Network Calculus in the Practice Available Bandwidth Estimation Problem

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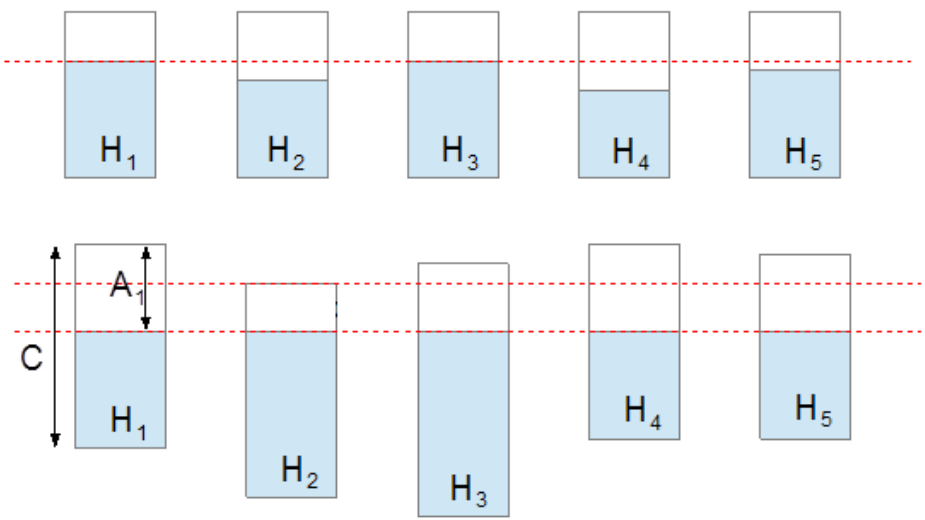
Outline

Available bandwidth estimation problem

Available bandwidth B on the route at the time t means **unused bandwidth** which an application can use without any influence on the transmission quality of existing flows on this route.

$$B(t) = \min_{1 \leqslant i \leqslant n} \{A_i(t)\}$$

- verification of SLA
- route selection
- network traffic engineering
- resource access control

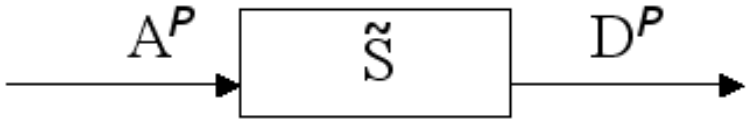


LFV method - Liebeherr, Fidler, Valaee (2008, 2010)

Passive measurement method

$$\tilde{S}(t) = D^p \oslash A^p(t)$$

$$f \oslash g(t) = \sup_{\tau} \{f(t+\tau) - g(\tau)\}$$



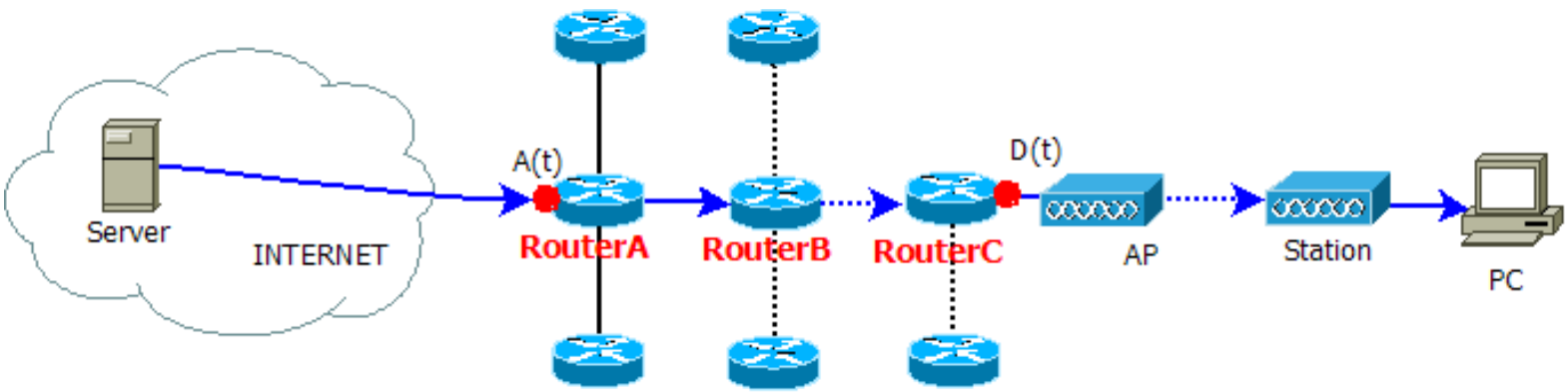
A^p and D^p are the arrival and departure functions measured from a traffic trace of one or more flows

- According to Liebeherr, Fidler and Valaee estimator $\tilde{S}$ is the best possible estimate of the actual service curve S (describing available bandwidth) that can be justified from measurements of A^p and D^p ($\tilde{S} \leqslant S$).

J. Liebeherr, M. Fidler, S. Valaee, A system-theoretic approach to bandwidth estimation, IEEE/ACM Transactions on Networking, vol. 18, no. 4, pp. 1040-1053, 2010

The objective

To use and verify the service curve $\tilde{S}$ based on the passive measurements for bandwidth estimation in **real ISP network**



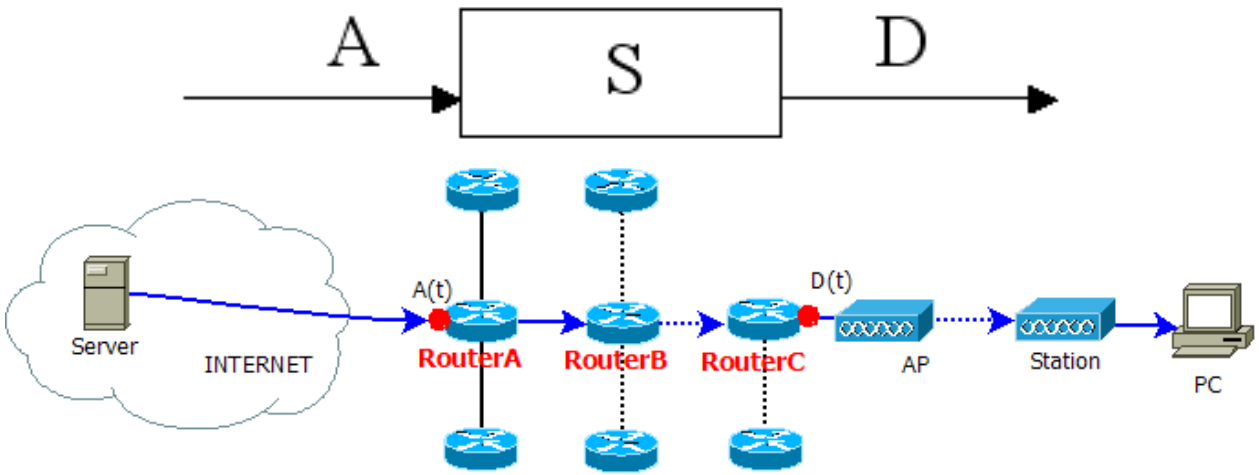
Characteristics of the research environment

ISP network

- Fiber optic link on contact with provider - 100 Mb/s
- Routers connected by wire and wireless links
- Stable wireless links - max 150 Mb/s, max 1 ms
- All routers experience cross traffic
- Tree topology (packets travel the same routes)
- Symmetrical and unsymmetrical links
- Individual and commercial customers
- Limitations on download and upload rate
- No other limitations
- Routers are able to save traffic to *.pcap* files

Methodology

1. **Internet traffic** was capturing on the selected interfaces of ISP devices
2. Traffic was filtering (single flow, set of flows)
3. Time series of $A(t)$ oraz $D(t)$ functions were generated
4. Values of the service curve $\tilde{S}$ were calculated in based LFV method

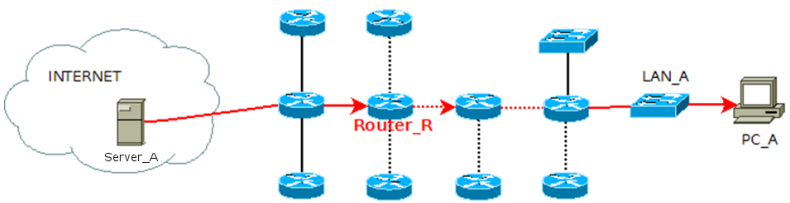


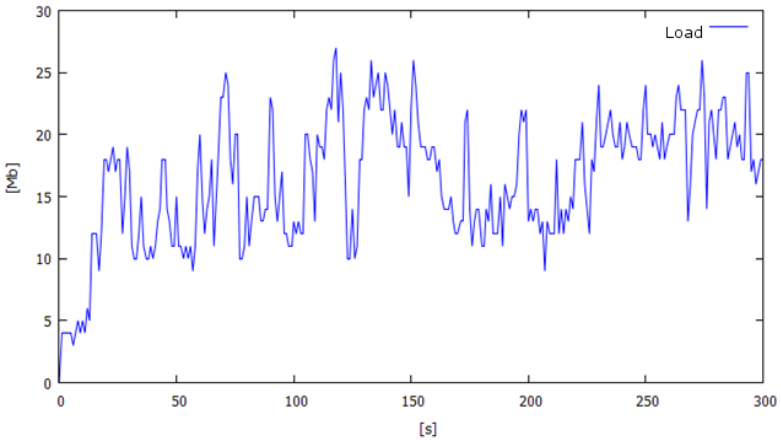
Specification of traffic probes

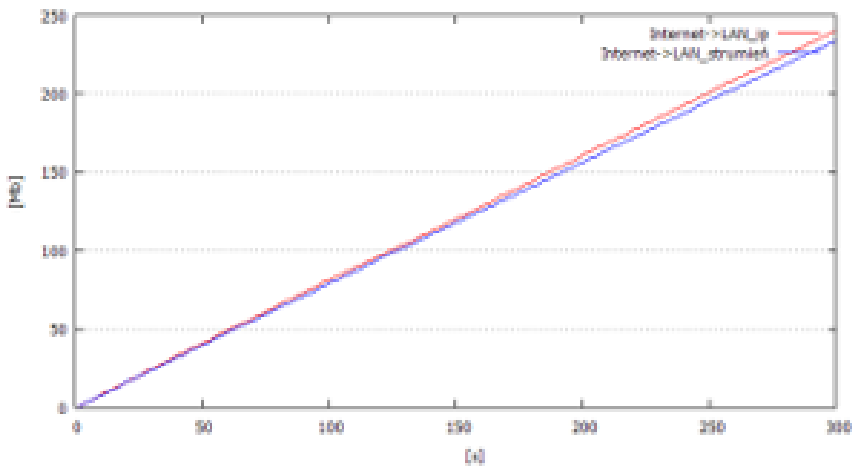
Direction	Duration	Time scale	Amount of observations
Service curve of the node			
Download	5min	1s	300
	1min	100ms	600
	1s	1ms	1000
	100ms	100μs	1000
Upload	5min	1s	300
	1min	100ms	600
	1s	1ms	1000
	100ms	100μs	1000
Network service curve			
Download	5min	1s	300
	1min	100ms	600
	1s	1ms	1000
	100ms	100μs	1000
Upload	5min	1s	300
	1min	100ms	600
	1s	1ms	1000
	100ms	100μs	1000

CASE 1: Single flow - in the node - download

Working day, about 3 PM, 5 minutes



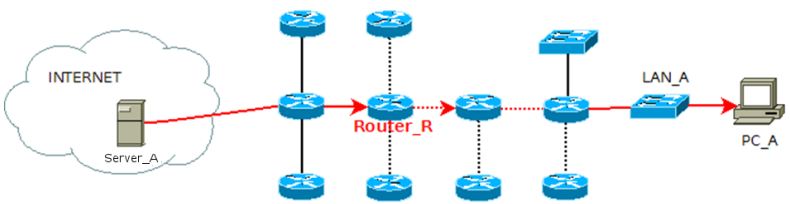




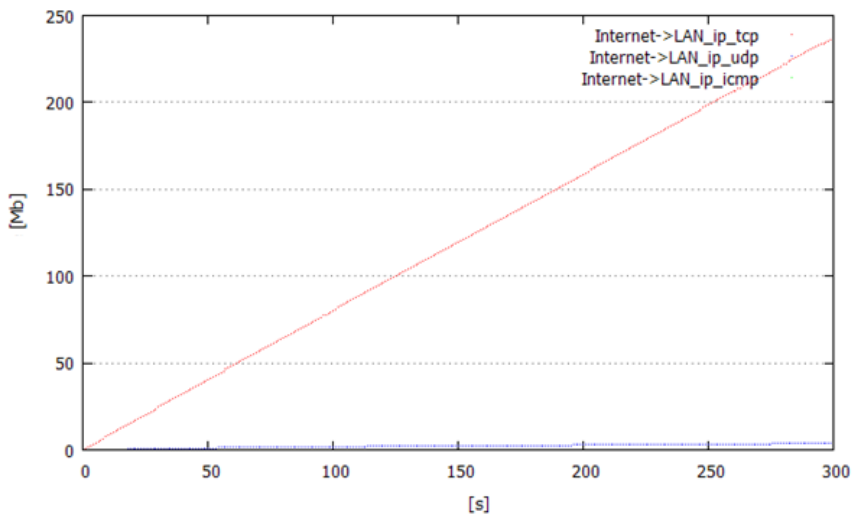
Duration: 300 s
Total traffic to PC_A: 31540420 B
Single flow: 30715218 B (97,4%)
Average rate to PC_A: 0,802 Mb/s

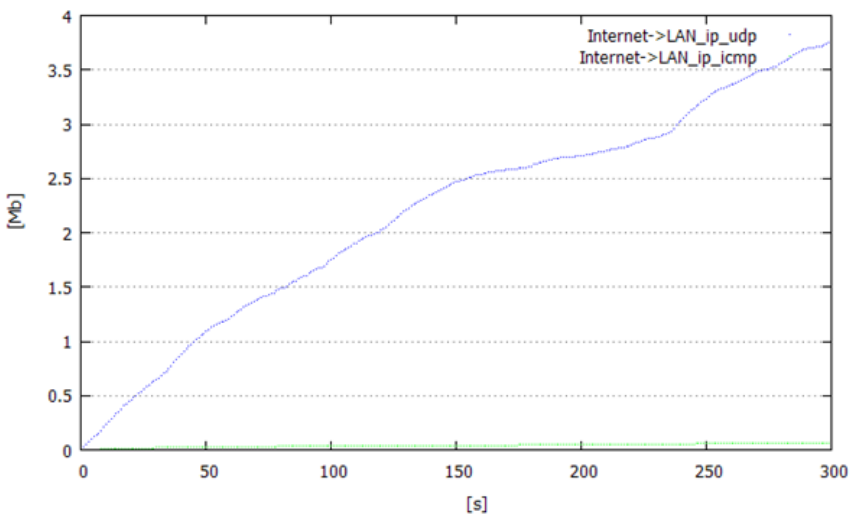
CASE 2: Types of network traffic - node - download

Working day, about 3 PM, 5 minutes

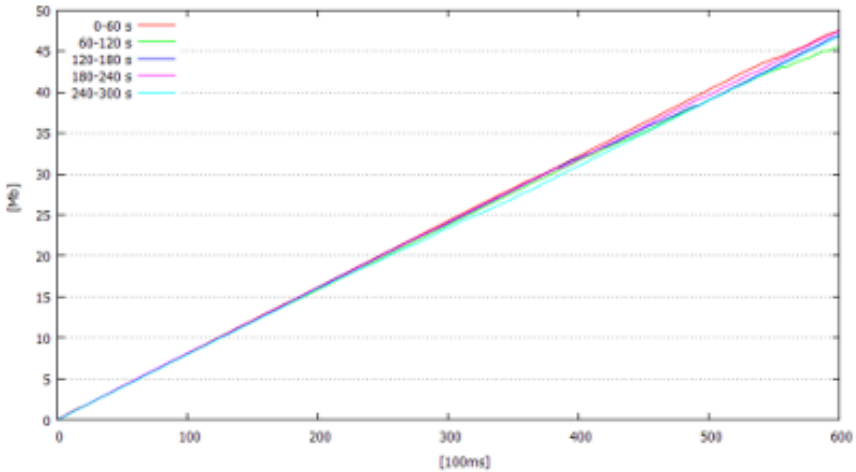


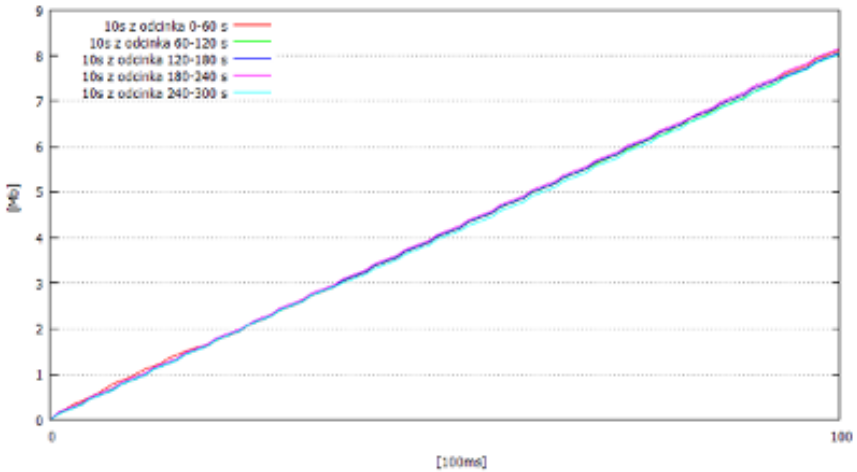
Protocol	Packets [%]	Bytes [%]
IPv4	100	100
TCP	79,62	98,12
UDP	19,09	1,72
ICMP	1,29	0,17

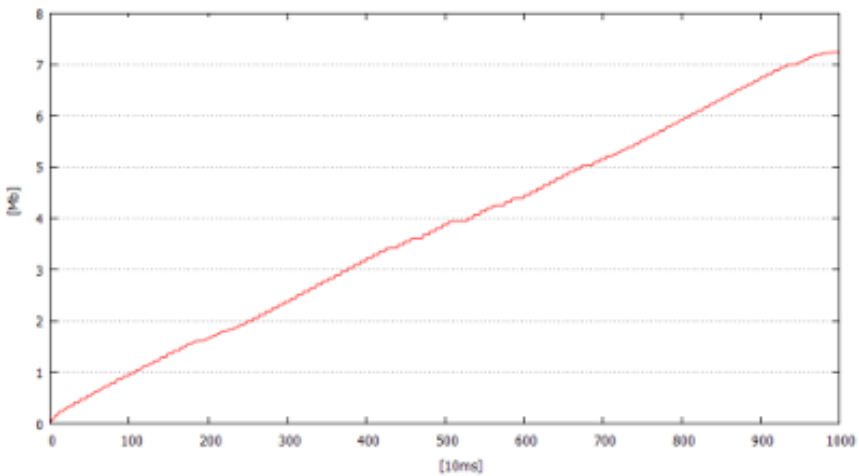


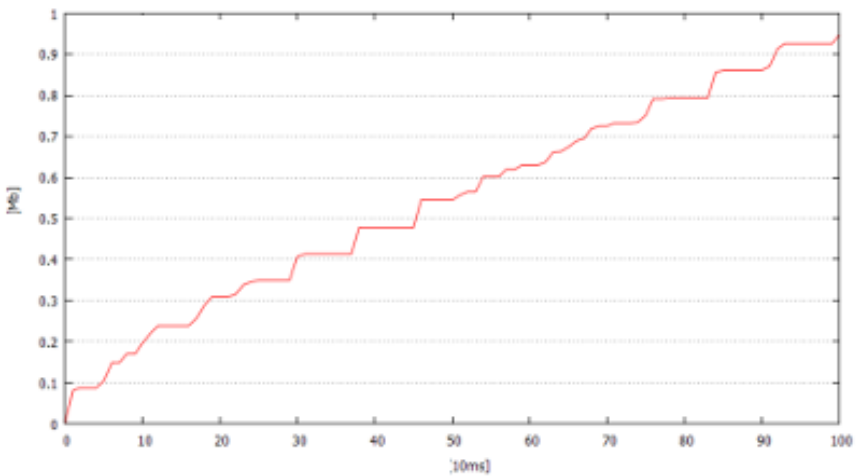


CASE 3: Single flow (60s, 10s, 10s, 1s)

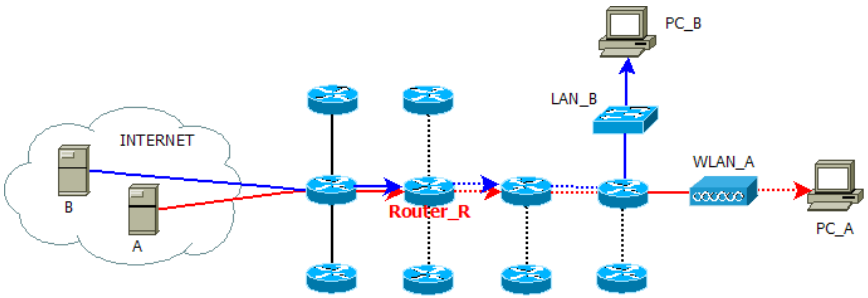


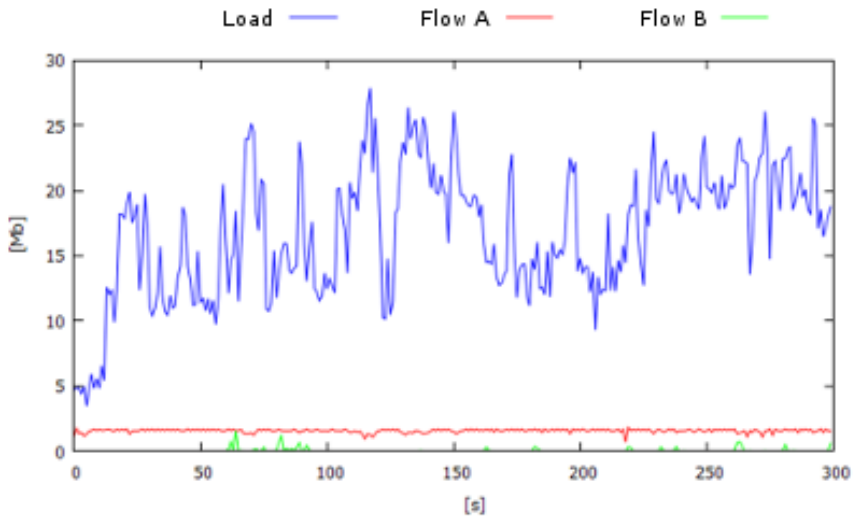






CASE 4: Traffic flows (A - HTTP, B - HTTPS)



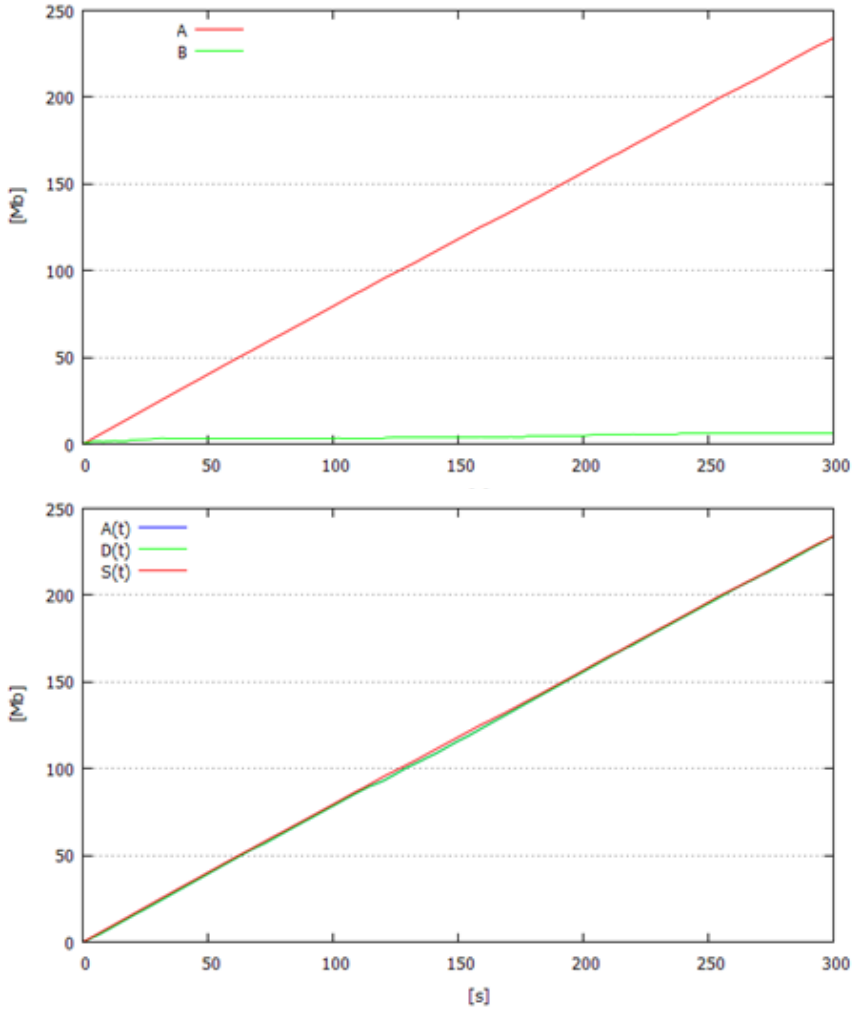


Average rate in the node: 17,7 Mb/s

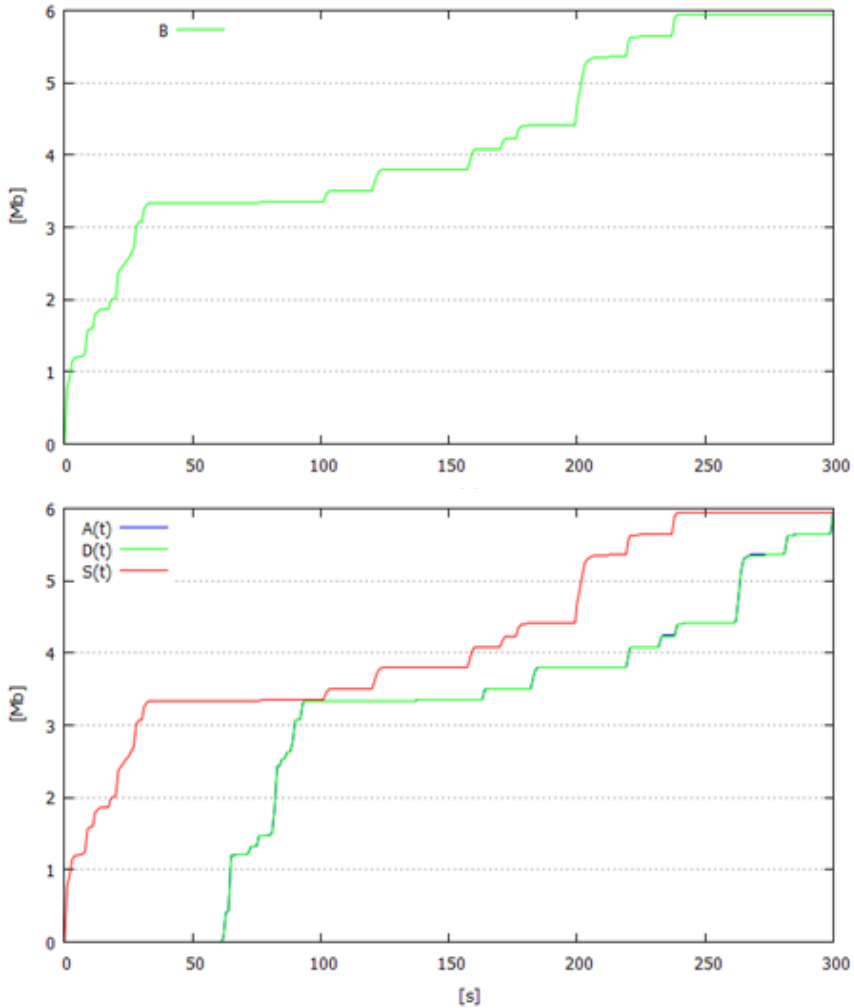
	Amount of packets	Amount of data which arrive to the node [B]	Average rate [Mb/s]	Amount of data which leave the node [B]	Average rate [Mb/s]
Flow A	21497	30670366	0,818	30670366	0,818
Flow B	812	780366	0,026	779694	0,026

CASE 4: Traffic flows (A - HTTP, B - HTTPS)

Flow A

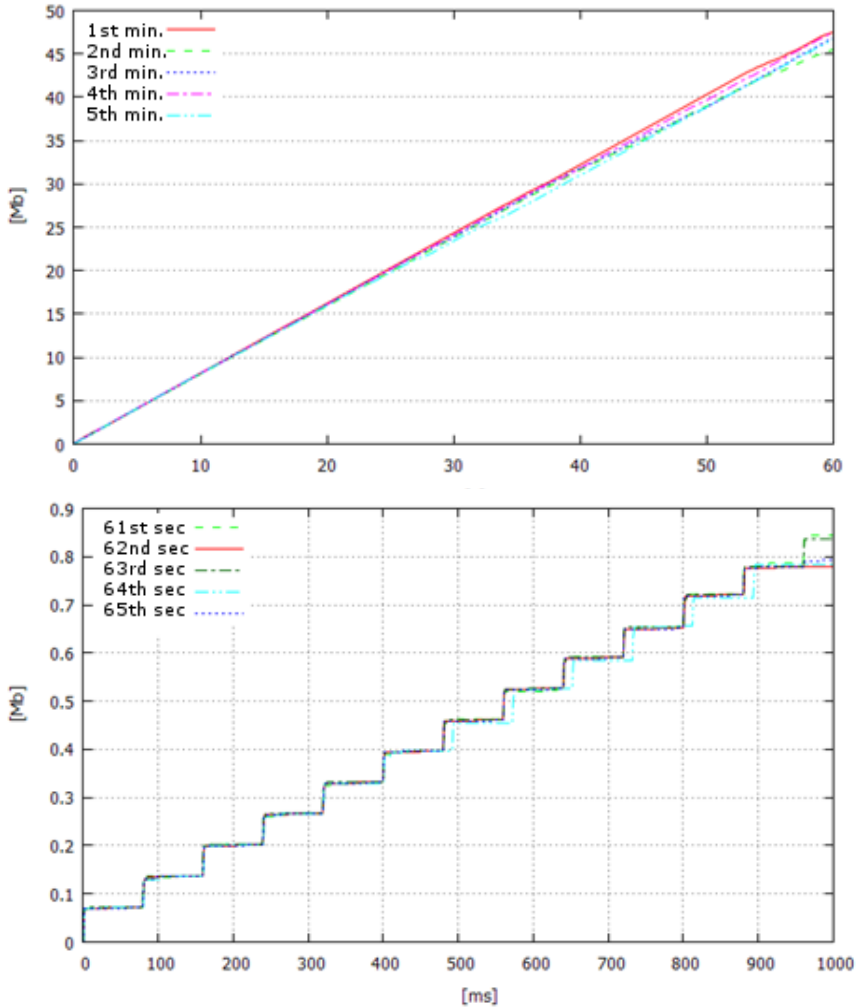


Flow B

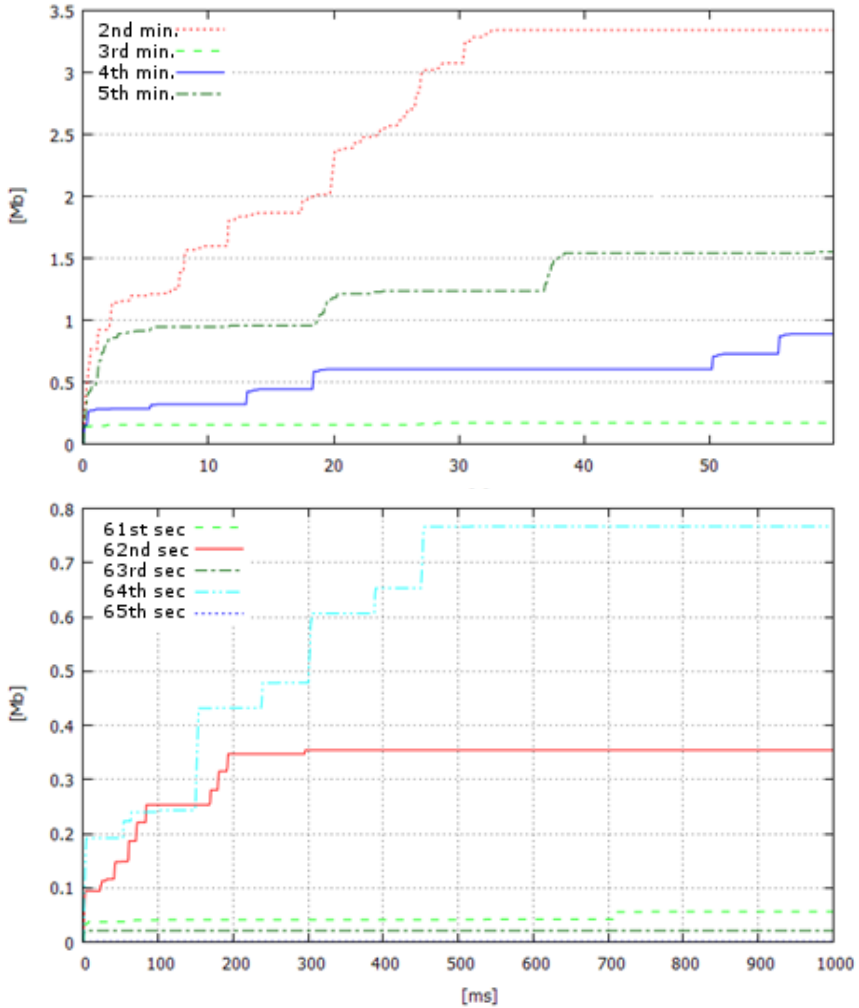


CASE 4: Traffic flows (A - HTTP, B - HTTPS)

Flow A

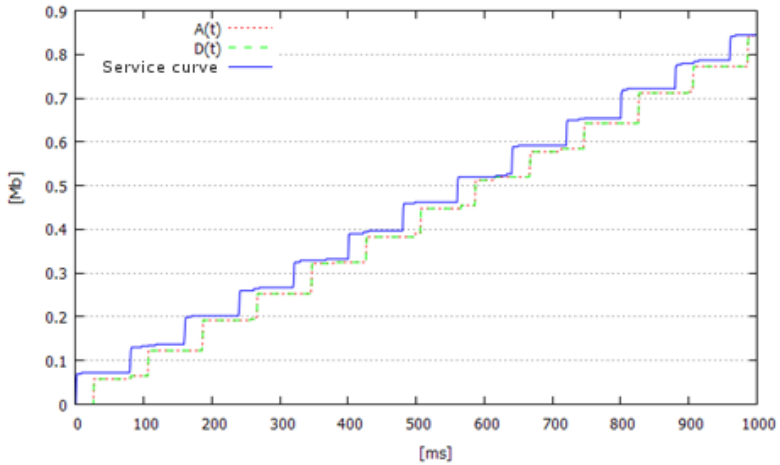


Flow B



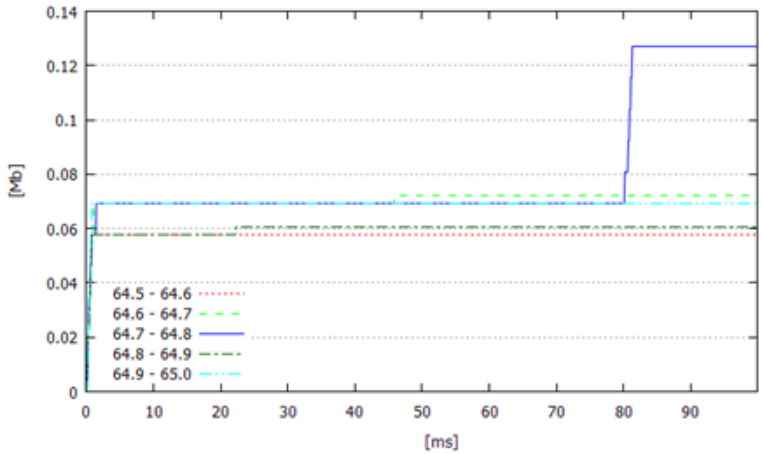
CASE 4: Traffic flows (A - HTTP)

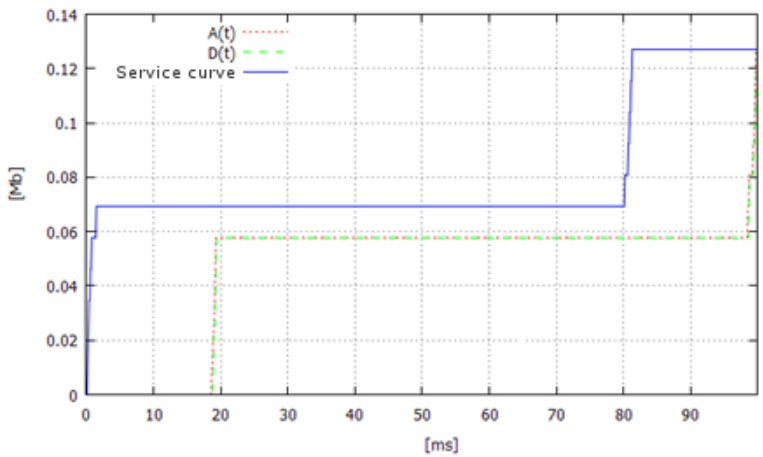
61. sec, interval: 1s, time scale: 1ms



Time [s]	Incoming data [b]	A(t)	Outcoming data [b]	D(t)
61.824	0	673712	0	673712
61.825	0	673712	0	673712
61.826	12112	685824	0	673712
61.827	60560	746384	72672	746384
61.828	0	746384	0	746384
61.829	0	746384	0	746384

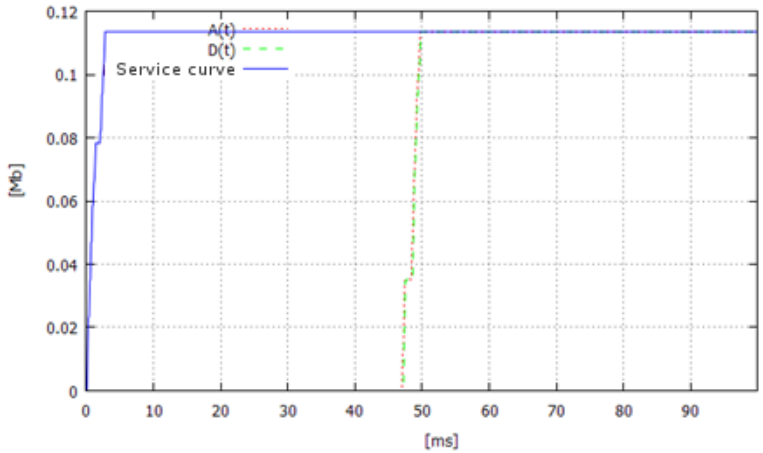
61. sec, interval: 100ms, time scale: 100μs



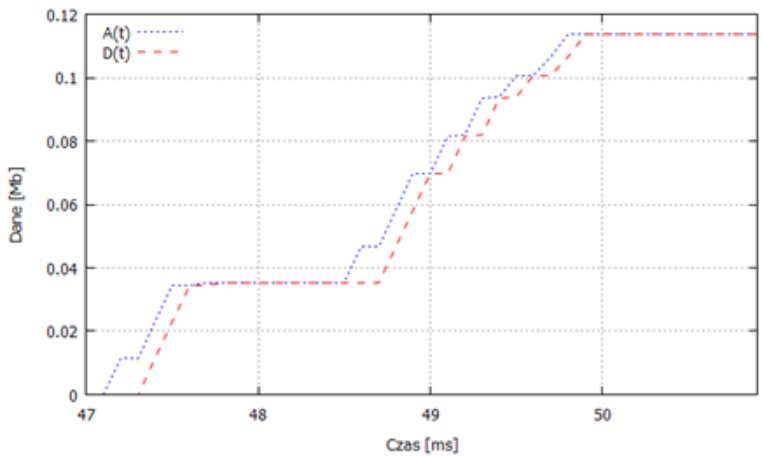


CASE 4: Traffic flows (B - HTTPS)

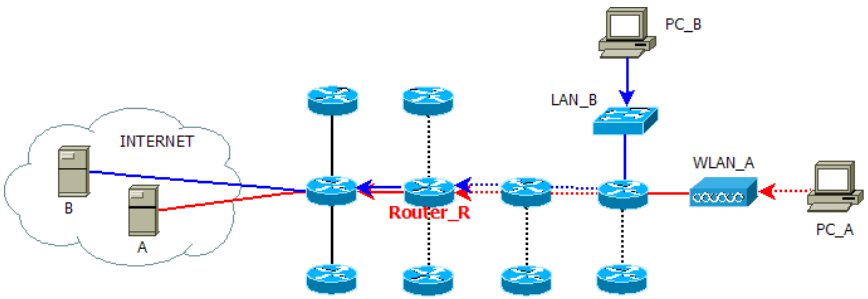
64.7-64.8 sec
Duration: 100ms
Time scale: 100μs



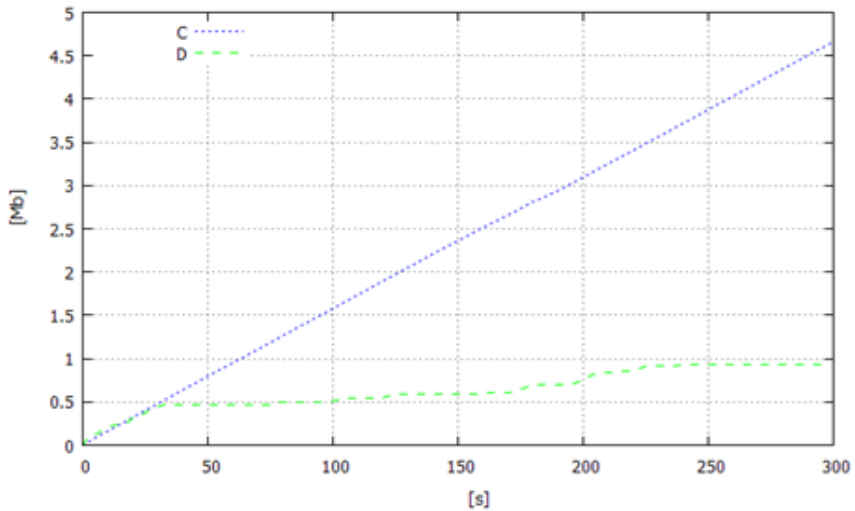
Time [s]	Incoming data [b]	A(t)	Outcoming data [b]	D(t)
64.7470	0	0	0	0
64.7471	12112	12112	0	0
64.7472	0	12112	0	0
64.7473	12112	24224	12112	12112
64.7474	12112	36336	12112	24224
64.7475	0	36336	12112	36336
64.7476	592	36928	0	36336
64.7477	0	36928	592	36928
64.7478	0	36928	0	36928
64.7479	0	36928	0	36928



CASE 5: Traffic flows (C - HTTP, D - HTTPS) - upload



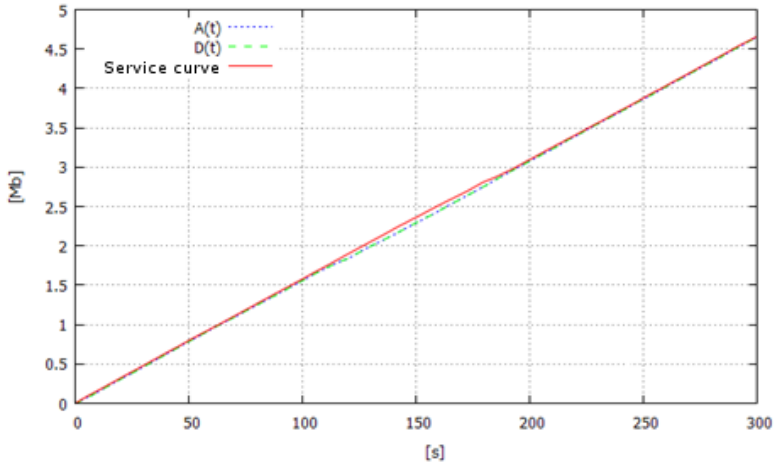
Time scale: 1s



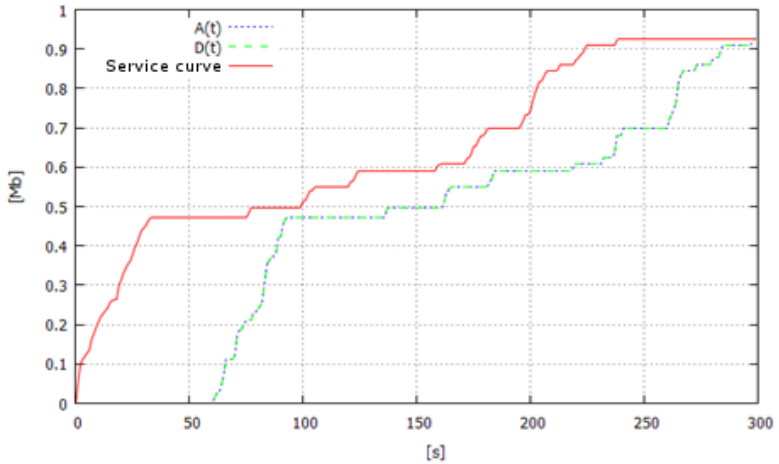
	Amount of packet	Amount of data which arrive to the node [B]	Average rate [Mb/s]	Amount of data which leave the node [B]	Average rate [Mb/s]
Flow C	10170	610320	0,016	549420	0,015
Flow D	459	121501	0,004	119587	0,004

CASE 5: Traffic flows (C - HTTP, D - HTTPS) - upload

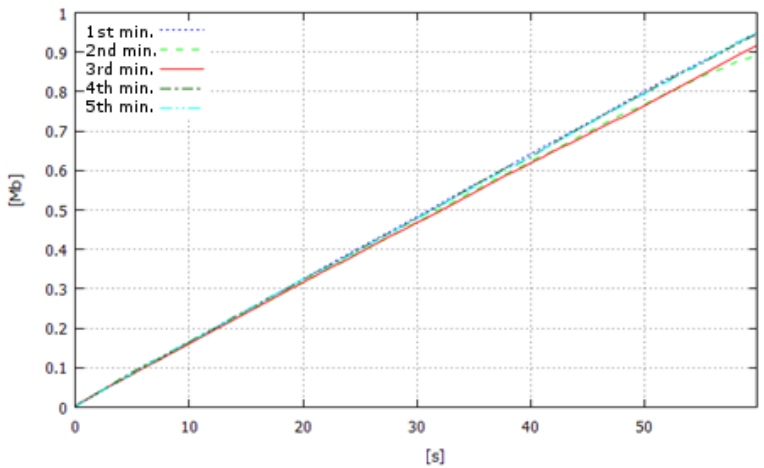
Flow C



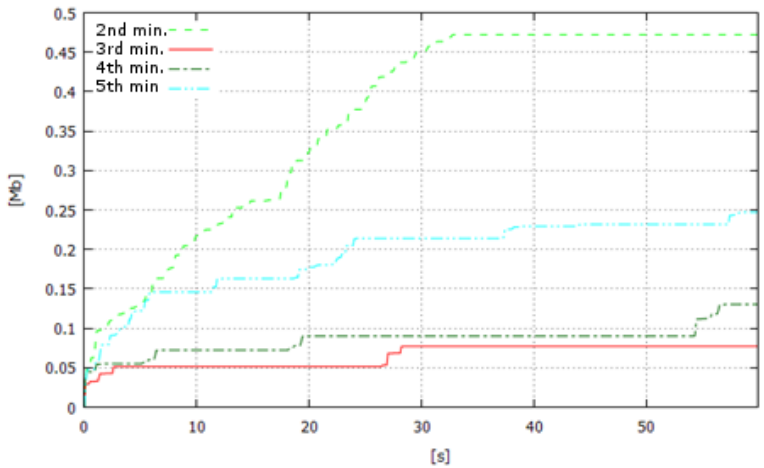
Flow D



Time scale: 100ms

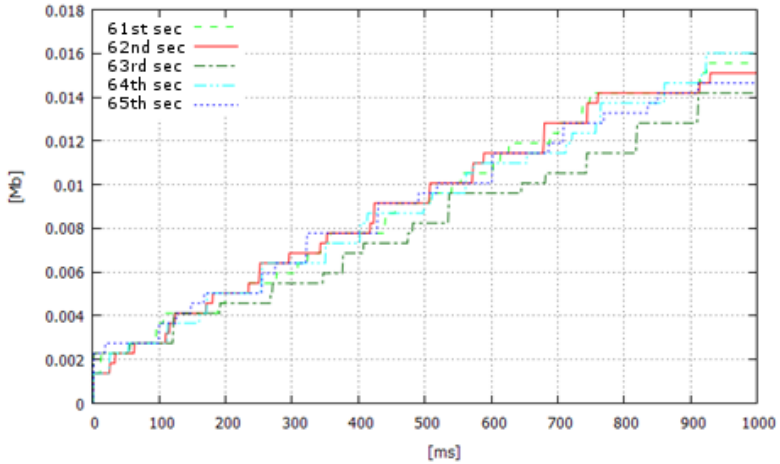


Time scale: 100ms

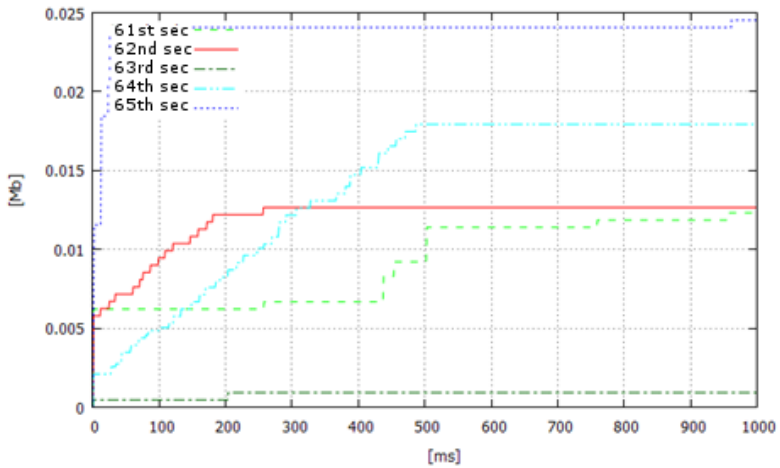


CASE 5: Traffic flows, upload, time scale: 1ms, interval: 1s

Flow C

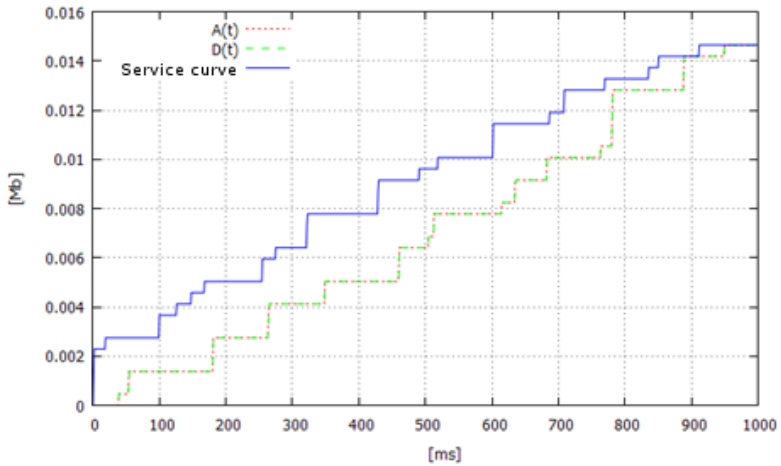


Flow D

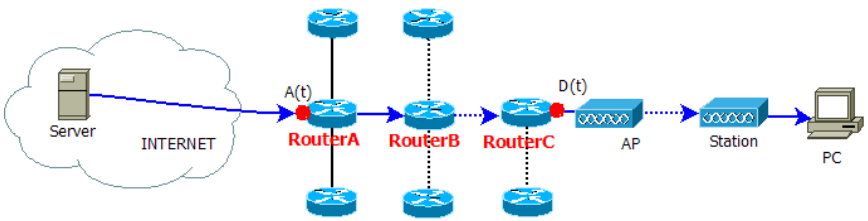


Flow C - 65th sec

Time [s]	Incoming data [b]	A(t)	Outcoming data [b]	D(t)
65.631	0	8640	0	8640
65.632	0	8640	0	8640
65.633	0	8640	0	8640
65.634	0	8640	0	8640
65.635	960	9600	480	9120
65.636	0	9600	480	9600
65.637	0	9600	0	9600
65.638	0	9600	0	9600
65.639	0	9600	0	9600

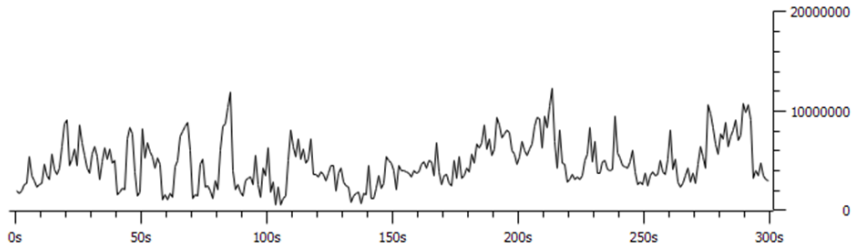


CASE 6: Network service curve

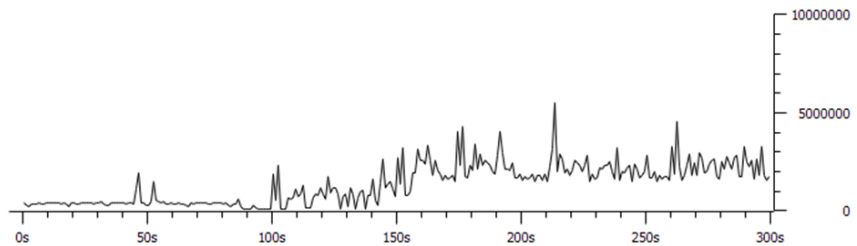


Customer
Download: 6560 kb/s (6,41 Mb/s)
Uplod: 512 kb/s (0,5 Mb/s)

Load router A [b]



Load router C [b]



CASE 6: Network service curve

Characteristics of flows – router A

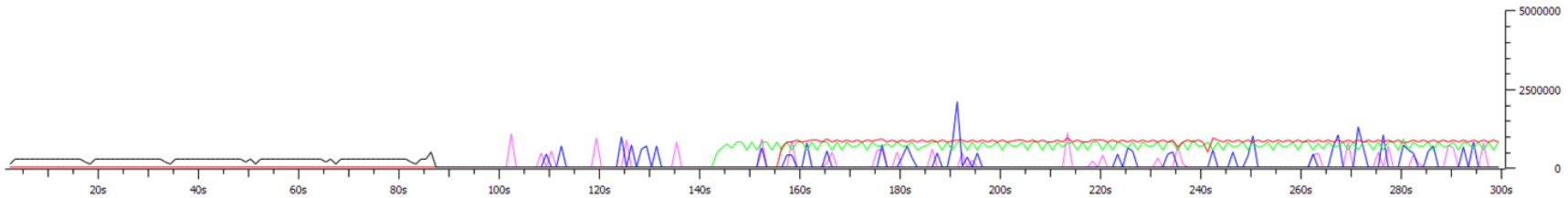
Flow	TCP port	Amount of packets download	Data [MB] download	Rate Mb/s	Amount of packets upload	Data [MB] upload	Rate Mb/s	Color
A	49349	10718	14,53	0,847	5303	0,28	0,016	red
B	49345	9368	13,19	0,708	4727	0,24	0,013	green
C	50257	2554	3,35	0,145	1367	0,097	0,004	blue
D	50262	1652	2,18	0,094	1076	0,079	0,003	pink
E	62380	1883	2,66	0,261	952	0,049	0,005	black

Characteristics of flows – router C

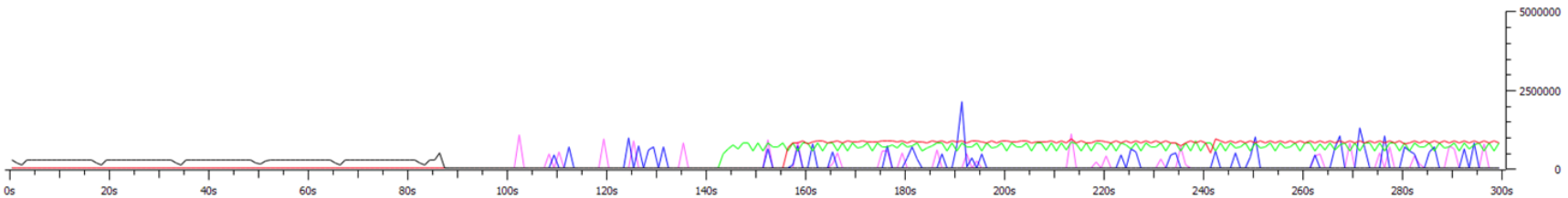
Flow	TCP port	Amount of packets download	Data [MB] download	Rate Mb/s	Amount of packets upload	Data [MB] upload	Rate Mb/s	Color
A	49349	10712	14,52	0,847	5304	0,305	0,018	red
B	49345	9361	13,19	0,707	4735	0,272	0,015	green
C	50257	2551	3,35	0,145	1368	0,104	0,005	blue
D	50262	1652	2,18	0,094	1076	0,082	0,004	pink
E	62380	1883	2,66	0,261	952	0,054	0,005	black

CASE 6: Network service curve

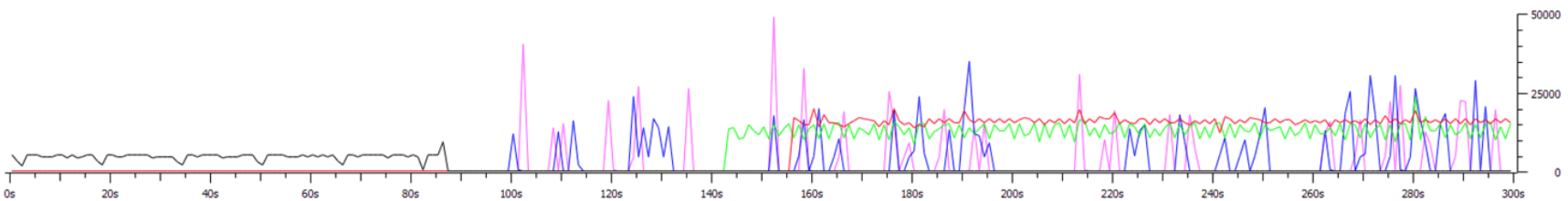
Router A - download [b]



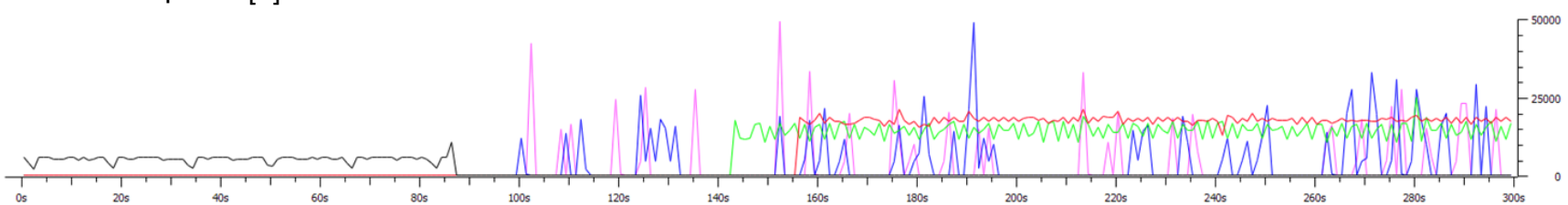
Router C - download [b]



Router A - upload [b]

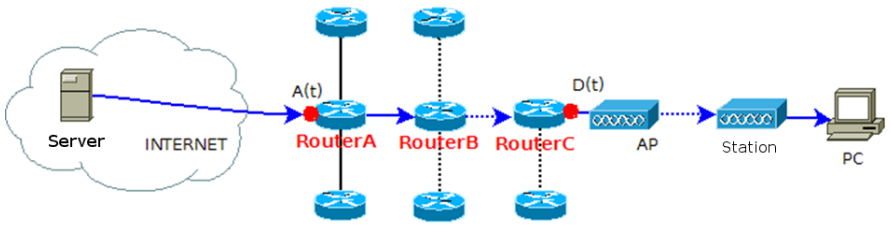


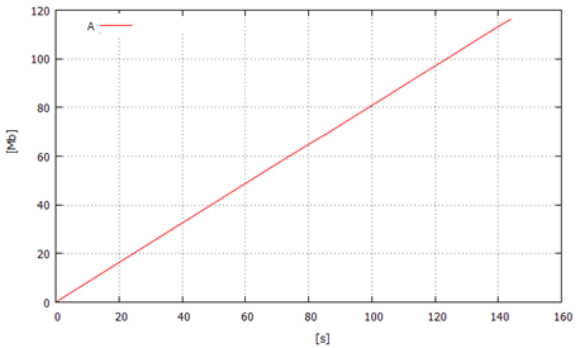
Router C - upload [b]

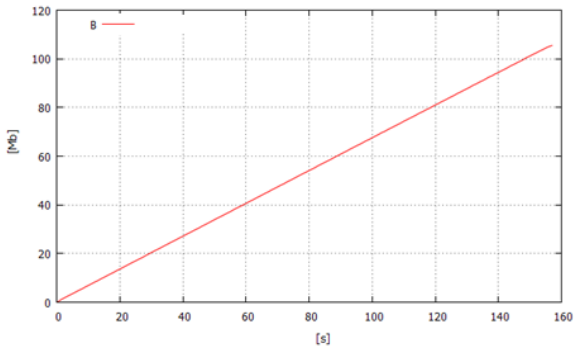


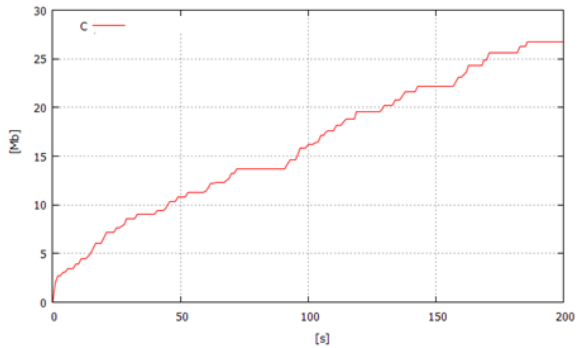
CASE 6: Network service curve - time scale: 1s - download

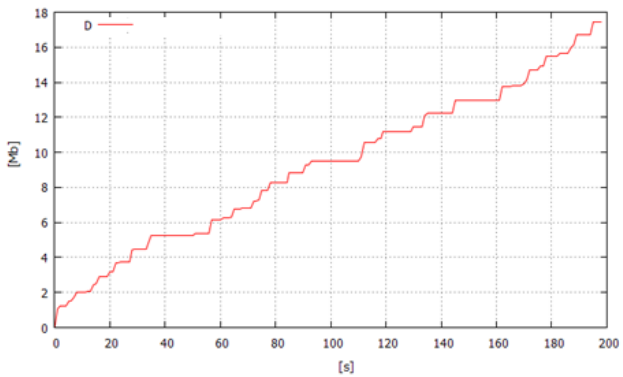
Flow	Duration [s]	Amount of data [Mb]	Average rate [Mb/s]
A	144	116,19	0,807
B	157	105,48	0,668
C	200	26,73	0,133
D	198	17,46	0,088
E	87	21,24	0,244

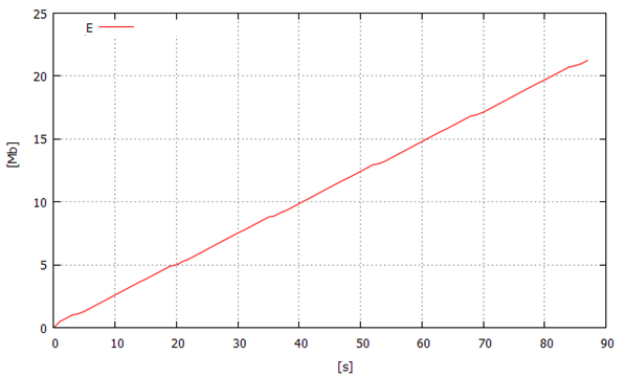






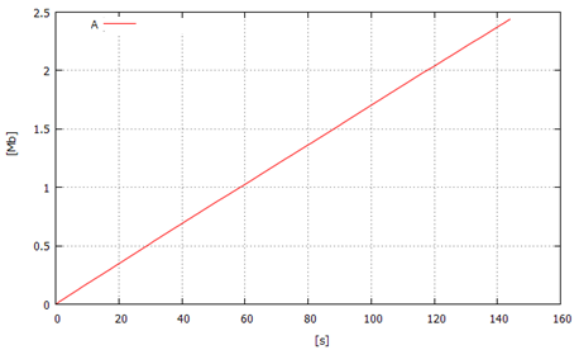


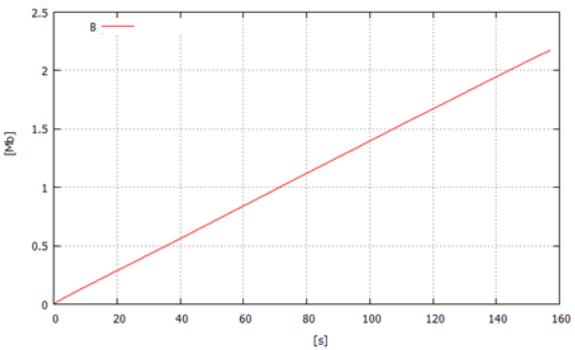


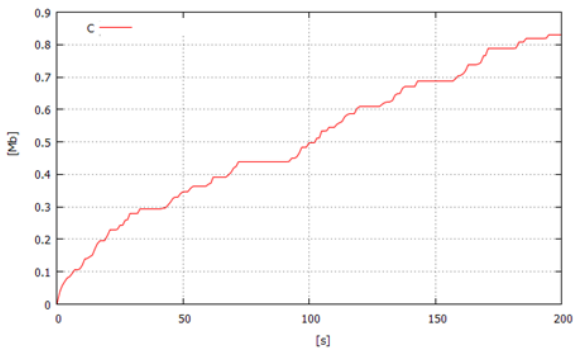


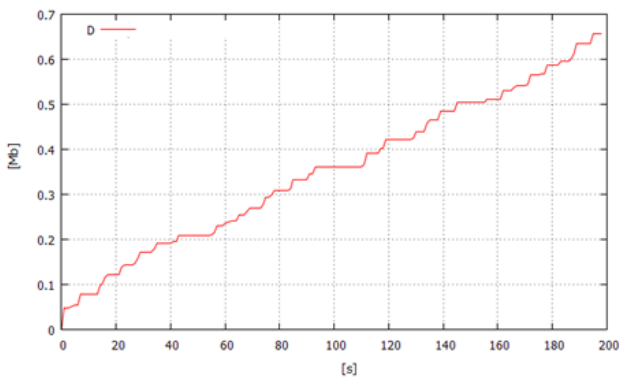
CASE 6: Network service curve - time scale: 1s - upload

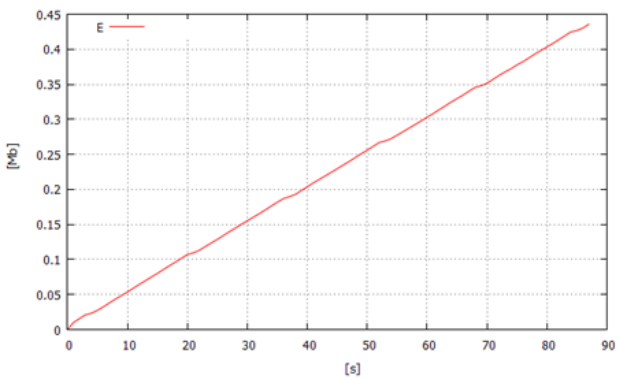
Flow	Duration [s]	Amount of data [Mb]	Average rate [Mb/s]
A	144	2,44	0,017
B	157	2,17	0,014
C	200	0,83	0,004
D	198	0,66	0,003
E	87	0,44	0,005



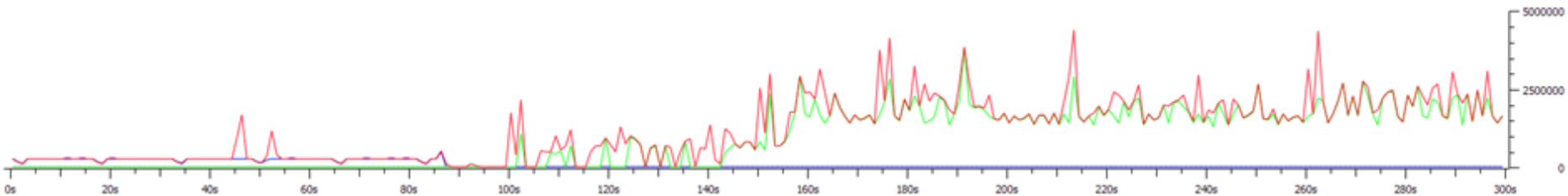




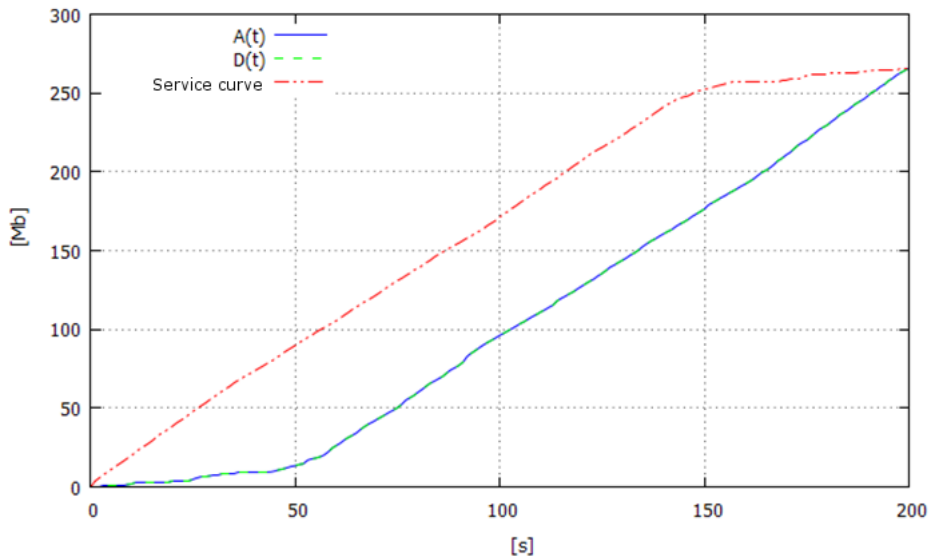




CASE 6: Network service curve - aggregated flows

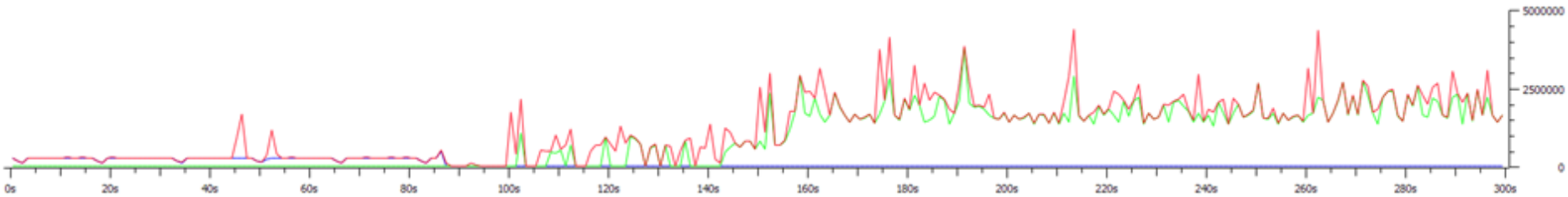


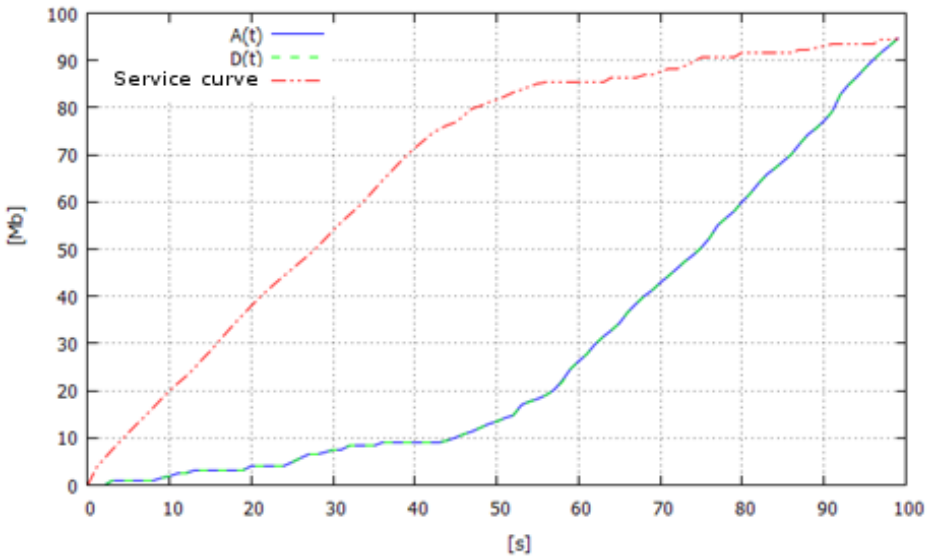
Red color - the total traffic generated to the customer
Green color - the sum of flows A-D
Blue color - the flow E

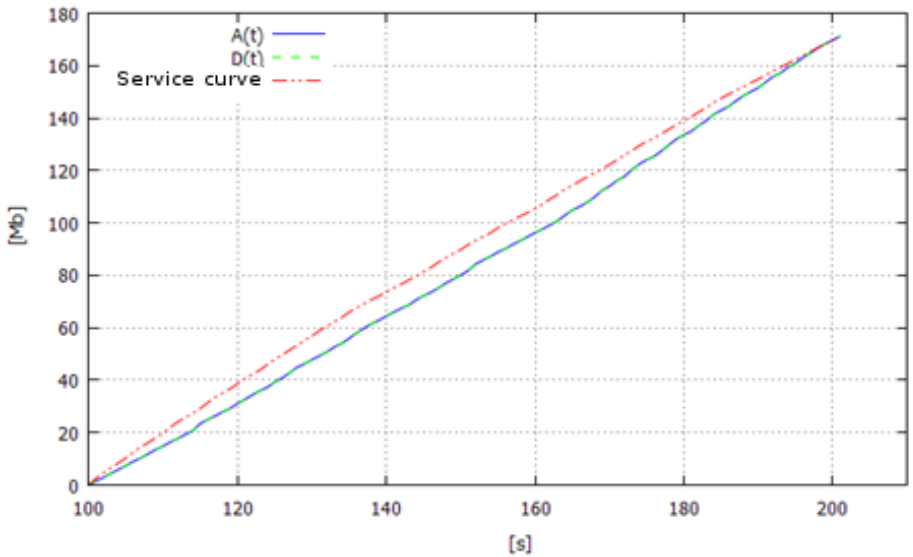


- Measurement length A-D: 200 s
- Amount of data: 265,86 Mb
- Average rate: 1,329 Mb/s
- Max rate: ok. 1,7 Mb/s
- Possible rate: 6,41 Mb/s
- Difference: ok. 4,7 Mb/s

CASE 6: Network service curve - aggregated flows



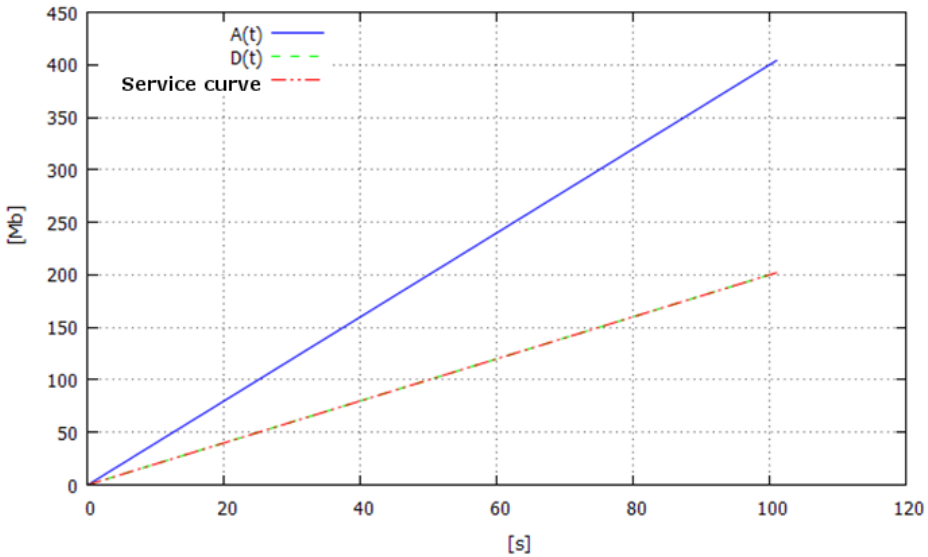




- Data: 94,64 Mb = 11,83 MB
- Average rate: 0,946 Mb/s

- Data: 171,23 Mb = 21,40 MB
- Average rate: 1,712 Mb/s

Simulations

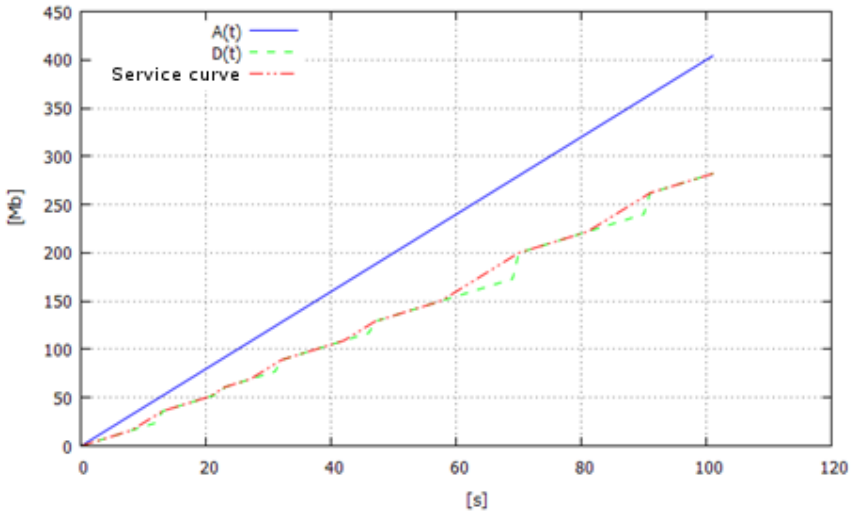


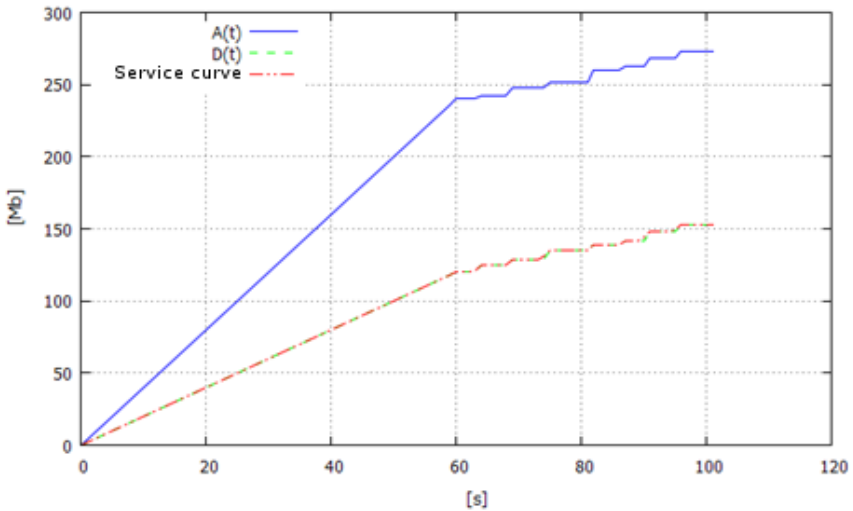
- Traffic arrives faster than it can be served
- Departure curve $D(t)$ covers the estimate of the service curve

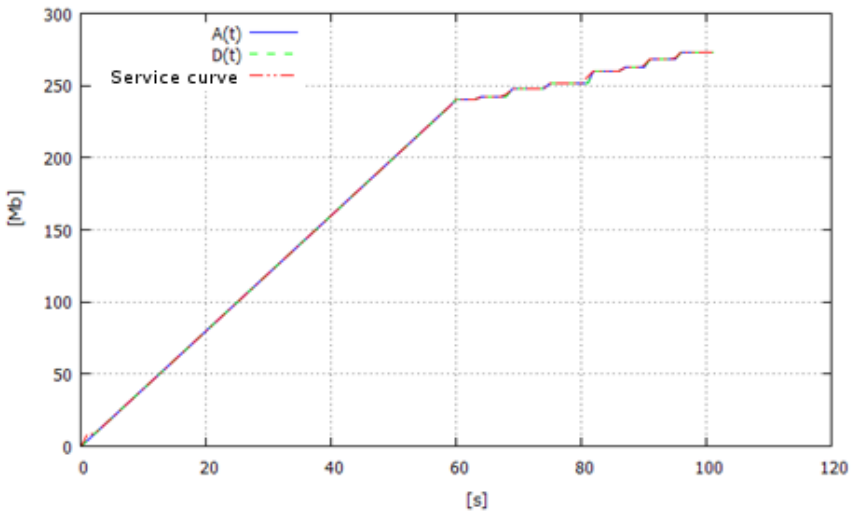
- $A(t) = 4t$
- $D(t) = 2t$

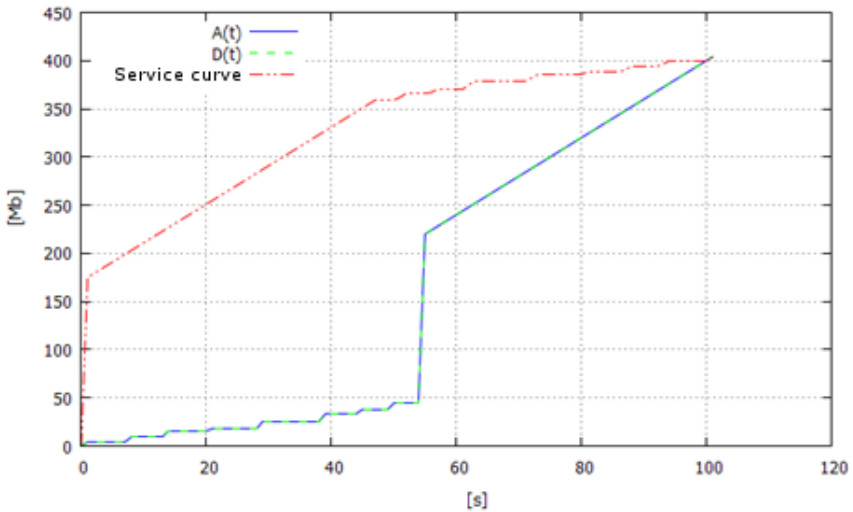
Notice that we have no information about capacity of the system.

Simulations

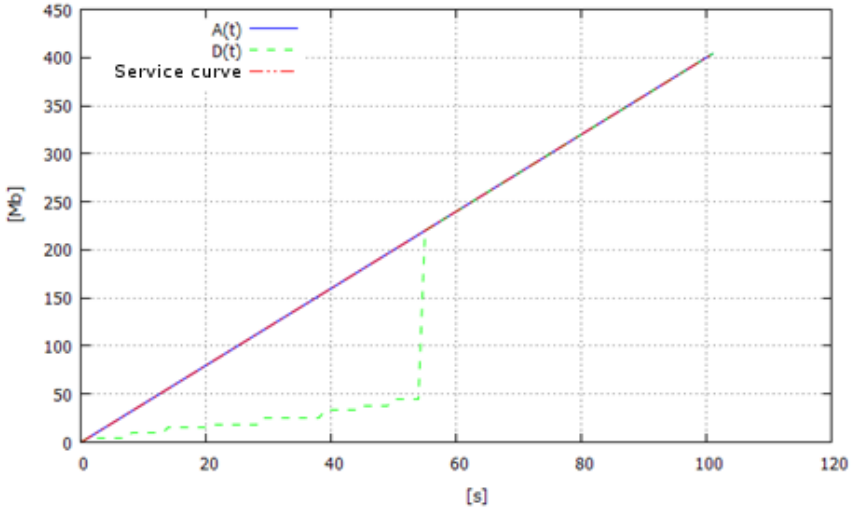


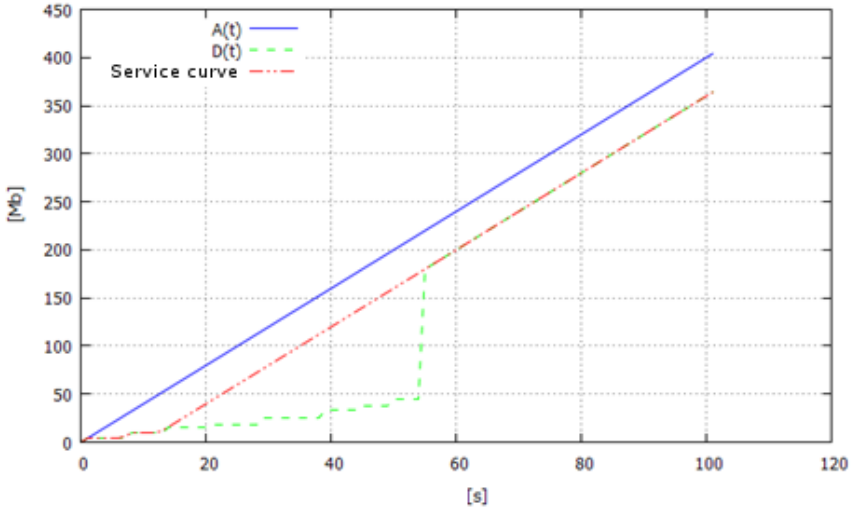


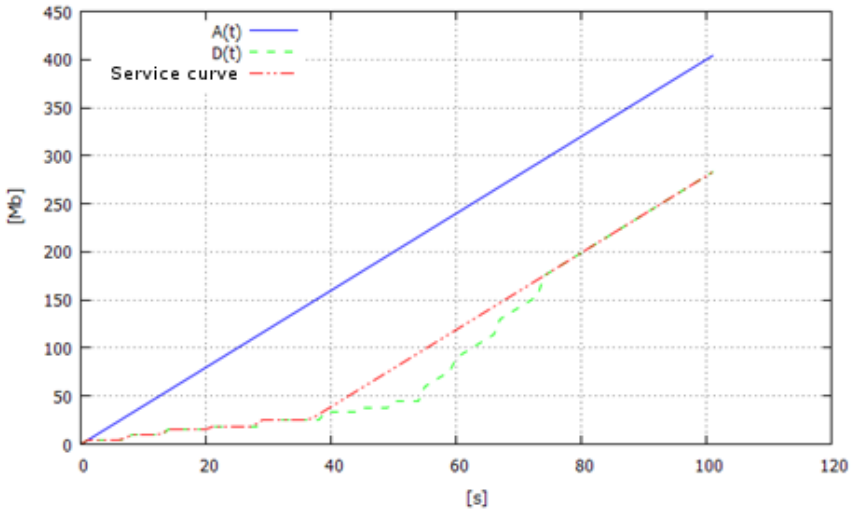


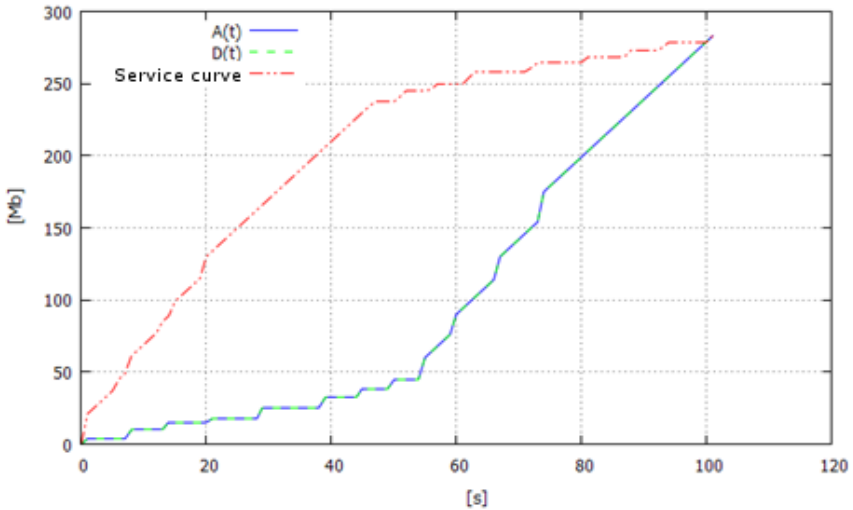


Simulations









Mathematical background

Theorem (1)

Let's assume that arrival and departure traffic have constant rate. Let r_A mean the rate of arrival traffic and r_D – the rate of corresponding departure traffic and let $r_D \leqslant r_A$. Then the estimate of the actual service curve $\tilde{S}$ has a slope of the departure curve D.

Proof.

If $r_D \leqslant r_A$, then

$$\tilde{S}(t) = \sup_{\tau} \{D^p(t+\tau) - A^p(\tau)\} = \sup_{\tau} \{r_D(t+\tau) - r_A\tau\} =$$

$$= \sup_{\tau} \{(r_D - r_A)\tau + r_D t\} = r_D t,$$

what finishes the proof.

Mathematical background

Theorem (2)

If the measurement has been made during time $[0, t_0]$*, then we have an equation*

$$\tilde{S}(t_0) = D^p(t_0).$$

Proof.
At time t_0 we have

$$\tilde{S}(t_0) = \sup_{\tau=0} \{D^p(t_0) - A^p(0)\} = D^p(t_0),$$

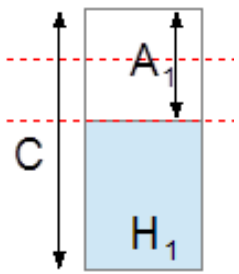
what finishes the proof.

Conclusions

- The estimate of service curve obtained by the passive measurement represents **possibility of bandwidth usage** and allows the evaluation of bandwidth
- The shorter time scales give more accurate (but not always useful) results
- In order to catch characteristic of estimate, short time scales require longer estimation time
- The moment of estimation starting has no influence on estimation result if estimation begins in advance
- Estimation of bandwidth usage is possible for particular flows as well as agregats of flows (IP addresses, single IP address, services)
- Estimation of bandwidth usage is possible in the single node as well as on the path of interconnected nodes

Available bandwidth estimation with LFV method

Available bandwidth **A** is the difference between the capacity of the system **C** and current bandwidth usage **H**.



Thank you
for your attention