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Frame Delay and Loss Analysis for Video Transmission over time-correlated 802.11A/G channels

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ABSTRACT

This paper presents simulation results for the transmission of unicast MAC frames over 802.11a/g. Fading channel models at various Doppler frequencies are developed to generate time-correlated SNR waveforms. These are then used together with a bit accurate MAC/PHY simulator to estimate the frame loss rate, the transmission delay, and the jitter for a steady flow of transmit frames. Time correlated channels are required to correctly simulate the bursty nature of packet loss in a wireless channel. The Doppler spread is shown to have a strong effect on the performance of the ARQ mechanism in the MAC layer. Delay is computed as the sum of the transmission delay and the accumulated queuing delay in the MAC buffer. Delay and frame loss are compared for time correlated and time uncorrelated fading channels. Compared to the slow fading case, in a fast fading channel fewer retransmissions are required and the end-to-end delay is significantly reduced. When channel conditions are poor the simulated delay and frame loss rate are seriously underestimated when time uncorrelated fading is assumed. To analyze the performance of video codecs, we show that a time correlated channel model must be combined with a dedicated 802.11a/g MAC/PHY simulation.

I. INTRODUCTION

IEEE 802.11 based WLANs are increasingly being used in video surveillance and multimedia distribution. The more recent 802.11a/g standard combines a COFDM physical layer (PHY) with the legacy 802.11 medium access control (MAC). When unicast transmissions are used, the MAC layer supports the automatic retransmission of errored data frames using a stop-and-wait ARQ mechanism. This technique improves the packet error rate (PER) observed at the higher layers. In the receiver, erroneous MAC frames are dropped, and hence only error-free frames are observed at the application layer. MAC frames that fail to be acknowledged are resent up to a maximum retry count. When the radio channel is characterized by a low signal to noise ratio (SNR), high frame loss rate (FLR), delay and jitter is encountered at the MAC layer. Delay and jitter occur as a consequence of variable frame retransmission and this degrades applications that rely on timely packet reception [1].

In the past few years many publications have investigated the performance of the 802.11 protocol, particularly in terms of frame loss and throughput. The importance of MAC layer retransmission and the ARQ retry limit has been stressed and its effect on frame loss and delay has been investigated. For example, [2] proposes a retransmission strategy for delay sensitive wireless transmission. A throughput analysis of WLANs was also reported in [3]. However, most studies are based on static channel models, where the PHY layer packet error rate is independent of time. It is well known that packet errors over a wireless medium are bursty in nature [4]. The packet error rate for consecutive packets is not independent, due to the time-correlated characteristics of the mobile channel. This paper shows how the delay and FLR are affected by the time-varying fading channel. Frame delay is severely underestimated when the correlation of errors is not taken into account. To the best of the authors' knowledge, very few publications address this issue. Some analytic performance studies have been presented, but these focus on throughput and packet loss. [5] presents a packet loss model and a throughput analysis using stochastic models; while [6] evaluates packet loss using the Gilbert-Elliot model. In [7] throughput estimation of an adaptive ARQ protocol is presented over a time-varying channel based on multiple-state Markov chains. This type of model is most suited to the simulation of slow fading channels [7]. Error burst lengths and the bursty nature of the wireless channel was studied in [4], with packet delay and loss rates explored in [8] via field trials.

The impact of Doppler spread on the packet loss and delay statistics for an 802.11 WLAN was investigated in [9] via experimental measurement. In [10], the packet loss rate and delay was analysed using a Jakes time-correlated Rayleigh fading simulator [11] for various Doppler frequencies. A detailed analysis of delay and frame loss based on MAC/PHY interaction and the effect of ARQ in a time-correlated fading channel is not reported in the literature.

In this paper we study the cross-layer performance of the IEEE 802.11a/g standard [12] by simulating MAC-to-MAC FLR (or frame error rate, FER) and delay. The simulator models the transmission of a time series of queued MAC frames over the wireless channel. To replicate the bursty nature of packet errors, an accurate time-correlated channel model is implemented based on the Power Spectral Density (PSD) of the radio channel. Frame delay takes into account the channel access control mechanism, MAC retransmissions and queuing delay in the transmit MAC buffer. This study focuses on FLR due to poor channel conditions and the impact of channel collisions are ignored.

Section II provides a brief description of the MAC and PHY layers relating to the IEEE 802.11a/g standard. Section III describes the fading channel model. Section IV describes the MAC frame simulator and section V analyzes the results obtained. Finally, section VI provides a set of conclusions.

II. OVERVIEW OF IEEE 802.11a/g

Medium Access Control (MAC): The IEEE 802.11 MAC offers shared access to the wireless channel using the CSMA/CA protocol. Use of the MAC Distributed Coordination Function (DCF) with the Basic Access scheme is assumed in this work. Before a station starts transmitting it must sense the medium to determine if another transmission is already active. Inter Frame Space (IFS) timing is used to control access to the channel. A station starts the transmit process after having sensed the medium for at least the duration of a DIFS (Distributed IFS). If the medium is found to be idle then the station must wait for a further random back-off period. If the channel remains idle during the back-off period then the station is clear to transmit a packet of data. Once the PHY layer packet has been sent, for unicast operation the station expects to receive an acknowledgement (ACK) within a SIFS (short IFS) time period. The next transmission cycle begins when the ACK is received (or the SIFS time period expires). If no ACK is received within the *ACKtimeout* = SIFS period, the MAC frame is scheduled for retransmission. This process continues until an ACK is successfully received, or the maximum retry count is reached, as specified by the *maxARQ* setting. *MaxARQ* is user defined, with typical values in the range 0-32. The back-off period after the DIFS interval is divided into slots, each of duration *Slot_Time*. It is possible for a station to transmit at the beginning of each slot, depending on the value of its back-off counter. The slot size, as well as the IFS timing, depends on the chosen PHY technology. Table I quotes the key timing parameters for the 802.11b/g MAC. The back-off time is defined as

$$T_{Bo} = BackoffCounter * Slot\_Time \quad (1)$$

The back-off counter is a random variable chosen from a uniform distribution in the range [0, W-1], where W represents the Contention Window (CW), based on an exponential back-off mechanism. The operation of the back-off counter is described in publications such as [3]. The contention window parameters are dependent on the PHY layer technology, as shown in Table I. A successful transmission cycle, when no retransmission is required, has a duration T_{succ} defined as

$$T_{succ} = \text{DIFS} + T_{Bo} + T_{Data} + \text{SIFS} + T_{ACK} \quad (2)$$

T_{Data} represents the duration of the PHY burst and depends on the packet length and the chosen link-speed. T_{ACK} represents the duration required to acknowledge successful reception of the MAC frame. If an ACK is not received within *ACKtimeout* =SIFS, the station makes a limited number of retransmission attempts, as specified by the *maxARQ* setting. Assuming that N retransmissions take place before a successful acknowledgement is received, the total duration of a successful transmission cycle is given by (3), where N<= *maxARQ*:

$$T_{tx} = N * (\text{DIFS} + T_{Data} + \text{SIFS}) + \sum_{i}^{N} T_{Bo,i} + T_{ACK} \quad (3)$$

TABLE I - MAC PARAMETRS

Parameter	802.11 b/g
Slot Time (μs)	20
SIFS (μs)	10
DIFS (μs)	50
CW_{min}	31
CW_{max}	1023
ACK (μs)	Mode Dependent
PHY Header length (μs)	96 - 192

Physical Layer (PHY): This paper assumes the use of the IEEE 802.11g PHY layer, which operates in the 2.4 GHz band. The detailed MAC/PHY model is also capable of supporting 802.11a in the 5 GHz band. 802.11a/g makes use of COFDM and provides 8 unique link-speeds via different combinations of modulation and coding, as specified in [12]. MAC data frames are mapped to PDU packets for transmission over the PHY layer. The PHY layer simulator previously described in [13] is used to perform bit accurate scrambling, convolutional encoding, interleaving and modulation. This model has been extended to support correlated time varying channel gains for each tap in the channel impulse response. Hence, the instantaneous SNR varies with time (depending on the Doppler Spread) and results are presented in terms of average FLR versus average SNR. All averaging is performed over the entire data transmission sequence, which may last for several hundred seconds. This PHY layer model is used to evaluate the outcome of each PDU packet transmission. A packet error is said to occur at the PHY layer if an error is encountered during the MAC layer Frame Check Sum (FCS) process.

III. CHANNEL MODEL

Analytical models of packet loss and throughput for IEEE 802.11 WLANs were previously reported using stochastic models, Markov chains or the Gilbert-Elliot model [5][6][7]. In this paper we use a time-varying channel model to replicate the time correlated nature of the SNR observed at the target station.

Since the instantaneous channel power varies slowly (compared to the packet duration) with time, the resulting packet errors at the PHY layer tend to be bursty. This implies that the probability of receiving a packet in error at the PHY layer is strongly correlated in time. Since the probability of error for neighbouring packets is correlated, it is inappropriate to model this mechanism independently on a per packet basis.

The channel model replicates multipath fading as a function of terminal velocity, carrier frequency and Doppler spectrum. The fading model is based on a Tapped Delay Line (TDL) with each tap experiencing Rayleigh or Ricean fading. The severity of the Rician fading on each tap is controlled via a set of K-factors. The spaced-time autocorrelation of the fading envelope is controlled via the definition of a PSD for each delay line. The autocorrelation is imposed onto a set of i.i.d. Rayleigh samples using a Doppler filter [14][15]. For the results given here, a single Rayleigh fading tap is used with a classical Jakes PSD [11]. Maximum Doppler frequencies of 4Hz, 24 Hz and 80Hz are considered.

The instantaneous signal power is simulated at the receiver for a given time period. To cover retransmissions, this needs to be longer than the time required to fill the transmit buffer. Given knowledge of the noise floor and the average received power over the entire time period, the level of signal attenuation required to model any given average SNR level is computed.

IV. DESCRIPTION OF SIMULATOR

The simulator is capable of predicting the MAC layer FLR (and most importantly the time pattern of these losses) as a function of average SNR, K-factor, PSD, link-speed and *maxARQ*. An end-to-end block diagram of the simulator is shown in fig. 1. The simulator generates evenly time spaced data packets of equal (and user definable) length assuming a Constant Bit Rate (CBR) source. These data packets arrive at the transmit 802.11 MAC and are encapsulated into MAC frames (one data packet mapped to one MAC frame). As a result, the terms packet and frame are used interchangeably hereon. The MAC frames are then passed through a buffer and ultimately encapsulated into PDUs for transmission over the wireless medium. Each transmit packet is either received successfully, in which case an ACK is sent back, or unsuccessfully. The information signal *r(k)*, for received packet *k*, is computed using equation (4), where $h_c(t_{k,r})$ represents the channel impulse response at the time of transmission, and *r* denotes the retransmission number.

$$r(k) = s(k) * h_c(t_{k,r}) \quad (4)$$

If a packet is received in error, it is sent again in the next available cycle, having contended for the medium. This occurs until the packet is received, or *r* reaches the *maxARQ* limit

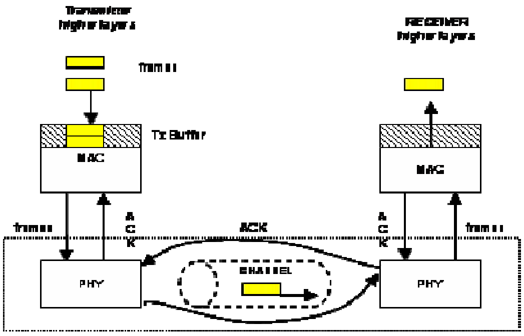


Fig. 1 Time series MAC/PHY simulator block diagram

For the k^{th} packet and r^{th} retransmission, the channel sample time $t_{k,r}$ is computed. If the channel coherence time is low (i.e. a fast changing channel), then the probability of error may improve significantly after several retransmissions. For a slowly changing channel the probability of error is unlikely to improve significantly over the short retransmission period. The FLR is computed at the transmit MAC as the ratio of lost frames (i.e. unacknowledged after retransmission up to *maxARQ*) to the total number of unique transmit frames (i.e. retransmit frames do not increment this counter). The total frame delay at the MAC, T_{tot}, is the sum of the transmission delay, T_{tran}, and the queuing delay, T_Q. For the *i*-th frame, the transmission delay of the resulting PDU ($T_{tran,i}$) is computed from equation (3). The transmission delay occurs as a result of the CSMA/CA protocol, the IFS timings, and any retransmissions that are required. The queuing delay represents the time spent in the MAC frame buffer prior to transmission. The queuing delay for the *i*-th frame, $T_{Q,i}$, is computed as the time difference between the start time of the first transmission cycle for the *i*-th frame transmission, $T_{tx,i}$, and the time the frame was submitted to the MAC queue, $T_{G,i}$ as shown in fig. 2.

$$T_{Q,i,}= T_{tx,i} - T_{G,I} \quad (5)$$

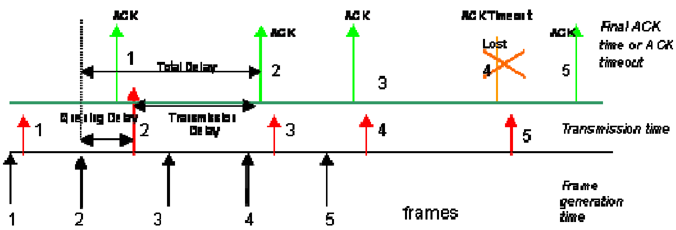
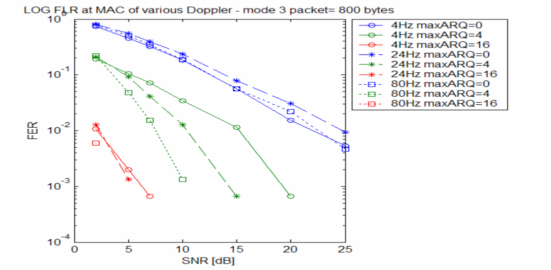


Fig 2. Example Timings for a series of MAC frames

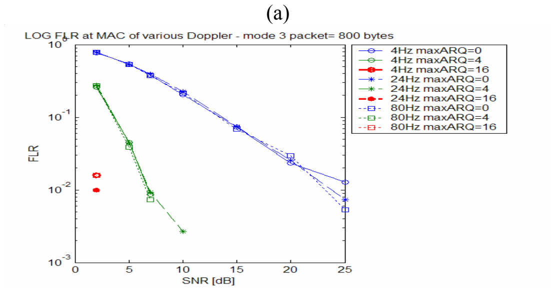
To compute the queuing delay, it is necessary to simulate a time series of MAC frames passing over the wireless medium. In this analysis, we assume an infinite transmit buffer. In order to *quantitatively* assess the impact of time-correlated channel modelling on the 802.11a/g performance, we simulate two cases: a) time-correlated packet transmissions/retransmissions, as described above and b) uncorrelated packet transmissions/ retransmissions. In the second case the packet errors are independent of time.

V. RESULTS AND ANALYSIS

For the following results, MAC frames are generated at a constant rate of 1 Mbps. The frame length is fixed, taking values of 800, 1200 and 1400 bytes. The mean SNR was varied over a range from 2-25dB. The *maxARQ* limit was varied from 0, 4 and 16. Each of the 8 PHY layer link-speeds was modelled. A time-varying channel response was generated for a period of 250 seconds. The maximum Doppler frequency was varied from 4Hz, 24Hz and 80Hz (corresponding to mobile speeds of 0.5m/s, 3m/s and 10m/s in a 2.4 GHz channel). Simulations were carried out for 1500 frames with a frame length of 800 bytes (resulting in around 10 seconds of transmit data). Results presented here are for link-speed 3 and frame length 800 bytes.



(a)

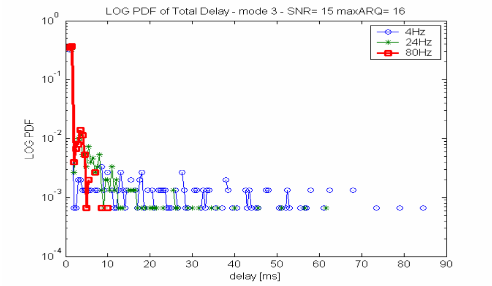


(b)

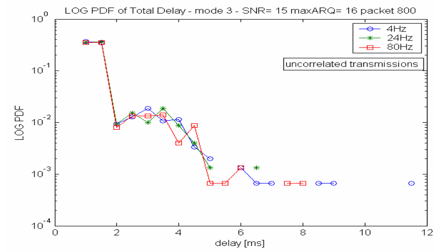
Fig 3 a-b. FLR at the MAC vs. SNR, for all Doppler frequencies and *maxARQ*=0, 4, 16 for a) correlated and b) uncorrelated transmissions

Fig. 3a shows the FLR at the MAC layer versus average SNR, with and without ARQ, for time-correlated transmissions based on the three Doppler frequencies mentioned above. It can be seen that the FLR improves with increasing ARQ. For a given *maxARQ,* the improvement in FLR is better for higher Doppler frequencies. When no ARQ is applied the channel performance is similar across all Doppler values. However, for *maxARQ* =4 and 16, the 80Hz channel clearly generates the lowest FLR. This occurs since ARQs are more effective at reducing the FLR when the channel decorrelates more rapidly with time. This result agrees with [10]. By comparison, when packet transmissions are uncorrelated in time, fig. 3b shows there is no difference in FLR with Doppler.

In fig. 4a the log of the Probability Distribution Function (PDF) for the total frame delay is shown for time-correlated transmissions. The mean SNR computed over the entire transmission period was 15dB, with *maxARQ* =16, and results were generated for all three Doppler frequencies. It can be seen that the total MAC-to-MAC delay increases significantly as the maximum Doppler frequency decreases, and this agrees well with results reported in [9], [10]. A peak delay of around 12ms was observed for a maximum 80Hz Doppler shift, while delays reached 85ms for a maximum 4Hz Doppler shift. In all cases the classic Jakes PSD was assumed. This increase in the perceived delay occurs since the number of required ARQs is lower in channels with higher Doppler spreads. This arises since the probability of significant channel improvement is much higher for a given number of ARQ in a fast changing channel. By comparison, fig. 4b shows the delay statistics for uncorrelated fading in each of the ARQ cycles. The total delay is now much lower for the same set of parameters, and clearly there is no difference between the Doppler frequencies (since the PSD no longer controls the correlation of the channel over time). The range of total delay in fig. 4b is very low, and is equal to the case with infinitely high Doppler spread. 802.11 simulations that assume uncorrelated fading in the retransmission cycles not only under predict the FER, but also seriously under predict the transmission delay.



(a)



(b)

Fig. 4 a-b. Log(PDF) of total frame delay when *maxARQ*=16, for Doppler frequencies 4, 24, 80Hz, a) for correlated - b) for uncorrelated transmissions

Using the total MAC-to-MAC delay as a function of average SNR, we now compute the percentage of frames that are delayed by more than a given threshold. A threshold of 100ms is used since this is a typical upper limit for real-time video transmission [1]. Excessively delayed frames beyond this value are ignored at the decoder and are thus treated as lost frames. We also compute the percentage of lost frames at the MAC layer, in addition to the sum of lost frames *and* excessively delayed frames (i.e. the effective FLR for the real-time video decoder). Fig. 5 shows these various percentages as a function of SNR. Correlated channel fading for a maximum Doppler frequency of 4Hz is assumed together with *maxARQ*=4.

Figs 6a and b show the percentage of effectively dropped frames (the sum of those dropped and/or excessively delayed) versus mean SNR in a time correlated channel, computed for each of the three Doppler frequencies for *maxARQ* values of 4 and 16. We observe that for the same *maxARQ,* the effective dropped frame rate decreases with increasing Doppler. The lowest percentages were obtained for the 80Hz channel, with near error free performance for average SNR values in excess of 7dB. This result occurs since the total delay encountered by a frame is much lower at higher Doppler frequencies. For the highest Doppler frequency and at high SNR the percentage of effective dropped frames is significantly lower for higher *maxARQ* values. At high SNR the improvement with increasing *maxARQ* is reduced for lower Doppler values. At low average SNR values we also observed that the percentage of effective dropped packets can increase with increasing *maxARQ*. This leads to the conclusion that there is a trade-off between excessively delayed frames and dropped frames as the number of ARQs increases and the mean SNR is low.

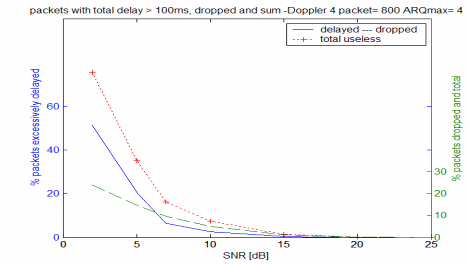
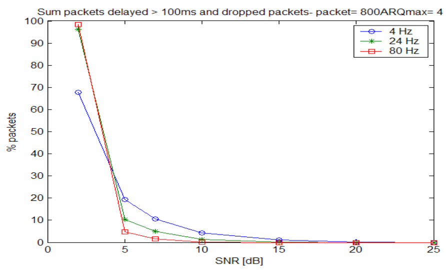
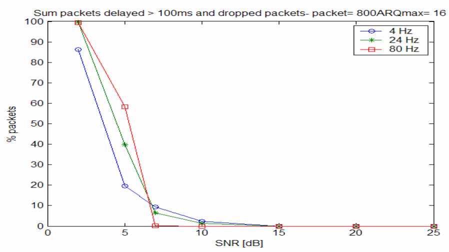


Fig. 5. Percentage of frames with total delay>100ms, of frames dropped, and of effective frames dropped vs. SNR for Doppler frequency 4Hz, *MaxARQ*=4



(a)



(b)

Fig. 6 a,b. Percentage of effective dropped frames vs. SNR for time correlated transmissions as a function of maximum Doppler frequency– top: *maxARQ*=4 –bottom: *maxARQ*=16

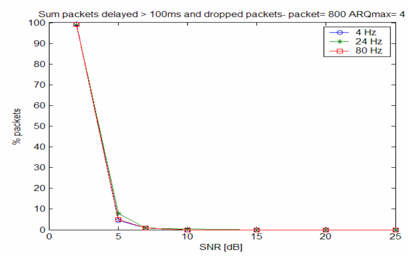


Fig. 7. Percentage of effective dropped frames vs. SNR for uncorrelated transmissions. *MaxARQ*=4.

Fig. 7 shows the percentage of effective dropped frames versus the mean SNR for uncorrelated transmissions. The percentage of effective dropped frames is lower than that shown previously for correlated transmissions (for all Doppler frequencies and for the same *maxARQ*). This occurs since the total delay is evaluated in the uncorrelated case with much fewer ARQs and with much lower FLR (as discussed in fig. 4b). Furthermore, the performance shown for the 4Hz Doppler channel with ARQ is much better than the correlated transmission case. Overall, if uncorrelated fading is used in the ARQ and packet transmission process then the resulting FLR and delay statistics seriously under predict the realistic case where spaced-time correlation is accurately modelled using knowledge of the PSD.

Fig. 8 shows, on the left, the PDF of delay between correctly received frames for a mean SNR=15dB, *maxARQ*=4, and on the right, the log(PDF) of the error burst length for *maxARQ*=4 and a mean SNR of 5dB. Time correlated transmissions are assumed for each of the three Doppler frequencies discussed earlier. We observe that delay decreases as Doppler shift increases, since the *maxARQ* limit is often not required when the fading causes the channel to change rapidly during the retransmission cycle. We define the error burst length as the number of consecutive frames dropped at the receiver. It can be seen that the error burst length decreases significantly with increasing channel Doppler shift. A similar trend is seen for different *maxARQ* values. These results agree well with the results reported in [10].

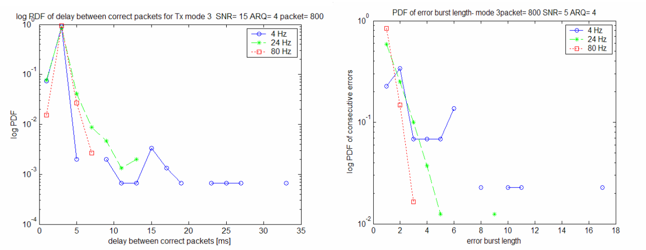


Fig. 8. (left) Log(PDF) of delay between correct frames *MaxARQ*=4, mean SNR=15dB - (right) Log(PDF) of error burst length *MaxARQ*=4, mean SNR=5dB

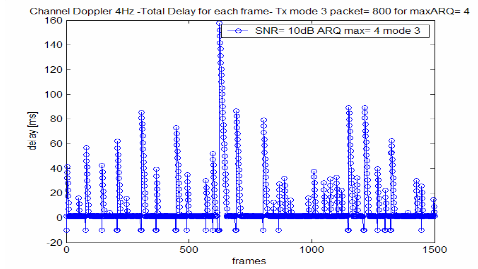


Fig. 9 Total delay per frame in the simulation flow for correlated transmissions, *maxARQ*=4, mean SNR=10 dB, Doppler=4Hz

In fig. 9 we observe the total delay for each transmit frame over a time correlated transmission for fixed values of Doppler, mean SNR, link-speed and *maxARQ*. Under poor channel conditions (low SNR) the transmit frames experience a high PER and hence a high likelihood of retransmission, which results in a rapid build up of queuing delay for subsequent frames. Fig. 9 shows an example where the total delay can build up to 160 ms, even with a low *maxARQ* value. Dropped frames are shown as marks on the delay=-10 ms line.

VI. CONCLUSIONS

While for video applications the reduction in FLR that normally accompanies an increase in *maxARQ* is desirable, for some scenarios and channel conditions the resulting increase in delay and jitter becomes unacceptable. Results show that in order to accurately model frame loss, error bursts and delay in an 802.11a/g system it is necessary to accurately model the radio channel, the PHY layer, and the stop-and-wait ARQ mechanism at the MAC layer.

Results demonstrate that it is vital to include a spaced-time correlated channel model. Time-correlated modelling includes the impact of Doppler on the ARQ mechanism. If the channel is correlated in time, ARQ packets are unlikely to be received correctly, and hence the FLR and delay will increase. Furthermore, for low Doppler spreads the length of the error bursts increase and these may have significant impact on error resilient video schemes.

For a slow fading time correlated channel the total delay is significantly higher than that estimated using a simple uncorrelated (packet to packet) fading channel. When ARQ is used, the percentage of packets delayed beyond 100ms was shown to increase together with the dropped packet rate for low Doppler spreads. A trade-off between delay and FLR can be achieved by adjusting the *maxARQ* parameter. For a given video application, it is possible to determine the best *maxARQ* value for any given Doppler frequency and mean channel SNR. Future work will explore the impact of error bursts, frame loss and delay on the 802.11a/g performance of error resilient video codecs for a range of Doppler spreads.

ACKNOWLEDGEMENTS

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