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Modelling unfairness in IEEE 802.11g networks with variable frame length

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Abstract. In this paper we consider variations in performance between different communicating pairs of nodes within a restricted network topology. This scenario highlights potential unfairness in network access, leading to one or more pair of communicating nodes being adversely penalised, potentially meaning that high bandwidth applications could not be supported. In particular we explore the effect that variable frame lengths can have on fairness, which suggests that reducing relative frame length variance at affected nodes might be one way to alleviate some of the effect of unfairness in network access.

Keywords: WLAN, IEEE 802.11g, Performance modelling, PEPA, Fairness.

1 Introduction

Wireless network access has been adopted across the world as the network medium of choice due primarily to ease of installation, ease of access from a wide range of devices and flexibility of access for roaming users. Amongst the range of access protocols available, the IEEE 802.11 family of protocols has become the standard for wireless networks [1]. The different IEEE 802.11 protocols (a/b/g/n) all have a similar structure, but different operating ranges (power, data rate, frame length etc) [12]. Fundamentally, the IEEE 802.11 families are controlling with the two main standards: Medium Access Control (MAC) and the physical layer. Access control is managed by Distributed Coordination Function (DCF) and Point Coordination Function (PCF), which supports support collision free and time restricted services.

Understanding the performance of wireless systems is clearly crucial in making appropriate choices for the provision of infrastructure and services. Clearly we need to know at least the expected network throughput and latency in order to know whether the network is able to support a given level of service. Fairness is concerned with the forced variability of throughput and latency at different nodes leading to different parts of the network attaining different levels of performance. In our previous works we considered models of unequal network access in IEEE802.11b and g [2, 3], based on an original model by Kloul and

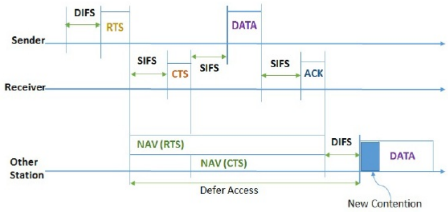
Valois [11]. From this we observed that fairness is affected by both transmission rate and frame length. In our modelled scenario short frames transmitted faster promoted a greater opportunity sharing of access, even under a pathologically unfair network topology. In practice it is not possible to simply set an arbitrarily short frame length and fast transmission rate as these factors also dictate the transmission range; in CSMA/CA neighbouring nodes need to be able to 'sense' a transmission in order to minimise and detect interference. For this reason wireless protocols generally provide only a small set of possible transmission rates with fixed, or at least minimum, frame lengths, allowing the network provider to choose an option which best fits their operating environment. In this paper we seek to relax these conditions to explore the effect of frame length variability on the fairness of network access. The model we propose and explore has many of the features of IEEE 802.11g, including the same average frame lengths. However, by introducing greater variability to the frame lengths we permit frames to be shorter than the prescribed IEEE 802.11g frame length, which would not be permitted in practice. Notwithstanding this practical limitation, the results provide greater insight into the fairness of wireless systems with highly variable frame lengths, including frame bursting provision in IEEE 802.11n.

This paper extends the model presented in [3] to study a number of deployment scenarios in IEEE 802.11g with variable frame lengths modelling using the stochastic process algebra PEPA [8]. The paper is organized as follows. Section 2 describes the model that we used in PEPA for each scenario and the parameters are presented in Section 3. The results and figures are given in Section 4. Section 5 explores the contribution of this work with some related work on the performance of IEEE 802.11 and in particular modelling with PEPA. Finally, conclusion and future works are provided in Section 6.

2 The model

2.1 Basic Access mechanism

The Basic Access (BA) method is widely used in 802.11 up to 802.11g [4]. It cooperates in either the Point Coordination Function (PCF needs a central control object) or the Distributed Coordination Function (DCF based on CSMA/CA). The DCF mechanism specifies two techniques for data transmission, which are the basic access method and two way handshake mechanism, in our study we focused solely on the basic access method. In BA, shown in Figure 1, a WLAN node listens to the channel to access it, when the medium is free to use with no congestion, then it can make its transmission. On successful receipt, the receiving node will transmit an acknowledgement (ACK). However, if two nodes attempt to transmit simultaneously, then collision occurs resulting in an unsuccessful transmission and an initiation of a back-off algorithm. An unsuccessful transmitting node waits for a random time (back-off) in the range [0, CW], where contention window CW is based on the number of transmission failures. The initial value of CW is 15 for 802.11g, it is doubled after every unsuccessful transmission, until it reaches to the maximum number (1023) and CW returns to the initial value after each ACK received (see [6, 10] for more detail). If the channel is not free to use, the node monitors the channel until it becomes idle. However, the node will not attempt to transmit immediately (as this approach clearly cause a collision with any other waiting nodes), but instead continues to listen for a further backoff period until it is satisfied that the channel is idle.

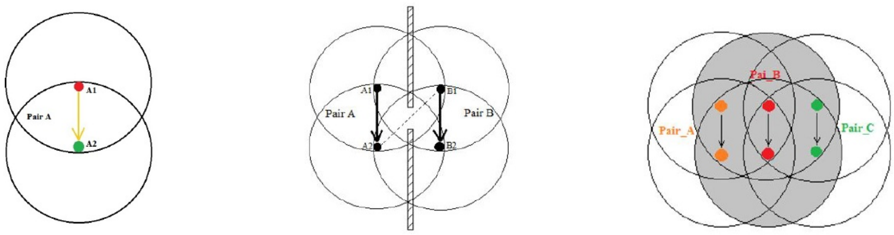


(a) RTC-CTS and Data-ACK scheme.

Attribute	Values of 802.11g
CW *min* and CW *max*	15(pure) and 1023
Slot time	$20\mu s$, $9\mu s$
SIFS	$10\mu s$
DIFS	$50\mu s$, $28\mu s$
EFIS	$364\mu s$

(b) Attribute values of 802.11g.

Fig. 1: Basic access method with 802.11g attributions



(a) Scenario 1. (b) Scenario 2. (c) Scenario 3.

Fig. 2: (One pair, Two pairs and Three pairs) scenarios.

2.2 Scenarios modelled with PEPA

We now consider a model of pairs of transmitting nodes competing to use the transmission channel as illustrated in Figure 2. We only consider cases where the demand for access is very high, in order to determine the maximum channel utilisation and throughput that can be achieved. The basic model (the one pair scenario) is used to derive a baseline throughput when there is no contention. The other two models (two and three pair scenarios) are used to explore how competition for access affects throughput and utilisation. If the system is fair then all nodes should experience the same throughput and utilisation (when all nodes have the same demand). However, the three pair scenario is pathologically unfair due to its rigid topology; the inner pair will be out-competed by their neighbours which can transmit simultaneously, whereas the inner pair must wait until neither outer pair is transmitting. We seek to explore how variable frame lengths affect the fairness in each scenario, using two transmission rates, one for “normal” short frames and one for “occasional” long frames.

One pair scenario (Scenario 1) This scenario is useful to illustrate the behaviour of the transmitting pairs and to provide a baseline performance. The model consists of two components; *Pair*, depicting the communicating nodes, and Med_F, depicting the transmission medium. `Pair` draws backoff and becomes `Pair0`, `Pair0` starts to count *DIFS* to `Pair1`. `Pair1` counts `backoff` in the same `Pair1` or it ends `backoff` to `Pair2a` (with probability α) or `Pair2b` (with probability $-\alpha$). `Pair2a` depicts transmission of short frames, whereas `Pair2b` specifies transmission of long frames ($\mu data_1 > \mu data_2$). `Pair3` counts the *SIFS* period, then an *ACK* is received in `Pair4`.

$$
\begin{aligned}
Pair &\stackrel{def}{=} (draw\_backoff, r).Pair0 \\
Pair0 &\stackrel{def}{=} (count\_difs, \mu difs).Pair1 \\
Pair1 &\stackrel{def}{=} (count\_backoff, p\mu bck).Pair1 + (end\_backoff, \alpha q\mu bck).Pair2a \\
&\quad +(end\_backoff, (1-\alpha)q\mu bck).Pair2b \\
Pair2a &\stackrel{def}{=} (transmit, \mu data_1).Pair3 \\
Pair2b &\stackrel{def}{=} (transmit, \mu data_2).Pair3 \\
Pair3 &\stackrel{def}{=} (count\_sifs, \mu sifs).Pair4 \\
Pair4 &\stackrel{def}{=} (ack, \mu ack).Pair
\end{aligned}
$$

$$
\begin{aligned}
Med\_F &\stackrel{def}{=} (transmit, \top).Med\_F1 + (count\_difs, \top).Med\_F \\
&\quad +(count\_backoff, \top).Med\_F + (end\_backoff, \top).Med\_F \\
Med\_F1 &\stackrel{def}{=} (transmit, \top).Med\_F2 + (ackA, \top).Med\_F \\
&\quad +(count\_difs, \top).Med\_F1 + (count\_backoff, \top).Med\_F1 \\
&\quad +(end\_backoff, \top).Med\_F1 \\
Med\_F2 &\stackrel{def}{=} (ack, \top).Med\_F1 + (count\_difs, \top).Med\_F2 \\
&\quad +(count\_backoff, \top).Med\_F2 + (end\_backoff, \top).Med\_F2
\end{aligned}
$$

$$Scenario1 \stackrel{def}{=} Pair \underset{\mathcal{K}}{\bowtie} Med\_F$$

Where $\mathcal{K} = \{transmit, ack, count\_difs, count\_backoff, end\_backoff\}$.

Two pairs scenario (*Scenario 2*): Here we have two asymmetric pairs interacting with a shared medium (see Figure 2 (b)). If, one node in a pair attempts to transmit, its partner node waits to receive an *ACK*. `Pair_A` behaves as in the previous model, having long and short frames, whereas `Pair_B` has only one frame length. Unlike the previous case we also need to consider contention and subsequent waiting for access, which adds additional behaviours to both model components. For this reason we model the choice of long or short frame at the very beginning of `Pair_A` , so that subsequent repeat attempts to transmit a long frame will also be long frames and not a new choice of long or short. The availability to transmit is controlled by the shared actions with the medium component. Frames blocked by the medium being busy with the other pair will experience a `queue` or `queueB` action and subsequent `wait` (`waitS` or `waitL` for short or long frames at `Pair_A`) before reattempting to transmit.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, \alpha * r).Pair\_A0S + (draw\_backoff, (1-\alpha) * r).Pair\_A0L \\
Pair\_A0S &\stackrel{def}{=} (count\_difs, \mu difs).Pair\_A1S + (queue, \top).Pair\_A5S \\
Pair\_A0L &\stackrel{def}{=} (count\_difs, \mu difs).Pair\_A1L + (queue, \top).Pair\_A5L \\
Pair\_A1S &\stackrel{def}{=} (count\_backoff, p\mu bck).Pair\_A1S + (end\_backoff, q\mu bck).Pair\_A2S \\
&\quad +(queue, \top).Pair\_A5S \\
Pair\_A1L &\stackrel{def}{=} (count\_backoff, p\mu bck).Pair\_A1L + (end\_backoff, q\mu bck).Pair\_A2L \\
&\quad +(queue, \top).Pair\_A5L \\
Pair\_A2S &\stackrel{def}{=} (transmit, \mu data1).Pair\_A3S + (queue, \top).Pair\_A5S \\
Pair\_A2L &\stackrel{def}{=} (transmit, \mu data2).Pair\_A3L + (queue, \top).Pair\_A5L \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu sifs).Pair\_A6 \\
Pair\_A4S &\stackrel{def}{=} (count\_difs, \mu difs).Pair\_A1S + (count\_eifs, \mu eifs).Pair\_A1S \\
&\quad +(queue, \top).Pair\_A5S \\
Pair\_A4L &\stackrel{def}{=} (count\_difs, \mu difs).Pair\_A1L + (count\_eifs, \mu eifs).Pair\_A1L \\
&\quad +(queue, \top).Pair\_A5L \\
Pair\_A5S &\stackrel{def}{=} (waitS, \mu data).Pair\_A4S \\
Pair\_A5L &\stackrel{def}{=} (waitL, \mu data).Pair\_A4L \\
Pair\_A6 &\stackrel{def}{=} (ack, \mu ack).Pair\_A
\end{aligned}
$$

$$
\begin{aligned}
Pair\_B &\stackrel{def}{=} (draw\_backoff, r).Pair\_B0 \\
Pair\_B0 &\stackrel{def}{=} (count\_difsB, \mu difs).Pair\_B1 + (queueB, \top).Pair\_B5 \\
Pair\_B1 &\stackrel{def}{=} (count\_backoffB, p\mu bck).Pair\_B1 + (end\_backoffB, q\mu bck).Pair\_B2 \\
&\quad +(queueB, \top).Pair\_B5 \\
Pair\_B2 &\stackrel{def}{=} (transmitB, \mu data).Pair\_B3 + (queueB, \top).Pair\_B5 \\
Pair\_B3 &\stackrel{def}{=} (count\_sifs, \mu sifs).Pair\_B6 \\
Pair\_B4 &\stackrel{def}{=} (count\_difsB, \mu difs).Pair\_B1 + (count\_eifsB, \mu eifs).Pair\_B1 \\
&\quad +(queueB, \top).Pair\_B5 \\
Pair\_B5 &\stackrel{def}{=} (wait, \mu data).Pair\_B4 \\
Pair\_B6 &\stackrel{def}{=} (ackB, \mu ack).Pair\_B
\end{aligned}
$$

$$
\begin{aligned}
Med\_F &\stackrel{def}{=} (transmit, \top).Med\_F2 + (transmitB, \top).Med\_F1 \\
&\quad +(count\_difs, \top).Med\_F + (count\_backoff, \top).Med\_F \\
&\quad +(end\_backoff, \top).Med\_F + (count\_eifs, \top).Med\_F \\
&\quad +(count\_difsB, \top).Med\_F + (count\_backoffB, \top).Med\_F \\
&\quad +(end\_backoffB, \top).Med\_F + (count\_eifsB, \top).Med\_F \\
Med\_F1 &\stackrel{def}{=} (ackB, \top).Med\_F + (queue, \lambda oc).Med\_F1 \\
Med\_F2 &\stackrel{def}{=} (transmit, \top).Med\_F3 + (ack, \top).Med\_F \\
&\quad +(queueB, \lambda oc).Med\_F2 + (count\_difs, \top).Med\_F2 \\
&\quad +(count\_backoff, \top).Med\_F2 + (end\_backoff, \top).Med\_F2 \\
&\quad +(count\_eifs, \top).Med\_F2 \\
Med\_F3 &\stackrel{def}{=} (ack, \top).Med\_F2 + (queueB, \lambda oc).Med\_F3 \\
&\quad +(count\_difs, \top).Med\_F3 + (count\_backoff, \top).Med\_F3 \\
&\quad +(end\_backoff, \top).Med\_F3 + (count\_eifs, \top).Med\_F3
\end{aligned}
$$

$$Scenario2 \stackrel{def}{=} ((Pair\_A \underset{\mathcal{K}}{\bowtie} Med\_F) \underset{\mathcal{L}}{\bowtie} Pair\_B$$

Where the sets of $\mathcal{K}$ and $\mathcal{L}$ are:
$\mathcal{K} = \{transmit, ack, queue, count\_difs, count\_backoff, end\_backoff, count\_eifs\}$.
$\mathcal{L} = \{transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

Three pairs scenario (*Scenario 3*) This final scenario consists of two symmetric outer pairs (`Pair_A` and `Pair_C`), one inner pair (`Pair_B`) and a shared medium (`Med_F`) (see Figure 2 (c). The outer pairs cannot hear one another and so may transmit independently. However both outer pairs are within the interference range of the inner pair, hence the inner pair can only transmit when the medium is quiescent. In our model the outer pairs have both long and short frames (modelled as `Pair_A` in the previous scenario) whereas the inner pair has only one frame type (modelled as `Pair_B` in the previous scenario). The model therefore only differs from the previous scenario in having two instances of `Pair_A` (the second renamed for clarity) and having a modified cooperation set.

$$Scenario3 \stackrel{def}{=} ((Pair\_A \| Pair\_C) \underset{\mathcal{K}}{\bowtie} Med\_F) \underset{\mathcal{L}}{\bowtie} Pair\_B$$

where $\mathcal{K} = \{transmit, ack, queue, count\_difs, count\_backoff, end\_backoff, count\_eifs\}$. And $\mathcal{L} = \{transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

3 Parameters

IEEE 802.11 has a very specific inter-frame spacing, which coordinates access to the medium for transmitting frames. For convenience, each pair in this paper has count back-off and end back-off actions with (p$\times\mu bck$) and (q$\times\mu bck$) rates respectively; we assume the values of **p** and **q** (q=1-p) are equal to 0.5. According to the definition of 802.11g and PHY standards, the possible data rate per stream are (6, 9, 12, 18, 24, 36, 48, and 54) Mbits/s [6, 10]. In this paper considered 6, 12, 36 and 54 Mbits/s as a sample of data rates, these rates have been applied with each of the frame payload size (700, 900, 1000, 1200, 1400 and 1500) bytes. The frames per time unit for arrival and departure rate are λoc=100000 and μ=200000 respectively. In this model (μack) shows as a rate of *ACK*, where μack=Channel throughput÷(Ack length=1 byte). If μack=1644.75 for 1 Mbits/s then for 6 Mbits/s it is 1071.42 (6 × 1644.75).

Inter-Frame Space (IFS) : Before each frame transmits, the length of the IFS is dependent on the previous frame type, if noise occurs, the required (*IFS*) is used. Possibly, when transmission of a particular frame ends and before another one starts the IFS applies a delay for the channel to stay clear. It is an essential idle period of time needed to ensure that other nodes may access the channel. The purpose of an *IFS* is to supply a waiting time for each frame transmission in a particular node, to allows the transmitted signal to reach another node (essential for listening). 802.11 have several IFS: *SIFS*, *DIFS*, *EIFS* and Slot time, see [6, 5, 9].

Short Inter-Frame Space (SIFS): SIFS is shortest IFS for highest priority transmissions used with DCF, measured by microseconds. It is important in 802.11 to better process a received frame. It is equal to 10μs in 802.11b/g/n.

DCF Inter-Frame Space (DIFS): DIFS is a medium priority waiting time after SIFS and much longer to monitor the medium. If the channel is idle again, the node waits for the *DIFS*. After the node determines that the channel is idle for a specific of time (*DIFS*) then it waits for another (*backoff*).
DIFS = SIFS + (2 × (Slot time =20 μs in 802.11b/g/n)).

Extended Inter-Frame Space (EIFS): When the node can detect a signal and *DIFS* is not functioning during collision, the transmission node uses EIFS instead of *DIFS*, (used with erroneous frame transmission). It is the longest of *IFS* but has the lowest priority after DIFS. in *DCF* it can derive by:
EIFS=SIFS+DIFS+transmission time(Ack-lowest basic rate).

Contention Window (CW): A node waits to minimise any collisions once experiments an idle channel with appropriate *IFS* (otherwise many waiting nodes might transmit simultaneously). In CSMA/CA, before sending any frame the node waits a random time back-off, it is selected by node from a Contention Window (*CW*). Faster back-off needs less waiting time, so transmission will be faster too, unless there is a collision. Back-off is chosen in [0, *CW*]. CW=CW*min* for all nodes if a node successfully transmits a packet, then receives an *ACK*. In the not transmission case, the node deals another (*backoff*), then the *CW* increases exponentially until it reaches CW*max*. Finally, the CW resets to CW*min* when the packet is received properly.
CW*min*=15, CW*max*=1023. CW*min* augmented by 2n-1 on each retry.
Backoff Time = (Random () mod (CW+1)) × Slot Time.
If BackoffTimer=b, where b is a random integer, also CW*min* <b< CW*max*
The mean of CW is calculated by: μbck=10^6 ÷ (Mean of CW × Time Slot).
The mean of μbck=7.5 and Time slot=$20\mu s$. The receiver sends an *ACK* if it gets a packet successfully, it is a precaution action to notify when collisions occur.

μdata and variance: The value of $\mu data$ can be obtained by (Data rate × (10^6÷8))÷ Packet payload size. The pair with one frame length uses $\mu data$ for the frame portion in the transmit and wait actions (see the depictions of `Pair_B`). For the pairs with two frame lengths we used $\mu data$ we obtained two different values, $\mu data1$ for the transmission of the short frames (proportion α) and $\mu data2$ for the long frames (proportion $1-\alpha$). We assume that the average frame length is the same for the two size pair as the one size pair, hence,

$$\frac{\alpha}{\mu data1} + \frac{1-\alpha}{\mu data2} = \frac{1}{\mu data}$$

If we assume that $\mu data1 = a\mu data2$, where $a > 1$, then

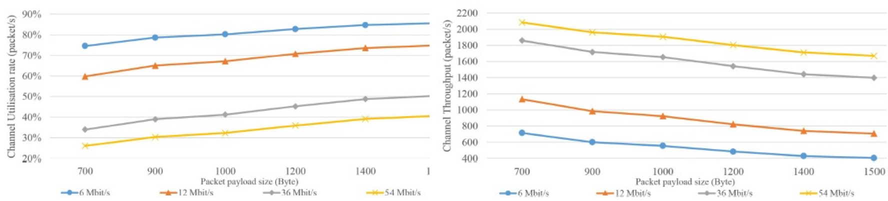
$$\mu data2 = \frac{\mu data(\alpha + a(1-\alpha))}{a}$$

In PEPA all actions are negative exponentially distributed. Hence the case where there is a single frame length, the transmit action duration is simply a negative exponentially distributed random variable. However, when we model the choice of two frame lengths this delay becomes a hyper-exponential. In the following experiments we fix $a = 100$ and vary the proportion of short frames, α, in order to change the variance of the frame transmission.

4 Results and Figures

4.1 Results of one pair scenario: Scenario 1

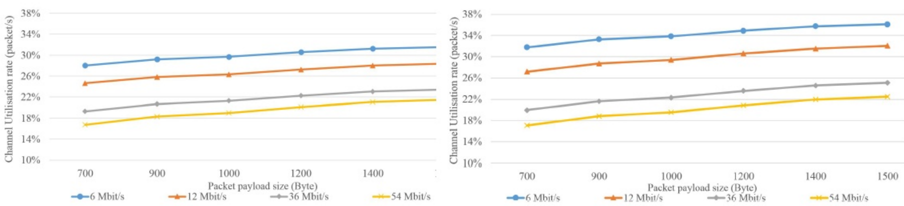
Figure 3 shows the average utilisation and throughput for the one pair scenario for different average frame lengths and transmission rates. In this scenario there is no competition and so altering the proportion of long and short frames makes no difference if the average frame length remains the same. There is a small amount of variation with frame length; the utilisation increases slightly and the throughput decreases slightly as the payload increases.



(a) Channel utilization. (b) Channel throughput.

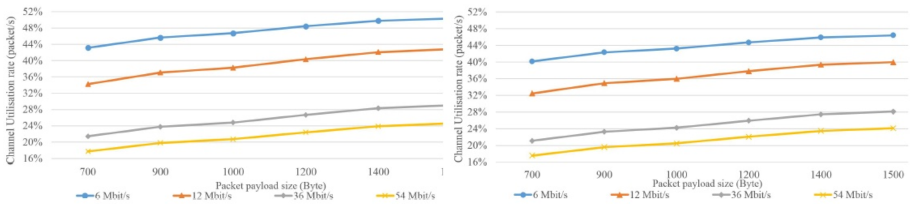
Fig. 3: Channel utilization and channel throughput for one pair (Scenario 1)

4.2 Results of two pairs scenario: Scenario 2



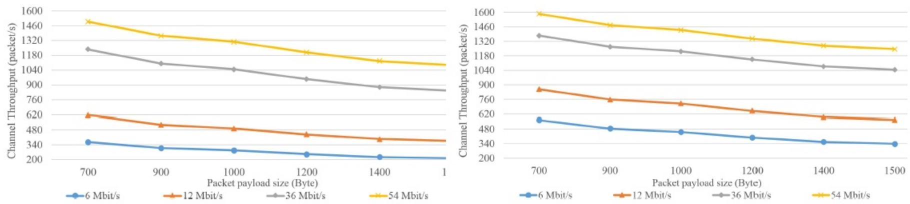
(a) Utilization of `Pair A` α=0.89. (b) Utilization of `Pair A` α=0.99.

Fig. 4: Utilization for `Pair A` α=0.89 and α=0.99 in (Scenario 2)



(a) Utilization for `Pair B` α=0.89. (b) Utilization for `Pair B` α=0.99.

Fig. 5: Utilization for `Pair B` α=0.89 and α=0.99 in (Scenario 2)

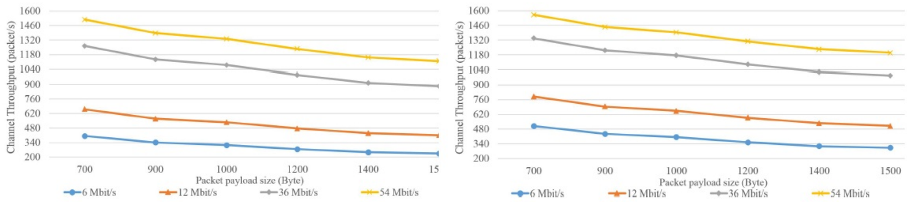


(a) Throughput of `Pair A`, α=0.89. (b) Throughput of `Pair B`, α=0.89.

Fig. 6: Throughput for `Pair A` α=0.89 and `Pair B` α=0.89 in (Scenario 2)

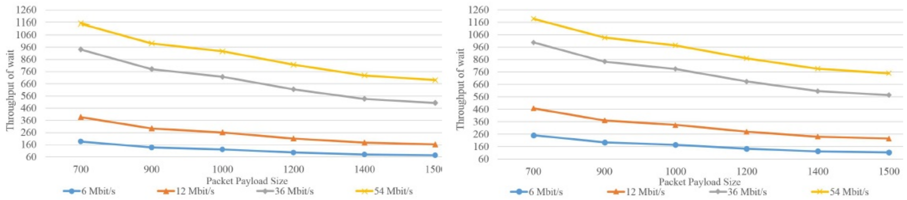
In this case the frame length variance is greater at `Pair A` than at `Pair B`. From Figures 4 and 5 we can clearly see that the medium utilisation is greater by `Pair B` than `Pair A`, but this effect is less when the proportion of long frames is reduced. When $\alpha = 0.89$ `Pair B` gains around a 15% utilisation advantage over `Pair A`, whereas when $\alpha = 0.99$ (fewer long frames) this advantage is around 8%. This effect is fairly consistent regardless of transmission rate. Figures 6 and 7 show the corresponding throughput results. In Figure 6 we show the throughput for both pairs when $\alpha = 0.89$. It is clear that `Pair B` has significantly better performance than `Pair A` under these conditions. However, when $\alpha = 0.99$ there is only a slight difference between the throughput at each pair. In each case the general trends of utilisation and throughput are consistent with the non-competitive case in Scenario 1. However, it is clear that variance in frame length is having a major impact on the share of resources available to each pair.

In order to better understand what is causing this unbalance in performance, we also studied the throughput of the *wait* action. In `Pair_A` waiting to transmit a long frame is denoted by *waitL* and *waitS* for short frames. In Figure 8 we observe that the throughput of *wait* in `Pair_B` is significantly increased between α=0.89 and 0.99, clearly showing that transmission is much more likely to be delayed when $\alpha = 0.99$. Furthermore we see that waiting is much more likely to occur when the transmission rate is high and the payload is small, simply because there are more occassions when a delay may happen. Figures 9 and 10 show the throughput of the *waitS* and *waitL* actions under the same values of



(a) Throughput of `Pair A`,α=0.99. (b) Throughput of `Pair B` α=0.99.

Fig. 7: Throughput for `Pair A` α=0.99 and `Pair B` α=0.99 in (Scenario 2)



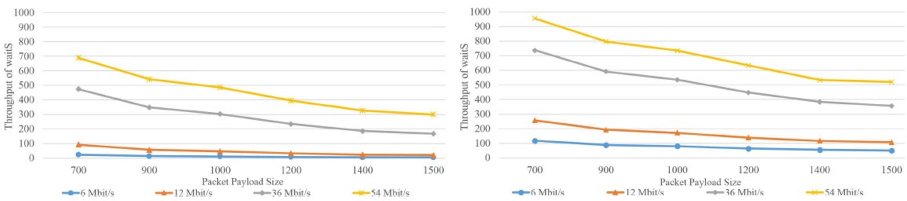
(a) Throughput of wait if α=0.89. (b) Throughput of wait if α=0.99.

Fig. 8: Throughput of wait for `Pair B` if α=0.89 and α=0.99 in (Scenario 2)

α. As for `Pair B`, we see that the throughput of $waitS$ at `Pair A` significantly increases when α increases from 0.89 to 0.99. The throughput of $waitL$ when $\alpha = 0.89$ is almost identical to that of $waitS$. However, when $\alpha = 0.99$ the throughput of $waitL$ is quite different. One aspect of this is that there are far fewer long frames when $\alpha = 0.99$. However we also observe that when the payload is small then the throughput of $waitL$ is less for high transmission rates than for lower transmission rates. The cumulative throughput of wait actions($waitS$ and $waitL$) at `Pair A` far exceeds that at `Pair B` when $\alpha = 0.89$. This corresponds to the lower performance of `Pair A` shown in Figures 4-7. However, when $\alpha = 0.99$ the cumulative throughput of wait actions at `Pair A` is only slightly higher than for `Pair B`, leading to the much closer performance noted earlier. It is clear that the behaviour of the wait actions, particularly $waitL$ has a significant impact on the fairness exhibited by this scenario.

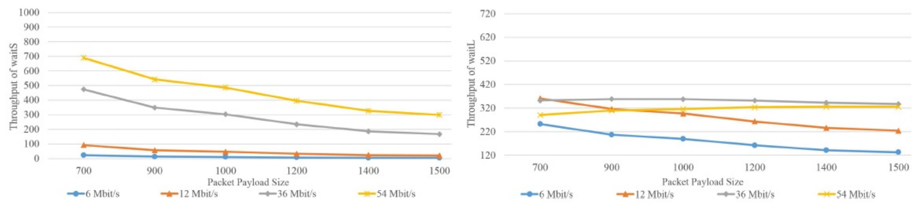
4.3 Results of three pairs scenario (Scenario 3)

We have observed that the higher variance of the hyper-exponential distribution can have a significant negative impact on performance in competitive situations. We now seek to exploit this observation in the three pair scenario which has been previously seen to be pathologically unfair [3]. By causing the outer pairs to have a higher variance we aim to reduce their topological advantage over the inner pair. Figure 11 shows the combined utilisation of the outer pairs when $\alpha = 0.89$ and 0.99. We see that when the transmission rate is low there is little



(a) Throughput of WaitS if α=0.89. (b) Throughput of WaitS if α=0.99.

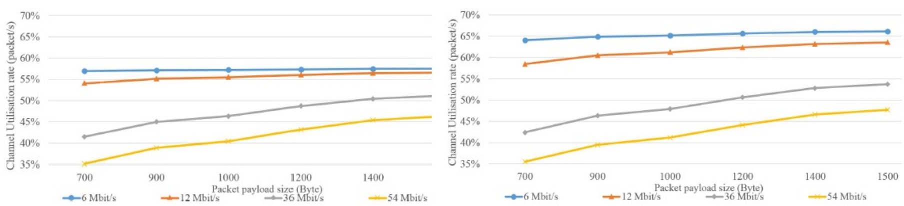
Fig. 9: Throughput of WaitS for `Pair A` if α=0.89 and α=0.99 in (Scenario 2)



(a) Throughput of WaitL if α=0.89. (b) Throughput of WaitL if α=0.99.

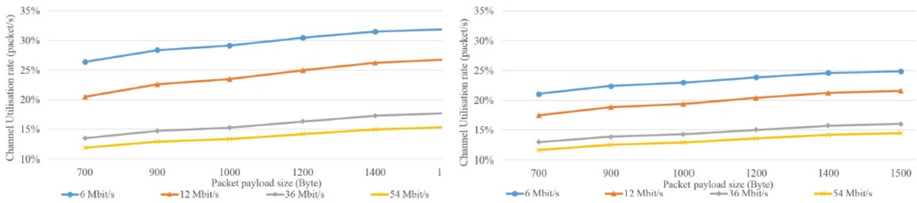
Fig. 10: Throughput of WaitL for `Pair A` if α=0.89 and α=0.99 in (Scenario 2)

variation with payload size, but greater variation as transmission rate increases. We also observe that the utilisation by the outer pairs increases by around 8% as α increases from 0.89 to 0.99. Figure 12 shows the corresponding utilisation by the inner pair. As expected, when $\alpha = 0.99$ then in all cases the outer pairs significantly outperform the inner pair. However, when $\alpha = 0.89$ and the transmission rate is 6 Mbit/s then the inner pair actually has a greater share of the medium than each of the outer pairs, except when the payload is very small. In all other cases the outer pairs still outperform the inner pairs, although the unfairness is clearly reduced compared with $\alpha = 0.99$.



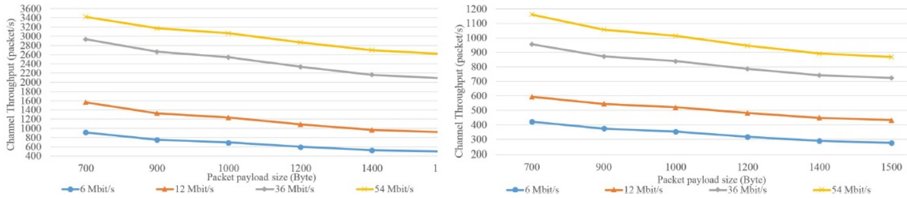
(a) Utilisation of `Outers`, α=0.89. (b) Utilisation of `Outers`, α=0.99.

Fig. 11: Utilisation of `Outers` if α=0.89 and 0.99 in (Scenario 3)



(a) Utilisation of `Inner`, α=0.89. (b) Utilisation of `Inner` α=0.99.

Fig. 12: Utilisation of `Inner` if α=0.89 and 0.99 in (Scenario 3) in (Scenario 3)

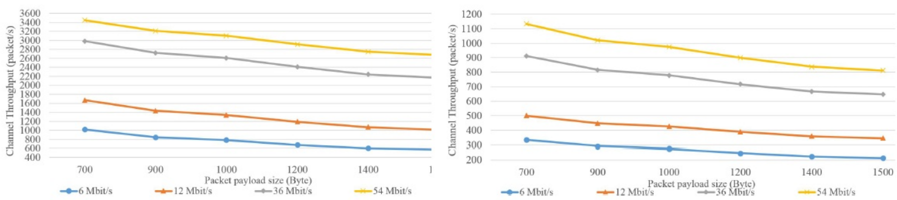


(a) Throughput of `Outers`,α=0.89. (b) Throughput of `Inner`,α=0.89.

Fig. 13: Throughput for `Outers` and `Inner` if α=0.89 in (Scenario 3)

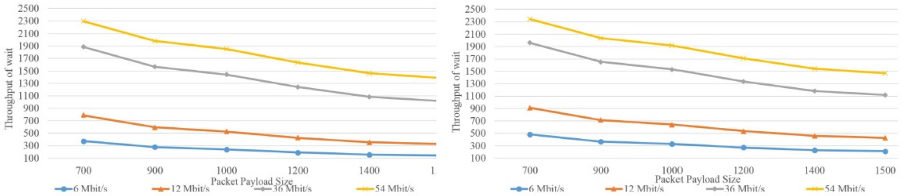
The corresponding throughput results are shown in Figures 13 and 14. We see that when $\alpha = 0.89$ and the transmission rate is 6 Mbit/s then the small advantage in utilisation when the payload is larger, leads to a significant advantage in throughput. This reversal of the pathological unfairness shows that modifying the variance can have a profound effect on the overall performance. However, this effect is limited in most cases and particularly at higher transmission rates, where the topological advantage still holds sway.

As in the previous scenario we now consider the throughput of the various wait actions in order to better understand the observed behaviour. Figure 15 shows the throughput of the *wait* action at the inner pair. The throughput of



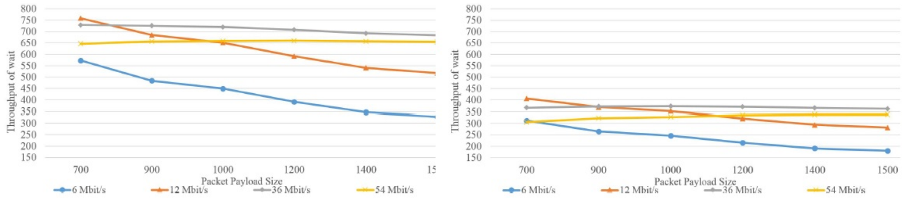
(a) Throughput of `Outers`,α=0.99. (b) Throughput of `Inner`,α=0.99.

Fig. 14: Throughput for `Outers` and `Inner` if α=0.99 in (Scenario 3)



(a) Throughput of `Wait`,α=0.89. (b) Throughput of `Wait`,α=0.99.

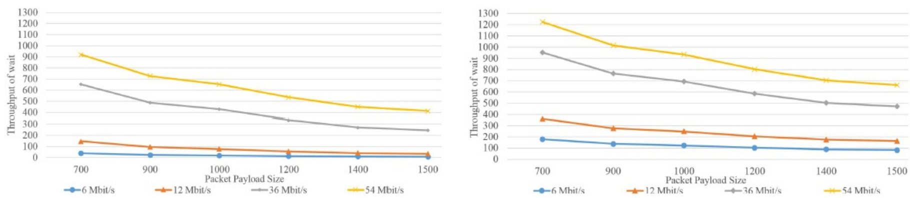
Fig. 15: Throughput of `Wait`,α=0.89 and 0.99 in (Scenario 3) in (Scenario 3)



(a) Throughput of `WaitL`,α=0.89. (b) Throughput of `WaitL`,α=0.99.

Fig. 16: Throughput of `WaitL` if α=0.89 and 0.99 in (Scenario 3)

wait at high transmission rates is hardly affected by α. However the slower transmission rates show some differences between $\alpha = 0.89$ and $\alpha = 0.99$. It is especially interesting to observe that the throughput of *wait* is very low when the transmission rate is 6 Mbit/s and α is 0.89. This clearly shows that very few transmissions are being queued. Figures 16 and 17 show the corresponding throughputs for *waitS* and *waitL* respectively, at the outer pairs. The throughput of *waitS* (Figure 17) increases significantly as α increases from 0.89 to 0.99. Furthermore we see that the throughput of *waitS* is very low when the transmission rate is 6 Mbit/s. The throughput of *waitL* (Figure 16) is substantially higher. This is not surprising given that long frames are much more likely to be



(a) Throughput of `WaitS`,α=0.89. (b) Throughput of `WaitS`,α=0.99.

Fig. 17: Throughput of `WaitS` if α=0.89 and 0.99 in (Scenario 3)

delayed under competition. Again we see that when $\alpha = 0.99$ the throughput of $waitL$ is much less than when $\alpha = 0.89$, in part due to the much lower proportion of long frames. We also observe the different profiles of the throughput of $waitL$ with different transmission rates. As in Scenario 2 we see that there is very little variation with payload when the transmission rate is high, but a decreasing profile when the transmission rate is low. This difference in behaviour is due to the interaction between the different inter-frame spaces and different frame transmission durations. The longer frames have less impact when the payload is large and transmission is slower, as all frames then take a significant length of time to transmit compared with the accumulated inter-frame spaces. However, when the transmission rate is faster or the payload is less, then the effect of variance is clearly greater.

5 Conclusion

In this paper, we analysed the performance modelling of fairness properties of the IEEE 802.11g using PEPA under heavy load. Thus we aim to derive the maximum total throughput and utilisation, but under such conditions we also demonstrate the maximum imbalance in the behaviour of the different pairs. We have introduced a hyper-exponential transmission of frames in order to study the effect of increased variance in frame length distribution. In the case where there is no competition for the medium it is clear that increased variance has no impact on the average utilisation and throughput. However, when there is competition, nodes with a higher variance experience a weaker performance as disproportionately long frames are more likely to be delayed.

The three pair scenario demonstrates a topologically unfair situation which has been previously shown to massively hinder the performance of the inner pair [2, 3, 11]. By introducing greater variance in the outer pairs not only reduced overall unfairness, but under certain conditions actually gave a slight advantage to the inner pair. These results show that controlling variance in transmission duration, as well as average duration, can have a significant impact on relative performance. A node which is severely impacted by topological unfairness might therefore attempt to decrease variance and mean by limiting frame sizes in order to increase performance.

This work forms part of an ongoing study into fairness and unfairness in wireless networks. The obvious next step is to consider more recent versions of IEEE 802.11, the most obvious candidate being IEEE 802.11n. This protocol includes a number of measures aimed at reducing the use of inter-frame spacing and consequently increasing efficiency and performance. One of those features most relevant to this work is that of so-called frame bursting, where several frames are sent by the same node in quick succession, negating the need to wait between frames to listen for other senders. Under the extreme topological conditions considered in the scenarios in this paper this may lead to nodes being treated unfairly, or conversely might allow deprived nodes a chance to send a backlog of frames. A further feature of potential interest when considering fairness is the co-existence of 802.11n with legacy systems operating 802.g, see [7] for example. The ultimate goal is clearly to consider end to end fairness in multi-hop networks with mobility [13, 14].

References

1. ISO/IEC standard for IT - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements part 11: WLAN medium access control (MAC) and physical layer (PHY) specifications (includes IEEE std 802.11, 1999 edition; IEEE std 802.11a.-1999; IEEE std 802.11b.-1999; IEEE std 802.11b.-1999/cor 1-2001; and IEEE std 802.11d.-2001). *ISO/IEC 8802-11 IEEE Std 802.11 Second edition 2005-08-01 ISO/IEC 8802 11:2005(E) IEEE Std 802.11i-2003 Edition*, pages 1–721, 2005.
2. C.O. Abdullah and N. Thomas. Formal performance modelling and analysis of IEEE 802.11 wireless LAN protocols. In *UK Performance Engineering Workshop*, 2015.
3. C.O. Abdullah and N. Thomas. Performance modelling of IEEE 802.11g wireless LAN protocols. In *Berlin 9th EAI International Conference on Performance Evaluation Methodologies and Tools*, 2015.
4. T.N.V.L. Alekhya, B. Mounika, E. Jyothi, and B.N. Bhandari. A waiting-time based backoff algorithm in the IEEE 802.11 based wireless networks. In *Communications (NCC), 2012 National Conference on*, pages 1–5, 2012.
5. C. Chou, K.G. Shin, and S.N. Shankar. Inter-frame space (IFS) based service differentiation for IEEE 802.11 wireless LANs. In *Proceedings of the 58th IEEE Vehicular Technology Conference*, volume 3, pages 1412–1416. IEEE, 2003.
6. A. Duda. Understanding the performance of 802.11 networks. In *Proceedings of the 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, volume 8, pages 1–6, 2008.
7. M. Galloway. Performance measurements of coexisting IEEE 802.11 g/n networks. In *Proceedings of the 49th Annual Southeast Regional Conference*, pages 173–178. ACM, 2011.
8. J. Hillston. *A compositional approach to performance modelling.* Cambridge University Press, 2005.
9. M.J. Ho, J. Wang, K. Shelby, and H. Haisch. IEEE 802.11g OFDM WLAN throughput performance. In *Proceedings of the 58th IEEE Vehicular Technology Conference*, volume 4, pages 2252–2256, 2003.
10. R. Khanduri, S. Rattan, and A. Uniyal. Understanding the features of IEEE 802. 11g in high data rate wireless LANs. *International Journal of Computer Applications*, 64(8), 2013.
11. L. Kloul and F. Valois. Investigating unfairness scenarios in MANET using 802.11b. In *Proceedings of the 2nd ACM international workshop on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, number 1-8, 2005.
12. K. Medepalli, P. Gopalakrishnan, D. Famolari, and T. Kodama. Voice capacity of IEEE 802.11 b, 802.11 a and 802.11 g wireless LANs. In *Global Telecommunications Conference, 2004. GLOBECOM'04. IEEE*, volume 3, pages 1549–1553, 2004.
13. O. Younes and N. Thomas. Analysis of the expected number of hops in mobile ad hoc networks with random waypoint mobility. *Electronic Notes in Theoretical Computer Science*, 275:143–158, 2011.
14. O. Younes and N. Thomas. Modelling and performance analysis of multi-hop ad hoc networks. *Simulation Modelling Practice and Theory*, 38:69–71, 2013.