Frame Delay Distribution Analysis of IEEE 802.11 Networks Using Signal Flow Graphs

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***Abstract*—Frame delay variance in CSMA/CA networks is large. Wireless applications may require both, limited mean delay and limited delay jitter. These parameters can be derived easily from cumulative distribution function (CDF) of frame delay. This paper applies Signal Flow Graphs (SFGs) to calculate the CDF of frame delay in IEEE 802.11 DCF WLANs. SFGs allow to establish a mathematical WLAN model for precise numerical calculation of frame delay based on generating functions. Both, medium reservation based on RTS/CTS and no reservation are studied and link adaptation is taken into account, too. Stations are assumed to always have a frame waiting for transmission. Our mathematical analysis results are compared for typical WLAN application scenarios to simulation results gained from the openWNS system level simulator.**

***Index Terms*—Wireless LAN, Simulation, Protocol**

I. Introduction

The perceived packet delay of ongoing data transmission is essential for the performance of many wireless applications, e.g. Voice over IP (VoIP) or Video Telephony. However, not only the mean packet delay of a radio access technology is of importance but also its distribution. In some cases even if the first moment appears to be within acceptable boundaries some quantiles of the distribution might violate the quality of service requirements. A method to calculate the Medium Access Control (MAC) delay of IEEE 802.11 WLAN would be an enabler to conduct a MAC frame analysis. In this paper a flexible Signal Flow Graph (SFG) model is presented useful to investigate the delay characteristics contributed by the MAC layer to applications in full detail. The beauty of the model is its extensibility to include more details like collisions of clear to send (CTS) messages, negative acknowledgements (NACK) or multi-hop links in the model analysis.

This paper is organized as follows: Section II presents briefly relevant parts of the IEEE 802.11 WLAN standard. Section III discusses related analysis work. In Section IV we introduce protocol behaviour that contributes to the frame delay. In Section V the SFG model is introduced to be evaluated for the example scenarios described in Section VI. The results of the analysis and validation are presented in Section VII. The paper ends with a conclusion and outlook.

II. IEEE 802.11 WLAN

The distributed coordination function (DCF) of standard IEEE 802.11 specifies a variant of carrier sense multiple access with collision avoidance (CSMA/CA) for medium access control. Data transmission is allowed only after the medium is sensed idle for a distributed interframe space (DIFS) duration. Additionally, a station ready to transmit must perform a random backoff: An integer number is drawn from the contention window (CW) $[0; CW_{min}]$ and decremented per idle slot time (SLOT) until it reaches zero. Then transmission starts. Otherwise, the station defers and continues counting down SLOT-wise when the medium is observed idle. Collisions occur if more than one station have decremented their integer counter to zero at the same SLOT. A collision is detected by means of a timeout set after transmission when awaiting an acknowledgement (ACK) reply from the receive station. Collided stations repeat transmission using a doubled CW for backoff, which size is limited by $CW_{max} = 2^m \cdot CW_{min} + 1$; a MAC frame is discarded after k unsuccessful retransmission attempts.

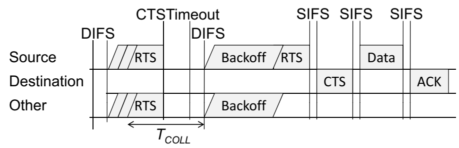


Fig. 1. RTS collision and successful transmission.

Optionally, a Request-To-Send (RTS) / Clear-To-Send (CTS) handshake can precede the sequence frame transmission, ACK. All stations overhearing either RTS or CTS must defer from medium access for the transmission duration carried in these frames. The full time spent to transmit a frame is the sum total of the transmission times of RTS τ_{RTS}, CTS τ_{CTS}, ACK τ_{ACK} and data frame $T_{\text{DATA}}(l, r)$ of length l sent with rate r. In case the data transmission fails a backoff phase follows and the sequence (RTS/CTS, Data, (N)ACK) is repeated until success. Accordingly, frame delay may comprise multiple sequences mentioned. As visible from Fig. 1, all transmissions are separated by the short interframe space (SIFS). With the help of RTS/CTS, a collision is already detected after CTSTimeout.

The length of $T_{\text{DATA}}(l, r)$ depends on the used physical layer (PHY) capabilities. Fig. 2 gives the frame format of a PHY protocol data unit (PPDU) according to IEEE 802.11a [1]. A PHY service data unit (PSDU) together with six tail bits

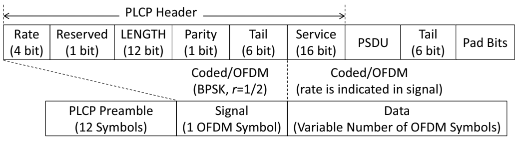


Fig. 2. WLAN PPDU Frame Format.

and possibly padding bits is coded with the rate indicated by the signal field. The signal field is one OFDM symbol long, including all settings required to decode the PSDU.

III. Related Work

CSMA models first have been presented in [2] to investigate throughput and delay of wireless networks. Bianchi [3] presented a CSMA/CA model to analyse IEEE 802.11 saturation throughput under DCF controlled medium access studied without and with RTS/CTS. A constant collision probability of a data frame is assumed there, independent of the number of retransmissions that a frame has suffered. Frames are dropped when the retry counter is exceeded. In addition, it is assumed that all stations always have a frame ready in their transmit buffers. In [4] Bianchi decoupled the backoff stage updating progress from the backoff counter which simplified the model. [3] defines the average access delay as the duration between the time instant the data frame is put into service and its successful delivery. A multitude of modifications of the model presented in [3] and [4] exist, e.g. [5], [6], but so far no detailed model is known allowing to calculate the cumulative distribution function (CDF) of the MAC layer frame delay. [7] provides an exact model of the access delay, the duration from the time instant the frame is ready to sent until the frame is sent comprising backoff and frame transmission. The model has been validated by simulation. A Markov process is specified and evaluated by matrix-based methods. It was found that the envelope of the access delay probability density function is hyper-exponential, as confirmed by this study. The main differences between [7] and this paper is that [7] provides the access delay whereas this paper gives the CDF of the full MAC frame delay including successful frame delivery, (negative)acknowledgement (ACK/NACK) and possible retransmissions of data frames. Similar to [7] we evaluate the delay experienced by a tagged station as introduced in [8]. The idea to model the MAC frame delay with SFGs has been motivated by [9] which used the SFGs to model the packet delay in GPRS. Similar to [10] and [11] that are based on each other we use delay generation functions (DGF) to calculate the frame delay distribution function, the difference is that we use SFGs, a graphical representation of the time components involved as part of the full delay. Further the model in [11] does not appear to fully represent the 802.11 protocol, especially with respect to the handling of idle slots when calculating the delay generation function.

IV. DCF Timing

One of the challenges of CSMA/CA backoff modeling is, that the time spent between two consecutive backoff slots varies. In the simplest case, when a tagged Station A is in backoff and no other station is starting to transmit and the medium continues to be idle, the backoff counter is decremented after each SLOT until frame transmission is started. If another Station C with a smaller backoff counter value starts its transmission, the tagged station stops its countdown and continues after the medium has been found idle for DIFS duration again. Then, a full transmission sequence is inserted between two backoff slots of the tagged station.

The duration T_{SUCC} of the interruption of Station A, when not colliding, is determined by the length of the data frame including a constant offset for RTS/CTS and ACK processing as presented by Fig. 3a, namely:

$$\begin{aligned} T_{\text{SUCC}} = \tau_{\text{RTS}} + \tau_{\text{SIFS}} + \tau_{\text{CTS}} + \tau_{\text{SIFS}} \\ + T_{\text{DATA}} + \tau_{\text{SIFS}} + \tau_{\text{ACK}} + \tau_{\text{DIFS}}, \end{aligned} \tag{1}$$

with τ_{DIFS}, τ_{SIFS} being the duration of DIFS and SIFS, respectively. In our model, to simplify the analysis, we assume that both, ACK and CTS are never lost. T_{SUCC} represents the duration the medium is busy for frame transmission. The data is already available at the destination before the ACK is transmitted and therefore the actual delay of the frame is reduced by the constant values of τ_{SIFS} and τ_{ACK}, which would not be correct if ACKs could be lost.

If Station C collides, e.g., caused by collision of its RTS at the respective receiver, Fig. 3b, Station C will not receive CTS and will timeout after a CTSTimeout, see Fig. 1:

$$\text{CTSTimeout} = \tau_{\text{SIFS}} + \tau_{\text{SLOT}} + \tau_{\text{RX}}. \tag{2}$$

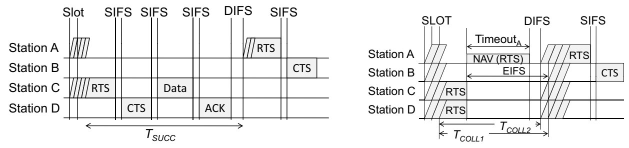
Parameter τ_{RX} is the delay until a PHY receive indication is issued, e.g. $25\mu s$ for PHY17. τ_{SLOT} is the duration of a SLOT. In the presented example (see Fig. 3b) Station A is able to decode the RTS sent by Station C, whereas Station B notices a collision on the medium. Therefore, the durations of the interruption of the backoff phase is T_{COLL2} for Station A, while Station B that also was in backoff phase must wait for T_{COLL1} only. Station A has received the Network Allocation Vector (NAV) from station C's RTS frame. Therefore, Station A is allowed to timeout according to [1] after:

$$\text{Timeout}_A = 2 \cdot \tau_{\text{SIFS}} + \tau_{CTS} + \tau_{\text{RX}} + 2 \cdot \tau_{\text{SLOT}}, \tag{3}$$

if no valid data frame is detected meanwhile. The duration of the interruption is $T_{COLL2} = \tau_{\text{RTS}} + \text{Timeout} + \tau_{\text{DIFS}}$. Station B is allowed to continue its backoff procedure after an extended interframe space (EIFS) has expired

$$\tau_{\text{EIFS}} = \tau_{\text{SIFS}} + \tau_{\text{ACK}} + \tau_{\text{DIFS}}, \tag{4}$$

so that the length of the interruption of Station B is $T_{COLL1} = \tau_{\text{RTS}} + \tau_{\text{EIFS}}$. In this example Station A is assumed to have the smallest backoff and transmits RTS/CTS successfully. From [3], for a given finite and fixed number of stations N, with initial CW_{min} and final CW_{max}, the collision probability p and the mean number of backoff slots ($\overline{BO}$) before successful frame transmission are obtained.



(a) Successful transmission. (b) RTS collisions.

Fig. 3. WLAN backoff interruptions.

V. DCF Signal Flow Graph Model

As in [3], we assume that frame transmissions of stations are independent and contend with a constant and independent collision probability p. Following [3] this assumption is the more accurate the larger the number of stations is, i.e. sufficiently accurate for $N \geq 10$. Section VII proofs that this assumption is adequate for the evaluated scenarios. In our analysis we focus on a tagged station, which backoff procedure is modeled in detail, whereas the remaining stations may be in arbitrary backoff stages. Each station is assumed to always have a data frame ready in its transmit buffer. Furthermore, RTS collisions are the only source of transmission errors. The method we use for analysis easy could also include erroneous data frames.

In the first backoff stage $i = 0$ the mean number of backoff slots $\overline{BO_0}$ equals $\frac{CW_{min}+1}{2}$ with probability $(1-p)$, see [3]. In the second backoff stage $i = 1$ the mean number of backoff slots $\overline{BO_1}$ is $\frac{2\cdot(CW_{min}+1)}{2}$ with probability $(1-p)\cdot p$. This can be repeated m times when $\frac{CW_{max}+1}{2}$ is reached. All remaining attempts have the same mean number of backoff slots:

$$\overline{BO_{m<i\leq k}} = 1/2(CW_{max}+1). \tag{5}$$

If the number of retransmission attempts is limited to k retries, the mean number of backoff slots $\overline{BO}$ with $W_i = CW_i$ is [11]:

$$\overline{BO} = \frac{1-p}{1-p^{k+1}} \cdot \left(\sum_{i=0}^{m-1} p^i \frac{(2^i W_i + 1)}{2} + \sum_{i=m}^{k} p^i \frac{(2^m W_i + 1)}{2}\right). \tag{6}$$

p can be expressed as a function of $\overline{BO}$ and N. A collision occurs, when two or more stations are transmitting in an arbitrary which happens with probability $\overline{BO}^{-1}$. If $N-1$ stations may collide at a receive station, the collision probability is [3]:

$$p = 1 - (1 - \overline{BO}^{-1})^{N-1}. \tag{7}$$

Each backoff slot contributes a delay τ_{SLOT} of the tagged station, if no other station is starting transmission, with delay generation function (DGF) of Eq. (8). If in a given backoff slot exactly one other station transmits, the delay contributed from this is T_{SUCC} with DGF in Eq. (9), but if more than one station transmit, the delay is T_{COLL1} with DGF in Eq. (10).

$$G_{\text{IDLE}}(z) = z^{\frac{\tau_{\text{SLOT}}}{\tau_{\text{SLOT}}}} = z, \tag{8}$$

$$G_{\text{SUCC}}(z) = z^{\lceil \frac{T_{\text{SUCC}}}{\tau_{SLOT}} \rceil} = z^l, \text{ with } l = \lceil \frac{T_{\text{SUCC}}}{\tau_{\text{SLOT}}} \rceil, \tag{9}$$

$$G_{COLL1}(z) = z^{\lceil \frac{T_{\text{COLL1}}}{\tau_{\text{SLOT}}} \rceil} = z^{l_c}, \text{ with } l_c = \lceil \frac{T_{\text{COLL1}}}{\tau_{\text{SLOT}}} \rceil. \tag{10}$$

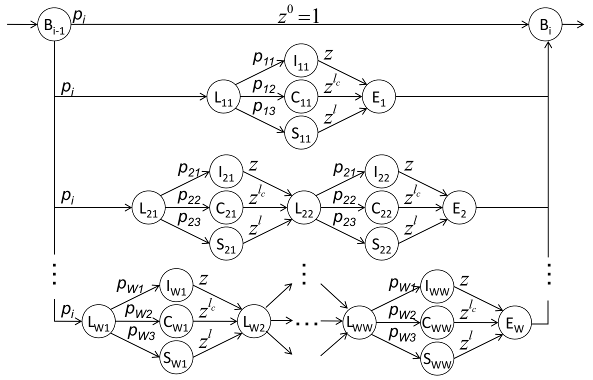


Fig. 4. WLAN SFG of one backoff stage, if a collision has happened before.

G_{SUCC} depends on frame length and data rate, Eq. (1).

Fig. 4 shows the signal flow graph (SFG) of delay of the tagged station contributed by a single backoff stage (B_i). Starting from backoff stage B_{i-1} a certain number of backoff slots is chosen with probability $p_i = CW_i^{-1}$. In view of the tagged station, each backoff slot $L_{ji}, j\epsilon[1, W]$ may experience one of three substates: idle slot (I_{ji}), successful transmission of another station (S_{ji}) or collision (C_{ji}) of RTS frames of other stations, with probabilities p_{j1}, p_{j2} and p_{j3}, respectively. These probabilities are independent of the actual number of a backoff slot j, so that the SFG can be simplified, see Fig. 5a. p_a is the probability of an occupied backoff slot, $1 - p_a$ for an idle slot and $p_a p_c$ of a collision, whilst $p_a(1 - p_c)$ is the probability of a successful transmission.

Fig. 5b shows the delay contribution $G_S(z)$ of one backoff slot:

$$G_S(z) = (1-p_a)\cdot z + p_a \cdot p_c \cdot z^{l_c} + p_a \cdot (1-p_c)\cdot z^l. \tag{11}$$

Eq. (11) simplifies Fig. 5b to become the SFG of Fig. 5c for a limited CW size. Since the maximum value of CW_i depends on the backoff stage i the influence of the loop must end there which is taken into account by the correction term $G_S^{CW_i+1}(z)$. The SFG in Fig. 5c can be further reduced, see Fig. 5d, representing the DGF $G_i(z)$ of backoff stage i to be

$$G_i(z) = (1 - G_S^{CW_i+1}(z)) \cdot [1 - G_S(z)]^{-1} \cdot p_i. \tag{12}$$

The complete SFG including all backoff stages is shown in Fig. 6. From the transmit state (T) where the tagged station is ready to transmit, backoff stage $B_0 (i = 0)$ is entered. With collision probability p the next backoff stage B_1 is entered, and probability $(1-p)$ the final state (F) is reached. If backoff stage B_k has been reached data transmission fails with probability p, the frame is dropped and error state (E) is entered. The SFG shown in Fig. 6 must be modified slightly to reflect the case that a successful data transmission happened before entering state (T). After transmission of the tagged station was successful, only this station can have a backoff counter of zero, whilst other stations have higher counter values. Therefore, the arrow for $p_0 \cdot z^0$ does not go to state B_0 but directly to state

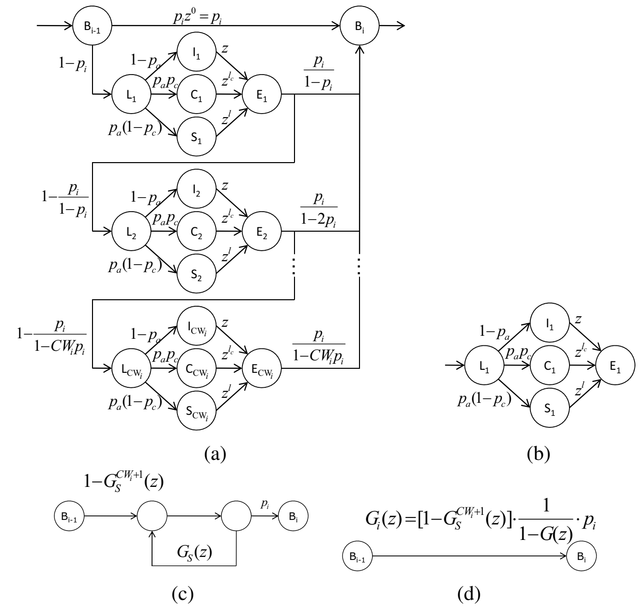


Fig. 5. Simplified SFG of one backoff step.

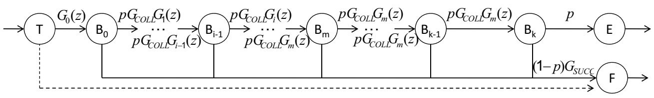


Fig. 6. SFG of the frame delay.

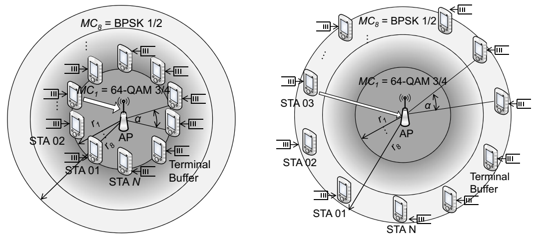
TABLE I
WLAN Modulation and Coding Schemes

Name	Modulation	Coding rate	Data bits per OFDM Symbol	Data rate (Mb/s)
MC_8	BPSK	1/2	24	6
MC_7	BPSK	3/4	36	9
MC_6	QPSK	1/2	48	12
MC_5	QPSK	3/4	72	18
MC_4	16-QAM	1/2	96	24
MC_3	16-QAM	3/4	144	36
MC_2	64-QAM	2/3	192	48
MC_1	64-QAM	3/4	216	54

F as shown by the dashed line in Fig. 6. This analysis applies to basic access, where RTS/CTS is omitted.

VI. Evaluated Scenarios

In our model signaling traffic, namely RTS, CTS, and ACK frames, is transmitted using modulation and coding scheme (MC) MC_8, see Table I. For data frames the employed MC may be MC_8 to MC_1 resulting in different numbers of bits per symbol and lengths of T_{DATA}. We consider an access point (AP) scenario as shown in Fig. 7. In Fig. 7a stations are assumed such close to the AP that all can use MC_1 resulting in the lowest possible frame delay. In Fig. 7b stations are assumed far from the AP so that MC_8 must be applied for data frames resulting in the largest possible delay. Stations are assumed to have always data ready waiting to be sent and separated by angle α, located at distance r_m from the AP.



(a) WLAN best case scenario. (b) WLAN worst case scenario.

Fig. 7. WLAN Scenarios.

VII. Analytical Evaluation and Validation by Simulation

In principle, the data size may vary frame by frame according to some distribution. The model presented would permit to consider any distribution of data size per frame, but in order to reduce complexity we assume a fixed size of 1500 Byte per data frame. However, the length l of the PSDU (see Fig. 2), depends on the MAC chosen and must be padded with N_P padding bits to ensure that the number of symbols N_{SYM} is an integer for the given amount of data bits per symbol N_{DBPS}. The size N_{DATA} of the Data field in Fig. 2 is calculated as [1]:

$$N_P = N_{\text{DATA}} - (16 + 8 \cdot l + 6) \tag{13}$$

$$N_{\text{SYM}} = \left\lceil \frac{16 + 8 \cdot l + 6}{N_{\text{DBPS}}} \right\rceil \tag{14}$$

$$N_{\text{DATA}} = N_{\text{SYM}} \cdot N_{\text{DBPS}}. \tag{15}$$

The frame duration results from the number of bits per frame divided by the MC data rate. The DGFs in Eqs. (8, 9, 10) have different likelihood depending on collision probability p, see Eq. (7) and collision probability p_c, namely

$$\begin{aligned} p' &= (N-1)\overline{BO}^{-1}(1-\overline{BO}^{-1})^{N-2}, \\ p_c &= (p - p')p^{-1}. \end{aligned} \tag{16}$$

Furthermore, each combination of possible interruptions must be considered. If the tagged station chooses n backoff slots, then the probability p_{occ} that a slots are occupied, meaning that at least one other station transmits, is:

$$p_{occ}(n, a) = \binom{n}{a} p^a (1-p)^{n-a}. \tag{17}$$

During an occupied slot the medium is busy, since one or more other stations are transmitting. Out of these a slots c slots may be occupied by collided frames with probability

$$p_{col}(a, c) = \binom{a}{c} p_c^c (1-p_c)^{a-c}. \tag{18}$$

As each combination of occupied slots is possible, it must be taken into account. The same is true for the number of collisions $c\epsilon[0; j]$ which might happen during the a occupied slots. For a certain given backoff n the DGF is:

$$G(n, z) = \sum_{a=0}^{n} \sum_{c=0}^{a} p_{occ} \cdot p_{col} \cdot z^{(n-a)+(a-c)l+cl_c} \qquad (19)$$

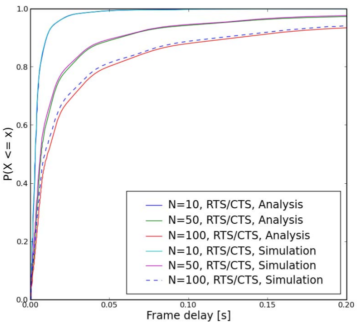
Besides durations of transmit sequences and collision of other stations inserted during the backoff phase of the tagged station, its frame duration contributes to the MAC frame delay, including failed RTS transmissions of the tagged station. The DGF for a successful frame transmission is G_{SUCC} as given in Eq. (9). In case of a failed frame transmission the CTS timeout applies contributing a delay of CTSTimeout, see Eq. (2). A failed transmission of the tagged station has a duration

$$G_{\mathrm{COLL}}(z) = z^{\lceil \frac{\tau_{\mathrm{RTS}} + \tau_{\mathrm{SIFS}} + \mathrm{CTSTimeout}}{\tau_{\mathrm{SLOT}}} \rceil}. \qquad (20)$$

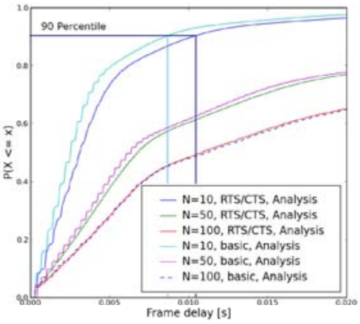
From this the overall DGF $G(z)$ is

$$\begin{aligned}
G_0(z) &= \frac{1-p}{1-p^{k+1}} G_{SUCC} p_0 \sum_{n=1}^{CW_0} G_0(n, z), && (21)\\
G_i(z) &= G_{i-1} p G_{\mathrm{COLL}} p_i \sum_{n=1}^{CW_i} G_i(n, z), && (22)\\
G_m(z) &= G_{m-1} p G_{\mathrm{COLL}} p_m \sum_{n=1}^{CW_m} G_m(n, z), && (23)\\
G_{m+1}(z) &= G_m p G_{\mathrm{COLL}} p_m \sum_{n=1}^{CW_m} G_m(n, z), && (24)\\
G_k(z) &= G_{k-1} p G_{\mathrm{COLL}} p_m \sum_{n=1}^{CW_m} G_m(n, z), && (25)\\
G(z) &= \sum_{i=0}^{k} G_i. && (26)
\end{aligned}$$

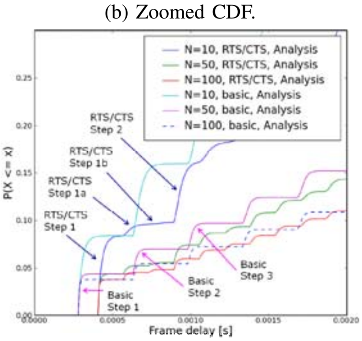
From Eq. (26) the CDF of frame delay is calculated, see Fig. 8a. The 90 percentile for $N = 10$ is reached at approximately $0.01\,\mathrm{s}$ for RTS/CTS and $0.009\,\mathrm{s}$ for basic access, respectively, whereas some rarely occurring frame delays range up to $2\,\mathrm{s}$. Fig. 8b zooms into the CDF and shows analytical results for both, RTS/CTS and basic access. In Fig. 8b the delay distribution is similar to the RTS/CTS results obtained in [7]. In Fig. 8c the CDF is zoomed to the smallest occurring delays. Step 1 for RTS and $N = 10$ and for basic access and $N = 50$, respectively, gives the probability for frame delay caused by idle slots. At most $CW_0 = 31$ slots may be occupied in the first backoff stage of the tagged station all contributing to Step 2. In basic access Step 2 is produced by either one occupied slot, being a successful frame transmissions or collision, or a collision of the tagged station, since $T_{\mathrm{COLL1}} = 17\,\mathrm{SLOT}$ and $T_{\mathrm{COLL}} = 16\,\mathrm{SLOT}$ have almost the same value. In RTS/CTS Step 2 is produced by successful transmissions only. Step 3 in basic access results from two occupied slots being either two collisions, successful frame transmissions of other stations, or combinations of both. In RTS/CTS the smallest delay is higher than in the basic access mode due to the additional RTS/CTS messages. For RTS/CTS Step 1 has two more small steps. Step 1a results from one, Step 1b from two RTS collisions. The influence of the interruptions of the tagged station's backoff process by other successful stations is represented by the large number of steps that are less prominent for higher delay values, due to the large number of combinations of used backoff slots. The long tail of the distribution results from the fact, that high delays resulting from interruptions of a successful multi-stage backoff process occur very unlikely but contribute large delay. We interpret the small differences visible between analysis and simulation to result from too short simulation runs not adequately containing rare long delay events.



(a) Frame delay CDF, analysis and simulation results $N = 10$ fall on each other.



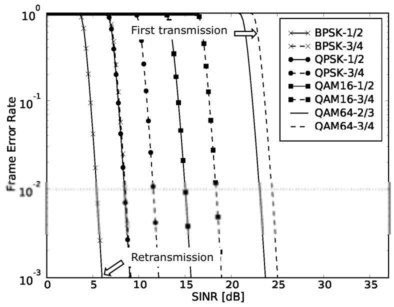
(b) Zoomed CDF.



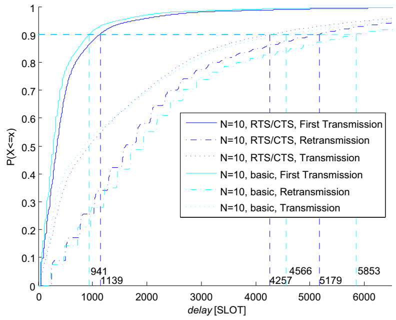
(c) Zoomed to smallest delays.

Fig. 8. Analysis and simulation results for MC_1 and $l = 1500\,\mathrm{Byte}$.

In reality there are more sources of data loss than RTS or frame collisions. If the received signal to noise and interference ratio (SINR) is too low for the chosen MC the frame is detected erroneous and a NACK is sent back to the tagged station. Fig. 9a shows the frame error rate (FER) versus SINR



(a) FER for different SINR and MCS.



(b) Analytic delay for FER $= 0.5$ under dynamic link adaptation between MC_1 and MC_8.

Fig. 9. Frame errors and retransmissions.

and possible MC switching points at $FER = 10^{-2}$. The station may retry to retransmit the frame using a more robust MC. Fig. 9b shows analytic results for dynamic link adaptation where a station starts with MC_1 and switches to MC_8 after the data frame was lost due to an error with $FER = 0.5$. For comparison curves from Fig. 8b are shown also.

Our analytical results have been compared to detailed event driven protocol simulation results using the WLAN module (WiFi-MAC) of the openWNS [12]. The parameter values used for analysis and simulation are summarized in Table II, and

$$\tau_{\text{DIFS}} = \tau_{\text{SIFS}} + 2 \cdot \tau_{\text{SLOT}}, \tag{27}$$

$$\tau_{\text{EIFS}} = \tau_{\text{SIFS}} + \tau_{\text{DIFS}} + \tau_{\text{ACK}}. \tag{28}$$

Delay evaluation in the simulator is based on a time resolution of $1\,\mu$s, which is the shortest possible time duration that may occur in the delay CDF. The simulation results appear to validate the analytical results, see Fig. 8a.

VIII. Conclusion & Outlook

We have introduces an SFG based model for the mathematical frame delay analysis of IEEE 802.11a DCF and have validated the results by simulation. The model can easily be extended to include an arrival process of user data blocks per station, variable size of data blocks and dynamic choice of the MC, dependent on the FER perceived in a foregoing transmission attempt to the same destination station. The modeling technique used is suited to also tackle more complex scenarios like hidden stations, multihop transmission and coexistence of concurrent systems operated in the same frequency band by using Hidden Markov Models to represent the related constraints. We are working towards results of a refined model.

TABLE II
WLAN DCF Parameters

Parameter	Value
aSlotTime (τ_{SLOT})	short = $9\,\mu$s
aSIFSTime (τ_{SIFS})	$16\,\mu$s
aPHY-RX-START-Delay	$25\,\mu$s
aPreambleLength	$16\,\mu$s
SERVICE size	2 Byte
TAIL size	6 bit
MAC header size	32 Byte
l=PSDU size	1500 Byte
RTS size	182 bit
CTS size	134 bit
ACK size	134 bit
N	10, 50, 100
aPLCPHeaderLength	$4\,\mu$s
CRC size	4 Byte
m	5
k	7
propagation delay (t_{prop})	0

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