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THE PERFORMANCE ANALYSIS OF WIFI DATA NETWORKS USED IN AUTOMATION SYSTEMS

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The networks with wireless links for transmission automation control applications traffic when packets have small size and applicationpayload is predictable are under consideration. Analytical model for packets delay estimations in the case of WiFi wireless networks is proposed. The specifications for physical layer 802.11 a/b/g/n are under consideration.The data from analytical model are compared with simulation and field experiments.

Keywords: WiFi, 802.11, 802.11 a/b/g/n, packet delay

1. Introduction

Wireless Local Area Networks based on 802.11technology (often called as WiFi) have become quite popular and widespread. The nature of links based on the radio channel and the access to the shared resource of this channel cause variable available bandwidth, variable packet delay and loss rate. This may prevent to the correct operation of the networked time-sensitive applications, such as multimedia or control applications.

In the automation area, there is a clear trend promoting the use of wireless control channels in the factory floor. Closing control loops over wireless networks is raising interest also in the automation systems of moving objects.

As an example of such system is a wireless electric recharge of driving vehicles (A.V. Gordyushins , R. Saltanovs , et, 2013) . For successful operation it is necessary to organize multiple streams of data between modules that transmit and receive energy and no wired links for data transfer are possible between such modules. For datastream providing system operating frequency synchronization demands are formulatedfor the data channel delay time. In this example of automation control the size of application packets is estimated as 72 bits, the latency of transmission of such packet need to be no more than 18 milliseconds, and the payload for such application traffic (for both data streams, one from energy receiving module and second from energy transmitting module) is estimated as 7,2 Kbps. The payload on the wireless channel obviously when it is common shared resource is proportional to the number of wireless links. So for considered simple system design of two modules and channel implementation on WiFi infrastructure architecture (all wireless links only between communicating nodes and Access Point) the requirements will be: for wireless link latency no more than 9 ms (two hops are needed to deliver a packet) and guaranteed network bandwidth for application traffic no less than 14,4 Kbps. Moreover, in the wireless links of the system high levels of electromagnetic interference is expected andcommunication media must provide multiple access opportunities for communication with multiple vehicles.

This example illustrates how automation control applications bring forward the demands to wireless links structure. It is obviously that the delay introduced by the network may degrade control performance or just make such control quite impossible. Therefore, a good estimation of the network latency together with network bandwidth will facilitate robust system designs.

In this paper the simple analytical model for the estimation of minimal possible latency of packets in the link and provided network bandwidth with “acceptable” performances for several WiFitechnologies (802.11 a/b/g/n) is considered.

To take into account the contention (competition) for radio recourse in the links,network with infrastructure architecture have been investigated by using different applications data rate on transport layer (UDP was a transport protocol). The network was simulated via NetSim(NetSim v. 6.1, 2013) simulation environment. The statistical data namely the statistical parameter of total application data (payload) delivered to their respective destination every second, characteristics of link latency (Queuing Delay, Medium Access Time, Transmission Time) and others have been collected from the simulations. The experimental data for different Access points (AP) and wireless host's adapters (802.11g/n) was collected to compare analytical and practical results for delivered network bandwidth.

2. Analytical model

In this paper we are developing a simple model for the packets delay and hence maximum UDP throughput of 802.11 networks so that acomparison can move beyond a simplecomparison of nominal bit rates for different PHY (physical layer) specifications 802.11 a/b/g/n. Such models are considered in many publications, we will follow to the to 802.11 specifications (M. Gast, 2002), clarifying article (M. Gast, 2003) and publication (Qiang Ni, 2005) to take into account the transmission of small UDP packets and differences for MAC (media access layer) of 802.11n specification.

2.1. Transactions

The basic transactional model assumesthat802.11 frame contain a single UDPpacket. To cope with the inherent unreliability of radiowaves, the 802.11 MAC requires positive acknowledgement of every transmission. Each UDP packetmust therefore be wrapped up in a frame exchange. The complete transaction consists of:

- Distributed Interframe Space (DIFS): this interframe time interval indicates that an exchange hascompleted, and it is safe to access the medium again.
- The data frame containing the UDP packet.
- A Short Interframe Space (SIFS), which is a small time gap between the data frame and itsacknowledgement.
- The 802.11 ACK frame.

Figure 1 shows the principle mechanism for sending frames using the foundational DCF (Distributed Coordination Function) access method. The same coordination function logic is active in every station in a basic service set (BSS) whenever the network is in operation. Stated differently, each station within a DCF follows the same channel access rules. Thismethod is contention-based, which means that each device "competes" with one another to gain access to the wireless medium. After a transmission opportunity is obtained and observed, the contention process begins again. As the original 802.11 network access method, DCF is the most simple channel access method; however, being the first access method, it lacks support for quality of service (QoS). In order to maintain support for non-QoS devices in QoS-enabled networks, support for DCF is required (mandatory for realization) for all 802.11 networks (M. Burton, 2009).

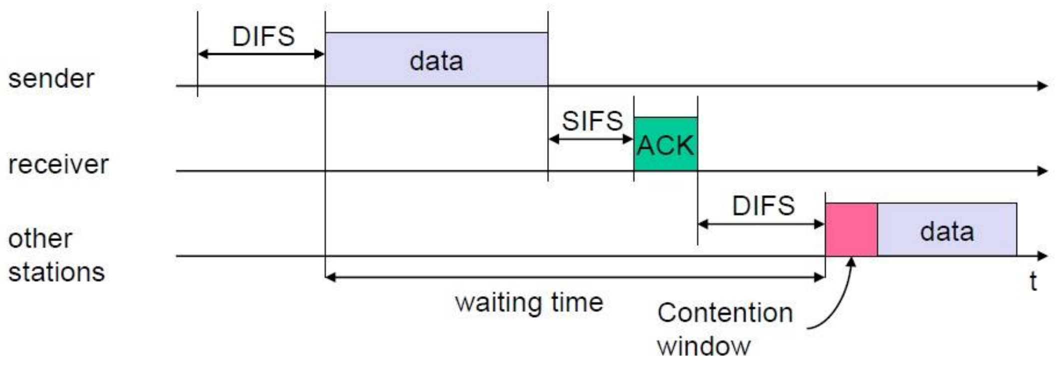

Figure 1. 802.11 DCF channel access mechanism for unicast frames

2.2. Encapsulation

In addition to the payload data, there are 36 additional bytes of dataadded in the encapsulation process. The 802.11 MAC header adds28 bytes of data for various control and management functions,error detection, and addressing. A further eight bytes are added bythe SNAP encapsulation header to identify the network layer protocol (M. Gast, 2002). The total size of the *l* application bytes encapsulated in UDP packet and in 802.11 MAC frame is:
l + 8 (for UDP header)+ 20 (for IP header) + 36 (for MAC frame) = (*l* + 64) bytes = (8*l* + 512) bits.

2.3. Throughput

In our study we are interesting in throughput of the network at the UDP payload layer. So, if $R_{Frame}$the frames rate on MAC layer, T_{Frame} is the time to deliver the frame in the link and each transaction delivers one data frame, the rate for the application data on UDP layer R_{App} according with encapsulation will be:

$$R_{App} = R_{AppP} \cdot 8l = R_{Frame} \cdot 8l = \frac{8l}{T_{Frame}} \qquad (1)$$

bits per seconds, where *l* – the size of application packet in bytes.By adding up the total time required for each component ofthe transaction, a frame transaction rate can be derived.

2.4. Frame delivery time estimations

The transactional model is simplified, it neglects important effect. First of all, it assumesa steady stream of well-ordered frames with no contention for the medium. 802.11 implementscollision avoidance and exponential back off (in contention window, see Figure 1), so in reality, the time between frame exchanges will belonger than one DIFS. Exponential back off in the presence of contention will further decreasethroughput. (M. Gast, 2003) estimates that contention for the medium would reducethe maximum throughput figures above by 25% to 50%, depending on the exact assumptions made. So, if we do not take into account the contention period, we will estimate the minimal time for frame delivery. Other wordsless frame delivery time may not be and, if it satisfies not control application requirements, the WiFi technology is not applicable in this case.

Estimations for 802.11b

The baseline speed comes from 802.11b. It is not as fast as the newer specifications, but we do the calculation for 802.11b first to compare with other. See table 1in what the parameters and calculations for different specifications are presented.First off, the basic timing numbers for 802.11b:
SIFS = 10 μs
Slot time = 20 μs
DIFS = 2 x Slot time + SIFS = 50 μs.

802.11b requires that a preamble be prepended to every frame before it is transmitted to the air. Thatpreamble may be either the traditional "long" preamble, which requires 192 μs for transmission, or itmay be an optional "short" preamble that requires only 96 μs. Support of the long preamble ismandatory, and is the default setting on most devices, so we will use in calculations only the long preamble.

802.11b running at the max speed (11 Mbps) divides data up into 8-bit symbols. There are (l+64) 8-bit blocks inthe UDPpacket. The 802.11 ACK does not haveSNAP headers, and is only 14 bytes long.Encoding the MAC frames is easy. 802.11b divides up the MAC frame into a series of 8-bit"symbols," and then transmits 1.375 million symbols per second. So add up the individual componentsof the transaction to get the total duration:
For 802.11 data frame: 192 μs + ((l+64)/1.375) μs;
For 802.11 ACK: 192 μs + (14/1.375) μs = 192 μs + 10μs= 202μs.

As it is also can be seen in table 1 transaction for 802.11b when *l*=10 bytes requires 508μs (T_{Frame}). At that duration, 1968 exchanges can complete per second. With a UDP payload of 10 bytes per exchange, the throughput from relationship (1) is 0.157 Mbps.

Estimations for 802.11a

802.11a is faster than 802.11b for two reasons: timing relationships between frames in the exchanges, and the encoding used by 802.11a does not require such long preambles forsynchronization. The basic timing numbers for 802.11a in table 1.

Like 802.11b, 802.11a divides data up into a series of symbols for transmission. However, theencoding used by 802.11a uses much larger symbols. At 54 Mbps, each symbol encodes 216 bits. Fora full listing of encoding block sizes, see Table 11-3 in (M. Gast, 2002). The OFDMencoding used by 802.11a adds six bits for encoding purposes to the end of the frame.The 802.11 ACK also requires just one symbol.Each frame is prepared for transmission in the air with a 20 μspreamble to synchronize the receiver.Following the 20 μs header is a series of symbols, each requiring 4 μs(216 bits divided on 54 Mbps) for transmission.

At 105μs per transaction, it is possible to complete 9524 exchanges per second. That corresponds to a throughput of 0,762 Mbps.

Estimations for 802.11g

802.11g operates in the same frequencyband as 802.11b, and is required to remain backwards-compatible. The encoding used by 802.11g willnot be recognized by 802.11b stations, so "protection" mechanisms are defined to limit the cross-talkin mixed b/g environments. Essentially, the protection mechanisms require that 802.11g stationsoperating at high rates pre-reserve the radio medium by using slower, 802.11b-compatible reservationmechanisms.

802.11g SIFS = 10 μs

802.11g short slot time = 9 μs (802.11g-only mode with no legacy stations)

802.11g long slot time = 20 μs (mixed mode requires slow slot time)

802.11g uses many of the same timing parameters as 802.11a. It inherits the short 10 μs SIFS time from 802.11b, but the high-ratecoding in 802.11g needs additional time. Therefore, 802.11g adds a 6 μs "signal extension" time at theend of every frame.

When no 802.11b stations are present, no protection is required. The 802.11g ERP-OFDM PHY is nearly identical to the 802.11a PHY, except that it operates in adifferent frequency band and uses a shorter SIFS time. Physical layer headers are identical, as is thecoding. Therefore, the calculation for the time required to transmit a frame is nearly identical, withonly minor changes to the interframe space times (see table 1).

The transaction length of only 802.11g is identical to 802.11a. So, At105μs per transaction, it is possible to complete 9524 exchanges per second. That corresponds to a throughput of 0,762 Mbps.

Once the first 802.11b station associates with an 802.11g access point, however, protection is required. Figure 2 shows the principle mechanism for sending frames using the foundational DCFaccess method with RTS/CTS frames for protection.

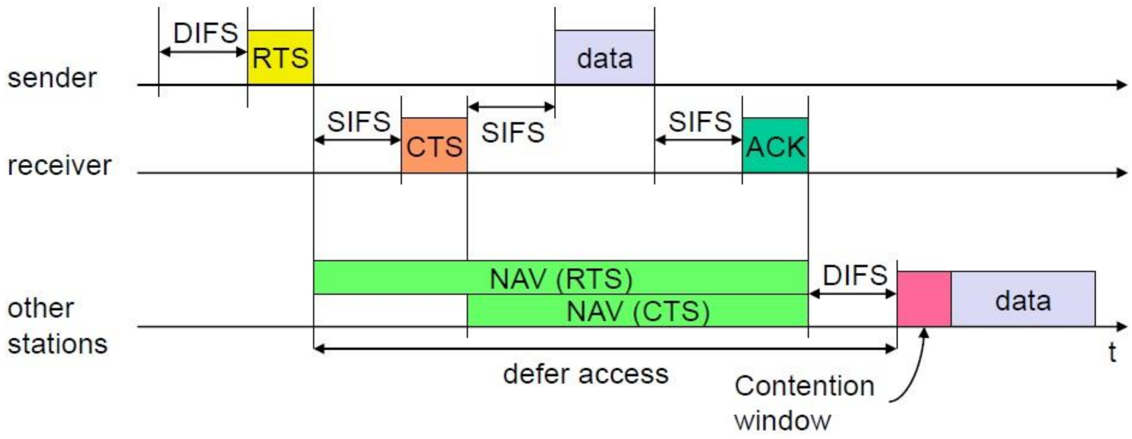

Figure 2. 802.11 DCF channel access mechanism for unicast frames with RTS/CTS frames exchange

The minimal protection contemplated by the standard is that 802.11g stations will protect the fast802.11g frame exchange with a slow Clear To Send (CTS) frame that locks out other stations access tothe medium. Protection dramatically reduces the maximum theoretical throughput because theadditional CTS transmission is required with its long 802.11b headers.Longer interframe spacing is required when legacy clients are connected and protection is engaged.The short slot time is only available when no 802.11b stations are present. Once they are present, theframe spacing reverts to the 802.11b standard.

Using only a CTS frame to reserve the medium is the minimum requirement, but it may fail in somecases where there are so-called "hidden nodes" that do not see the CTS. To fully reserve the medium,the initial edition of the 802.11 standard included a two-frame exchange that would fully announce theimpending transmission composed of a Request To Send (RTS) frame followed by the CTS frame.Although the standard requires only a CTS-to-self, using the full RTS/CTS will better protect the innerexchange from interference. The final calculation is quite similar to the previous one.

The total transaction time is 556μs per transaction, so only 1798 transactions can complete per second, and the throughput drops back into digits 0,143 Mbps.

Estimations for 802.11n

At the MAC layer, 802.11n use several new MAC, including the frame aggregation, blockacknowledgement, and bi-directional data transmission (H.C. Lee, 2011).At the PHY layer,802.11n will use MIMO (Multiple-Input Multiple-Output) and OFDM. It supports up to atransmission rate of 600 Mbps and is backward compatible with IEEE 802.11a/b/g. In our simple model we will use many timing parameters that are equal to parameters of 802.11a/g as in (Qiang Ni, 2005). They are shown in table 1. PHY layer peak rate will be 54 · k Mbps and number of bits per symbol 216·k, where k=(1,2,3….).

In our case of small application packets the total transaction time is 106μs per transaction, so 9434 transactions can complete per second, and the throughput is still 0,762 Mbps as for 802.11a/g case.

Table 1. Parameters, taken into account in analytical model, for estimation of T_{Frame}- the time to deliver frame through one wireless link, application packet size 10 bytes, maximal bit rate on PHY layer

Specifiedparametrs	**802.11b**	**802.11a**	**802.11g-only BSS**	**802.11g Protection RTS/CTS**	**802.11n**
l application packet size [bytes]	10	10	10	10	10
SIFS [μs]	10	16	10	10	16
Slottime [μs]	20	9	9	20	9
DIFS = 2 x Slot time + SIFS [μs]	50	34	28	50	34
Preambleofframe [μs]	192	20	20	192 or 20	20
Max raw data rate [Mbps]	11	54	54	11 or 54	108
Transaction elements steps	**Time for transection elements [μs]**				
1. DIFS	50	34	28	50	34
2. RTS 20bytes				207	
3. SIFS				10	
4. CTS 14bytes				202	
5. SIFS				10	
6. 801.11 Data	246	31	37	37	32
7. SIFS	10	16	10	10	16
8. 802.11 ACK 14bytes	202	24	30	30	24
$\mathbf{T_{Frame}}$ **[μs]**	508	105	105	556	106

In table 2 the calculations for different WiFi technologies are generalized and expressed through specified in specifications figures, application packets size and "physical" bit rate in the wireless link.

Table 2. Relationships for T_{Frame} estimations for different specifications. UDP packets, application packet size l [bytes], R_{raw}-bit rate on PHY layer [Mbps]

	802.11b	**802.11a**	**802.11g-only BSS**	**802.11g Protection RTS/CTS**	**802.11n**
T_{Frame} [µs]	$444+\frac{8(l+78)}{R_{raw}}$	$94+\frac{8(l+64)+6}{R_{raw}}$	$94+\frac{8(l+64)+6}{R_{raw}}$	$520+\frac{8(l+234)+6}{R_{raw}}$	$100+\frac{8(l+64)+6}{R_{raw}}$

2.5. Packets delays

In principal there is a latency of application packets on the path from initial to end node due to the time to deliver frame in one link T_{Frame}, calculated on the previous steps, and queuing in the nodes at the time when radio channel is busy for transmitting another frames. It is true, if radio channel is common recourse as for an example in BSS, when all nodes are communicating through access point AP.

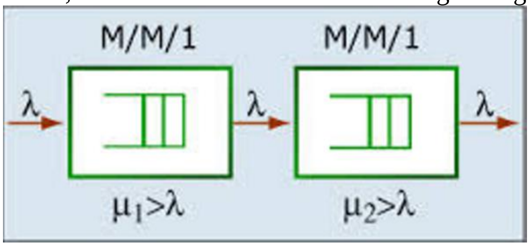

Figure 3. Queuing model of the channel with two links

According to the Queueing Theory, when requests with intensity λ are coming on sequence of serving nodes on what service is made with intensity μ and when time intervals between requests and time of request's service are exponentially distributed (so called M/M/1model) the average service time will be:

$$\bar{t} = \frac{1}{\mu} + \frac{1}{\mu} \cdot \frac{\rho}{1-\rho}, \text{ where } \rho=\lambda/\mu \text{ and } 0 \le \rho < 1 \qquad (2.1)$$

Simplification of real world processes in this model for packets delay is obvious, but it accepted in many cases for the estimations in computer networks design. This model can be "easy improved". For an example we may use M/G/1 instead M/M/1 approximation, when service tame has an arbitrary distribution and the average service time instead (2.1) will be:

$$\bar{t} = \frac{1}{\mu} + \frac{1}{\mu} \cdot \frac{\rho(1+c^2)}{2(1-\rho)}, \text{ where } c = \frac{\sqrt{D(t)}}{\bar{t}} \qquad (2.2)$$

D(t)- the variance of service time (for exponential distribution of service time c=1).

Using (2.1) or (2.2), we can estimate the application packets delay D_{App}through the path of several links. For (2.1) we have:

$$D_{App_i} = \sum_n (T_{Frame_{i,n}} \cdot \frac{1}{1 - T_{Frame_{i,n}} \cdot \sum_{i,n} R_{AppP_{i,n}}}), \text{ where} \qquad (3)$$

*n*enumerateslinks on the paths of packets, and *i*enumerates the applications.For the clarification of relationship (3) several examples.

Example1

Node1, connected through WiFi channel to AP, transmits to Node2. Node2 is connected to AP with wired network. If we neglect with the delay in wired network, (3) gives:

$$D_{App} = T_{Frame} \cdot \frac{1}{1 - R_{AppP} \cdot T_{Frame}} \tag{3.1}$$

Example 2

Node1 and Node2 are in the same BSS and Node 1 transmits to Node2. So, we have 2 wireless links and (3)gives:

$$D_{App} = 2 \cdot T_{Frame} \cdot \frac{1}{1 - 2 \cdot R_{AppP} \cdot T_{Frame}} \tag{3.2.1}$$

On the basis of M/G/1 model for this example 2 we receive:

$$D_{App} = 2 \cdot T_{Frame} \cdot \frac{1 + (c^2 - 1) \cdot R_{AppP} \cdot T_{Frame}}{1 - 2 \cdot R_{AppP} \cdot T_{Frame}} \tag{3.2.2}$$

Example 3

Node1 and Node2 are in the same BSS. Node 1 transmits to Node2 and Node2 transmits to Node1. If characteristics of application traffic for Node1 and Node2 are the same, the delay of packets in both directions from (3) will be:

$$D_{App} = 2 \cdot T_{Frame} \cdot \frac{1}{1 - 4 \cdot R_{AppP} \cdot T_{Frame}} \tag{3.3.1}$$

On the basis of M/G/1 model for this example 3 we receive:

$$D_{App} = 2 \cdot T_{Frame} \cdot \frac{1 + 2 \cdot (c^2 - 1) \cdot R_{AppP} \cdot T_{Frame}}{1 - 4 \cdot R_{AppP} \cdot T_{Frame}} \tag{3.3.2}$$

Example 4

Node1 and Node2 are in different BSSs generated by AP_1 and AP_2. APs are connected through wired network. Characteristics of application’s traffic are different: from Node1 to Node2 data rate is R_{App1} and from Node2 to Node1data rate is R_{App2}. Moreover the times of frames delivery are different for applications and links (for an example in BSS_1 802.11g-only is but in BSS_2 802.11g with RTS/CTS protection is on). For transmission from Node1 to Node2 in BSS_1 link the frame time is $T_{Frame11}$ and in BSS_2 link $T_{Frame12}$. Respectively for packet stream from Node2 to Node1 the times are $T_{Frame22}$ and $T_{Frame21}$. In this case from (3):
For the delay of packets from Node1

$$D_{App1} = T_{Frame11} \cdot \frac{1}{1 - (R_{AppP1} + R_{AppP2}) \cdot T_{Frame11}} + T_{Frame12} \cdot \frac{1}{1 - (R_{AppP1} + R_{AppP2}) \cdot T_{Frame12}},$$

and for the delay of packets from Node2

$$D_{App2} = T_{Frame22} \cdot \frac{1}{1 - (R_{AppP1} + R_{AppP2}) \cdot T_{Frame22}} + T_{Frame21} \cdot \frac{1}{1 - (R_{AppP1} + R_{AppP2}) \cdot T_{Frame21}}$$

2.6. Network bandwidth for applications

For automation control applications we suppose that network bandwidth will be acceptable if traffic of packets can be delivered and the delay of packets remains in acceptable range. We will not write general relations for the bandwidth they are pretty obvious for our model of delays in the packagedelivery but we will consider maximal possible and “acceptable” bandwidth for the example 2 from topic 2.5 Packets delays.

For this case (Node1 and Node2 are in the same BSS and Node 1 transmits to Node2, we have 2 wireless links) from (3.2.1) (or from (3.2.2)) the maximal application possible throughput or maximal bandwidth can be achieved when expression in the denominator is equal to zero, hence:

$$R_{App}^{Max} \equiv B_{App}^{Max} = R_{AppP}^{Max} \cdot 8 \cdot l = \frac{8l}{2T_{Frame}} \text{ in bits per second,} \quad (4)$$

as above, *l*– the size of application packets in bytes.

But, when application data rate achieves its maximum, the number of packets in queues and packets delay tends to infinity. In many practical cases it is reasonable to limit the packet delay to some value. If we accept that the average delay not greater than two its possible minimal values (physical sense – only one packet waits in a queue, see (2.1)), then for our example 2:

$$B_{App} = \frac{8l}{4T_{Frame}} \quad (5)$$

This bandwidth should be considered as "acceptable" in the sense that if application data rate R_{App} not exceeds bandwidth B_{App} the package delay will be in the range $D_{App}^{Min} \le D_{App} \le 2D_{App}^{Min}$.

Completely analogous for the example 3 (Node1 and Node2 are in the same BSS. Node 1 transmits to Node2 and Node2 transmits to Node1) the acceptable network bandwidth will be:

$$B_{App} = \frac{8l}{8T_{Frame}} \quad (6)$$

2.7. Analytical model summarization

Thus,developed on previous steps model, gives the basis for the estimations of delays in application packets delivery through the network with wireless links. The delay on every packet path in our model is a function of network structure $\vec{S}$, structure of payload on application level $\vec{R}_{App}$ and parameters of wireless technologies $\vec{P}$ used in the wireless links. Calculations for delays $D_{App}(\vec{S},\vec{R}_{App},\vec{T}_{Frame})$ function are presented in topic (2.5. Packets delays) and MAC frames transmission time through wireless links for different WiFi specifications $T_{Frame}(\vec{P},l)$ calculations are presented in table 2. Application payload (the size of packets *l*) is carried by UDP transport layer protocol.

3. Simulation

For the validation of analytical estimations we have performed several numeric simulations. The simulation and analytical results for two network and application payloadstructures what we have considered in the topic 2.5. Packets delays are presented on figure 4 and figure 5. The structures were from Example 2 and Example 3. The payload in all cases is provided by "small" UDP packets, the application part size is 10 bytes. On figure 4 the results for 802.11b wireless links and on figure 5 for 802.11g-only. As the simulation environment NetSim(NetSim v. 6.1, 2013) were used.

On figure 4 we can see, that for simulation of Example 2 (Node1 and Node2 are in the same BSS and Node 1 transmits to Node2, communications through links under 802.11b specification take place) packets delay time per link is about 2 milliseconds when application payload is near 39 kilobits per second (refer to points on the graph marked as rhomb as shown on legend panel). We refer to delay per link because in all our cases the parameters of all links were the same. For Example 2 only one path exists (from Node 1 to Node 2) and the delay on the path will be multiplied by two (4 ms in case above).

The analytical model calculated as (3.2.1) (curve "Ex2,M/M/1" on the graph) gives us in this case near 1 ms but calculated as (3.2.2) (curve "Ex2,M/G/1,c=1,6"), if we suppose c=1.6, gives estimation near 1.9 ms.

On the graph also the “acceptable” bandwidth is shown (line “Ex2 bandwidth” for Example 2, when R_{App}=39.4 Kbps and line “Ex3 bandwidth” for Example 3, when R_{App}=19.7 Kbps), calculated as (5) and (6) respectively.

On figure 5 (when WiFi technology 802.11g-only for the links is used) one can see other numerical values but similar dependences.

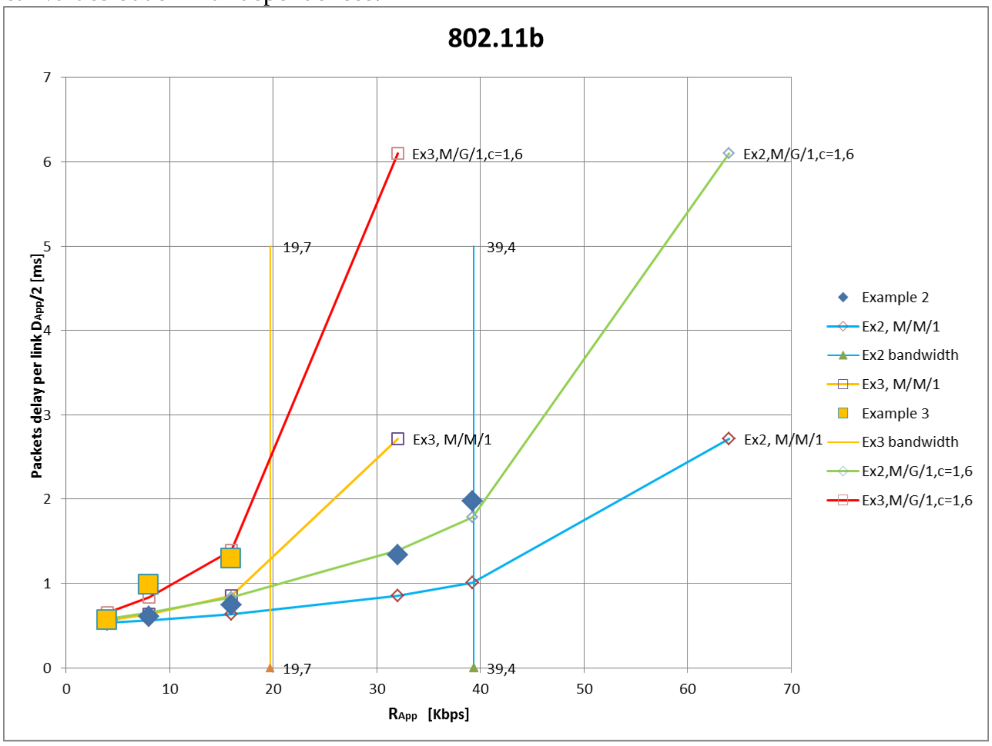

Figure 4.Simulation and analytical results for structures of Example 2 and Example 3. 802.11b links in BSS

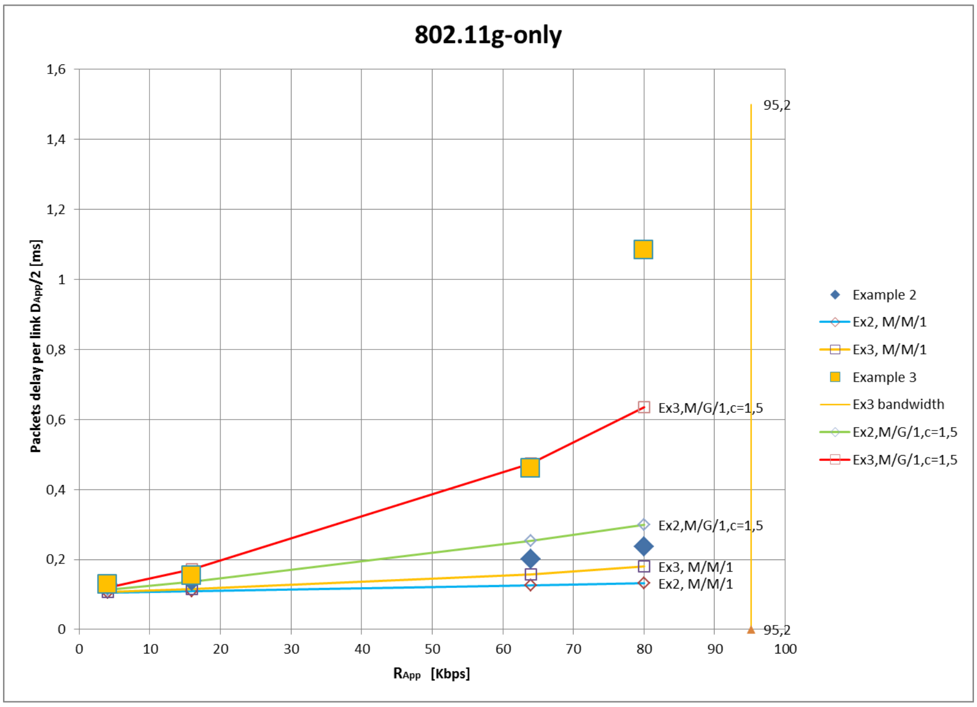

Figure 5.Simulation and analytical results for structures of Example 2 and Example 3. 802.11g-only links in BSS

Comparing simulation and analytical model results, one can go to conclusion that they are in a good correspondence in appropriate range of payloads. The range is lager for M/G/1 than M/M/1 analytical model approximation. The range of such “validity” (for M/G/1) is from zero to about “acceptable” bandwidth calculated for M/M/1 model ((5) and (6) for Example 2 and Example 3). Using M/G/1 approximation, one needs to know variation coefficient c (see (3.2.2) and (3.3.2)) for the distributions of time in frame delivery through wireless link. For our simulation models it was found in the range 1.5 – 1.6. For many processes in computer systems this coefficient not greater than 3. In our cases we can recommend for estimations to take c from the range 1 – 3 (1 when exponential distribution is supposed, 1.5 for “optimistic” and till 3 for “pessimistic” estimations).

4. Experiments

For the validation of some analytical estimation several experiments have been made on real WiFi networks with different types of computer wireless adapters and Access Points. In this paper we present the results for measuring maximal possible throughput on application level from what frame transfer time under experimental circumstances can be received. In this experiments the network structure was as in Example 1 (Node1, connected through WiFi channel to AP, transmits to Node2. Node2 is connected to AP with wired network). The UDP packets with application data size of 10 bytes perform the payload on one Node1-wireless link-AP-wired link-Node2 in this case. Jperf version 2.0.2 utility as network performance measurement tool was used. The measurement results are presented in table 3.

Table 3. The measurement results for maximal throughput

Type of AP used	TP-Link 150M Wireless Lite N Router		Wireless-N Gigabit Router WRT350N	
AP mode	802.11g only		54 Mbps	
Measured parameters	Maximal throughput [Kbps]	Jitter [ms]	Maximal throughput [Kbps]	Jitter [ms]
Mean value for 10 time intervals, one interval 1s	451	0.173	433	
Standard deviation	7.87	0.242	25.06	
10 byte packet delivery time [ms]	0.177		0.185	

Using results from experiments we can check significance of some our analytical estimations. So, 10 byte packet delivery time indicated as 0,177 ms we can compare with T_{Frame} estimation in table 1 for 802.11g-only column (0,105 ms) as our experiment structure corresponds to Example 1for what the maximal throughput due to (3.1) will be achieved at the bitrate $1/T_{Frame}$. Estimations in table 1 give the minimal possible T_{Frame} (the concurrent process for the wireless media is not taken into account, also we neglect of the delays in hardware/software structures of Nodes and wired network). So, the correspondence of analytical and experimental figures is sufficient. Also from the experiment we can estimate the variance coefficient c from measuring of jitter, and it is of the order of 1.4 what is consistent with our recommendations in the topic (3.Simulation).

5. Conclusions

In the matter of fact we have proposed an approach for the estimations of application packets delay time on propagation paths through the network in what wireless links are present. It is done on the basis of analytical model summarized in this article topic (2.7. Analytical modelsummarization). Packets delays have often restricted due to automation control applications and need to be in appropriate range of values for the working diapason of application’s payload. Our analytical model gives the relationships between delays and bit rate on application level.

The delays in wireless links frames transfer are considered for 802.11 MAC layer specifications (often called as WiFi). Only DCF (Distributed Coordination Function) access method was under consideration and PHY layer specifications 802.11 a/b/g/n were analyzed. On transport layer of the network UDP protocol was used which carry application packets of small size (no packetization is performed as for Voice over IP case) and this is often a demand of automation control applications.

In wireless channel no pass loss, fading and interference was supposed but those effects may be taken into account in analytical model by reducing maximal possible raw bit rate given by specifications of PHY layer to some lover bit rate (also according with specifications).

If we proceed with the example of wireless electric recharge of driving vehicles system what demands for data transmission were formulated in introduction of this article. When network design suppose communication between system modules through one Access Point, using the analytical model one can receive the next estimations:

Table 4. Values for comparing application demands and possibilities of WiFi technologies

	Demand of the system	**WiFi technology 802.11 b**		**WiFi technology 802.11 g-only**	
		For raw speed 1Mbps	**For raw speed 11Mps**	**For raw speed 6Mbps**	**For raw speed 54Mbps**
Application packet size	72 bit	72 bit	72 bit	72 bit	72 bit
Data rate for one application stream	7.2 Kbps	7.2 Kbps	7.2 Kbps	7.2 Kbps	7.2 Kbps
Packets delay on the path of two links	18 ms	5.4 ms	1.44 ms	0.43 ms	0.23 ms

Comparing the value in table 4 (18 ms with 5.4, 1.44, 0.43, 0.23 ms) one can make a conclusion that both technologies 802.11b and 802.11g are applicable for wireless system design of considered structure and payload even in the case when sufficient disturbances can be expected in wireless channel.

Performed simulations and field experiments are not in contradictions with proposed analytical model.

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