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Formal Performance Modelling and Analysis of IEEE 802.11b Wireless LAN Protocols

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About the authors

Choman Othman Abdullah is a PhD student in the School of Computing Science under the supervision of Dr Nigel Thomas. He received his B.Sc. in Computer Science and Statistics in 2007 from the University of Sulaimani, Kurdistan of Iraq, and his M.Sc. in Information Technology in 2011 in the School of Computer Science at Bharati Vidyapeeth University, Pune, India. He is interested in Network and Wireless Network, Performance of Wireless with IEEE 802.11 and MANET. His main research area is Modelling and Performance Evaluation Process Algebra (PEPA) of Wireless Protocols Describing with IEEE 802.11.

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Suggested keywords

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Formal Performance Modelling and Analysis of IEEE 802.11b Wireless LAN Protocols

Choman Othman Abdullah¹,²* Nigel Thomas ²†

Abstract

The IEEE 802.11 family of protocols for wireless local area networks have been used widely for many years. In this paper we present a PEPA model for 802.11b operating under a number of scenarios which highlight different performance issues, and the channel access in terms of utilisation, throughput with fairness and unfairness are studied in this paper. In particular we study the issue of fairness when there is competition for access to the transmission channel.

Keywords. Performance analysis, IEEE 802.11b, WLAN, PEPA and Fairness.

1 Introduction

Today, many hotspots has WLAN technology, it is rapidly arise into everywhere. The similar protocols are used and applications are supported in both W-LANs and wired-LANs, both LANs are operated in the same way. In WLANs when two or more nodes are linked together, and wireless media is used as a connections between them are called Wireless Local Area Network (WLAN). Lately, in many hotspots WLAN has appeared as a widespread technology. Comfortability and movability are increased popularity of WLAN. In the past decade, the 802.11 family of protocols have been the standard for wireless local area networks [1, 10]. IEEE 802.11 is categorised as a set of protocols, such as 802.11 a/b/g/n/ac, with very similar structure, but different operating ranges (power, data rate, message length etc). These protocols are valuable to use for sharing the wireless communication medium, meanwhile, physical layer and medium access control (MAC) protocols are required for this standard. MAC layer can address several problems for instance hidden problem, accessing the channel, and movability. Nowadays, most researcher are studied on packet loss, latency, throughput or others measurements. Determining the optimum characteristics for transmission in a specific usage scenario prior to deployment, is clearly a problem of considerable practical relevance. There are many simulations techniques and packages which can be used to build or analyse models of WLAN and mobile environments. While simulations can support a detailed representation of protocol actions, the approach may suffer from excessively long run times, making parameter optimisation infeasible in general. A typical solution to this problem is to employ some form of stochastic modelling technique to create an abstract representation of the system which can solved analytically or numerically to derive measures of interest, which can then be verified using simulation as necessary. Both simulation and mathematical modelling can suffer from problems of lack of behavioural insight and lack of modelling reusability (as a new bespoke model potentially needs to be created for every new scenario). Formal modelling techniques, such as stochastic Petri nets, stochastic automata and stochastic process algebra, seek to overcome these issues by providing a high level modelling paradigm which can used to reason about the model behaviour and to derive numerical solutions to predict performance.

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Performance modelling has been employed successfully to evaluate the performance of (current and future) networking systems for many decades (see [15] for a general overview). There have been many attempts to model different aspects of IEEE 802.11 using a wide variety of methods. The majority of these studies have used simulation, which can give a good indication of predicted performance, but provide limited insight on the behaviour which leads to this performance. Formal modelling techniques, such as stochastic process algebra, allow the modeller to reason about properties of a model via explicit naming of components and actions. However, constructing large process algebra models with complicated internal component behaviour is a difficult task. Despite this there are a small number of published studies which have used process algebra to model aspects of IEEE 802.11, see [3,12,18].

The aim of this paper is to investigate the fairness of IEEE 802.11b using the stochastic process algebra PEPA [11]. The approach is based on that of Kloul and Valois [12], extended to consider additional analysis that is available now in the latest tools for PEPA and in considering additional scenarios. Initially we develop a model where there are a number of pairs of nodes, with communication within each pair. The pairs may be within signal range of each other, so must compete for access to the medium. Specifically, we studied on two pairs, three pairs, four pairs and hidden node scenario. These scenarios are used to better understand the behaviour of the protocol and to establish a baseline for further analysis. The derived performance metrics of interest include the utilisation of the medium and the throughput of each pair of nodes.

This paper is organized as follows. In Section 2 we discuss a background and related work to summarise some knowledge about IEEE 802.11 and PEPA. In Section 3, we give the model that we used in PEPA. Section 4 is for parameters and experimental set up. The results and figures with explanations are given in Section 5. Then, Section 6 is for conclusion and future works.

2 Background and Related work

2.1 IEEE 802.11

IEEE 802.11 categorised to a/b/g/n/ac and etc. Each of them has a specific performance, transmission speed and signal range, and they are a realistic standard in WLAN. Many researcher has been worked on IEEE 802.11 in term of rate adaptation scheme, performance of IEEE 802.11 MAC layer, and performance metric systems. Zhai et al. [22] attempted to characterize the probability distribution model of the MAC layer packet service time. They have argued, it has been based on deriving and creating function of the probability mass function of the inter-departure interval, but, it seems, they have worked on delay mean, throughput at several traffic loads and evaluate a performance metric systems only. In [17] explained that to access the medium for any devices the capability and fairness are most important for reaching great effectiveness in numerous wireless devices and traffics. However, other research studied on backoff algorithm on ad hoc and multi-hop ad hoc, they have been described performance and fairness concerns as a part of 802.11 MAC protocol. Razafindralambo and Valois [16] explored a symmetric hidden terminal scenario to analyse three pairs scenario for four backoff algorithms, and for understanding the performance of backoff algorithms in multi-hop ad hoc, they have evaluated the performance of each backoff algorithms from efficiency point of view and when possible from a fairness by using PEPA. However, it seems they did not consider the retry limit, reducing and increasing process for fairness performance metrics. Short-term and long-term fairness have investigated performance evaluation of WLAN protocol of fairness for accessing channel [12] for the communicating pairs in term of medium utilization and throughput. Many research are studied on basic access mechanism, specially DCF (Distributed Coordination Function), DCF with RTS/CTS (Request to Send/Clear to Send), and PCF (Point Coordination Function) (see [18] and [23] for more information). We focused on DCF protocol (CSMA/CA) to study on each scenarios in term of channel access. O.Younes and N.Thomas are studied on hidden node with IEEE 802.11 DCF MAC Protocol in Multi-Hop Ad Hoc Networks [21] by using SRN models. Moreover, the predictable number of hops in mobile ad hoc networks among any random source-destination pair in multi-hop ad hoc networks are investigated with random waypoint mobility in [20]. We considered on single hop transmission and studied on two pairs and three pairs scenarios (see our former paper [2]), also four pairs and hidden node scenarios to demonstrate performance modelling of WLAN protocols with IEEE 802.11b to better understanding the protocol behaviour.

Many simulations techniques used to analyse WLAN models. While simulations can
support a detailed representation of protocol actions, the approach may suffer from excessively long run times, making parameter optimisation infeasible in general. A typical solution to this is to employ some form of stochastic modelling technique (see for example [7,14] to create an abstract representation of the system. PEPA [11] is a compositional algebraic modelling formalism used to efficiently specify and analyse models of computer systems, multimedia applications and communication systems. According to Hillston [11], PEPA was "developed to investigate how the compositional features of process algebra might impact upon the practice of performance modelling. From a PEPA specification it is possible to analyse a module using a Continuous Time Markov Chain (CTMC), system of ordinary differential equations (ODEs) or by stochastic simulation.

Argent-Katwala et al. [3] studied on wireless network protocols and performance models of the 802.11 in term of its QoS based on PEPA. They argued that most of the technologies have been developed to enhance the reliability of computer networks. In wireless communications protocols security is mandated needs in exchanging data, which must be delivered within a specific time. Moreover, they used PEPA to find properties which it can not be easy to find manually in term of computing quantitative, passage time and increase higher probability for performance demands in wireless communication. Sridhar and Ciobanu [18] by using PA and PEPA focused on DCP within IEEE 802.11, which it uses (CSMA/CA) and backoff mechanism. They described handoff mechanism, quantitative analysis and channel mobility. Likewise, they assessed handoff mechanism and improved π-calculus with numerator in WLAN, which is data can be pass in always by allowed mediums to another one. Kloul and Valois [12] studied on performance analysis of the 802.11b protocol by using performance modelling., Particularly, they investigated unfairness scenario in MANET, as they studied on three different scenarios. Three pairs scenario is one of these scenarios. However, this scenario has been studied for the first time in [4]. In addition, they have interested on system behaviour to measure and investigate the performance of 802.11b protocol. Similarly, we have studied on three pairs scenarios, then we shows that there are uncertainty of fairness for accessing the channel for two pairs and unfairness for three pairs scenario in term of medium utilization and throughput.

The effect of overhead bits, backoff times to occupy the medium, the arrangement of the data being sent and the numbers of nodes in a specific hotspots are effective to analyse the WLAN performance. Markovian process algebra Performance Evaluation Process Algebra (PEPA) [11] will be used to specify and analyse models of IEEE 802.11b [8]. We are focused on backoff algorithm as a part of the MAC protocol and a mechanism that have been used to avoid collisions. Additionally, during collision and before the node retransmitting to access the channel, the node will be wait for a short of time (backoff) which is a good technique in basic access mechanism (see [13] and [5]). In dissimilar scenarios number of nodes are effecting the system performance, throughput and utilisation in the IEEE 802.11 WLAN, once node increases, the collision increases too, the channel utilization rate decline, the total throughput and utilisation will rise down [8]. Based on PEPA and by using stochastic process algebra, this research will study on modelling and analysis the performance of IEEE 802.11 protocols and to develop a set of PEPA models to study the different behaviours. Accordingly, we might be better understanding of the potential of formal modelling in the evaluation of wireless network protocols, and extend the set of techniques available to network analysis in each scenario.

Finally, Duda [6] has argued that the issue of unfairness, as highlighted in the above research, is a consequence of the manner in which 802.11b was implemented on early switches and that modifications made to later switches alleviate this problem. However, this does not seem to have been shown empirically by any researchers. By implementing a model which shows unfairness as reported by Kloul and Valois [12] and then modifying this as described by Duda [6], it will be possible to further investigate this claim.

In the current paper we study 802.11b in term of channel access, by using PEPA with dissimilar scenarios.

### 3 The model

#### 3.1 Basic access mechanism

Basic access mechanism (BSA) is important in wireless system. In any WLAN to access the medium the node initially listens to the channel, to make sure that the channel is free to send. When the medium is free to use with no congestion, the node can make a transaction successfully. Moreover, when collision occur and in case of unsuccessful transition, the node...
is waiting for random time (backoff) in the range \([0, \text{CW}]\), where, \(\text{CW}\) is the contention window. \(\text{CW}_{\text{min}}\) is \([31]\), and it doubles up to the \(\text{CW}_{\text{max}}\) \([1023]\), under 802.11b (see \([6, 9]\)). \(\text{CW}\) can return to the initial value after each successful transmission. If two nodes transmit simultaneously, then a collision occurs. When collisions are detected the transmitting nodes will backoff before attempting to retransmit. Furthermore, in 802.11b after each frame transmission, in case of collision, the Inter-Frame Space (IFS) is applied. The minimum fixed and shortest interval of time is called Short-IFS (10µs). Distributed-IFS (50µs) when the channel is idle, and the packet is communicated if the backoff is equal to zero. After the node notices a transmission and if the channel is free to use, the backoff decreases. Finally, the decrementation starts again through a DIFS, while the channel stays as an idle. Nevertheless, before sending next frame, instead of DIFS an Extended-IFS (364µs) will apply, whenever, the node notices a signal for the duration of the backoff. Also, when the transmission positively completed, the receiver sends an ACK after SIFS. Figure 1 shows basic access mechanism, and Table 1 typical values of the IEEE 802.11b protocol.

![Figure 1: RTC-CTS and Data-ACK scheme.](image)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CW}<em>{\text{min}}, \text{CW}</em>{\text{max}})</td>
<td>31, and 1023</td>
</tr>
<tr>
<td>Slot time</td>
<td>20µs</td>
</tr>
<tr>
<td>SIFS</td>
<td>10µs</td>
</tr>
<tr>
<td>DIFS</td>
<td>50µs</td>
</tr>
<tr>
<td>EIFS</td>
<td>364µs</td>
</tr>
</tbody>
</table>

Table 1: Attribute values of IEEE 802.11b protocol.

### 3.2 Scenarios with a PEPA

#### 3.2.1 The two pairs scenario (scenario 1)

In our research we started with a two pairs scenario see Figure 2, and Figure 3 shows three pairs scenario. Essentially, in two pairs scenario (A and B) has been used as two symmetric and independent node pairs. Once one node attempts to transmit, the other one in the pair waits to receive.

The model in the scenario 1 is interacting between three components (Pair A, Pair B, and Medium F). Pair A and Pair B are equally occupying the medium (Medium F). During sending the packet Pair A draw backoff to Pair A0, then Pair A0 starts to count the DIFS to Pair A1 or stay in the queue with Pair A5, and Pair A5 it waits with Pair A4. Similarly, all SIFS and EIFS will count till the backoff end, then the packet can transmit in Pair A2 then successfully will ACK in Pair A6.
Sequential Component Process of Pair A and Pair B component.

Pair\_A \triangleq (draw\_backoff, r).Pair\_A0
Pair\_A0 \triangleq (count\_difs, \mu\_difs).Pair\_A1+(queue, T).Pair\_A5
Pair\_A1 \triangleq (count\_backoff, \mu\_bck).Pair\_A1+(end\_backoff, \mu\_bck).Pair\_A2+(queue, T).Pair\_A5
Pair\_A2 \triangleq (transmit, \mu\_data).Pair\_A3+(queue, T).Pair\_A5
Pair\_A3 \triangleq (count\_sifs, \mu\_sifs).Pair\_A6
Pair\_A4 \triangleq (count\_difs, \mu\_difs).Pair\_A1+(count\_eifs, \mu\_eifs).Pair\_A1+(queue, T).Pair\_A5
Pair\_A5 \triangleq (wait, \mu\_data).Pair\_A4
Pair\_A6 \triangleq (ack, \mu\_ack).Pair\_A
Pair\_B \triangleq (draw\_backoff, r).Pair\_B0
Pair\_B0 \triangleq (count\_difsB, \mu\_difsB).Pair\_B1+(queueB, T).Pair\_B5
Pair\_B2 \triangleq (transmitB, \mu\_data).Pair\_B3+(queueB, T).Pair\_B5
Pair\_B3 \triangleq (count\_sifsB, \mu\_sifsB).Pair\_A6
Pair\_B5 \triangleq (wait, \mu\_data).Pair\_B4
Pair\_B6 \triangleq (ackB, \mu\_ackB).Pair\_B

The complete system: The shared medium is cooperated with by both pairs equally. If the first one starts to use the medium then the second one stops trying to transmit and versa. All components are interacting with this cooperation sets:

\[
\text{scenario} \triangleq ((\text{Pair}\_A \boxtimes \text{Medium}_F) \boxtimes \text{Pair}\_B)
\]

where \( K = \{\text{transmit}, \text{ack}, \text{queue}, \text{count\_difs}, \text{count\_backoff}, \text{end\_backoff}, \text{count\_eifs}\} \).
\( L = \{\text{transmit}, \text{ackB}, \text{queueB}, \text{count\_difsB}, \text{count\_backoffB}, \text{end\_backoffB}, \text{count\_eifsB}\} \).
Component of Medium F:

\[\text{Medium}_F \equiv (\text{transmit}, \top).\text{Medium}_{F2} + (\text{transmitB, } \top).\text{Medium}_{F1} + (\text{count\_difs}, \top).\text{Medium}_F + (\text{count\_backoff}, \top).\text{Medium}_F + (\text{end\_backoff}, \top).\text{Medium}_F + (\text{count\_eifs}, \top).\text{Medium}_F + (\text{count\_difsB}, \top).\text{Medium}_F + (\text{count\_backoffB, } \top).\text{Medium}_F + (\text{end\_backoffB}, \top).\text{Medium}_F + (\text{count\_eifsB}, \top).\text{Medium}_F\]

\[\text{Medium}_{F1} \equiv (\text{ackB, } \top).\text{Medium}_F + (\text{queue}, \lambda_{\text{oc}}).\text{Medium}_F\]

\[\text{Medium}_{F2} \equiv (\text{transmit}, \top).\text{Medium}_{F3} + (\text{ack, } \top).\text{Medium}_F + (\text{queueB, } \lambda_{\text{oc}}).\text{Medium}_{F2} + (\text{count\_difs}, \top).\text{Medium}_F + (\text{count\_backoff}, \top).\text{Medium}_{F2} + (\text{end\_backoff}, \top).\text{Medium}_{F2} + (\text{count\_eifs}, \top).\text{Medium}_{F2}\]

\[\text{Medium}_{F3} \equiv (\text{ack, } \top).\text{Medium}_{F2} + (\text{queueB, } \lambda_{\text{oc}}).\text{Medium}_F + (\text{count\_difs, } \top).\text{Medium}_{F3} + (\text{count\_backoff}, \top).\text{Medium}_{F3} + (\text{end\_backoff}, \top).\text{Medium}_{F3} + (\text{count\_eifs, } \top).\text{Medium}_{F3}\]

3.2.2 The three pairs scenario (scenario 2)

(Pairs A, B and C and the medium) are denoted by Pair_A, Pair_B, Pair_C, and Medium_F respectively in this scenario. A and C are symmetric as two externals. The externals cannot hear each other as they lie outside each others transmission range, but the central can hear both of them. If one of the external is transmitting then the central cannot; it is queuing till the channel is free to use. However, the second external cannot see the busy channel and so both the externals may transmit simultaneously. Thus, the central pair has less chance to access the medium and hence this scenario is called the unfairness scenario. Moreover, the central one has been unfairly disadvantaged as it is been out competed by externals.

PEPA model: In this model all pairs are collaborated with a medium. Either the medium is occupied by any external or central pairs.

Sequential Component Process Pair A/C Component (Externals)

\[\text{Pair}_A \equiv (\text{draw\_backoff, } r).\text{Pair}_A\]
\[\text{Pair}_0 \equiv (\text{count\_difs, } \mu_{\text{difs}}).\text{Pair}_1 + (\text{queue, } \top).\text{Pair}_A\]
\[\text{Pair}_1 \equiv (\text{count\_backoff, } \mu_{\text{backoff}}).\text{Pair}_1 + (\text{end\_backoff, } \mu_{\text{backoff}}).\text{Pair}_A\]
\[\text{Pair}_2 \equiv (\text{transmit, } \mu_{\text{data}}).\text{Pair}_2 + (\text{queue, } \top).\text{Pair}_A\]
\[\text{Pair}_3 \equiv (\text{count\_eifs, } \mu_{\text{eifs}}).\text{Pair}_A\]
\[\text{Pair}_4 \equiv (\text{count\_difs, } \mu_{\text{difs}}).\text{Pair}_4 + (\text{queue, } \top).\text{Pair}_A\]
\[\text{Pair}_5 \equiv (\text{ack, } \mu_{\text{ack}}).\text{Pair}_A\]
\[\text{Pair}_6 \equiv (\text{draw\_backoff, } r).\text{Pair}_B\]
\[\text{Pair}_7 \equiv (\text{count\_difsB, } \mu_{\text{difsB}}).\text{Pair}_1 + (\text{queueB, } \top).\text{Pair}_B\]
\[\text{Pair}_8 \equiv (\text{count\_backoffB, } \mu_{\text{backoffB}}).\text{Pair}_1 + (\text{end\_backoffB, } \mu_{\text{backoffB}}).\text{Pair}_B\]
\[\text{Pair}_9 \equiv (\text{transmitB, } \mu_{\text{data}}).\text{Pair}_9 + (\text{queueB, } \top).\text{Pair}_B\]
\[\text{Pair}_{10} \equiv (\text{count\_eifsB, } \mu_{\text{eifsB}}).\text{Pair}_A\]
\[\text{Pair}_{11} \equiv (\text{count\_difsB, } \mu_{\text{difsB}}).\text{Pair}_{11} + (\text{queueB, } \top).\text{Pair}_B\]
\[\text{Pair}_{12} \equiv (\text{wait, } \mu_{\text{data}}).\text{Pair}_{12}\]
\[\text{Pair}_{13} \equiv (\text{ack, } \mu_{\text{ack}}).\text{Pair}_B\]

The complete system: This section shows how this model can communication. Component A can communicate with B through the medium F, but both external pairs cannot interact with each other; this symbol || shows that, here is the cooperation sets that are defined as:

\[\text{scenario2} \equiv ((\text{Pair}_A || \text{Pair}_C) \bowtie K \text{Medium}_F) \bowtie \text{Pair}_B\]

where \( K = \{\text{transmit, ack, queue, count\_difs, count\_backoff, end\_backoff, count\_eifs}\}\) and \( L = \{\text{transmit, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB}\}\).
Component of Medium $F$:

$Medium_F \overset{def}{=} (\text{transmit}, T).Medium_F + (\text{transmitB}, T).Medium_F$

$+ (\text{count_difs}, T).Medium_F + (\text{count_backoff}, T).Medium_F$

$+ (\text{end_backoff}, T).Medium_F + (\text{count_eifs}, T).Medium_F$

$+ (\text{count_difsB}, T).Medium_F + (\text{count_backoffB}, T).Medium_F$

$+ (\text{end_backoffB}, T).Medium_F + (\text{count_eifsB}, T).Medium_F$

$Medium_F1 \overset{def}{=} (\text{ackB}, T).Medium_F + (\text{queue}, \lambda_{oc}).Medium_F$

$Medium_F2 \overset{def}{=} (\text{transmit}, T).Medium_F3 + (\text{ack}, T).Medium_F$

$+ (\text{queueB}, \lambda_{oc}).Medium_F3 + (\text{ack}, T).Medium_F2$

$+ (\text{count_backoff}, T).Medium_F2 + (\text{end_backoff}, T).Medium_F2$

$+ (\text{count_eifs}, T).Medium_F2$

$Medium_F3 \overset{def}{=} (\text{ack}, T).Medium_F2 + (\text{queueB}, \lambda_{oc}).Medium_F3$

$+ (\text{count_difs}, T).Medium_F3 + (\text{count_backoff}, T).Medium_F3$

$+ (\text{end_backoff}, T).Medium_F3 + (\text{count_eifs}, T).Medium_F3$

3.2.3 The four nodes scenario (scenario 3)

Essentially, the four pairs scenario has two central pairs and two external pairs Figure 5. Basically, there are five main components, which are (pair A, pair B, pair C and pair D) and medium, as a matter of fact (pair A) and (pair D) are external, independent and symmetric pairs. And, (pair B and pair C) are central pairs, see the PEPA model for more information. If (pair A and pair D) are transmitting then (pair B and pair C) are blocked, and if (pair B and pair D) are transmitting then (pair A and pair C) are blocked, similarly if (pair A and pair C) are transmitting then (pair B and pair D) are blocked. Here, we can understand that the both central pairs has less chance to access the medium rather than the external pairs. Pair C is not a complete fair, because pair A and pair C are penalized, in the same time it is not penalized like the three node scenario, the reason for that, if pair A is transmitting then the pair C still has a chance to access the channel. Similarly, if pair D is transmitting then pair B has a chance to access the channel too. By this approach the other different scenario is not reasonably fair such as three pairs scenario. Finally, the four pairs scenario is better that the three pairs scenario.

**PEPA model of four pairs scenario:** The medium has collaborate with external and central pairs as they are symmetric. Either it is occupied by any external or central pairs. Component $Pair_A/Pair_D$ and $Pair_B$. See the sequential component process of pair A/C (externals pairs), and the sequential component process of central pair.

**Note:** All (B, C and D) pairs are the same as Pair A.
Medium_F ≡ (transmitA, T).Medium_A
+ (transmitB, T).Medium_B
+ (transmitC, T).Medium_C
+ (transmitD, T).Medium_D
+ (countifsA, T).Medium_A
+ (countifsB, T).Medium_B
+ (countifsC, T).Medium_C
+ (countifsD, T).Medium_D
+ (endackoffA, T).Medium_A
+ (endackoffB, T).Medium_B
+ (endackoffC, T).Medium_C
+ (endackoffD, T).Medium_D
+ (lambdaoc).Medium_A

Medium_A ≡ (transmitC, T).Medium_AC
+ (transmitD, T).Medium_AD
+ (ackA, T).Medium_F
+ (queueB, lambdaoc).Medium_A

Medium_D ≡ (transmitA, T).Medium_AD
+ (transmitB, T).Medium_BD
+ (ackD, T).Medium_F
+ (queueC, lambdaoc).Medium_D

Medium_B ≡ (transmitD, T).Medium_BD
+ (ackB, T).Medium_F
+ (ackC, T).Medium_C
+ (queueD, lambdaoc).Medium_C

Medium_C ≡ (ackA, T).Medium_D
+ (ackD, T).Medium_A
+ (queueB, lambdaoc).Medium_AD
+ (queueC, lambdaoc).Medium_AD

Medium_AD ≡ (ackB, T).Medium_D
+ (ackD, T).Medium_B
+ (queueA, lambdaoc).Medium_BD
+ (queueC, lambdaoc).Medium_BD

Medium_BD ≡ (ackA, T).Medium_C
+ (ackC, T).Medium_A
+ (queueB, lambdaoc).Medium_AC
+ (queueC, lambdaoc).Medium_AC

The complete system: The model can communicate between all components. Component A can communicate with B through the medium F, but both external pairs cannot interact with each other, this symbol || shows that, this scenario is cooperated between all components that are defined as:

\[ \text{Stc.2 \equiv (Pair_A || Pair_B || Pair_C || Pair_D) \Delta \{ Mediums \} } \]

where \( L = \{ \text{transmitA, ackA, queueA, countifsA, countackoffA, endackoffA, countifsA, transmitB} \)
\( , \text{ackB, queueB, countifsB, countackoffB, endackoffB, countifsB, transmitC, ackC, queueC, countifsC} \)
\( , \text{countackoffC, endackoffC, countifsC, transmitD, ackD, queueD, countifsD, countackoffD, endackoffD} \)
\( , \text{countifsD} \)
3.2.4 The hidden nodes scenario (scenario 4)

This scenario has pair A, pair B [both are similar], and the medium component as they are denoted by Pair_A, Pair_B and Med_S respectively. This scenario is not free of collision and it will be happened when each pairs want to transmit at the same time. Whilst the first node is "listening" on the network it can access the channel as it is free to send any packets for the second one at the same time, meanwhile, the second one cannot hear the first one and it look like the channel is free to use. From the Figure 4 it shows that both Pair_A1 and Pair_B1, Pair_A2 and Pair_B2 and Pair_A3 are independent respectively. Generally, when Pair_A is attempting to transmit and access the medium, the Pair_B are hidden from it, so Pair_A cannot receive acknowledgement, in this situation Pair_A start to retransmitting the packets after resizing the CW. When collision are occur and Pair_A waits or resize the CW for a period of time in case if the channel are busy till it is free to use. From this point of view this scenario is called the unfairness scenario to access the channel. Component A and B:

Both (Pair_A) and (Pair_B) are similar and we are shown only A in this paper.

\[
\begin{align*}
Pair_A & \\
& \equiv (\text{draw,ackoff}, r).Pair_A0 \\
Pair_A0 & \\
& \equiv (\text{count,ifs, modifs}).Pair_A1 \\
Pair_A1 & \\
& \equiv (\text{count,ackoff, pmubck}).Pair_A1 \ \\
& + (\text{end,ackoff, qmubck}).Pair_A2 \\
Pair_A2 & \\
& \equiv (\text{transmit, modata}).Pair_A3 \\
Pair_A3 & \\
& \equiv (\text{count,ifs, musifs}).Pair_A6 \\
Pair_A6 & \\
& \equiv (\text{ack, muack}).Pair_A \ \\
& + (\text{collision, T}).(\text{resize}, W, s).Pair_A
\end{align*}
\]

Component (Med_S) is totally used by pair A and pair B, either it is occupied by both then collision are occur. Additionally, each pairs are hidden from the other that is why the medium is not totally share.

\[
\begin{align*}
Med_S & \equiv (\text{transmit, T}).Med_S1 + (\text{transmitB, T}).Med_S2 \\
Med_S1 & \equiv (\text{ack, T}).Med_S + (\text{transmitB, T}).Med_S3 \\
Med_S2 & \equiv (\text{transmit, T}).Med_S + (\text{ackB, T}).Med_S \\
Med_S3 & \equiv (\text{collision, re}).Med_S
\end{align*}
\]

The complete system: The total share medium is cooperated with both pairs equally. If the first one starts to use it then the second one stops to transmit and vice versa. All components are interacting with this cooperation sets:

When the value of \(K = \{\text{collision}\}\) and \(L = \{\text{transmit, ack, transmitB, ackB, collision}\}\)

\[\text{Sce.} 1 \equiv (\text{Pair}_A \Box_K \text{Pair}_B) \Box_L \text{Medium}_S\]

4 Parameters

We have used 0.5 as a probability values of \(p\) and \(q\) as an assumption \((q = 1 - p)\). The values of \(\lambda_{\text{in}}\) and \(r\) are 100000 and 200000 respectively; these are the same values that have been used in [12]. According to the IEEE 802.11b definition and PHY standards, the data rate per stream are \((1, 2, 5.5, \text{ and } 11) \text{ Mbit/s } [19]\), equal to \((125000, 250000, 687500 \text{ and } 1375000) \text{ Bytes/s} \) respectively. We have applied these rates with packet payload size \((700, 900, 1000, 1200, 1400 \text{ and } 1500) \text{ Bytes}\). And, the packets per time unit for arrival and departure rate are \((\lambda \text{ and } \mu)\) respectively. In this model \(\mu_{\text{ack}}\) is the rate of \(ACK\) of packets, \(\mu_{\text{ack}} = \text{Channel throughput}/(\text{Ack length}=1\text{Byte})\). Also, \(\mu_{\text{data}}\) is a rate of waiting action for packages, as it is calculated by channel throughput \(\div\) Packet payload, after multiplying with \(10^{-6}\) it changes to Bytes per second. WLAN is used the CSMA/CA for collision avoidance, it is crucially used for performance improvement and precisely for sharing the medium equally. It is using three main techniques \((\text{IFS, CW and ACK})\).
4.1 Inter-Frame Space (IFS)

802.11 is a fundamentally giant system of timers. Afterward each frame transmission on the medium, if nosiness are occur, the require Inter-Frame Space (IFS) is used in 802.11 protocol. Possibly, when transmitting of any particular frame ends then another one starts the IFS can apply as smallest number when the channel have to stay clear. It is an idle and essential period of time. The main crucial of an IFS is to supply waiting time during each frame transmission in a particular node, then, it allows the transmitted signal to another node. 802.11 protocol has deal with SIFS, DIFS, EIFS and Slot time, see [5,6].

4.1.1 Short Inter-Frame Space (SIFS)

SIFS is the minimum Inter-Frame time and highest priority transmissions used with DCF. It is a fixed and shortest value, and it is measured by micro seconds. SIFS is an important in 802.11 to better process a received frame. It is equal to 10µs in 802.11b/g/n.

4.1.2 DCF Inter-Frame Space (DIFS)

DIFS is a medium priority waiting time after SIFS to monitor the medium. If the channel is idle again, the node is practicing DIFS. Usually the DIFS is longer than SIFS, after the node defer the idle of the channel for a specific of time (DIFS) then it waits for another period of time (backoff).

\[
DIFS = SIFS + (2 \times (\text{Slot time} = 20 \mu s \text{ in 802.11b/g/n})).
\]

4.1.3 Extended Inter-Frame Space (EIFS)

When the node can detect the signal but the DIFS is not functioning for sending nextframe during collision, the transmission node is using EIFS instead of DIFS. It is the longest of the IFS, but, it is lowest priority after DIFS. EIFS (in DCF) can derive by:

\[
\text{EIFS} = \text{SIFS} + \text{DIFS} + \text{transmission time of Ack frame at lowest basic rate}.
\]

4.2 Contention Window (CW)

After a node has experimental an idle channel with appropriate IFS, the node is waiting because of any collisions. Before sending any frame the node waits randomly. In CSMA/CA it is called backoff, it is selected by node from a Contention Window (CW). Faster backoff needs less time to spend, then transmission will be faster too. Backoff is chosen over \([0, CW]\), and \(CW = CW_{min}\) for all station or nodes if a node successfully transmits a packet and then receives an ACK. But in the case of not transmitted successfully, the node is dealing another (backoff), then the CW size is increased exponentially till it is obtained to the CWmax. Finally, the CW is reset to CWmin when the packet is received properly. CW and backoff can shows as follows:

\[
\text{CW}_{min} = 31, \text{CW}_{max} = 1023. \text{ And } CW_{min} \text{ augmented by } 2n-1 \text{ on each retry}
\]

\[
\text{Backoff Time} = (\text{Random} () \mod (\text{CW+1})) \times \text{Slot Time}.
\]

If \(\text{Backoff Time} = b\), when \(b\) is a random integer, also \(CW_{min} < b < CW_{max}\)

We have used the mean of CW to calculate \(\mu_{bck}\) by \(-10^{-6}/\text{Mean of CW} \times \text{Time Slot}\)

4.3 Data Rates and ACK

ACK send by receiver when it gets the packet successfully, it is precautions action when collisions occur. ACK in 802.11b protocol is deal with data rate \((1, 2, 5.5, \text{ and } 11)\) Mbit/s, each \(\mu_{ack}\) is equal to \((1644.74, 3289.5, 9046.125 \text{ and } 18092.25)\) Bytes/s respectively. Then, \(\mu_{data}\) can obtain for each of them by \(\mu_{ack} \times \text{packet payload size}\).
5 Results and Figures

5.1 Performance results of the two pairs scenario (scenario 1)

After we have run PEPA to analyse 802.11b performance, we have obtained different results. We have used \((r, \lambda_{oc}, \mu_{difs}, \mu_{sifs}, \mu_{eifs})\) \((200000, 100000, 20000, 100000, 2747.3)\) respectively, to measure the utilisation and throughput, and to better understand the model behaviour. The given formula for the channel utilisation:

\[
\text{Channel utilisation} = P(\text{Medium}_F \land (\text{Pair}_A \lor \text{Pair}_B)) + P(\text{Medium}_F1) + P(\text{Medium}_F2)
\]

Figure 6 shows the channel utilization rate increases if the packet payload size increases, for the data rate \((1, 2, 5.5, \text{and } 11)\) Mbit/s. Because the occupied channel time increases as the packet payload size increases. In 11Mbit/s the packet can send faster for actual rate transmission. Hence, we can see the channel utilization rate in (1Mbit/s) is increasing while the packet payload size is increasing for the same speed and similarly, it is the same for all speeds, accordingly we can see that the actual transmission rate will faster. Likewise, the probability transmission for the channel utilisation increases once the packet payload size increases also, see the Figure 7. However, the channel throughput decrease when the packet payload size increase, this is because the channel occupancy time always is increasing with increasing the packet payload size from 700 -1500 bytes, see the Figure 8. Finally, in throughput if we have faster backoff, we need less time to transmit. Which means we will get faster transition in fewer time. If, the backoff ends successfully, then the medium can use equally by each A and B for transmitting data, formally the sender receives an ACK.

![Figure 6](image6.png)

![Figure 7](image7.png)

Figure 6: Channel utilization rate for the two pairs scenario (scenario 1).

Figure 7: Probability transmission for the channel utilization (scenario 1).

In this scenario, the obtained results of each pairs are equal as they are symmetric. They are equally occupying the channel. Figure 9 is shown the channel utilisation for pair A (it is similar for pair B), for each speed it is increasing when the packet payload size increases, for the data rate \((1, 2, 5.5, \text{and } 11)\) Mbit/s. Because the occupied channel time increases as the packet payload size increases. In 11Mbit/s the packet can send faster for actual rate transmission. Hence, we can see the channel utilization rate in (1Mbit/s) is increasing while the packet payload size is increasing for the same speed and similarly, it is the same for all speeds, accordingly we can see that the actual transmission rate will faster. Likewise, the probability transmission for the channel utilisation increases once the packet payload size increases also, see the Figure 7. However, the channel throughput decrease when the packet payload size increase, this is because the channel occupancy time always is increasing with increasing the packet payload size from 700 -1500 bytes, see the Figure 8. Finally, in throughput if we have faster backoff, we need less time to transmit. Which means we will get faster transition in fewer time. If, the backoff ends successfully, then the medium can use equally by each A and B for transmitting data, formally the sender receives an ACK.
size is increasing, as a channel occupancy time is increasing too. Hence, each pair can access the medium equally. Finally, we can call this scenario as a fairness scenario.

5.2 Performance results of the three pairs scenario (scenario 2)

The three pairs scenario is another scenario to demonstrate effects of unfairness. In this system both external pairs (A/C) are fully independent. And they are using the channel equally. But, the behaviour of the central pair (B) are not the same as external pairs. The rate declarations and parameters in this scenario are the same as previews scenario. Finally, measuring the probability of transmit of this model has calculated by this formula:

\[
\text{Probability of transmission} = \Pr[\text{Medium}_F \text{ and (Pair}_A^2, \text{Pair}_B^2 \text{ or Pair}_C^2)]
\]

Firstly, we have studied on the probability of transmission. It is equal to 78% for 1Mbit/s then acknowledge it, also it is increasing by increasing the packet payload size. But the probability of transmission decreases for (1, 2, 5.5, and 11) Mbit/s respectively. It seems the all pairs are compete to access the medium, see the Figure 10. Additionally, we have studied on the channel utilisation for externals, it increases if the packet payload size increases. As long as both External pairs are transmitting at the same time without collision. This is caused by the channel use time increasing, because of the packet size is increasing at the same time, they can occupy the channel equally as two symmetric pairs. See the given formula and the obtained results in Figure 11.
Channel utilisation = Total utilisation × Throughput A / Total throughput (AckA and AckB)

Moreover, the channel utilisation of the central is similar to externals, but, it is much lower than the externals, because of the central has very limited to access the channel, most time the channel is occupied by the externals, see the Figure 12. Channel utilisation = Total utilisation × Throughput B / Total throughput (AckA and AckB)

As the channel utilisation rate increase we understand that the unfairness unusual, so for fastest transmit we need to increase the packet size or transmit at lower throughput.

Finally, the channel throughput decreases as the packet payload size increases. But, it is not like the channel utilisation rates, because the channel occupancy time. The fastest channel in transmitting packet will occupy less time in this channel, Figure 13 shows externals and Figure 14 central. However, accessing the channel by the central pair is limited compare to the external pairs. In term of throughput, this scenario is unfairness and it is not significant for all pairs. Clearly, the central pair is out competed by others and it is unfairly disadvantaged but the external one is fairly advantaged.

5.3 Results of the four nodes scenario (scenario 3)

In the four nodes scenario we have studied on probability of transmission see Figure 15. In this model the probability of transmission for 1Mbit/s is 72% then ACK it, also it is increasing when the packet payload size is increasing too, but the probability of transmission decreases by increase the speed of transmission from (1, 2, 5.5, 11) Mbit/s respectively. It seems that the all pairs are compete to access the medium.
Probability of transmission = \( Pr[\text{Medium}_F \land (\text{Pair}_A2 \lor \text{Pair}_B2 \lor \text{Pair}_C2 \lor \text{Pair}_D2)] \)

Also, we have studied on external pairs (A2D2) and the central pairs (B2C2) for the channel utilisation, we calculated the total utilisation for all pairs, see Figure 16. The total utilisation rate increases as the packet payload size increases too, this is because of the duration of occupant the channel is increasing for pair A and D, and they can occupy the channel.

Channel utilisation = Summation of channel utilisation + (1-P [Medium]).

The total channel utilisation rate in four pairs scenario is less than the other scenar-
ios. In four pairs case the channel utilisation easily cannot calculate similar others like (three pairs), because of one of the central and one of the external pair are transmitting at the same time. The better way to analyse it, is calculate the channel utilisation for external and central pairs separately as it is shown in next section. It shows how much time are used in the medium by each central and external pairs fairly.

Furthermore, we have used the following formula for measuring the utilisation for the external pairs in this scenario, and the obtained results are shown in the Figure 17. The channel utilisation for external pair is the same as the total channel utilisation, this rate is increasing when the packet payload size is increasing too, and it is the same for the second external pair, because they are symmetric. The Figure 17 is shown the value of first external pair, accordingly, the external pairs are occupied the channel equally, also when external pairs are communicated the central pairs are congested. Correspondingly, we calculated the channel utilisation for central pairs separately to better understand the way to access the channel as can be seen in the next section.

Channel utilisation (External pairs) = Total Utilisation * Throughput A / Total Throughput (AckA, AckB, AckC and AckD)

Here, both external pairs and the central pairs are occupied the channel equally as they are symmetric.

We studied on channel utilisation for central too, channel utilisation for central pairs increases as the packet payload size increases too. Each central pair has very limited to access the medium, most time the medium is occupied by the external pairs. In this
scenario (four pairs scenario) the two central pairs (B and C) are used the channel in the same time, moreover, each of them can hear each other and the external neighbour. In this case the rate of central utilisation decrease than the external utilisation rate. Also, it is calculated by this formula, and see the Figure 18:

\[
\text{Channel utilisation (central pairs) = Total Utilisation * Throughput B / Total Throughput (AckA, AckB, AckC and AckD).}
\]

In the four pairs scenario the channel utilisation rate for each pair is more significant compared to the three pairs scenario.

Finally channel throughput in (Sc.2) decreases if the packet payload size increases, compare it to the three node case it is lower, because of the channel occupancy time channel throughput is not similar for the channel utilisation rate for both external and central pairs. Which means the fastest channel in transmitting packet will occupy less time in this channel. Figure 19 and 20 are shown the channel throughput for external and channel throughput for central perspective, it decreases when packet payload size increases, and it is lower if we compare to the external throughput. In term of throughput in this scenario we can see this is unfairness and it is not significant for all pairs. The central pair is out computed by others and it is unfairly disadvantageous, but the external one is fairly advantageous.

Figure 17: Channel utilisation rate for external pairs (scenario 3).

5.4 Results of the hidden node scenario (scenario 4)

Through studying on this scenario we can show the result of unfairness on each of the medium utilisation and throughput. For measuring the utilisation, throughput and collision of this model in this scenario we have used the above parameters and the given formula, firstly it is shown the channel utilisation rate for both pairs:

\[
\text{Channel utilisation = } P[\text{Med}_S \land (A2 \lor B2)] + P[\text{Med}_S1] + P[\text{Med}_S2] + P[\text{Med}_S3].
\]
After running the PEPA, we obtained the channel utilisation rate as it is shown in Figure 21. The channel utilization rate for Pair A and B increases if the packet payload size increases too, for the data rate [1, 2, 5.5, and 11] Mbit/s. The cause of this increase, it seems that the first pair is spent most of the time for transmitting and the sender node spent most of the time for retransmitting this is generally because of collisions that occur in this scenario. Always the sender seems that the channel is free to use, but in the real it might be used by the other one. Moreover, in the hidden node scenario all pairs cannot hear each other, which is why they cannot acknowledge.
According to Figure 22, we can understand that the channel utilisation rate for Pair A are increasing when as the packet payload size are increasing too. Moreover, channel utilisation rate is quite similar for Pair B. The channel utilisation rate for pair A and B are equal to the total utilisation in the preview figure.

![Figure 22: Channel utilization rate for pair A (scenario 4).](image)

Moreover, we have studied on probability transmission for each pairs (A and B), see Figure 23, as it is obtained by the given formula: Channel utilisation = \( P[\text{Medium}_S \land (\text{Pair\_A2 or Pair\_B2})] \).

![Figure 23: Probability transmission of (A and B) (scenario 4).](image)

From Figure 23 we can see that the probability of transmission of A and B increases when the packet payload size increases during collisions. However, the channel
throughput for A and B decreases as the packet payload size increases, see the Figure 24. Each pairs is trying to occupy the channel, in the same time they are hidden from each other. In the hidden nodes scenario ACK cannot receive successfully during the transmission, that is why the sender node retransmit the messages till receive the acknowledgement. Hence, each pair cannot access the medium equally.

Moreover, in this scenario the probability of medium sharing between A and B decreases once the packet payload size increase too. See the Figure 25. This is because of the same reason which is explained for channel throughput in Figure 24. The given formula has used: \( P[(\text{Medium}_S \land \text{Pair}_A) \lor (\text{Medium}_S \land \text{Pair}_A)] \).

Figure 25: Medium sharing of hidden node scenario (scenario 4).

Figure 26: Collision of transmission (scenario 4).

The Figure 26 shows the collision of transmission rate in (Sec.1). In our experiment the rate of collision are decreases as the packet payload size increases. In addition, it is the same for the probability of collision, for instance it is about 17% for 1 Mbit/s. In both Figures 26 and 27 the bigger packet need less time to transmit and it is spent less time in the medium, which means decrease the collisions. Generally, each pairs want to transmit at the same of time but they cannot hear each other’s, because of collision phenomenon they cannot acknowledge properly.
6 Conclusion

WLAN is commonly used by users around the world, and easily installation support users to make a connection between two or more nodes without using cable. Today, numerous WLAN devices are based on IEEE 802.11 protocols, and nowadays many researchers have studied on the performance of IEEE 802.11 protocols. Specially, medium access methods (PCF and DCF). In this paper we have concentrated on the DCF mechanism, and we have studied and analysed the performance of IEEE 802.11b protocol in term of the throughput and utilization using PEPA. We studied scenarios with two and three transmitting node pairs to better understand fairness. In the scenario 1, once the packet payload size increases, the utilization of both pairs increases too or slowing transmission are staying longer. The speed of packet is effected, when the speed of the transaction are increasing, and the packet can send faster for actual rate transmission, this scenario is a totally fair scenario because each pairs can access the channel equally. However, the scenario 2 shows the channel access and medium sharing is unfair, because the central pair has less chance to access the channel compared to the externals. The central one cannot compete the other pairs, hence, we can understand the central pair is unfairly disadvantaged, as it waits most of time to use the medium while the external pairs have access. Finally, in term of throughput with the faster backoff, the transmission are complete in a shorter time, then the medium can be used by each pairs and the sender receives an ACK.

In the four pairs scenario (scenario 3), external pairs without collision can transmit at the same time. This is caused by the channel use time is increasing because of the packet size is increasing at the same time, both external pairs can occupy the channel longer than the central pairs. Moreover, in this scenario by increasing nodes we can get more fairness situation, and each external fairly access the channel rather than central one. The central one are penalize, with two penalise pairs. In the hidden nodes scenario (scenario 4) each pairs cannot hear from each other, and they are trying to occupy the packets, it seems that the sender spent more time to receive an acknowledgement for the duration of decreasing the backoff because of the collision occur in this scenario, the transmitter attempt to retransmit the message.

In the future, we will expand current experiment to investigate another scenario. Future work will explore the existing protocol to design new models for another protocol. We will follow nearly tasks that are helpful to understand and redesign new models such as 802.11g/n and make a comparison with 802.11b. Many aspects could be considered for future directions, in term of collision we will look for the new protocol with new issues, might be it will support us to develop new model that improves performance evaluation issues in wireless communication protocols.
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