]

- In downlink (uplink) pre-tests, client
  - Opens n = 3 TCP connections against test server
  - Requests the server to send a data block of size s = 4096 B (sends data blocks of size s)
  - In loop, requests a data block of double size compared to the last step until time d = 2 seconds is reached (sends a data block of double size)
  - TCP RWND of each connection opened for download (upload) test
- Download (upload) test
  - Client (server) records time and amount of data received up to t = 7 seconds (approximately)
  - n TCP connections are closed

Speedtest part of Open Nettest [12]

- Latency test
  - Client sends p = 10 “pings” in short intervals to the test server
  - “ping” = short strings via one of the TCP connections
  - Server returns same message as acknowledgement
  - Client measures response time
  - Median value is displayed
- Jitter - delay variation calculated as mean deviation based on the samples collected for latency test
- Packet Loss – any of packets from latency test lost?

- Provides only very approximate results

QoS part of Open Nettest [12]

- Simulated VoIP call with 2 s duration
  - Verification of possibility using particular UDP ports
  - Mean jitter for both directions calculated
- Unmodified content (detection of HTTP-proxy)
  - Test server downloads data, calculates a hash value
  - The client downloads the same data, calculates the hash value
  - The control server compares the two hashes
- Website download & rendering
  - Client downloads defined web pages and builds these web pages in a background browser
  - The app monitors the size of the website, the HTTP response code from the server, the header data of the response, time of the download and the rendering of the page

QoS part of Open Nettest [12]

- Transparent connection (detection of Non-transparent proxy)
  - The client sends a random incorrect, falsified or incomplete request
  - Faulty request can be changed by non-transparent proxy
  - The server behaves like an echo service
  - The transmitted and received header data are compared
  - Tested for several ports including TCP/80 and TCP/25
- Domain Name System (DNS)
  - The client sends a set of DNS queries (> 30)
  - The response from the resolver that was automatically assigned to the client by the ISP will be compared with the known and correct results
  - Check if third-party resolver is reachable by additional DNS queries

QoS part of Open Nettest [12]

- Particular TCP and UDP ports
  - The client sends TCP or UDP packets to the specified port and waits for a reply
  - The test server responds to them
  - 16 common TCP ports + 11 UDP ports are tested

- Total of 74 QoS tests to be done
  - All tests can be easily extended or modified
  - Total length of tests ~35 s @ Samsung Galaxy S7, Android 7.0
  - Duration depends on success rate of tests

Speedtest part of Open Nettest [12]

- Limitations because of values of:
  - *n* (number of TCP connections)
  - *t* (length of the test)
  - *p* (number of pings)
- Difference from standard recommendations?
  - Possibilities given by common OS
  - To be able to finish the test in any environment
  - To shorten the duration of the test as much as possible
  - To limit data consumption

Tests not supported by Open Nettest yet [12]

- Traceroute test
  - Traceroute from client based on UDP and TTL value tuning
- Virtual Private Network (VPN)-based tests
- IP addresses blocking test
  - Problem is the determination of possibly blocked IP address
- Video streaming tests
  - Data stream comparable to a normal video streaming session
  - Video streaming session from public streaming platform
  - Problem of data limit consumption
- Effect of specialized services on IAS
  - Not an easy task, not single measurement

Why type of interconnection with other networks matters

- Two big providers in CZ, similar technologies, similar speeds

CZ Target #	RTT_1 [ms]	RTT_2 [ms]	Difference
1	33	23	43%
2	17	10	70%
3	21	9	133%
4	17	9	89%
5	17	4	325%
6	17	9	89%
7	10	5	100%
8	23	5	360%
9	44	32	38%
10	46	31	48%

- Provider #1 not peering with target networks
- Provider #2 peers locally

Iperf (iperf3) software tool [15]

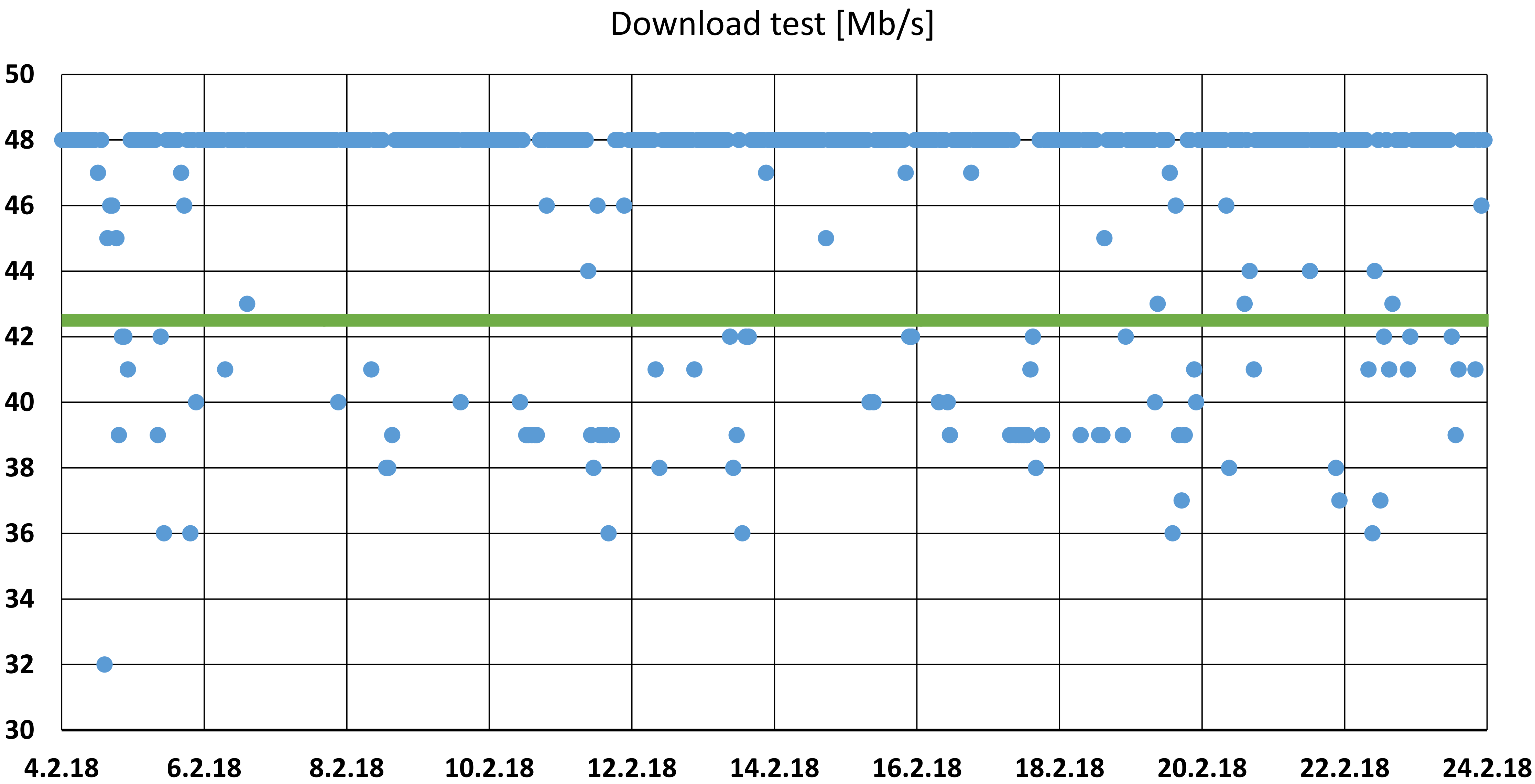
- Active measurements of the maximum achievable L7 throughput (download or upload)
- Synthetic traffic via TCP, UDP with IPv4 or IPv6
- Needs two sides
  - `iperf3 -s`
  - `iperf3 -c` *`host`*
- Tuning and verification of setting necessary [`-t 60 -P 8 -R -w 512K`]
- Higher number of streams (n > 1) should be preferred, parameter `-P`

iperf3

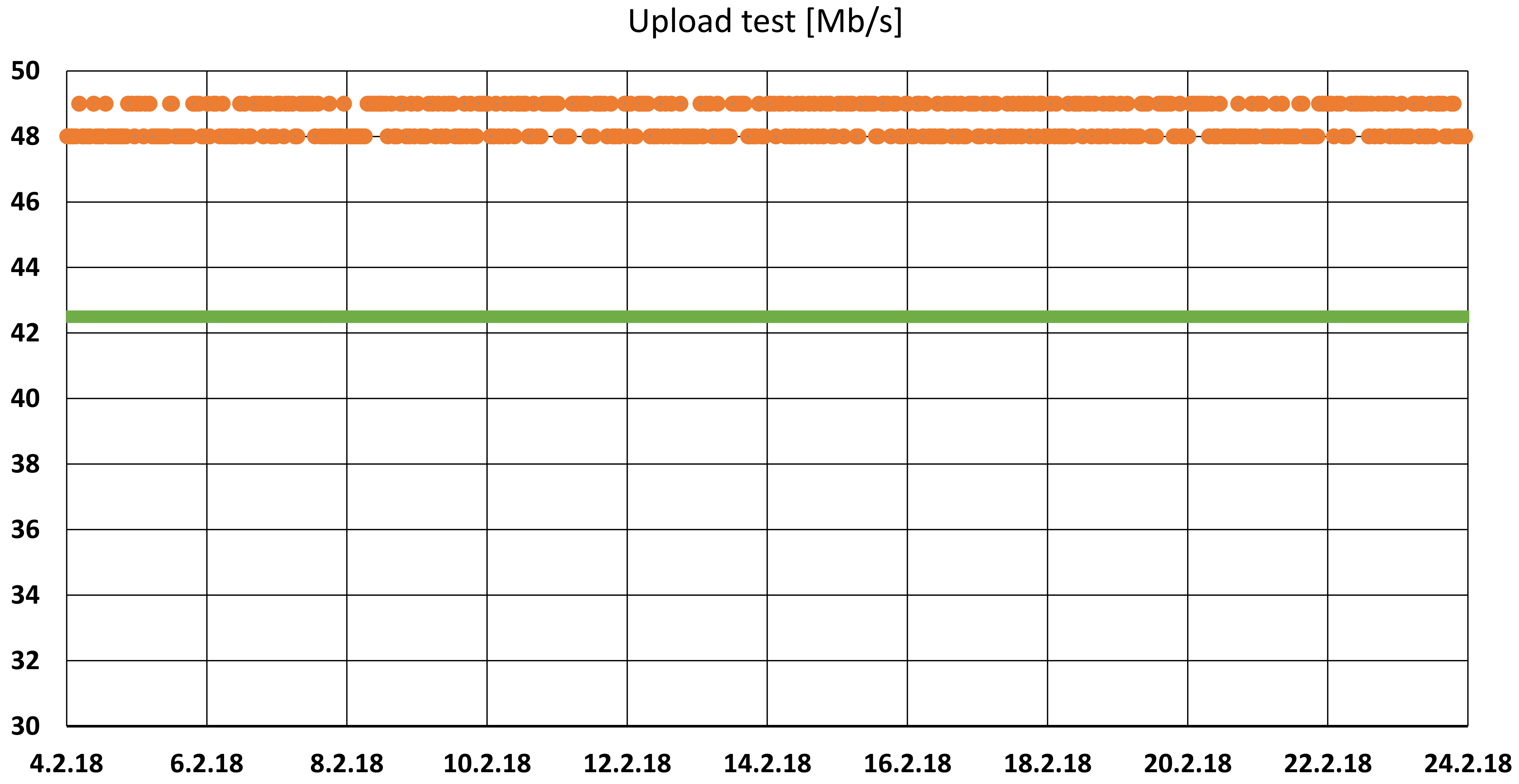
Simple HW probe (hi-performance & open-source router)

- Turris Omnia router (Czech product)
- Funded partially by Indiegogo campaign (2016)
  - $1,223,230 USD raised
- With long-term software support
- Frequent security updates and firewall rules updates (cooperative security of Turris network)
- Currently supports also speedtests
  - 1 Gb/s ports
  - Download, Upload, Latency
  - Can be scheduled to be run once/hour (random time)

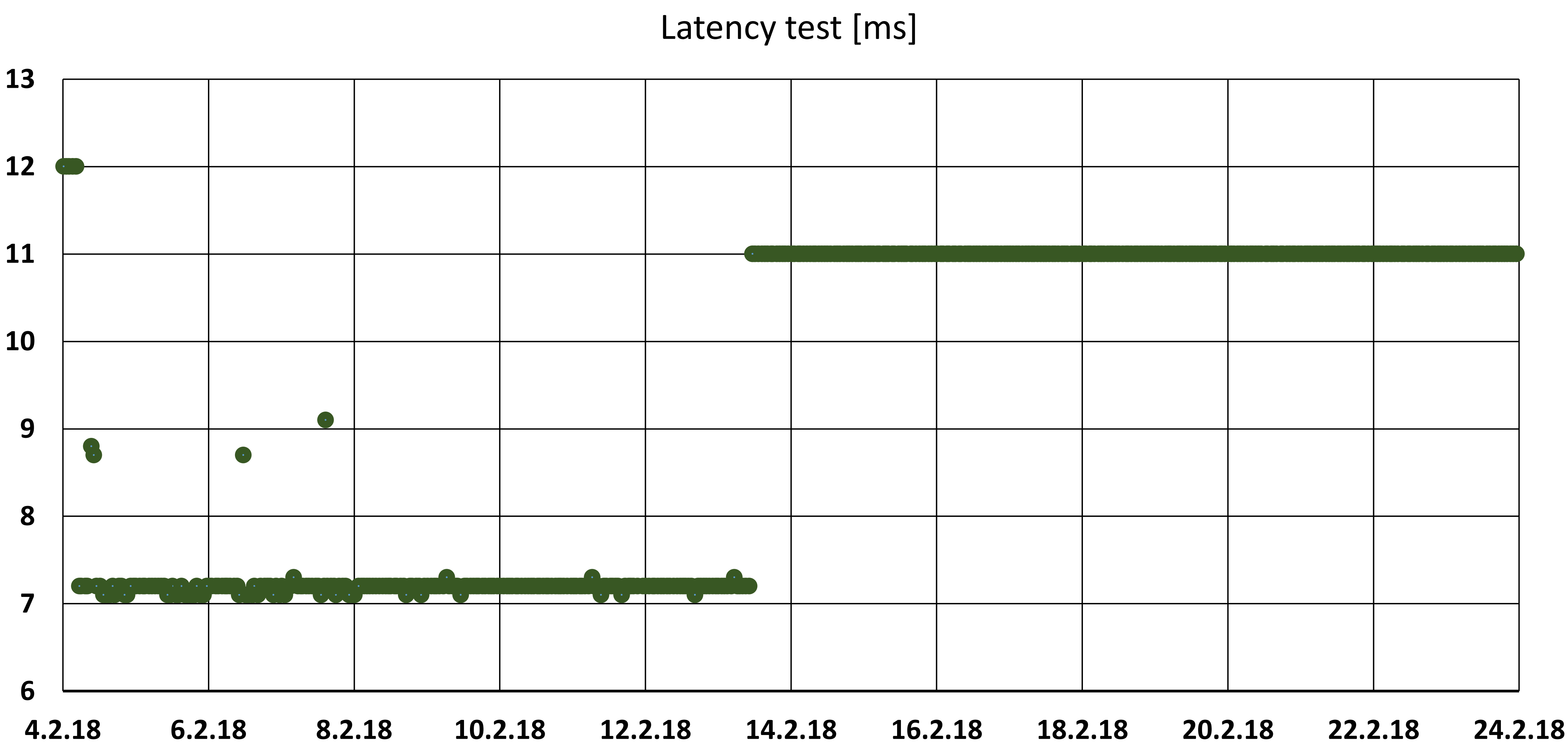
Example results of HW probe (repeated tests)



Example results of HW probe (repeated tests)



Example results of HW probe (repeated tests)



Professional HW equipment

- Usually expensive but providing high performance (up to 100 Gb/s)
- Not all standards supported
- Detailed setting of TCP protocol
  - Sometimes limited (e.g. TCP RWND = 64 kB)
- Used in pairs or against server
- Useful for
  - Service activations
  - Long-term tests

Conclusions

- Testing and evaluation of IP-based transfers not an easy task
- Measurement over the networks always tricky
- Measured layer changes obtained results, recalculation theoretically possible
- IPv4 & IPv6 supported – both should be tested separately
- The most difficult setup in case of „long fat“ links
- Virtualization or off-loading techniques impact possible throughput
- Not focus on results of one test with one tool

Additional reading

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Thank you

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