Sgardoni, V., Ferre, P. L., Doufexi, A., Nix, A. R., & Bull, D. (2007). Frame delay, loss rate and throughput analysis for video applications over time correlated 802.11a/g channels. In IEEE International Conference on Signal Processing and Communications, 2007, ICSPC 2007. (pp. 408 - 411). Dubai: Institute of Electrical and Electronics Engineering, Inc. (IEEE). 10.1109/ICSPC.2007.4728342

2007 IEEE International Conference on Signal Processing and Communications (ICSPC 2007), 24-27 November 2007, Dubai, United Arab Emirates

Frame Delay, Loss Rate and Throughput Analysis for Video Applications 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 spreads are developed to generate time-correlated SNR waveforms. These are used in a bit accurate MAC/PHY simulator to estimate frame loss rate, transmission delay, jitter and throughput 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 802.11 ARQ at the MAC layer. Compared to the slow fading case, in a fast fading channel fewer MAC layer retransmissions are required and the end-to-end delay is significantly reduced. Under poor channel conditions the simulated delay and frame loss rate are seriously underestimated if time-uncorrelated fading is assumed.

Index Terms—MAC, ARQ, QoS, WLAN IEEE 802.11

1. INTRODUCTION

IEEE 802.11 based WLANs are increasingly being used in video surveillance and multimedia distribution networks. The more recent 802.11a/g standard combines a COFDM physical layer (PHY) with the legacy 802.11 medium access control (MAC). For unicast transmissions, the MAC layer supports the automatic retransmission of errored data frames using a stop-and-wait ARQ mechanism. 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].

The performance of the 802.11 protocol has been widely studies in the literature [2]. However, as discussed in [3], most studies are based on static channel models, where the PHY layer packet error rate (PER) is independent of time. It is well known that packet errors over a wireless medium are bursty in nature [4]. The PER for consecutive packets is not independent, due to the time-correlated characteristics of the mobile channel. In [5], throughput estimation of an adaptive ARQ protocol was 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 [5]. The impact of Doppler spread on the packet loss and delay statistics for an 802.11 WLAN was investigated in [6] via experimental measurement. In [7], the packet loss rate and delay was analysed using a Jakes time-correlated Rayleigh fading simulator for various Doppler frequencies. In [3] it was shown that frame delay and frame loss are severely underestimated when the correlation of errors is not taken into account.

In this paper we study the cross-layer performance of the IEEE 802.11a/g standard [8] by simulating MAC-to-MAC FLR, frame delay and throughput for a time varying channel. This is achieved by simulating the transmission of a time series of queued MAC frames. The bursty nature of the packet error is replicated by implementing an accurate time-correlated channel model, based on the classic Jakes Power Spectral Density (PSD) of the radio channel. This study focuses on the throughput and frame delay resulting from poor channel conditions. The impact of channel collisions (due to user contention) is ignored.

Section 2 provides a brief description of the MAC and PHY layers relating to the IEEE 802.11a/g standard. Section 3 describes the fading channel model. Section 4 describes the MAC/PHY frame simulator and section 5 analyses the results obtained. Finally, section 6 provides a set of conclusions.

2. OVERVIEW OF IEEE 802.11a/g

Medium Access Control (MAC): The IEEE 802.11 MAC offers multi-user support via a distributed co-ordination function (DCF) and a Basic Access scheme based on the CSMA/CA protocol. A detailed description of this mechanism is available in the literature [2][3].

Once a PHY layer packet has been sent, for unicast operation the station expects to receive an acknowledgement (ACK). This process is described in [2], where the duration T_{succ} of a successful transmission cycle, without any retransmissions, is defined as:

$$T_{succ} = \mathrm{DIFS} + T_{Bo} + T_{Data} + \mathrm{SIFS} + T_{ACK} \qquad (1)$$

T_{Data} represents the duration of the PHY burst and depends on the packet length and the chosen link-speed. T_{Bo} represents the back-off period as described in [2]. T_{ACK} represents the duration required to receive an ACK for the MAC frame. If no ACK is received within the *ACKtimeout*= SIFS period, the MAC frame is scheduled for retransmission. Retransmissions continue until an ACK is successfully received, or the maximum retry count *maxARQ* is reached. *MaxARQ* is user defined, with typical values in the range 0-32. This process is described in [3], where the total duration of a successful transmission cycle is given by:

$$T_{tx} = N * (\mathrm{DIFS} + T_{Data} + \mathrm{SIFS}) + \sum_{i}^{N} T_{Bo,i} + T_{ACK} \qquad (2)$$

In equation (2) we assume that N retransmissions tare required before an ACK is received and that N<= *maxARQ*.

Physical Layer (PHY): This paper assumes the use of the IEEE 802.11a/g PHY layers, which operate in the 5.1GHz and 2.4GHz bands respectively. 802.11a/g makes use of COFDM and provides 8 unique link-speeds via different combinations of modulation and coding [8]. MAC data frames are mapped to PDU packets for transmission over the PHY layer. The PHY layer simulator described in [9] supports correlated time-varying channel gains for each tap in the channel impulse response, as described in [3]. Hence, the instantaneous SNR

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varies with time (depending on the Doppler spread). Results are presented here as a function of mean SNR, averaged 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.

3. CHANNEL MODEL

In this paper a time-varying channel model is used to replicate the time correlated nature of the instantaneous SNR observed at the target station, as in [3]. Since the instantaneous channel power varies slowly with time (compared to the packet duration), 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. Thus, 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 spread. The fading model is based on a tapped delay line (TDL) with each tap experiencing Rayleigh or Ricean fading. The severity of the Ricean 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 [10]. For the results given here, a single Rayleigh fading tap is used with a classical Jakes PSD. 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. 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.

4. DESCRIPTION OF SIMULATOR

The simulator used here is described in detail in [3]. It is capable of predicting the MAC layer FLR and 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) video source. These data packets arrive at the 802.11 MAC transmitter and are encapsulated one by one into MAC frames. 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, or unsuccessfully. The information signal $r(k)$, for received packet k, is computed using equation (3) as the convolution of the signal sent $s(k)$ with the channel impulse response at the time of transmission, $h_c(t_{k,r})$, where r denotes the retransmission number. For the k^{th} packet and r^{th} retransmission, the channel sample time $t_{k,r}$ is computed:

$$r(k) = s(k) * h_c(t_{k,r}) \tag{3}$$

The simulator computes the transmission delay of each frame i ($T_{tx,i}$) using equation (2), together with the queuing time spent in the MAC frame buffer prior to transmission. 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).

If the channel coherence time is low (i.e. a fast changing channel), 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.

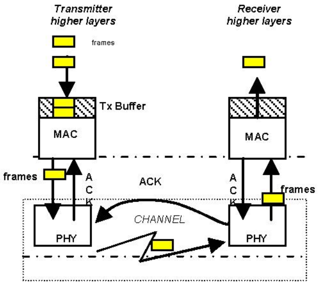


Fig. 1 Time series MAC/PHY simulator block diagram

If the channel coherence time is low (i.e. a fast changing channel), 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.

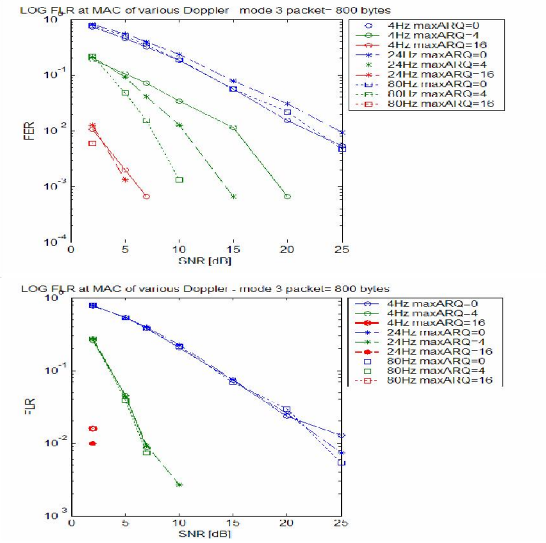
In this analysis, we assume an infinite transmit buffer. In order to *quantitatively* assess the impact of time-correlated channel modelling on the 802.11a/g performance, we simulate two cases of packet transmission and retransmission: a) time-correlated, as described above and b) time uncorrelated. In the latter case the packet errors are independent of time.

5. RESULTS AND ANALYSIS

For the following results, MAC frames are generated at a constant rate of 1 Mbps. The mean SNR was varied over the range 2-25dB. The *maxARQ* limit was also adjusted [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 at 2.4GHz). The frame length was fixed. Results are presented for simulations using link-speed 3 and frame lengths of 800 bytes. 1500 frames were transmit over a duration of approximately 10 seconds.

Fig. 2a shows the FLR at the MAC layer versus average SNR, with and without ARQ, for time-correlated transmissions based on the three Doppler frequencies quoted earlier. 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 [7]. By comparison, when packet transmissions are uncorrelated in time, fig. 2b shows there is no difference in FLR with Doppler.

In fig. 3 the log of the Probability Distribution Function (PDF) for the total frame delay is shown for time-correlated transmissions for all three Doppler frequencies. It can be seen that the total MAC-to-MAC delay increases significantly as the maximum Doppler shift decreases, and this agrees well with results reported in [6][7]. A peak delay of around 12ms was observed for a maximum 80Hz Doppler shift, while delays reached 85ms for a maximum 4Hz Doppler shift. 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. From the delay statistics reported in [3] for uncorrelated fading channel we conclude that the total delay reported here for correlated channels is much higher (for the same set of parameters). We also note that for uncorrelated channels there is no performance difference as a function of Doppler frequency.



(a)

(b)

Fig. 2 a-b MAC FLR vs. SNR, all Doppler freq. - *maxARQ*=0,4,16 for a) correlated and b) uncorrelated transmissions

Figs 4a and 4b show the transmission delay of packets received correctly (given in equation (2) i.e. not including queuing delay), averaged over a time window of 33ms, plotted over the duration of 1500 packets for a time-correlated channel with mean SNR=10dB and for maximum Doppler shifts of 24Hz and 80Hz respectively. The variance of delay is greater when *maxARQ* is high and the channel decorrelates slowly, e.g. for the lower Doppler shift. This results in a jitter problem and requires a jitter buffer prior to the video decoder. For a Doppler shift of 80Hz the variance is small. Transmission delays are set to -10ms if no correct packets were received during that time window. At 1Mbps around five 800-byte frames arrive at the MAC transmitter during the 33ms time window.

The time pattern of FLR at the receiving MAC layer is shown in fig. 5. Instantaneous FLR is computed for every time window as the ratio of lost frames to the total number of frames transmitted in the particular time window. The FLR fluctuates greatly in time when *maxARQ*=0, according to the instantaneous channel SNR. For *maxARQ*=16 we see that packets are rarely lost (although jitter and throughput become a problem). FLR is set to -0.2 for time windows where no received frames were observed at the MAC layer. It is clear that there are periods when the channel is so bad that a single frame transmission is repeated up to *maxARQ* and still fails to be delivered. This delays all the following frames in the transmit MAC queue. This is particularly obvious for *maxARQ*=16. Comparing fig. 5 with the transmission delay results of fig. 4a (obtained for the same simulation parameters) we can see that transmission delay builds up around the same periods as high FLR.

Using the total MAC-to-MAC delay, we compute the percentage of frames that are delayed by more than 100ms, since this is a typical upper limit for real-time video transmission [1]. Excessively delayed frames beyond this value are ignored at the video decoder and are thus treated similarly to lost frames. We can compute the *effective FLR* for the real-time video decoder as the ratio of the sum of lost frames at the MAC layer *and* excessively delayed frames to the total number of unique transmit frames. Figs 6a and b show the percentage of effective dropped frames versus mean SNR in a time correlated channel, computed for all three Doppler frequencies and for *maxARQ*= 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, particularly for high *maxARQ* values, as explained in [3]. 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 frame loss as the number of ARQs increases and the mean SNR is low.

To study the relationship between throughput and transmission delay we compute the number of bytes transmitted correctly over the total transmission time (not including queuing time) for each time window. We call this ratio the "transmission efficiency", which is a measure similar to throughput.

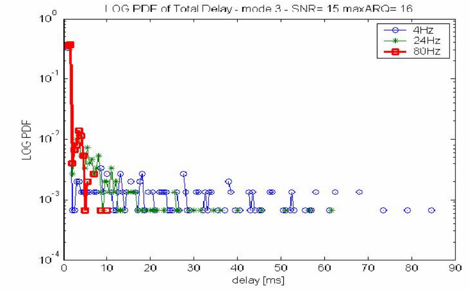
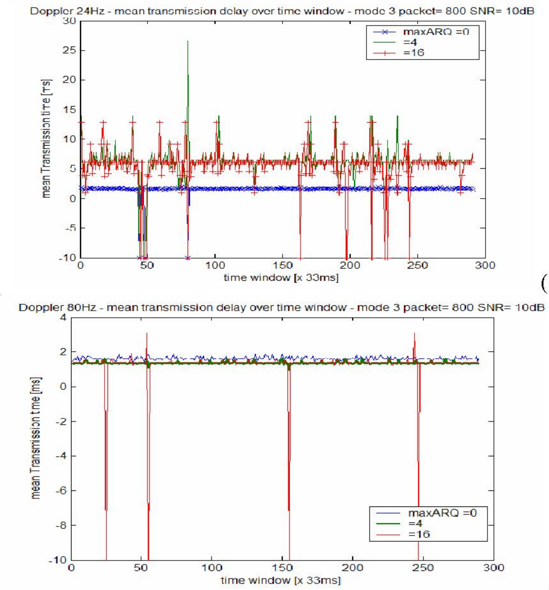


Fig. 3 Log(PDF) of total frame delay when *maxARQ*=16, for Doppler shifts 4, 24, 80Hz, mean SNR=15dB



(a)

(b)

Fig. 4 a-b Average transmission delay over time, mean SNR=10dB *maxARQ*=0,4,16, for Doppler shift a) 24Hz, b) 80Hz

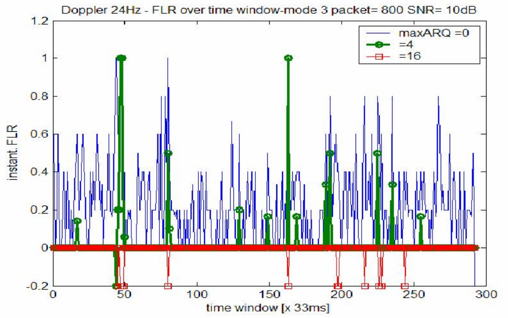
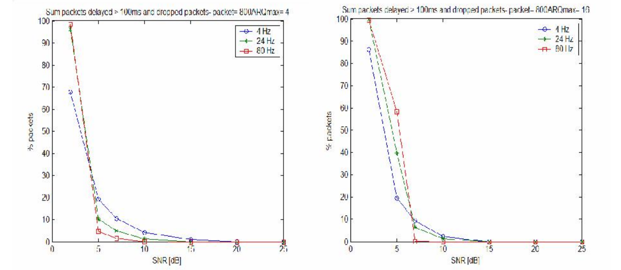
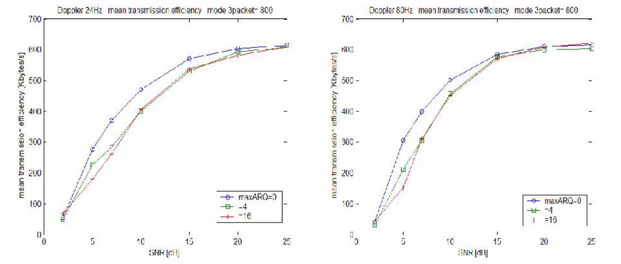


Fig. 5 FLR over time, mean SNR=10dB, *maxARQ*=0,4,16, for Doppler shift 24Hz



(a) *maxARQ* =4 (b) *maxARQ* =16

Fig. 6 a-b Percentage of effective dropped frames vs. SNR for time correlated transmissions as a function of max Doppler frequency



(a) Doppler 24Hz (b) Doppler 80Hz

Fig. 7 a-b Mean transmission efficiency vs. SNR, maxARQ=0,4,16

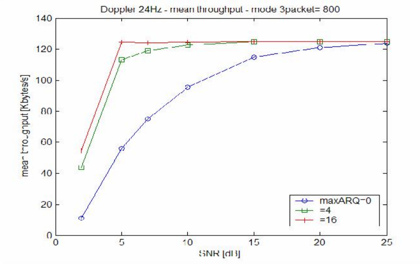


Fig. 8 Mean throughput vs. SNR, maxARQ=0,4,16, Doppler 24Hz

Figs 7a and b show the transmission efficiency averaged in time versus mean channel SNR, for *maxARQ*=0, 4, 16 for the 24Hz and 80Hz channels. We observe that transmission efficiency increases for higher *maxARQ* only when SNR is high and for the 80Hz channel. When the channel is poor, however, efficiency is higher by about 40% if no ARQs are applied, for both Doppler shifts. This occurs since the transmission time per packet is low without ARQ. Therefore, the FLR improvement with ARQ comes at the cost of throughput (and also jitter).

Fig. 8 shows the mean throughput, averaged in time, versus the mean channel SNR, for *maxARQ*=0, 4, 16, for a 24Hz channel. Instantaneous throughput is calculated as the ratio of correctly received bytes divided by the calculation window period (33ms in this case). The mean throughput is computed over the transmission of 1500 packets for a correlated channel.

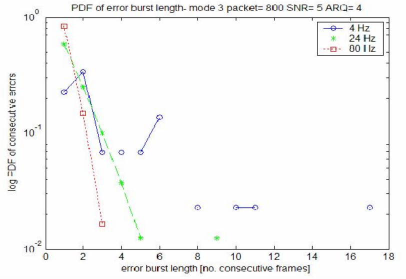


Fig. 9 Log(PDF) of error burst length for time correlated transmissions. *MaxARQ*=4, mean SNR=5dB

Fig. 9 shows the log(PDF) of the error burst length for *maxARQ*=4 and a mean SNR of 5dB. The error burst length is defined as the number of consecutive frames dropped at the receiver. 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 those previously reported in [7].

6. CONCLUSIONS

The reduction in FLR that normally accompanies an increase in *maxARQ* is often associated with an unacceptable increase in delay and jitter for video applications. In order to accurately model frame loss rate, error bursts, delay and throughput in an 802.11a/g system it is vital to use a spaced-time correlated channel model, which includes the impact of Doppler spread on the ARQ mechanism in the MAC layer. Furthermore, the error burst length depends on the Doppler spread and these will have a significant impact on the performance of error resilient video schemes. For a slow fading time-correlated channel it is shown that the total delay is significantly higher than that estimated from a simple uncorrelated fading channel. When ARQ is used, the percentage of packets delayed beyond 100ms increases for low Doppler spreads and the improvement in FLR occurs at the cost of throughput. 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 rate and delay on the 802.11a/g performance of error resilient video codecs for a range of Doppler spreads.

ACKNOWLEDGEMENTS

This work was partly funded by the Department of Trade and Industry (DTI UK), Technology Programme project, VISUALISE.

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