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Analysis of Short Latencies In Industrial Network Environments*

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Abstract. *The bibliography shows the typical shape of probability density function (PDF) that describe network latencies. The paper presents the results of the measurements of the PDF of Round Trip Time (RTT) in real network environments. The results show, that the appropriate PDFs are significantly differentiated and depend on the kind of the network, its load, peers load, logic of applications, etc. The PDF measurments is focused on industrial network control programs transmissions, where only loses and short delays are important .*

1. Introduction

Modern devices require multiple of sensors and actuators connected to a control engine (or engines) by fieldbus networks – typically versions of serial links, sometimes, if higher bandwidth is required, via special technologies like Profibus [5], ARINC [8] or token ring or bus technologies or – esp. today – via special versions of Ethernet [1].

Standard solutions give very good QoS capabilities (delay, jitter, loss ratio), however they require dedicated hardware, hence they are expensive. The popular cheap solution – RS232/485 – require many cables. In case of more advanced systems (e.g. aicrafts) such approach requires kilometers of wires and tons of copper [8]. Moreover if some sensor fails there is the problem with replacement. Some systems are very susceptible on wire cluster failure and their management is quite expensive.

Therefore different approach gains popularity. Usage of standard and cheap devices and technologies, especially wireless, exactly the same like this one, that

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is used in an office networking (sometimes with different casing or suppliers). Such devices are produced in high volumes and therefore they are cheap, standard, easy to replace, and give high degree of compatibility. Unfortunately producers of the popular devices did not take into account QoS properties. For last few years, the situation gets better and the possibility of the defining layer 2, 3, 4+ priorities turns into a standard.

In many situations a control traffic is transmitted together with a general traffic therefore, however privileged, it is not independent. Especially the wireless technology is sensitive to background traffic and noise.

Control applications must deal with packet or frame loss, which is common in the wireless networks. Moreover, if a packet delay (possibly as a result of the retransmission) is too large, that the packets payload become useless. If latencies are fixed and there are no loses, then the control law synthesis is quite simple, but in the case of the uncertainty of the loss ratio (or delay) there is necessity of taking into consideration the probability density function (PDF) of both side latencies.

The bibliography points theoretical shapes of PDF's of RTT. These PDFs are considered as exponential, Poisson or Erlang distribution, sometimes as a Pareto distribution [3, 6, 7]. The paper presents the measurments of the PDFs in the real networks and discuss the differences in relation to the bibliography.

Most of the measurments was performed using two different application level strategies: "stop and wait" (SW) suitable for the low latency control loop without any looses, and "in flight" (IF) strategy suitable for the medium and high latency networks, and especially – for unreliable links. In both strategies 22 byte control payload is transmitted using the standard 28 byte UDP overhead (supplemented by the link level overhead). In IF strategy one station sends packets every ~1ms ($^1/_{1024}$ s) independent on the other side traffic. In the SW strategy packets are sent exactly after receiving peer packet or after timeout. The IF strategy is significantly more suitable for real-time systems due to the immunity on loses and transfer delays. However, the PDFs of the overall latencies (network, end systems and possible relays) are complex in this case.

2. Transport technologies

The paper considers the following technologies: switched Fastethernet, Ethernet, multirelay MAN, 802.11g, Bluetooth (BT). In most cases dedicated links, normal traffic and congestioned links are taken into account. Except BT, one of the parts of the transmission path is always the full duplex (FD) Fastethernet. The WAN technologies are not considered due to difficulties of its application to device control. The MAN network is represented by transmission through following links and devices: Eth 10Mbps half duplex (HD), Switch Eth 100Mbps FD, Router on Linux, Eth 100Mbps FD, Router/Switch Cisco 3550, Eth 1Gbps FD, Router/Switch Cisco 6500, Eth 100Mbps FD, Switch, Eth 100Mbps FD, PIX 515, Eth 100Mbps FD, Switch, Eth 100Mbps FD, and in the opposite direction. The properties of the 802.11 network (one hop) is considered in the excellent and the poor radio conditions using two different access points (AP). The detailed results of the experiments are presented in the Appendix; Duration of the experiments was about 40min (2^{32}ns) each.

Figures 1-2 present the PDFs obtained during communication of two nodes connected via the 100Mbps FD switch. Figure 1 – when the link is dedicated to the observed traffic, and figure 2 – in presence of the normal traffic in different networks. Figure 3 presents PDF obtained in the network where one side is connected to 10Mbps hub, when SW algorithm is used. Computers on both sides have CPU utilization on level < 5%. The source of the notch in the PDF peak (figure 1) is unknown, but one found out, that this phenomenon is always present, but its depth depends on the switch fabric, and higher class switches gives more shallow notches.

Figure 4 presents the PDF obtained during observation of the low loaded network traffic transmitted via the 100Mbps switch, where one peer is heavy loaded. The bimodal shape of that PDF is a result of the computer scheduling algorithm. The distance between peaks depends on the OS context switch interval.

Figure 5 presents the PDF obtained in the same as the previous situation obtained using IF algorithm. The effect of the computer overload is negligible.

Figures 6-7 present results obtained in a MAN network. Figure 6 – using SW algorithm and figure 7 – using IF algorithm. While simple SW algorithm generates RTT's PDF "similar" to Poisson or Erlang (even exponential) distributions, then application of the IF algorithm generates 4-modal distribution independent on the level of congestions (but not overcongestions), computer load, etc. Such distributions are results of the IF algorithm itself, where the delay between the packet arrival and the answer changes in range of zero to the sampling interval.

On figures 8-11 we present results of experiments on the standard WLAN 802.11g network with an excellent signal strength using the SW algorithm (figures 8-9) and the IF algorithm (figures 10-11). Figures 8, 10 presents results obtained, when the traffic has passed dedicated links, and figures 9, 11 when the network was congestioned by a very large file transfer.

On figures 12-13 we present results of the measurements, when the traffic was passed by the dedicated link, when a very low strength signal was received, and using different Access Points. Only the SW algorithm can be used because the IF algorithm with ratio 1ms is too fast and due to the internal driver buffering the RTTs the average and median of the PDF was about 1s (sic!), that makes such an algorithm unusable. The same considers Bluetooth 1.2 network, where the appropriate PDF is presented on fig. 15.

Figure 8 and 13 show the results of using different Access Points. Note, the line marks are used consequently, and a better AP in excellent radio conditions gives significantly worse results in poor radio conditions.

This phenomenon is a result both of the higher radio sensitivity of AP2 (linksys WAG200G – signal power measured at the client is on the level about

–78dBm) and the number of retries of unacknowledged frames. In both AP (as well as at the station) such a configuration parameter was inaccessible (according to standard's recommendation – 4 in standard DIFS access and 7 – in VCS method), but is different.

Figure 14 shows results of the application of the secure access to the 802.11 network. As it is widely known [2], the 802.11 is inappropriately constructed from the point of view of the security. Therefore it includes some extensions (WEP, WPA, WPA2 and possibly TKIP) in this area [2]. However, these protocols cause a significantly longer association time as is described in the bibliography, and they influence transmission latencies. The tests show high dependency of this parameter on the access point's fabric and for AP2, WEP ciphering has no measurable impact on delays, similar to WPA. However application of the strong WPA2 cipher (128-bit AES) delays transmission about 100us. Both the mobile equipment and the AP have the hardware supporting AES.

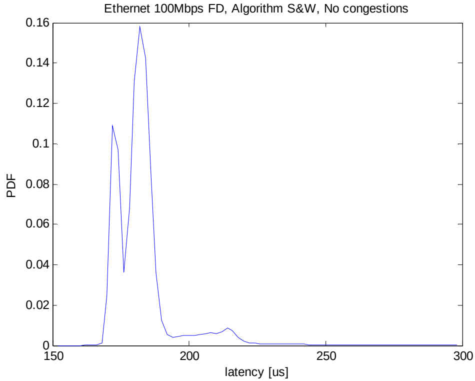

Fig. 1. PDF obtained during communications via dedicated 100Mbps FD Ethernet. Algorithm SW.

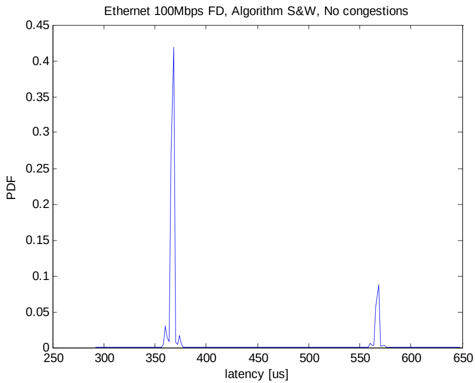

Fig. 2. PDF obtained during communications via normal loaded 100Mbps FD Ethernet. Algorithm SW.

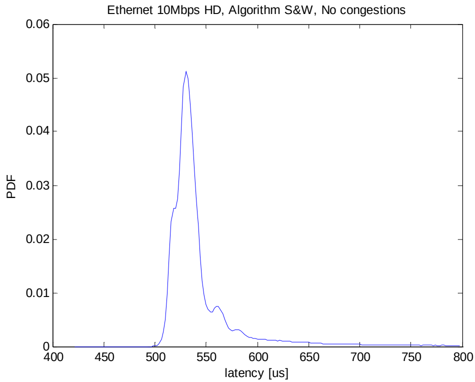

Fig. 3. PDF obtained during communications via normal loaded 10Mbps HD Ethernet. Algorithm SW.

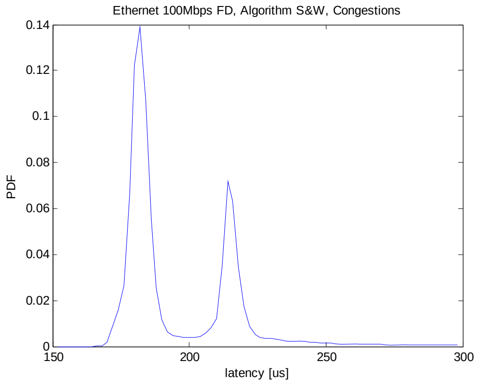

Fig. 4. PDF obtained during communications via dedicated 100Mbps FD Ethernet. Algorithm SW. Peer heavy loaded

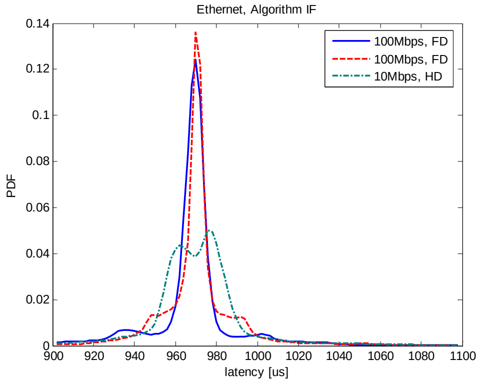

Fig. 5. PDF obtained during communications via different Ethernets. Algorithm IF.

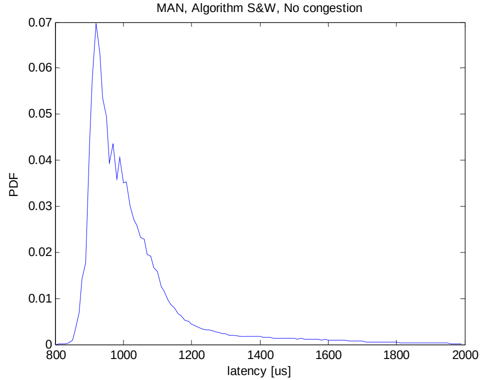

Fig. 6. PDF obtained during communications via multiple fast relays in campus network. Algorithm SW.

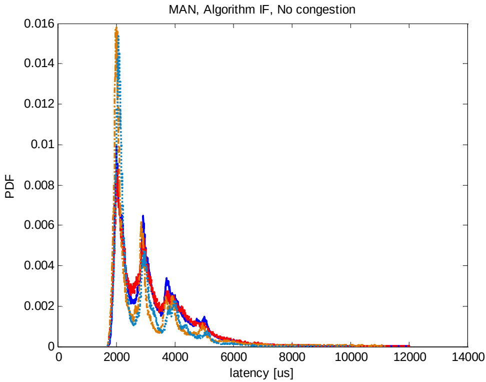

Fig. 7. PDFs obtained during communications via multiple fast relays in campus network. Algorithm IF.

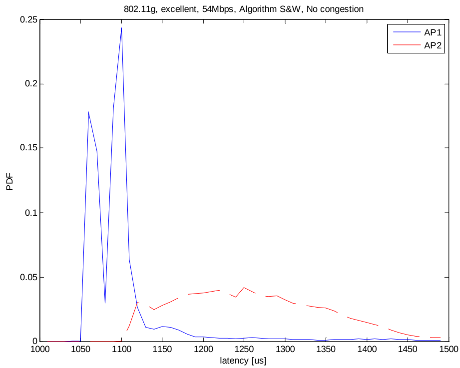

Fig. 8. PDF obtained during communications via dedicated WLAN. Algorithm SW. Two different AP were used.

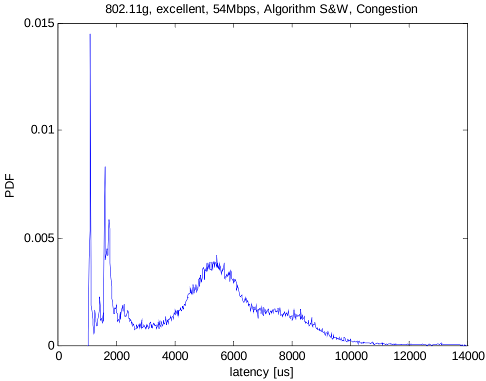

Fig. 9. PDF obtained during communications via overcongestioned WLAN. Algorithm SW.

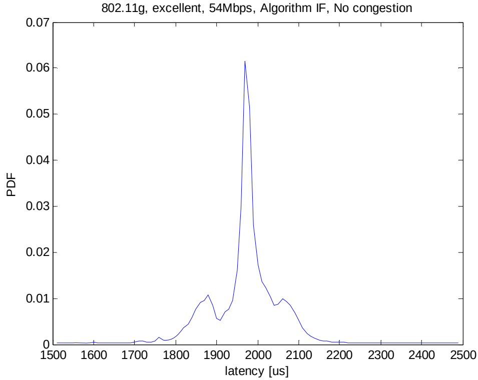

Fig. 10. PDF obtained during communications via dedicated WLAN. Algorithm IF.

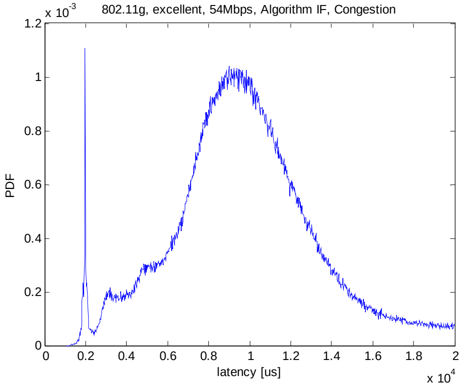

Fig. 11. PDF obtained during communications via overcongestioned WLAN. Algorithm IF.

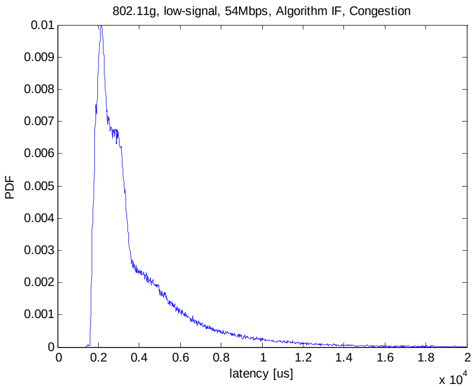

Fig. 12. PDF obtained during communications via dedicated WLAN while receiving signal had very low level. Algorithm SW

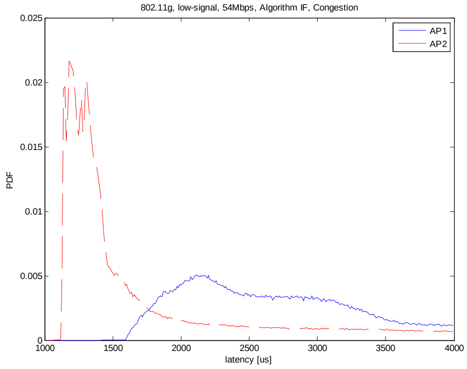

Fig. 13. PDF obtained during communications via dedicated WLAN while receiving signal had very low level. Algorithm SW on different Access Points

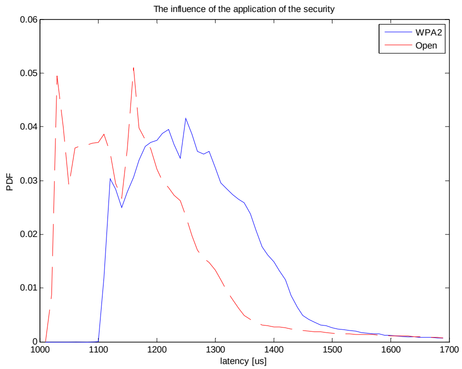

Fig. 14. Security effect on WLAN 902.11g

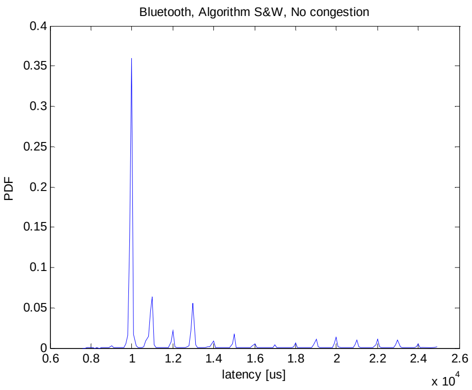

Fig. 15. PDF obtained during communications via BT (1.2) network. Algorithm SW.

3. Conclusions

The experiments show the PDFs of RTT obtained in different networks significantly differ from theoretical results published in bibliography. Only in particular cases obtained PDF is similar to the Poisson or exponential distributions. The PDF depends on network properties but also on the operating system properties, and on the control algorithm. The knowledge of the PDF in specific networks is necessary to synthesis of the network feedback control.

While Ethernet or multihop Ethernet (MAN) networks fits excellent into the network control systems requirements, the WiFi networks is very susceptible to the environmental noise, and it is difficult to hold desired QoS, mostly due to the needless link level retransmissions. Standard 802.11e should improve the situation. Unfortunately the proper drivers was inaccessible during experiments. As expected, good properties were obtained using the WPAN networks.

The situation theoretically could be improved using higher quality AP, where it is possible to setup retransmission count, power control, contention window limits etc. Unfortunately such AP was unavailable during the test as well. Moreover such AP is quite expensive, and this feature partially violates assumption of using low-end – hence cheap – devices.

Acknowledgments

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Appendix. Numerical Results

Description	**No of samples**	**Min RTT [µs]**
Ethernet 100 FD, dedicated. Alg. SW	5337224	163
Ethernet 100 FD, normal traffic. Alg. SW	4633215	263
Ethernet 10 HD, normal traffic. Alg. SW	2700973	499
Ethernet 100 FD, dedicated. Peer heavy loaded. Alg. SW	501425	167
Ethernet 100 FD, dedicated. Alg. IF	883253	41
Ethernet 100 FD, normal traffic. Alg. IF	2139202	318
Ethernet 10 HD, normal traffic. Alg. IF	2128430	536
Multirelay MAN, Alg SW	1562185	811
Multirelay MAN, Alg IF	1545740	1698
Multirelay MAN, Alg IF	438567	1680
Multirelay MAN, Alg IF	571649	1669
Multirelay MAN, Alg IF	1637754	1698
Multirelay MAN, Alg IF, Peer heavy loaded	217880	1685
WLAN, 54Mbps, Signal Excellent, link dedicated, Algorithm SW (AP1)	1240340	1038
WLAN, 54Mbps, Signal Excellent, link dedicated, Algorithm SW (AP2, WPA2)	1564061	1129
WLAN, 54Mbps, Signal Excellent, link overcongestioned, Algorithm SW	114848	1065

WLAN, 54Mbps, Signal Excellent, link dedicated, Algorithm IF	2147080	1126
WLAN, 54Mbps, Signal Excellent, link overcongestioned, Algorithm IF	2136649	1263
WLAN, 54Mbps, Signal Low, link dedicated, Algorithm SW (AP1)	495409	1421
WLAN, 54Mbps, Signal Low, link dedicated, Algorithm SW (AP2)	495409	1123
WLAN, 54Mbps, Signal Excellent, link dedicated, Algorithm SW (AP2, Open)	1706029	1023
Bluetooth, 1Mbps link dedicated, Algorithm SW	170632	7811