Performance Modelling of Fairness in IEEE 802.11 Wireless LAN Protocols.

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This thesis is dedicated to my loving parents, who tirelessly taught me that the best kind of knowledge can be accomplished if it is done one step at a time.

Declaration

I hereby declare and confirm, that the thesis has been composed by myself, except where specific reference is made to the work of others. To the best of my knowledge, I solemnly certify that the work contains no material which has been accepted for the award of any other degree or diploma in my name or any other degree or professional qualification in any other university or other tertiary institution. My contribution and dissertation are authentic as well as the presented study which have been generated by me as the result of my own original research, except as specified in the text and Acknowledgements. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution.

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Abstract

Wireless communication has become a key technology in the modern world, allowing network services to be delivered in almost any environment, without the need for potentially expensive and invasive fixed cable solutions. However, the level of performance experienced by wireless devices varies tremendously on location and time. Understanding the factors which can cause variability of service is therefore of clear practical and theoretical interest.

In this thesis we explore the performance of the IEEE 802.11 family of wireless protocols, which have become the de facto standard for Wireless Local Area Networks (WLANs). The specific performance issue which is investigated is the unfairness which can arise due to the spatial position of nodes in the network. In this work we characterise unfairness in terms of the difference in performance (e.g. throughput) experienced by different pairs of communicating nodes within a network. Models are presented using the Markovian process algebra PEPA which depict different scenarios with three of the main protocols, IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. The analysis shows that performance is affected by the presence of other nodes (including in the well-known hidden node case), by the speed of data and the size of the frames being transmitted.

The collection of models and analysis in this thesis collectively provides not only an insight into fairness in IEEE 802.11 networks, but it also represents a significant use case in modelling network protocols using PEPA. PEPA and other stochastic process algebra are extremely powerful tools for efficiently specifying models which might be very complex to study using conventional simulation approaches. Furthermore the tool support for PEPA facilitates the rapid solution of models to derive key metrics which enable the modeller to gain an understanding of the network behaviour across a wide range of operating conditions.

From the results we can see that short frames promote a greater fairness due to the more frequent spaces between frames allowing other senders to transmit. An interesting consequence of these findings is the observation that varying frame length can play a role in addressing topological unfairness, which leads to the analysis of a novel model of IEEE 802.11g with variable frame lengths. While varying frame lengths might not always be practically possible, as frames need to be long enough for collisions to be detected, IEEE 802.11n supports a number of mechanisms for frame aggregation, where successive frames may be sent in series with little or no delay between them. We therefore present a novel model of IEEE 802.11n with frame aggregation to explore how this approach affects fairness and, potentially, can be used to address unfairness by allowing affected nodes to transmit longer frame bursts.

Table of contents

List of figures

List of tables

Glossary

List of Acronyms

LAN : Local Area Network

WAN : Wide Area Network

WLAN : Wireless Local Area Network

AP : Access Point

OSI : Open Systems Interconnection

ISO : International Standards Organization

ISM : Industrial, Scientific and Medical

QoS : Quality of Service

TCP/IP : Transmission Control Protocol/Internet Protocol

DLL : Data Link Layer

LLC : Logical Link Control

CSMA/CA : Carrier Sense Multiple Access with Collision Avoidance

CSMA/CD : Carrier Sense Multiple Access with Collision Detection

DCF : Distributed Coordination Function

PCF : Point Coordination Function

MAC : Media Access Control

PHY : Physical Layer

WiFi : Wireless Fidelity

IEEE : Institute of Electrical and Electronics Engineers

RF : Radio Frequency

IR : Infrared

OFDM : Orthogonal Frequency Division Multiplexing

DS : Direct Sequence

DSSS : Direct Sequence Spread Spectrum

FHSS : Frequency Hopping Spread Spectrum

MIMO : Multiple-Input Multiple-Output

TXOP : Transmission Opportunity

SGI : Short Guard Interval

SDU : Service Data Unit

MSDU : Media Access Control Service Data Unit

A-MSDU : Aggregate / Media Access Control Service Data Unit

PDU : Protocol Data Unit

MPDU : Media Access Control Protocol Data Unit

A-MPDU : Aggregate / Media Access Control Protocol Data Unit

bsp : bits per second

Mbps or Mbit/s : Megabits per second

μs : Microseconds

ns : Nanoseconds

F : Frequency

Hz : Hertz

MHz : Mega Hertz

GHz : Gega Hertz

MANET : Mobile Ad Hoc Network

HT : High Throughput

RTC : Request to Send

CTS : Clear to Send

RTC-CTS : Request to Send / Clear to Send

ACK : Acknowledgement

BA or BACK : Block Acknowledgement

BAR : Block Acknowledgement Request

CW : Contention Window size

CWmin : Minimum Contention Window

CWmax : Maximum Contention Window

IFS : Inter-Frame Space

SIFS : Short Inter-Frame Space

DIFS : DCF Inter-Frame Space (Distributed Coordination Function Inter-Frame Space)

EIFS : Extended Inter-Frame Space

RIFS : Reduced Inter-Frame Space

PEPA : Performance Evaluation Process Algebra

CTMC : Continuous Time Markov Chain

ODEs : Ordinary Differential Equations

Med : Medium

WaitS : Waiting time for Short frames

WaitL : Waiting time for Long frames

Chapter 1

Introduction.

Computer networking is an essential part of modern life and large parts of commerce and society rely on it to provide efficient and fast communication. There are many technologies which form this interconnection of devices and while much of it relies on fixed cables to form a communication medium, wireless technology is also extremely important to maintain connectivity when cabling is impractical for some reason. One of the wireless technologies used is known as Wireless Local Area Networks, or WLANs. WLANs are a collection of devices which communicate solely through wireless (typically radio wave) transmission. Early wireless networks would use high power radio signals to connect nodes across a wide area. Typically such networks would have had a central hub which would control communication in a star topology. In contrast Wireless Local Area Networks (WLANs) have no fixed topology (indeed nodes could be mobile) and use relatively short range communications. In order to connect across a wider area nodes can forward messages on to each other. Hence each node or device in the Wireless Local Area Network, WLAN, can act as a sender, a receiver and a router.

Wireless Local Area Networks (WLANs) have become an important piece of technology to provide cost effective and flexible computer communications in many environments and therefore understanding the performance characteristics of WLANs is vital in order to obtain efficient and effective deployments. Many aspects of this problem have been studied over the years, using different methods and in different contexts. A major part of this work has focused on increasing the maximum throughput which can be obtained, however it is generally more important to be able to predict the performance that will be experienced in practice by every device in a network, rather than focusing on the maximum or average performance that might be achieved across the network. Hence in this thesis we focus on understanding differences in performance which might be experienced by different devices in the same network. If all devices have the opportunity to experience the same performance, then we would say that the network and the protocols which support it are fair. However, in practice it is unlikely that all devices will have the same experience. The degree to which devices experience the same performance is referred to as the fairness of the network and, in contrast, the degree to which they are different is unfairness.

Over the years the speeds and demands of WLANs have increased substantially, but one aspect has remained the same, namely that most WLAN protocols are based on contention for access to the transmission medium with attempts at simultaneous transmission by multiple senders resulting in collisions. Collisions cause interference in a signal reception, which means any messages so affected will need to be retransmitted. Thus it is easy to see that collisions cause bandwidth to be wasted and so avoiding collisions is a major part of the performance of any WLAN protocol. However, measures which are intended to reduce collisions to increase overall performance may also contribute to unfairness in certain situations. Understanding what these situations may be and consequently developing methods to adapt the network to reduce their negative impact is therefore of clear theoretical and practical interest.

1.1 Motivations.

There are several challenges and characteristics associated with WLAN protocols, especially, in terms of performance issues and fairness matters when several nodes of pairs attempts to access the medium. Therefore, the performance fairness of WLAN can be affected by many factors, such as, the number of devices to be used the medium, frames size, probability of collision, network area size, interactions between nodes and topological structure of a network. To the best of our knowledge, there is a dearth of analytical research so far to analyse the performance modelling of fairness under such conditions.

In this thesis the IEEE 802.11 family of Wireless Local Area Network (WLAN) protocols are studied using the Markovian process algebra PEPA. Using a process algebra such as PEPA it is possible to specify and analyse abstract models of systems in a concise and efficient manner. Thus it is possible to explore a wide range of scenarios using a common set of concepts without the need to run numerous complex simulations. Despite the advantages offered by process algebra, most network studies are undertaken using simulation. Therefore one motivation of this thesis is to show that a significant and informative study on network performance can be undertaken using PEPA. The models presented are not large and hence numerically solving the resultant Continuous Time Markov Chain, CTMC, is not a problem and existing methods and tools are more than adequate for this purpose. The challenge therefore is in specifying suitable models and defining appropriate experiments. We have used PEPA in several experiments, which involved isolation and management of different parameters. Due to time constraints and complexity, we have not used simulations. PEPA also has an abstraction process, which improves investigation of specific parameter ranges. This means we are able to consider a wide range of outcomes, from our models. Finally, a small set of combination will be affordable in the PEPA. This allow us to construct the definition and the behaviour of components, throughout the activities. PEPA modelling is time efficient, so we can build and analyse the model to initiate the interactions between components and activities as simulations.

IEEE 802.11 consists of a number of protocols which have evolved over the years as transmission speeds and bandwidths have increased. Each version of IEEE 802.11 is based on the same underlying behaviour, although details are changed in each case. Another objective of this study therefore is to compare the performance of different versions of IEEE 802.11 and observe how their properties affect possible unfairness. This thesis examines several versions of protocols in terms of performance modelling and fairness matters. Also it illustrates, is the actual finding in old version of protocol still relative to new version of protocol? Is the fairness issue in old standard still can be found in a new standard? The final motivation is to investigate mechanism which might be used to reduce unfairness when it occurs. In this respect we look in detail at the variation in communication duration which might occur when we employ variable length frames or frame aggregation.

1.2 Contributions.

The study presented in this thesis makes a number of key contributions as shown in the following.

- We specify and analyse a model of the hidden node problem for both IEEE 802.11b and 802.11g protocols. The details are presented in Chapter 3.
- We have introduced a fairness property in IEEE 802.11b protocol used PEPA and analyse scenarios which give rise to unfairness. The details are provided in Chapter 4.
- We present and evaluate a novel model for IEEE 802.11g protocol and analyse scenarios which give rise to unfairness. The details are presented in Chapter 5.
- We further extend our model for IEEE 802.11g protocol to consider the effect of variable frame length on fairness. More information are shown in Chapter 5
- Finally, we proposal a novel model for IEEE 802.11n protocol by focusing on the evaluation of the impact of frame bursting on fairness. In particular we consider how limiting the degree of bursting at some nodes may allow others to recover from unfair performance. See Chapter 6 for more details.

Overall the thesis contributes a major study on network protocols using PEPA. To the best of our knowledge this is the first such study of this scale to be attempted.

1.3 Thesis outline.

- Chapter 2 presents a review of the literature related work to the performance of the IEEE 802.11 protocols and introduces the PEPA modelling language.
- Chapter 3 examines a PEPA model of IEEE 802.11b and IEEE 802.11g under the hidden nodes problem by studying the channel utilisation, probability of transmission, channel throughput and collision probability.
- Chapter 4 presents the formal performance modelling of IEEE 802.11b protocol and introduces three scenarios where fairness is studied. Metrics are derived from the resultant PEPA models which allow the degree of fairness to be evaluated under different parameters.
- Chapter 5 explores the performance modelling and fairness of IEEE 802.11g protocol. Fairness is considered in four scenarios and again metrics are derived in order to determine the factors which affect fairness. As a result of this analysis a further model is investigated where frame length is variable.

- Chapter 6 will describe and analyse a model of IEEE 802.11n by studying the frame bursting measures aimed at reducing the use of Inter-Frame Spacing to increase its performance. The effect of frame bursting on fairness is considered and it is proposed that unfairness can be significantly reduced by manipulation of the burst lengths at competing nodes.
- Chapter 7 will present the overall conclusions of the thesis and propose some areas of further investigation.

1.4 Publications.

During the course of this PhD, the main contributed of this research study to the following peer-reviewed are published regarding to the IEEE 802.11b, IEEE 802.11g and IEEE 802.11n protocols by using Performance Evaluation Process Algebra PEPA, with the obtained results and scenarios of the models for each protocols:

1. C.O. Abdullah and N. Thomas. A PEPA model of IEEE 802.11b/g with hidden nodes. In *Computer Performance Engineering: 13th European Workshop on Performance Engineering*, pages 126-140. Springer, 2016.
(In the content of Chapter 3.)

2. C.O. Abdullah and N. Thomas. Formal performance modelling and analysis of IEEE 802.11 wireless LAN protocols. In *UK Performance Engineering Workshop*. University of Leeds, 2015.
(In the content of Chapter 4.)

3. C.O. Abdullah and N. Thomas. Performance modelling of IEEE 802.11g wireless LAN. In *9th EAI International Conference on Performance Evaluation Methodologies and Tools*. 2015.
(In the content of Chapter 5.)

4. C.O. Abdullah and N. Thomas. Modelling unfairness in IEEE 802.11g networks with variable frame length. In *International Conference on Analytical and Stochastic Modelling Techniques and Applications*, pages 223-238. Springer, 2016.
(In the content of Chapter 5.)

Chapter 2

Background and related work

This chapter will present a literature summary of previous studies, providing the rationale to our research question. This review will focus on the analysis of performance fairness of IEEE 802.11 protocols and a critique of that work. Section 2.1 contains a brief introduction to computer LANs, WLANs, WiFi standards and the OSI model. The IEEE 802.11 protocols / WiFi standards provides further studies to indicate the general scope of this area; IEEE 802.11 MAC layer and the basic access mechanism are also presented in this section. Section 2.2 presents the Performance Evaluation Process Algebra PEPA modelling language used throughout this thesis. The syntax of PEPA and Continuous Time Markov Chain (CTMC) are shown in this section. Section 2.3 explores the related work of the literature review conducted by our research. The previous literature of performance analysis of IEEE 802.11 applications are presented in this section; specifically MAC sub layer protocol and DCF mechanism, hidden node phenomenon, fairness of IEEE 802.11 protocols and modelling network protocols with PEPA. Section 2.4 briefly shows the context of the next chapters in this thesis. Finally, Section 2.5 concludes the literature review with a chapter summary.

2.1 LANs, WLANs, WiFi standards and the OSI model.

Computer information technology has been researched widely across a variety of disciplines; with an emerging field of wireless communication networking. The growing centralisation of computing technology in our daily work and social lives means that instant sharing of resources is crucial; highlighting the need for effective network systems. Computer networks have evolved through the necessity of communication capabilities. The process of sharing resources in computer networks is achieved by two or more interconnected nodes. Each node tries to communicate via a medium, either cable or wireless media can be established as a connection. Accordingly, there are a variety of types of computer networks, for instance, LANs, WANs and Data Communication Systems. Specifically, Wireless computing and WLAN have been growing rapidly as it allows many users to obtain network services without joining tethered to any wire. This section gives an overview about LANs, WLANs and IEEE 802.11 protocols.

2.1.1 Local Area Networks (LANs).

Local Area Networks (LANs) are a common type of computer network, which can be constructed by consisting a group of computers or peripherals to each other through a common communications wire. Any device in LANs would be able to connect to each other directly (in a peer to peer connections) or through a hub, switch or central server, within a distinct geographic site, such as offices or commercial establishments. Figure 2.1 illustrates a basic LANs diagram as an example of LAN network, which different devices will interact via cables by using a central switch to establish connections, also a central server will provide more software and hardware resources in this LAN. LANs provide wide resources to users and end devices, such as printer or network storage in a specific range, usage, and high speeds. The functionality of LANs increases with having a central server, which can provide more resources, including hardware, file, and software resource sharing. Also, sending data, voices and images are another crucial functionality of Local Area Networks (LANs). In addition, low cost, installation with scalability, expanding and maintenance are significantly increased with the use of LANs. The following shows the most specific features of LANs:

- Devices in LANs are connected in a confined or single geographical area, such as campus.
- LANs can be managed and administrated by an individual or groups.
- High speed data has been provided to internal and intermediary devices.
- The data error rate is very low since its transferred in a limited distance.
- Different topology can be initiated and multiple devices can be installed to share a medium.

Within a positional group of buildings and in the limited geographical places, different Local Area Networks (LANs) can be connected to each other to span a wider area networks by using routers. The characteristics of LANs can be significantly increased by this expansion.

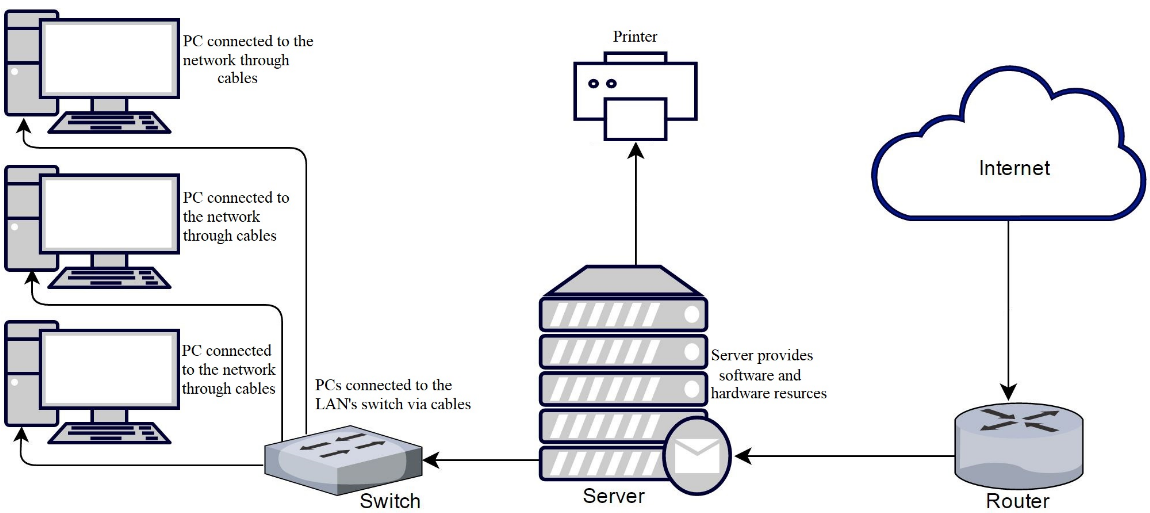


Fig. 2.1 The basic Local Area Networks (LANs) diagram.

2.1.2 Wireless Local Area Networks (WLANs).

With a tremendous increase of the productivity in communications in the last few decades, Wireless Local Area Networks (WLAN) has developed to be used indoors and outdoors. Due to scalability, ability to move and flexibility to access data, it has increased pervasively to cover many hotspots such as hotels, airport lounges, and offices. Easy installation and low-cost maintenance are increasing the popularity of WLAN. Numerous Local Area Networks (LANs) may use wireless technologies that can be found in many devices, which the wireless network technology will support users to move within the coverage area without restrictions, Figure 2.2 shows an example of WLAN in which different nodes communication via wireless. This figure illustrates different nodes (it could be laptops, tablets, mobile phones or any other wireless devices.) are interacting through the base station known as an AP (wireless Access Point) to gain services. Pahlavan and Krishnamurthy [62] have argued that the WLAN advancement has affected the consequence of mobility on computer networks. Gast [31] shows that the dominant standard of WLAN solution is IEEE 802.11 protocols because of the low cost, high speed and easy development.

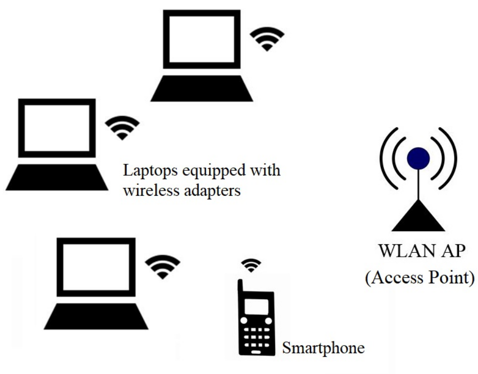


Fig. 2.2 Wireless Local Area Networks (WLANs).

Relying on the area, one or more Access Points will be required to obtain connection as a bridge between the wired and WLAN in any spots. Figure 2.3 shows an established network between LANs and WLANs, as several workstations among the LANs (it could be personal computers or notebooks) are connected to the central server via the switch by using cables to access services. The main switch in this LAN is connected to a WLAN-AP by using a cable to expand the network in this area. Similarly, in this network the WLAN-AP will provide services to other wireless nodes. These wireless nodes are equipped with wireless adapters to be able to communicate to each other to access services without using cables. Wireless network will mainly reduce the use of wire in connections and become more user friendly, but it does not entirely remove cables in networking. Rapid use of WLAN by numerous users to access the channel have given rise to the WLAN performance issue. WLANs relies on IEEE 802.11 standards; a Media Access Control MAC protocol can be used to access the medium which is based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA has a similarity to Ethernet's Carrier Sense Multiple Access with Collision Detection (CSMA/CD), but it operates in a different way. Data Link Layer operates to send and receive data between two hosts within the same area (details are shown in Section 2.1.4). In our research, we have studied the CSMA/CA in WLAN, specifically, IEEE 802.11 protocols and MAC layer. In this thesis, we examined different scenarios to show how nodes compete to access the media by using framing techniques, how data can flow and receive via the media, using Media Access Control (MCA).

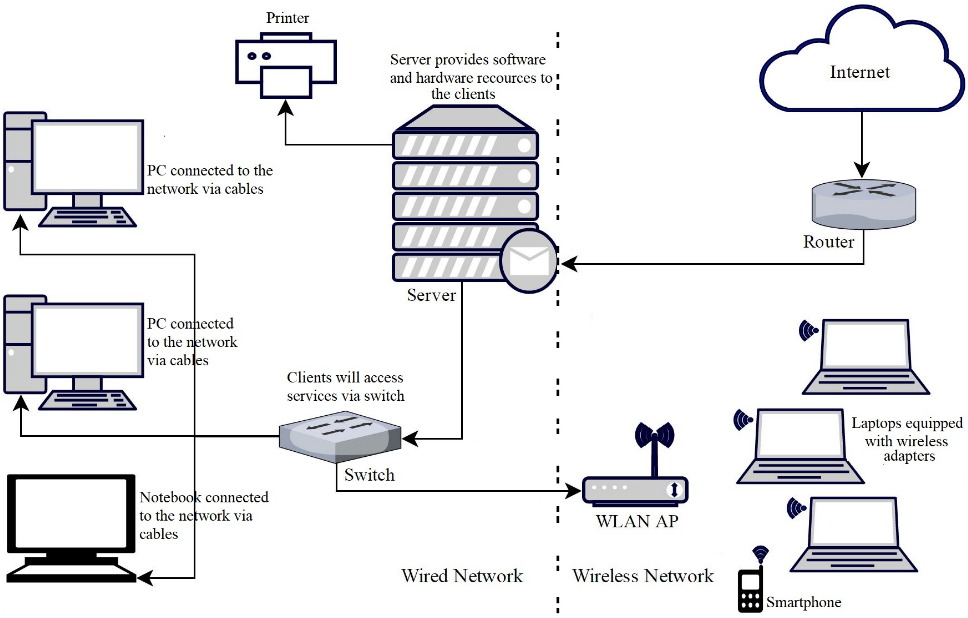


Fig. 2.3 Wireless Area Network and Local Area Networks.

Wireless Local Area Networks (WLANs) have more flexible characteristics to address and deliver data compared to LANs. The most specific features of WLANs are shown below:

- WLAN expands easily and it goes completely wireless in a single geographical site.
- WLAN uses high-frequency radio waves to communicate between nodes.
- High bandwidth allocated for wireless systems.
- IEEE 802.11 identified the technologies for WLANs by using the MAC protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for sharing channel.

Any node in WLANs will use high-speed data transmission or radio frequencies to communicate and transmit within a small region. The performance of WLAN is not similar to wired LAN, as the WLAN uses different bandwidths to exchange data, also interferences might affect the performance of WLAN. Accordingly, IEEE 802.ll and Bluetooth technology have been acquired by the evolution of wireless systems. In the past decade, the IEEE 802.11 family of protocols have been the standard for WLANs [1]. IEEE 802.11 is committee categorised as a set of protocols, IEEE 802.11 **a/b/g/n/ac** and etc., with very similar structure, but different operating ranges (power, data rate, message length etc) see [3, 37]. Each of them has a specific performance, transmission speed and signal range, and they are very essential standards in WLAN. The WLAN standard slightly evolves from time to time in different manners (e.g data rates and speeds), which most of these standards are not always compatible with one another. Various devices and organisations are using different standards in communications, as they are always seeking the best protocol to provide a higher performance.

WLAN devices communicate by using the IEEE 802.11 protocols with the wireless distribution methods, spread spectrum and orthogonal frequency-division multiplexing (OFDM). These popular methods allow users to move frequently within the coverage area. A general review of the IEEE 802.11 Physical layer (PHY) amendments and their dependencies are shown in Figure 2.4. This figure explains different protocol operates on specific bands and modulations from old version to new version, such as 802.11b and 11g are used 2.4 GHz band only. Most common bands which are shown in the following have been distributed and appropriated in usage for unlicensed industrial, scientific, and medical (ISM) (for more information see [9]).

- 900 MHz (902 to 928 MHz)
- 2.4 GHz (2.4 to 2.4835 GHz) (IEEE 802.11b/g/n operates in this frequency range)
- IEEE 802.11a/11n and 11ac operates in 5 GHz (5.15 to 5.35 and 5.725 to 5.825 GHz)

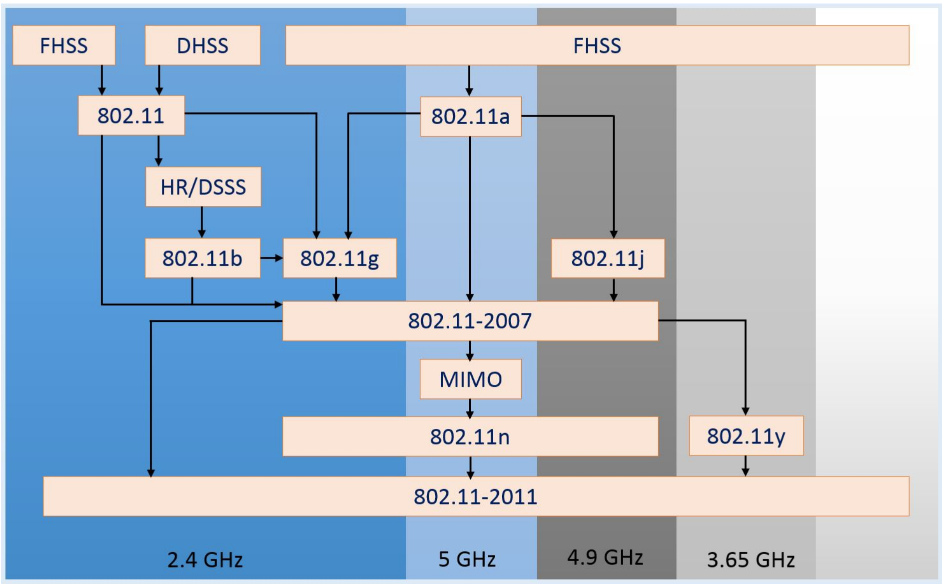


Fig. 2.4 IEEE 802.11 PHY layer amendments [37].

2.1.3 Wireless Fidelity (Wi-Fi) standards.

Wireless Fidelity (Wi-Fi) is a general wireless networking technology, which it uses radio waves to wirelessly transmit data across networks for providing network connectivity. WiFi radio signal provides wireless high-speed Internet and network connections. WiFi is based on Institute of Electrical and Electronics Engineers (IEEE) standards on WLAN devices, specifically, it is based on the IEEE 802.11 standards. It can determine the range and speed of a WiFi network. The main difference between WLAN and WiFi is that WLAN is wireless network and WiFi is a technology used within a WLAN. Any mobile user would be able to connect to the WLAN, via a radio frequencies to transmit data. But, the technology of Wireless Fidelity (Wi-Fi) as a trademark of Wi-Fi Alliance, is a type of WLANs that use specifications in IEEE 802.11. Hence, to create most of WLAN networks in a specific area, then WiFi technology is required with devices based on IEEE 802.11 standards to exchange data at high speeds without wire. Generally, the newer standard can provide the higher speed, with different ranges which can be compatible with older standards. It seems, the lack of sustainability of Wifi speeds could reduce people's satisfaction in terms of sharing resources. Numerous factors can affect the WiFi such as the way of setting up the router, any interferences around the devices to access the router and the distance of the router from the devices. WLANs standards significantly affect the performance of WiFi. WLANs standards are competing to improve better in use in every generations. Currently, in a variety of devices, lots of standards are in use (Table 2.1 and 2.2 shows some of WLANs standards, see [24] for more details). Some WiFi standards become a legacy in producing a new protocol. IEEE [1] have been developing for these standards for WLANs and Wireless Metropolitan Area Networks (WMANs) for many years; using both radio frequency (RF) and infrared (IR). In our research throughout this thesis we have concentrated on the examination of the IEEE 802.11b/g/n protocols, as the main popular wireless networking standards.

Table 2.1 IEEE 802.11 network PHY standards [3].

IEEE 802.11 standards	Release Date	Frequency by (GHz)	Bandwidth by (MHz)	MIMO stream	Modulation Type	Range by meter
IEEE 802.11	Jun - 97	2.4	22	NA	DSSS, FHSS	20
IEEE 802.11a	Sep - 99	5	20	NA	OFDM	35
IEEE 802.11b	Sep - 99	2.4	22	NA	DSSS	35
IEEE 802.11g	Jun - 03	2.4	20	NA	OFDM	38
IEEE 802.11n	Oct - 09	2.4/5	20/40	4	MIMO - OFDM	40

Table 2.2 IEEE 802.11 data rates [3, 37].

IEEE 802.11 standards	Bandwidth by (MHz)	Data rate by (Mbps)
IEEE 802.11	22	1,2
IEEE 802.11a	20	6, 9, 12, 18, 24, 36, 48, 54
IEEE 802.11b	22	1, 2, 5.5, 11
IEEE 802.11g	20	6, 9, 12, 18, 24, 36, 48, 54
IEEE 802.11n	20	400 ns GI : 7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2
		800 ns GI : 6.5, 13, 19.5, 26, 39, 52, 58.5, 65
	40	400 ns GI : 15, 30, 45, 60, 90, 120, 135, 150
		800 ns GI : 13.5, 27, 40.5, 54, 81, 108, 121.5, 135

WiFi standards operate in different channels, with the diversity usage of standards using different bands. The most widely used standard operates on the 2.4 GHz band. Other standards have adopted the 5 GHz band which can be compatible with 2.4 GHz. Majority of the WiFi versions operate between 2400 and 2500 MHz. Generally, 5 GHz can transmit data faster, but it might be accessible in the smaller range than the 2.4 GHz. Some standards and WiFi devices are used one band in transmission either the 2.4 GHz or 5 GHz, however others can use both bands. A short summary of the bands are presented in the below which are used by the IEEE 802.11 systems. (Figure 2.5 shows IEEE 802.11 channels, for more information see [16, 21]).

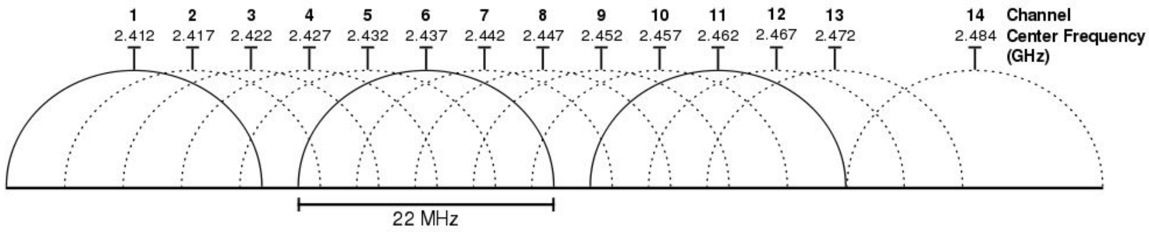


Fig. 2.5 The IEEE 802.11 channels in the 2.4 GHz [21].

IEEE 802.11 family has several specifications, some of them are briefly described in below:

- **802.11-1997**: In 1997 the first original version of the IEEE 802.11 was introduced. It was modified in 1999 to improve compatibility with data communication equipments. This standard is identified 1 and 2 Mbps raw data rates, unfortunately the protocol was too slow for most applications. The infrared (IR) signals, Frequency Hopping Spread Spectrum (FHSS) or Direct-Sequence Spread Spectrum (DSSS) has been used to transmit data in this standard. This standard was superseded by IEEE 802.11b, see [37] for more details.

- **IEEE 802.11b**: This protocol is extended from 802.11 specification which is an IEEE development for WLANs. It is applied to WLANs and provided the data rate up to 11 Mbps in transmission. IEEE 802.11b uses the CSMA/CA media access method as it has defined in the original standard. The unprotected 2.4 GHz is operated for digital communication in this standard. It is called 802.11 high rate or WiFi protocol and it uses the DSSS as a modulation technique as a one of two types of spread spectrum radio. This standard was established for first time in 1999, then in early 2000 appeared and it has been used widely in many devices especially once the throughput of IEEE 802.11b has increased (see [37] for more details). Despite the low cost of this protocol and its wider signal range, it is not easily obstructed. But this protocol is not massively in use because of its slowest maximum speed and it might interfere with home appliances on the unregulated frequency band. In our thesis the mentioned standard within the IEEE 802.11 family is relevant, which contributed to our research interest to examine the protocol performance.

- **IEEE 802.11a**: This standard is similar to IEEE 802.11b, it was ratified in 1999 as the same time as IEEE 802.11b was released. It offers a speed up to 54 Mbps at the expense of much shorter range, while it uses 5 GHz. However, the IEEE 802.11a is an obsolete standard, but it is still supported by many new access points for backward compatibility. The IEEE 802.11a operates in between 5.725 GHz and 5.850 GHz and the orthogonal frequency-division multiplexing (OFDM) (See [27]). IEEE 802.11a network has less interference than IEEE 802.11b, because it provides more available channels, and because the frequency spectrum employed by the IEEE 802.11b (2.400 GHz to 2.4835 GHz) is shared with various household appliances and medical devices. The higher cost of the IEEE 802.11a makes more likely to be used on business networks also its more easily obstructed, while the IEEE 802.11b can be used on home market. It seems, the IEEE 802.11a covers much less than the area of a comparable IEEE 802.11b and IEEE 802.11g.

- **The IEEE 802.11g**: A third modulation standard was published in 2003 after IEEE 802.11b and IEEE 802.11a. The combination of IEEE 802.11b and IEEE 802.11a features have been made IEEE 802.11g standard more effective. This protocol uses OFDM modulation, the same as IEEE 802.11a but it operates in the 2.4 GHz band similar to IEEE 802.11b. The IEEE 802.11g protocol provides at a maximum data rate in transmission up to 54 Mbps (with data rates of 48, 36, 24, 18, 11, 5.5, 2, and 1 Mbps), which it makes more in use widely and differs compared to IEEE 802.11b as it uses OFDM. In most devices the IEEE 802.11g protocol is fully backward compatible with the IEEE 802.11b standard. Both protocols have occupied many devices since they have been published (these protocols are still in use in different devices around us, but due to a big improvement in IEEE 802.11g the use of IEEE 802.11b will reduced). IEEE 802.11g is a fast maximum speed protocol with having good signal range, which is not easily obstructed. But it seems, IEEE 802.11g standard is more costly than IEEE 802.11b protocol[14, 77].

- **The IEEE 802.11n**: This protocol has been amended in the previous IEEE 802.11 standards to improve both data rates and further range in transmission. It was ratified in 2009 and it binds tightly the characteristic of the earlier standards IEEE 802.11a/b/g and it uses OFDM. In terms of WLAN throughput performance of IEEE 802.11n nearly quadruples IEEE 802.11g. The Multiple-Input Multiple-Output antennas (MIMO) is one of the improvements in this standard to increase data rates, more details are showing in Section 2.1.5 and Chapter 6. This protocol is successfully designed to operate on the 2.4 GHz and the 5 GHz bands, while the prior protocols operate only in one band. This standard operates at a maximum data rate to 600 Mbps and it is more successful in uses for indoor wireless LANs for bandwidths of up to 100 MHz in the both frequencies. It is one of the fastest maximum speed and best signal range protocol with better resistant to signal interference from outside sources. The IEEE 802.11n MAC layer enhancements bring the protocol more in use which include frame aggregation (multiple data frames has been merged into one aggregation) and Block Acknowledgement (BACK) scheme. BACK has been changed to acknowledge many received frames and supports a reverse direction mechanism, which allows transmission in both directions. Finally, beside the MIMO technology, channel bonding is another enhancement at the Physical later (PHY) enhancement in this standard. Furthermore, many researchers have studied the IEEE 802.11n in different ways, some studied on the MIMO technology, other has studied on the performance of IEEE 802.11n standard. Hajlaoui and Jabri [35] focus on the adhoc networks performance examining the effect of most of the proposed IEEE 802.11n MAC and PHY layer. In our research we have studied the performance of the IEEE 802.11n protocol by creating a model and analyse the fairness of this standard in terms of channel throughput, channel utilisation, probability of using channel and etc. To the best of our knowledge, ours is the first study to analyse the IEEE 802.11n protocol by using PEPA.

2.1.4 The OSI model and IEEE 802.11 MAC layer.

The computer network protocol has been designed and standardised by an Open Systems Interconnection Reference Model (OSI Model), for which the International Organization for Standardization (ISO) is responsible. The facility of data communication in any computer system and telecommunication has been characterised by this model. This model is a representation of each commutating node. It describes a networking framework to implement protocols in seven layers. These seven network architecture layers form stacks from top to bottom. Figure 2.6 shows the OSI model and Transmission Control Protocol/Internet Protocol (TCP/IP), also see [72] for more details.

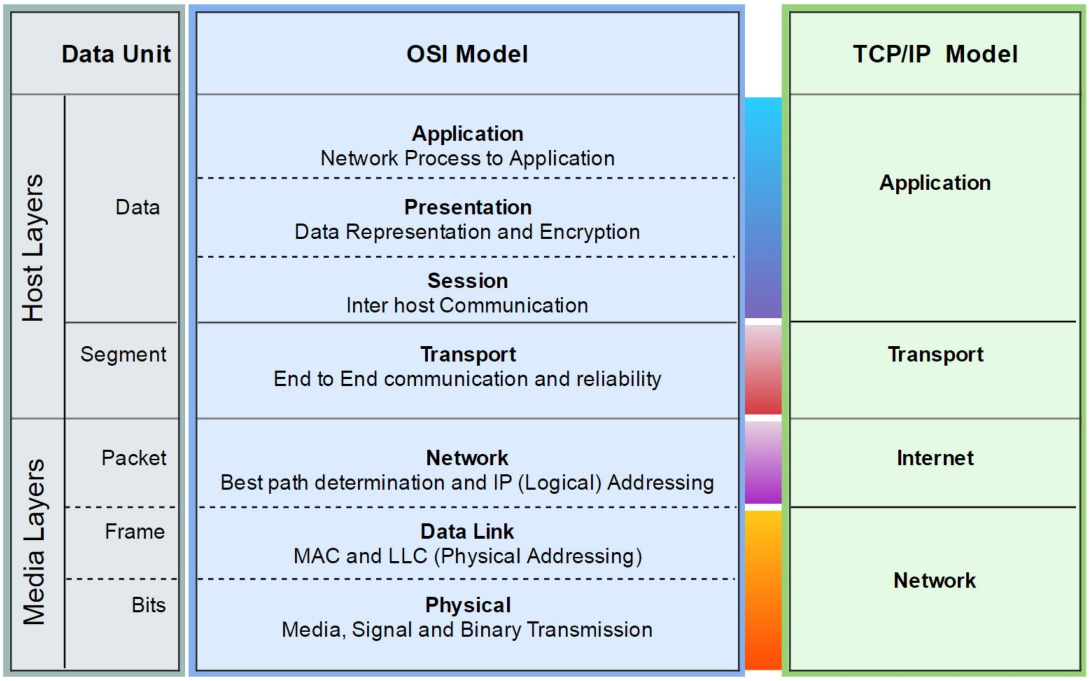


Fig. 2.6 The OSI seven layers model and TCP/IP four layers model [72].

Each layer in OSI model provide services to the above layer, while it receives service from the below one. For example, the Data Link Layer (DLL) provides to service requests from the layer above (Network Layer) and issues service requests to the below one (Physical Layer). In the Physical layer and Data Link Layer, LAN protocols are functioning. Data transfer has been provided in the DLL between network devices; the detection and correction of errors that may occur in the PHY is a function in this layer. Also, packing and unpacking data into frames operates in this layer too. It means the process between each stack within network communications can be associated and occupied from upper and lower stacks. In our research, we have chosen to study the DLL and PHY layers. More specifically, we have concentrated to study in between layer range delivery DLL and PHY. Hence, we have examined the IEEE 802.11 protocols concentrated within the Medium Access Control (MAC) sub-layer.

The data and error-free transfer is provided in the DLL from one node to another. The Data Link Layer (DLL) is divided into two main data communication networks protocol sub-layer, which are the Logical Link Control (LLC) and Medium Access Control (MAC) layers, Figure 2.7 is shown the depiction of MAC layer.

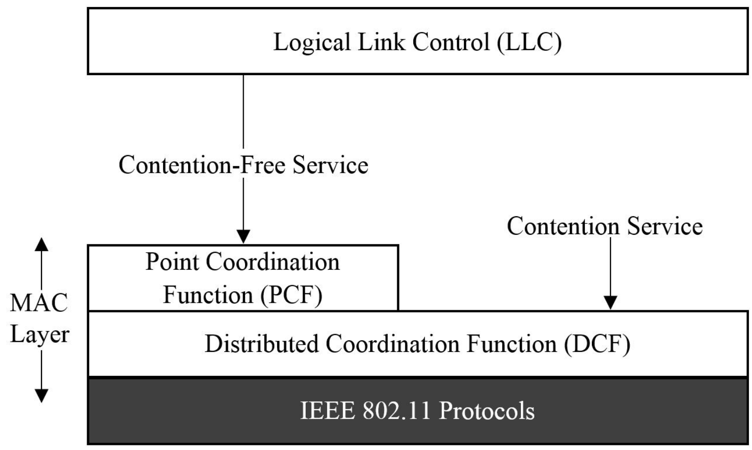


Fig. 2.7 IEEE 802.11: LLC and MAC protocol stack [72].

Additionally, in IEEE 802.11 standards the Distributed Coordination Function (DCF) and Point Coordination Function (PCF) are defined as the two main forms of medium access (more relevant details can be found in [2]). The DCF utilises Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol with binary exponential backoff, it is the de-facto standard at the MAC layer. IEEE 802.11b and IEEE 802.11g protocols are use the CSMA/CA to minimise the occurrence of collisions between simultaneously transmitted data (see the Section 2.3 for more literature reviews). Collision does not use the DCF to detect function as the stations cannot detect collision by listening to their own transmission; instead of that the method of handshaking is employed to acknowledge receipt. The MAC layer deployed in IEEE 802.11 protocols provides a variety of functions in the operation of 802.11-based WLANs and it manages communications between 802.11 stations. Table 2.3 shows the process between each stack within network communications can be associated and occupied in upper to and lower stacks.

Table 2.3 IEEE 802.11 protocol stack (OSI layers) [51].

<table>
<tr><td rowspan="3">Upper layers</td><td colspan="6">Applications layer</td></tr>
<tr><td colspan="6">Transport layer</td></tr>
<tr><td colspan="6">Network layer</td></tr>
<tr><td rowspan="2">Data Link layer</td><td colspan="6">Logical Link Control</td></tr>
<tr><td colspan="6">MAC ayer</td></tr>
<tr><td>Physical layer</td><td>802.11a
OFDM</td><td>802.11b
DSSS</td><td>802.11g
OFDM</td><td>802.11n
OFDM
DSSS/CCK</td><td>802.11ac
OFDM
DSSS/CKK</td><td>...</td></tr>
</table>

Data encapsulation is one function of MAC protocol before transmission happens, which includes frame assembly. Frame parsing and error detection is another function when data is received. Furthermore, alongside reduced collisions, the main role of MAC is coordinating access to the shared radio channel. Moreover, any station attempts to obtain or gain access the medium first, such as a radio channel then it permits to transmit data through it. MAC protocol in different aspects have been studied. Particularly, the performance of IEEE 802.11 protocols have investigated in numerous studies. For instance, Lee [51] has investigated the MAC throughput and delay performance in WLAN of the basic transmission mode, the evaluation of saturation throughput with bit errors appearing in the transmitting channel has been analysed.

Further details about the performance of Medium Access Control (MAC) protocol in IEEE 802.11 protocols and the literature reviews are presented in the next sections. In our research, we have focused on the MAC layer to study the sharing media by different nodes. We have shown, how nodes can access and compete the connection for sending data and to analyse the performance of fairness in IEEE 802.11 Wireless Local Area Network (WLAN) protocols.

2.1.5 Basic access mechanism.

The basic access mechanism is a crucial method in wireless systems and it is widely used in IEEE 802.11 standards. Fundamentally, medium access timing in IEEE 802.11 will cooperate by using one of two different modes, which are the basic DCF (based on CSMA/CA) and the optional PCF (needs a central control object). The basic access mechanism in 802.11 is DCF, which is a common technique used up to 802.11g [10], and in 802.11n it has been enhanced and approved. The DCF method specifies this mechanism and two way handshake method as two techniques for data transmission, This study focused on the basic access mechanism to analyse 802.11 protocols (see, [61]).

Initially, in WLAN, a node senses the medium to discover if it is free to use; if so, then the node can make its transmission. On successful receipt, a receiving node will transmit an (*ACK*). However, if two nodes within transmission range attempt to transmit simultaneously, then a collision occurs resulting in an unsuccessful transmission and an initiation of the backoff algorithm. Unsuccessful node waits for a random time slot (backoff period), which this time slot is randomly drawn any interval value from zero to CW in the range of $[0, CW]$ before transmitting, where the CW (Contention Window) is based on the number of transmission failures. The initial value of CW is 31 for IEEE 802.11b, 15 for IEEE 802.11g and 802.11n. The CW is doubled after every unsuccessful transmission, until it reaches to the maximum number 1023 (see [23, 25, 40, 45] and [80] for detailed explorations of the backoff algorithm). The CW returns to the initial value after each *ACK* revived. When the backoff period has expired, the node again senses the network to see if it is free to use. The aim of the backoff is to try to avoid repeated collisions between competing nodes, as it is unlikely that two nodes will choose the same random backoff period. The more collisions occur, the larger the contention window and hence the less likely that another collision will occur. If the medium is sensed to be busy then the node will wait for a period before retrying. This is so that multiple waiting nodes will not immediately try to transmit once the medium is quiet, which would obviously cause a collision (see [48]).

If all nodes can hear other nodes, i.e. they are within sensing range of each others, consequently, the basic access mechanism will eliminate almost all collisions. There would still be a very small window when collisions could occur, which would be the time it takes a signal to traverse the sensing range, but this would be relatively insignificant in such small high speed networks. But, in practice most networks cover a much larger area than the sensing range of a single node. Thus, there is a possibility that two nodes which lie outside each other's sensing range, will choose to transmit simultaneously, to nodes which are within the transmission range of both senders. Although, the senders cannot hear each other's transmission, an intended recipient will hear both transmissions overlaid. This results in interference and hence the non-delivery of the frame. Such a frame would clearly not be successfully received and so an acknowledgement would not be sent. The sending nodes would wait for an acknowledgement for a period and then start the backoff process once determining that the acknowledgement is not forthcoming.

As the backoff technique preferably correlates with collision avoidance, if the channel is occupied by any node(s) then the backoff is set with a slot of time ($20\mu s$). After each frame transmission, in case of collision, the required Inter-Frame Space (*IFS*) is applied. The minimum fixed and shortest interval of time is called Short-*IFS* ($10\mu s$) for IEEE 802.11b and 802.11g see [48]. The channel activity can be monitored by nodes, when the backoff has been generated. If the channel is idle for an adequately long time, Distributed Inter-Frame Space *DIFS*, ($50\mu s$) then the node decreases the backoff. When the backoff is returned to zero, then the packet can transmit. Alternatively, if the channel is not free to use, the node monitors the channel until it becomes idle. Then the node decreases its backoff. Once the node detect that the channel is free and backoff decreases then it starts transmit. After a period of transmission, if the medium remains idle throughout a *DIFS*, the decrementation starts again. In effect, during the backoff decrementation, if the node detects a signal but, because of any congestion, not a transmission in progress, the node practises an Extended-*IFS* ($364\mu s$) instead of *DIFS*. After a successful transmission, an *ACK* will receive after Short Inter-Frame Space *SIFS*. Table 6.1 shows typical values of the IEEE 802.11 protocols and Figure 2.8 shows the basic access mechanism.

Table 2.4 Attribute values of IEEE 802.11b/g and 802.11n [25, 45, 75].

Attribute	Typical value		
	IEEE 802.11b	IEEE 802.11g	IEEE 802.11n
CWmin, and CWmax	31, and 1023	15(pure), and 1023	15(mean=7.5), and 1023
Slot time	$20\{\mu s\}$	$20\{\mu s\}$, $9\{\mu s\}$	$20\{\mu s\}$, $9\{\mu s\}$
SIFS	$10\{\mu s\}$	$10\{\mu s\}$	$16\{\mu s\}$
DIFS	$50\{\mu s\}$	$50\{\mu s\}$, $28\{\mu s\}$	$34\{\mu s\}$
EIFS	$364\{\mu s\}$	$364\{\mu s\}$	$160\{\mu s\}$

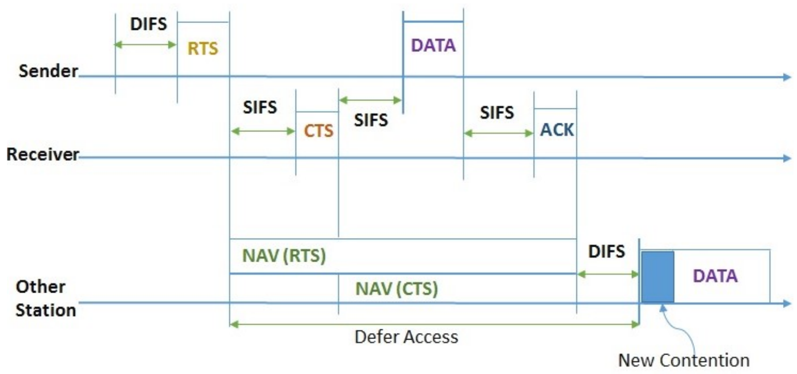


Fig. 2.8 RTS-CTS and Data-ACK scheme [61].

The basic access mechanism in the newest protocols is a similar due to legacy family standards. More recent published protocols, such as IEEE 802.11n standard is introduced with the main enhancements in the Physical layer (PHY) and Media Access Control (MAC) sub-layer based on the foundation of IEEE 802.11a/b/g/e protocols. These improvements provide a higher performance in IEEE 802.11n protocol by raising the data rates in the PHY layer and hence increasing MAC layer efficiency, [59, 79].

The Multiple-Input Multiple-Output (MIMO) technology, Short Guard Intervals (SGI), enhanced modulation and Coding schemes are enhances in the Physical Layer (PHY). The MIMO is used in IEEE 802.11n protocol to increase speed and data rates by using multiple transmitters and receivers at the same time by the sender and the receiver. MIMO antennas uses a Spatial Multiplexing transmission technique to transmit independent and multiple data streams simultaneously, that support users to obtain the maximum use of the available bandwidth. Another technical improvement that increases throughput in IEEE 802.11n is channel bonding. This is a combination of two or more communication links or adjacent channels in which to increase the amount of data that can be transmitted. In general, Guard Interval can be used in communications to avoid interference among symbol transmissions (the space between characters being transmitted) from multipath effect. Most IEEE 802.11 protocols use 800 ns as a guard interval. But in IEEE 802.11n, the interval time become 400 ns as a Short Guard Interval (SGI), this shorter period of time for symbol transmission can be used to improve the throughput. Frame aggregation and Block Acknowledgement (BACK) are introduced in MAC layer, which it helps to acknowledged a set of frame. A large number of researchers have studied on such protocol to improve the PHY and MAC layer. In our research, we studied the impact of enhancements of MAC layer in different scenarios. The MAC improvements in IEEE 802.11n protocol, which we have studied in our research are shown in Figure 2.9, as we have modelled these enhancements separately by using PEPA (more details are given in Chapter 6).

Despite the similarity in the IEEE 802.11n protocol with older protocols, such as IEEE 802.11g, some values of attributes and IFS slightly differ in IEEE 802.11n. Table 6.1 presents more details about the attribute values of IEEE 802.11b/g/n protocols and their comparison. Basically, in IEEE 802.11n the $SIFS$ is $16\mu s$ and the Distributed IFS ($DIFS$) is $34\mu s$, when the slot time is $9\mu s$ and the $EIFS$ is $160\mu s$. Additionally, the IEEE 802.11n standard has a much shorter IFS which is Reduced-IFS ($2\mu s$). $RIFS$ improves the efficiency of repeated transmissions to the same receiver and it is used only when Block Acknowledgement (BACK) is enabled.

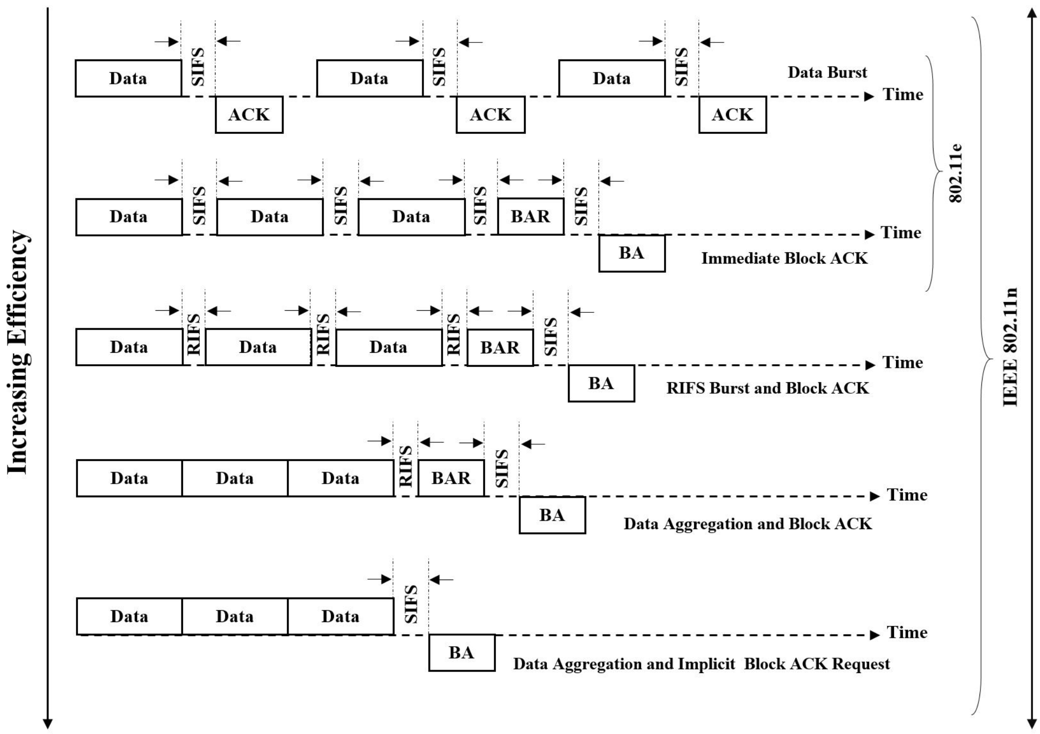


Fig. 2.9 IEEE 802.11n MAC layer enhancements [47, 79].

2.2 Performance Evaluation Process Algebra (PEPA).

This section introduces Performance Evaluation Process Algebra (PEPA), which is the main modelling technique that has been used in this research. PEPA is a stochastic process algebra and a compositional algebraic modelling formalism which was introduced by Jane Hillston [38]. PEPA is used and applied in practice to efficiently specify, build and analyse models of a wide variety of system for the performance evaluation of models: such as computer systems, mobile phone usage [29], multimedia applications [18], grid system [73] and communication systems. PEPA is suitable to check, formulate and calculate performance properties and measures. Components in PEPA models can be run in parallel and perform activities. PEPA describes a component performing an activity of type α at activity rate r in a pair consisting which is denoted by (α, r) when $\alpha \in$ A as an action type, and rate $r \in \mathbb{R}^+ \cup \top$, when $\top$ denotes a passive rate, which another component must determine the rate of the activity.

According to Hillston [38], PEPA was "developed to investigate how the compositional features of process algebra might impact upon the practice of performance modelling". The PEPA Eclipse Plug-in tool [33] supports a range of powerful analysis techniques for Continuous Time Markov Chain (CTMC), systems of Ordinary Differential Equations (ODEs) or stochastic simulation which allows modellers to derive results (both transient and steady state, with relative ease). The features of PEPA, compositionality, formality and abstraction, have encouraged us to use it for analysis our study, which might not be easily achieved in other modelling techniques. As stated by Hillston in [38], uncomplicated models of any system can be built up without any explicit notational support. However, to build up modelling on any system, such as a computer system, quickly becomes complex to do so. Hence, the main active features of process algebras such as, PEPA, is to make tools more friendly for the modeller. In the following we are shown the most important PEPA features and definitions:

- **Parsimony:** PEPA is a very economic to use, with few components and easy to access that it is considerably and flexibility to the modeller to utilise the most features in this technique.
- **Formal definition:** A formal interpretation has been available by structured operational semantics provides for all expressions. The notions of equivalence can be given a formal basis for the comparison and manipulation of models and components.
- **Compositionality:** The interaction between the main system and subsystems gives more ability to model the system to use in a proper way. In PEPA tool, the cooperation combinatory forms is powerful as the fundamental of composition. The model simplification and aggregation techniques can be developed which are complementary to this mixture.

2.2.1 The syntax and description of PEPA.

Hillston argued that PEPA can provide a useful modelling formalism to investigate properties of protocols and other well defined systems [38]. PEPA models specifies in terms of components which interact through shared actions. Actions in PEPA have a duration, which is determined by a rate parameter of the negative exponential distribution. In shared actions a rate may be given by one or both interacting components, with the result determined by the slowest participant. In WLAN networks, components can be any node and transmission media and shared actions can be thought of as the transmission of messages from one node to another via medium. The combination of all components into a single system gives rise to labelled transition system, where the transitions between states are negative exponentially distributed actions, hence the resultant system is a CTMC. Each activity has a specific action type, and in any system a unique type can be found inside each discrete action, and countable set includes all possible types.

The formalism syntax of PEPA:

The structure of PEPA is not complicated, as the components and activities are the primaries in this language; small set of combinators are available which is the main combinators in PEPA: prefix, choice, co-operation and hiding. Further general information, details and structured operational semantics on PEPA can be found in [38]. The main syntax and brief discussion of PEPA is defined by the following, the further details are shown the names of PEPA constructions and their intended interpretations:

$P ::= (\alpha, r).P \mid P \underset{L}{\bowtie} Q \mid P + Q \mid P/L \mid A$

- **Prefix:** $(\alpha, r).P$

  The fundamental building block of a sequential component is called prefix and it is the basic mechanism. The process $(\alpha, r).P$ performs activity of action type α at rate r before progressing to behave as component P. Similarly, with a shared activity $\top$ symbol can be used as a passive participation instead of the r rate. In PEPA the actions are assumed to have a duration or delay.

- **Choice:** $P+Q$
  In between two or more possible processes the competition can be create, the process $(\alpha,r).P+(\beta,s).Q$ any one of α will win the race (the process subsequently behaves as P) or β (the process subsequently behaves as Q).

- **Co-operation:** $P \underset{L}{\bowtie} Q$
  The components proceed independently with any activities, and each two "co-operands" are required to operate in the co-operation to join for those activities which are specified in the co-operation set: in the process of the component of $P+Q$ represents the main system, $P \underset{L}{\bowtie} Q$ where $L=(\alpha,\beta)$ the processes P and Q must co-operate on activities α and β but any other activities may be executed separately. The reversed compound agent theorem gives a set of sufficient conditions for a co-operation to have a product form stationary distribution. In the PEPA $P \parallel Q$ means the parallel combinator, the more concise notation $P \parallel Q$ to abbreviate for $P \underset{L}{\bowtie} Q$, where $L=\emptyset$.

- **Hiding:** P/L
  The P/L conducts as P except that any activities of types within the set L are hidden. The process P/a hides the activity "a" from view and prevents other processes from joining with it.

- **Constant:** $A \stackrel{def}{=} P$
  A constant, A, is given the behaviour of the component P.

2.2.2 Continuous Time Markov Chain (CTMC).

PEPA has two main semantic interpretations. The first interprets of PEPA is a Continuous-Time Markov Chain (CTMC). The CTMC can be used to evaluate the performance of a relatively small system. Hillston introduces a second characteristic and interpretation of PEPA models, which is an Ordinary Differential Equations (ODEs) [39]. The ODEs approximate a massive discrete-state system as a continuous-state system. In our study, as we do not have a large number of repeated components, we only considered CTMC solution to analyse the behaviour of a system.

A simple example.

We have illustrated the derivation of the Continuous-Time Markov Chain (CTMC) by presenting a simple system in PEPA. Figure 2.10 shows the interpretation example of a PEPA model in which a sender has a task to send a message to a receiver. It shows how the components are interacting. We can derive the balance equations to find the steady state probabilities. This example considers the sender that tries to finish its task and it receives an Acknowledgment (ACK) from the receiver. Both sender and receiver as the two main required components, are staged in this model to processe and communicate the cyclical task via the medium.

Firstly, the sender listens the carrier before sending a message to S_Quiet. *Sender* has two options, either becomes S_Quiet via an action $listen\_S$ with a rate $p*l$, or if the carrier is busy then the sender will wait for a period of time in a state S_Busy in an action $listen\_S$ with a rate

$(1-p)*l$. If the medium is quiet then the sender can take an action and it transmits its message from the state *S_Quiet* with a rate m. Also, in this state the receiver senses the medium to send back an ACK in an action of *ack* with a passive rate $\top$ (to acknowledge the sender that the message has been received). When the medium is busy and the state has a choice to *S_Busy*, then it waits for a while in an action *wait_S* with a rate w to *Sender*. This process is similar in a state of *Receiver*, which it sends a *message* in a rate $\top$ to *Receiver′*. However, *Receiver′* has two options, which can listen the medium in an action *listen_R* with a rate $p*l$ to *R_Quiet*, or in an action *listen_R* with a rate $(1-p)*l$ goes to *R_Busy*. If it has a choice to *R_Quiet*, then an ACK will be sent in an action *ack* with a rate a to *Receiver*. But, if it goes to *R_Busy* then in an action *wait_R* it will wait for a short period of time with a rate w to *Receiver′*. It means if the receiver has successfully received the message, then it will listen the medium to send back an ACK. If the medium is quiet, then the ACK will be sent by the receiver if not it wait for a while. This process will be continued by the sender and receiver by listening to the medium until the medium becomes an idle.

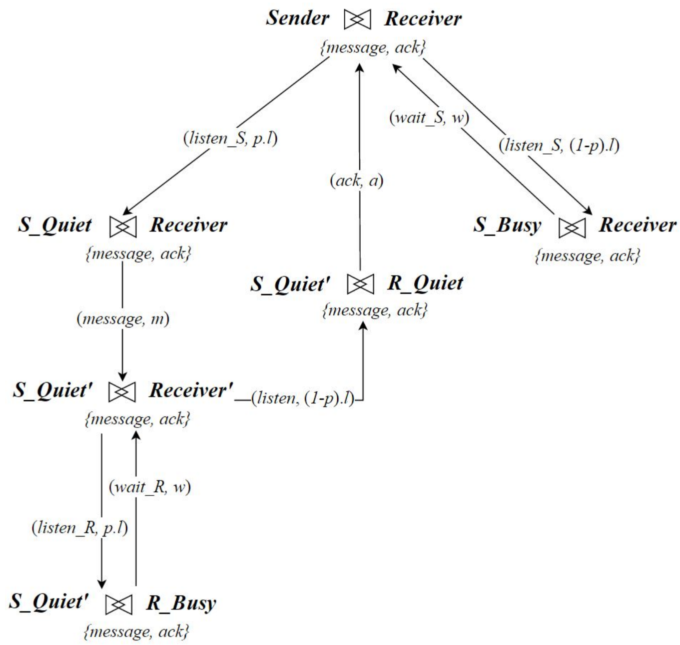


Fig. 2.10 Underlying CTMC of the simple PEPA model of a sender and receiver.

The required and sequential components in this PEPA model:.

$$\begin{aligned}
Sender &\stackrel{def}{=} (listen_S, p*l).S_Quiet + (listen_S, (1-p)*l).S_Busy \\
S_Quiet &\stackrel{def}{=} (message, m).(ack, \top).Sender \\
S_Busy &\stackrel{def}{=} (wait_S, w).Sender \\
Receiver &\stackrel{def}{=} (message, \top).Receiver' \\
Receiver' &\stackrel{def}{=} (listen_R, p*l).R_Quiet + (listen_R, (1-p)*l).R_Busy \\
R_Quiet &\stackrel{def}{=} (ack, a).Receiver \\
R_Busy &\stackrel{def}{=} (wait_R, w).Receiver'
\end{aligned}$$

The complete system: As mentioned either the sender or receiver can use the medium if it is not busy. In the case of occupying the medium by one of them, the other one stops trying to transmit till the medium become idle and vice versa. In this system all components are interacting with the following cooperation set:

$$Sender \underset{K}{\bowtie} Receiver$$

Where $K = \{message, ack\}$.

In this model, the sender and receiver are cooperating over two activities; which are an action *message*, at rate m and an action *ack*, at rate a. This model give rise to a Continuous-Time Markov Chain (CTMC) with six states. The contained nodes in this derivation graph are represented the components and its derivatives. The possible transitions between the corresponding components, action type and action rate are shown in Figure 2.10.

From the above specifications, the steady states can be derived. Let us assume these states of the underlying process can be labelled as x_0,......, x_5, which it can be identified as:

$$x_0 \leftrightarrow Sender \underset{K}{\bowtie} Receiver$$

$$x_1 \leftrightarrow S\_Busy \underset{K}{\bowtie} Receiver$$

$$x_2 \leftrightarrow S\_Quiet \underset{K}{\bowtie} Receiver$$

$$x_3 \leftrightarrow S\_Quiet' \underset{K}{\bowtie} Receiver'$$

$$x_4 \leftrightarrow S\_Quiet' \underset{K}{\bowtie} R\_Busy$$

$$x_5 \leftrightarrow S\_Quiet' \underset{K}{\bowtie} R\_Quiet$$

Denote by π_i the steady state probability of being in state x_i. From this PEPA model and the given specifications with the above states, by using Gaussian elimination, we can find the steady states solution and the global balance equations to find the steady states probability ($\sum_{i=0}^{5} \pi_i$) with the normalisation condition as follows:

$$l\pi_0 = a\pi_5 + w\pi_1$$

$$w\pi_1 = (1-p)l\pi_0$$

$$m\pi_2 = pl\pi_0$$

$$l\pi_3 = m\pi_2 + w\pi_4$$

$$w\pi_4 = pl\pi_3$$

$$a\pi_5 = (1-p)l\pi_3$$

$$\sum_{i=0}^{5} \pi_i = 1$$

Many steady states metrics of interest, such as average throughput and average response time can be found from these steady states probabilities.

2.3 Related work.

2.3.1 Performance analysis of IEEE 802.11 protocols.

The IEEE 802.11 protocols as a standard for WLAN has been studied by many researchers in various terms included power, data rate and message length. Determining the optimum characteristics for transmission in a specific scenario prior to deployment is clearly a problem of considerable practical relevance. There are many simulation techniques and packages which can be used to build or analyse models of Wirelss Local Area Network (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 (see for example [32, 57]) to create an abstract representation of the system, this can be 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 be used to reason about the model behaviour and to derive numerical solutions to predict performance.

Mokdad *et al* [60] studied a Petri Nets model and stochastic automata networks in terms of evaluation the performance of MAC protocol for wireless sensor networks. Patel and Lobiyal in [63] examined an analytical study on the performances evaluation in IEEE 802.11 DCF and backoff procedure in terms of throughput and delay. Furthermore, Maadani and Motamedi in their research proposed an analytical models for IEEE 802.11 DCF mechanism in saturated traffic and noisy industrial applications [53]. Additionally, Maadani and Baseri [52] studied the performance evaluation of OFDM modulation in IEEE 802.11 in different scenarios by examining on computing nodes, packets size, retry limit and delay metrics. However, other researchers used different simulation tools such as NS-3 GloMoSiM or OMNet++ [17] to investigate the performance of networking protocols. Several scenarios have been studied by Baldo *et al* [15] as they have used the NS-3 model of the IEEE 802.11 MAC to present and make a comparison the obtained results from the simulator to the testbed. Hossain *et al* [41] and Weng and Chen [82] used markov chain to study the performance and models of the IEEE 802.11 standard.

The performance of the WLAN protocols scheme has been studied in the literature by examining different methods, metrics and assumptions. There are many performance studies, which have been reported to reduce the different problem of 802.11 standards. As a consequence of the proliferation of protocols, there have been many performance studies considering different properties and issues [11, 65]. Whilst the performance modelling has been employed successfully to evaluate the performance of (current and future) networking systems for many decades (see [66] for a general overview). Understanding the performance characteristics of wireless networks is vital in order to obtain efficient and effective deployments. The system performance in wireless networks has been impacted by different factors, such as packet destination distribution and network topology (it is an arrangement of elements in network, including devices and connection links). Min *et al* [56] discussed these impacts and they have studied and applied a model to investigate the Quality of Service (QoS) performance metrics in an environment that integrates WLAN and wireless mesh. A limitation of their research is that they have only relied to study IEEE 802.16 protocol. But, in our research we have studied how these impacts will affect the performance of IEEE 802.11 protocols.

Likewise, performance evaluation and modelling of the Wireless Local Area Network (WLAN) protocols have been considered in [74] and specifically the IEEE 802.11 DCF for real-time control. This study has evaluated throughput and packet delay under the real-time traffic condition via a mathematical model. There have been many attempts to model different aspects of IEEE 802.11 using a wide variety of methods.

The theoretical analysis method used by Lee [50] to measure error-free and errorprone wireless channel with the higher transmission rate for IEEE 802.11g. Lee only studied the capacity throughput performance and he argued that when the speed of mobile of a station is increased, the throughput is reduced. But, he did not consider the channel utilisation and did not argue for dissimilar scenario with numerous nodes. Vucinic *et al* [78] considered the performance degradation of IEEE 802.11g in terms of access delay for dissimilar nodes and throughput, as they analysed collision probability, channel access delay and throughput. Ho *et al* [40] concentrated on WLAN throughput performance, as they have argued that the best 802.11g OFDM throughput performance can be obtained in specific slow time. Additionally, Kanduri *et al* [45] have studied the structures of IEEE 802.11g in maximum data rate WLANs, as it might increase Wireless Local Area Network (WLAN) requests by users.

Many researchers have studied basic access mechanism, Distributed Coordination Functions (DCF) with Request to Send / Clear to Send (RTS/CTS) and PCF (Figure 2.11 shows the basic access and RTS/CTS methods handshake, see [25, 71, 89]). Scarpa and Serrano [54] have proposed a model to analyse DCF mechanism of the multi-hop CSMA/CA on IEEE 802.11g protocol. They used a Markovian agent model to represent the behaviour of wireless nodes (for the scenario of two interacting wireless stations). In their study they have not considered the interference between nodes and the medium, also numerous nodes have not been studied.

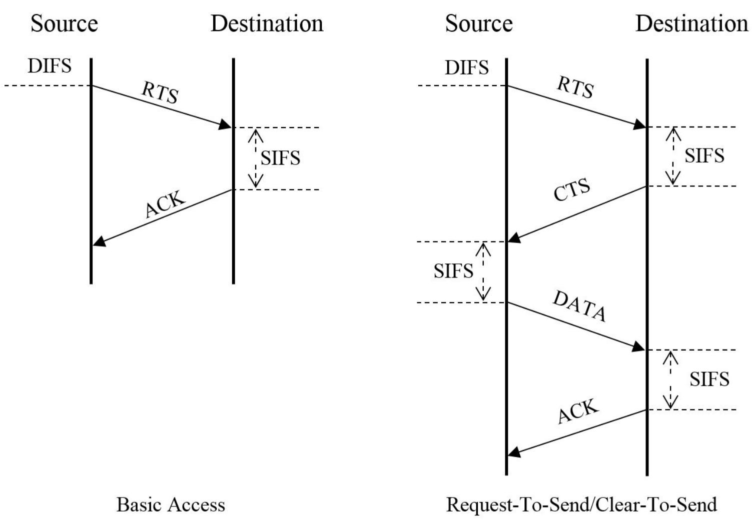


Fig. 2.11 The basic access and RTS/CTS methods handshake with ACK [86, 87].

IEEE 802.11n protocol is slowly replacing the old protocols, although, it still coexists with other protocols, such as IEEE 802.11g. Galloway [30] has studied on the effects of coexisting both IEEE 802.11n and IEEE 802.11g protocols in wireless devices. Many researchers have studied IEEE 802.11n standard in terms of PHY values to increase the higher data rates, and MAC enhancements to reduce overhead via various aspects such as single with multiple rates and Acknowledgment (ACK) with delay ACK [28, 83].

IEEE 802.11n standard, the Multiple-Input and Multiple-Output (MIMO) antenna provides higher speed, wide range and reliability over IEEE 802.11b/g. Hajlaoui *et al* [36] introduced a MIMO-based PHY and Frame Aggregation in the MAC layer. In the terms of fairness, they have investigated the effect of MAC scheme and physical layer features on the adhoc networks performance. In their paper, they concentrated on frame aggregation on the support of voice and video applications in wireless networks, they have claimed that "The frame aggregation mechanism of 802.11n MAC layer can improve the efficiency of channel utilisation by reducing the protocol overheads." Charfi *et al* [19] have studied the analytical model for throughput, QoS provisioning in WLANs and the 802.11n performance for multimedia traffics. The evaluation studied required bandwidth and tolerated delays are therefore satisfied for real-time traffics.

Likewise, performance analysis of, Aggregation-Media Access Chanel Protocol Data Unit (A-MPDU) and Aggregation-Media Access Chanel Service Data Unit (A-MSDU) are used in IEEE 802.11n to reduce the protocol timing overheads, which they have been studied in a literature. Such as, Saif *et al* [68] have studied A-MSDU schemes to analyse the performance of 802.11n, reduces the aggregation headers and implements a retransmission control over the individual subframes. According to MPDU and ACK in the 802.11n, Arif and Sari [13] have studied the analytical model to investigate the throughput values from packets that has been transmitted, in their model they have shown the impact of using frame aggregation of A-MSDU and Block Acknowledgment (BACK) schemes with High Throughput HT-PHY layer.

2.3.2 Hidden node problem.

One well known phenomenon in wireless networks is the hidden node problem [55]. This phenomenon arises when two nodes attempt to transmit which are out of range of one another (and hence cannot detect each other's transmission) but one or both of the intended recipients is within range of both transmitting nodes. Thus, the recipient will only hear the distorted signal created by the interference of the overlaid transmissions and cannot therefore receive the intended message. In the general case, the transmitting nodes will not be able to detect this interference and so will not know that there has been a collision. In some protocols, the receiving node might transmit a jamming signal, which would have the effect of resetting any transmissions. However, it is more likely that the transmitting nodes will only know that their message was unsuccessful because they will not receive an acknowledgement from the recipient. They will then attempt to resend the failed message, with possibly the same outcome. It should be clear that there is no simple way to avoid the hidden node problem and that it may have a significant effect on network performance. As such, modelling situations with hidden nodes is clearly of practical interest.

Figure 2.12 illustrates the hidden nodes problem, from this figure we can see that the node A and C are hidden from each other but not from node B. Thus, node A and C may assume that the channel is free to be used, then both nodes might send packets simultaneously, which it causes the collision, and as both nodes are hidden from each other then they can not detect any collision might occur during transmitting. This causes the channel to be wasted during the period of transmission of external nodes. Despite the popularity of the hidden nodes problem in wireless networks, limited studies have addressed it. IEEE 802.11 DCF in the presence of hidden terminals for each basic access and RTS/CTS modes has analysed by using Markov chain for two-dimensional analytical model by Rakhi and Rishi Pal [44]. Additionally, Younes and Thomas have studied hidden node with IEEE 802.11 DCF MAC protocol in multi-hop ad hoc networks [87] by using SRN (Stochastic Reward Net) models.

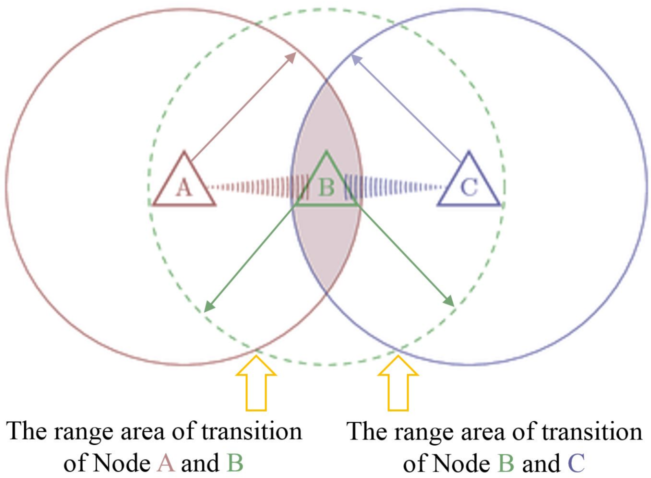


Fig. 2.12 The hidden terminal problem [70].

A small number of analytical studies have been proposed in considering the effect of the hidden nodes on the performance of IEEE 802.11. A simple analytical model has been presented in [81] to derive the saturation throughput of MAC protocols based on Request to Send and Clear to Send (RTS/CTS) method in multi-hop networks. The model was only validated under heavy traffic assumption. In [42] the throughput of the IEEE 802.11 DCF scheme with hidden nodes problem in a multi-hop ad hoc network was analysed when the carrier sensing range is equal to the transmission range. Hou *et al* [43] undertook an analytical study to derive the throughput of IEEE 802.11 DCF with hidden nodes in a multi-hop ad hoc network. The main drawback of this work is that the state of retransmission counter is not taken into account when obtaining the collision probability. Ekici and Yongacoglu [26] proposed an analytical model for IEEE 802.11 DCF in symmetric networks in the presence of the hidden nodes and unsaturated traffic. The model assumes that the collision probability is constant regardless of the state retransmission counter.

Razafindralambo and Valois [67] explored a symmetric hidden terminal scenario to analyse three pairs scenario for four backoff algorithms. The performance of backoff algorithms in multi-hop ad hoc, was evaluated for 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.

2.3.3 Fairness of IEEE 802.11 protocols.

In a computer system, fairness can be used to show that users, devices or applications are receiving a fair share of system resources. For example, in the WLAN system fairness can be determined when all nodes can equally access or share the medium. If one or more nodes has less opportunity to gain access to the medium, then it creates an unfair scenario.

A number of researchers have explored fairness and unfairness in the IEEE 802.11 protocols. For example, Mohamadeou and Othman [58] have investigated the analytical evaluation of unfairness problem in Wireless Local Area Networks (WLANs). In their study they have suggested a new mathematical model to describe the performance and impacts of WLAN dynamic behaviour.

Several studies have considered IEEE 802.11 standards in terms of the rate adaptation scheme, performance of IEEE 802.11 MAC layer, and performance metric systems. Zhai *et al* [88] 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 a function of the probability mass function of the inter-departure interval. Shehadeh and Chasaki have explained that to access the medium for any devices the capacity and fairness are most important for reaching great effectiveness in numerous wireless devices and traffics [69]. Kuptsov *et al* assessed fairness in IEEE 802.11g protocol by studying the backoff and contention window mechanisms [49]. Here poor fairness arises as unsuccessful nodes are obliged to remain unsuccessful in terms of channel access, while the standard backoff protocol allows successful nodes to access the medium successfully for long periods.

Short Term and Long Term fairness have investigated by Kloul and Valois, as they have established performance evaluation of WLAN protocol of fairness to access channel for the communicating pairs in terms of medium utilisation and throughput [46]. It seems, they have only studied few scenarios to investigate the fairness on IEEE 802.11b protocol only and they have not examined other protocols.

Duda [25] has argued that the issue of unfairness, as highlighted in the above research, is a consequence of the manner in which IEEE 802.11b protocol was implemented on early switches and that modifications made to later switches alleviate this problem. However, this does not seem to have been confirmed empirically by any researchers.

2.3.4 Modelling network protocols with PEPA.

Despite the WLAN modelling progress and benefits of using PEPA tool to model and analyse protocols. There are very few examples in the literature where PEPA has been used to study the performance modelling of the IEEE 802.11 family, especially the latest protocol, such as IEEE 802.11n protocol. Argent-Katwala *et al* [12] studied WLAN protocols and performance models of the IEEE 802.11 in terms of its Quality of Service (QoS) based on PEPA. They argued that most of the technologies have been developed to enhance the reliability of computer networks. In wireless communication protocols, security is mandated as it needs in exchanging data, which must be delivered within a specific time. Moreover, they used PEPA to find properties which cannot be easy to find manually in terms of computing quantitative, passage time and increase higher probability for performance demands in wireless communication.

Sridhar and Ciobanu [71] used process algebra and PEPA focused on Distributed Coordinated Function (DCF) within IEEE 802.11, which it uses (CSMA/CA) and backoff mechanism. They described handoff mechanism, quantitative analysis and channel mobility. Kloul and Valois [46] studied performance analysis of the IEEE 802.11b protocol using the Performance Evaluation Process Algebra (PEPA) to develop two models of network topologies which have an effect on the performance of IEEE 802.11b. Particularly, they investigated an unfairness scenario in MANET. In addition, they were interested in system behaviour to measure and investigate the performance of IEEE 802.11b protocol with different scenarios (three pairs scenario is one of them). However, this scenario has studied for the first time by Chaudet *et al* in [20]. Similarly, in our research we have studied the three pairs scenarios. In our study, we have shown that uncertainty of fairness to access the channel for two pairs and unfairness for three pairs scenario in terms of medium utilisation and throughput using the same approach as [46].

Different mechanism and technique have been used to analyse IEEE 802.11n protocol; but, there is no research in IEEE 802.11n standard by using PEPA in the literature. Based on our knowledge, we are the first to study the IEEE 802.11n protocol for the channel throughput, channel utilisation and channel access by process algebra.

2.4 Context of this thesis.

This research has indicated the emphasis of different issues and scenarios to investigate and evaluate the fairness of channel access, due to topographic effects in the layout of communicating nodes under IEEE 802.11 protocols. We have examined dissimilar scenarios by concentrating on the stochastic process algebra PEPA and MAC layer. We have demonstrated performance modelling of WLAN protocols to develop a better understanding the protocol behaviour. The hidden node problem is a first problem that has been analysed in this thesis, as it is a fundamental problem that has an impact on performance of WLAN. In the Chapter 3, we will investigate the performance modelling of IEEE 802.11b and IEEE 802.11g protocols subject to the hidden node problem using PEPA. By studying this phenomenon, we will show that faster transmission yields better maximum throughput and the slower the speed of transmission relative to the IFS duration, the greater the probability of collision in transmission, for the details see our paper [8]. No signal will be detected before transmission in our model of the hidden nodes problem and so if the other node is already transmitting then a collision will definitely occur. Once the collision is detected (the results in a non-delivery which is generally only detectable by the sender through the lack of an acknowledgement) then the node will enter its backoff process in an attempt to avoid a repeated of the collision. In this chapter, we will also present the sensitivity of backoff rate for 802.11g protocol.

After presenting of the analyses of the hidden node problem of IEEE 802.11b and 802.11g protocols in the Chapter 3. Then, the analytical models of the (un)fairness of IEEE 802.11b, IEEE 802.11g and IEEE 802.11n protocols due to pathologic topological effects will present in the Chapter 4, 5 and 6 respectively. Particularly, in our paper [4] we extended the analysis of neighbourhood competition in the IEEE 802.11b protocol. The fairness has been reported on the two pairs scenario, but unfairness has highlighted on the three pairs and four pairs scenario as the central pair(s) has been penalised by external pairs, the details are shown in the Chapter 4 in this thesis. Moreover, in this chapter we will illustrate a fairness metric of channel utilisation for three and four pairs scenario with sensitivity of backoff rate. Finally, we will investigate the sensitivity to geometric assumption, where CW augmented. Additionally, we have extended our study from the IEEE 802.11b protocol to investigate more about the IEEE 802.11g protocol by using PEPA, see our paper [7] and Chapter 5 will present the details.

Two main parts are contained regarding to IEEE 802.11g protocol in the Chapter 5. The first part of this chapter will consider the various deployment scenarios in the 802.11g protocol and it observes that fairness is affected by both transmission rate and frame length. The second part of the Chapter 5 shows our modelled scenario which 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 Carrier Sense Multiple Access with Collision Avoidance (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 its operating environment.

In the second part in the Chapter 5, 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 protocol, including the same average frame lengths. However, by introducing greater variability to the frame lengths, we allow 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 standard. To consider the fairness of three deployment scenarios in IEEE 802.11g protocol see our previously published papers [7, 6]. In addition, fairness metric of channel utilisation for three and four pairs scenario, and sensitivity of backoff rate will present in the both parts of this chapter. Finally, in the second part we will consider to investigate the range of variable frame lengths.

Chapter 6 develops models the topological scenarios of IEEE 802.11n protocol. We will observe (un)fairness issue to analyse the protocol with PEPA by studying frame bursting, including measures aimed at reducing the use of Inter-Frame Spacing to increase its performance. The one pair, two pairs and three pairs scenarios examined by focusing on the number of frame size between central pair and external pairs. We investigated less unfairness in the central pair in comparison to the previous protocols with having larger frames to be sent compared to the external pairs. Finally, we will consider the sensitivity to geometric assumption in two pairs scenario, when a pair has exact frames to be sent.

Finally, Chapter 7 will present the conclusion of this thesis. Specifically, we will summarise our contributions, limitations of our research and recommendations for future study.

2.5 Chapter summary.

This chapter has highlighted the background and related work of IEEE 802.11 networks. This background knowledge allows us to have sufficient understanding of the problem domain leading into subsequent chapters and to provide a rational that can be stated our research problems. Section 2.1 is presented the Local Area Networks (LANs), Wireless Local Area Networks (WANs) and IEEE 802.11 protocols. Also, the WiFi standards, IEEE 802.11 protocols and more precisely the 802.11-1997, IEEE 802.11b, IEEE 802.11a, IEEE 802.11g and IEEE 802.11n protocols have been presented respectively. In addition, OSI model with the IEEE 802.11 DCF MAC protocol and medium access control techniques were considered in this section. Section 2.2 is introduced the Performance Evaluation Process Algebra (PEPA) as the main modelling technique and method that we used in this research. A compositional approach to performance modelling, the syntax of PEPA and Continuous Time Markov Chain (CTMC) with a simple example has been presented in this section. Therefore, Section 2.3 is shown the related work, in order to investigate stochastic process algebra PEPA the relevant studies were presented. Precisely, the prior studies on the performance analysis of IEEE 802.11 protocol is discussed. In particular, the related work of the hidden node problem, and fairness issue of IEEE 802.11 and modelling network protocols with PEPA are shown respectively in this section. Finally, a summary of the context of this thesis has been highlighted in Section 2.4. The next chapters will use these presented knowledges to analyse and study the WLAN protocols. The next chapter will present our experimental study on a PEPA model of the hidden node problem, that it is developed for IEEE 802.11b and IEEE 802.11g protocols. This will further explore the performance of IEEE 802.11 protocols subject to the hidden node phenomenon using the stochastic process algebra PEPA.

Chapter 3

A PEPA model of IEEE 802.11b/g of the hidden node problem

3.1 Introduction.

This chapter presents the effect of the hidden node problem in WLANs. This is a well known phenomenon in WLAN, this problem occurs where a receiver can detect transmissions from two separate senders that are out of range of each other. Hence the senders are unable to detect the presence of each other's transmission and are hence unable to avoid a collision at the receiver.

This chapter explores a model of the hidden node problem in the IEEE 802.11b and 802.11g protocols, where access is controlled by the Distributed Coordinated Function (DCF). IEEE 802.11b and 802.11g protocols uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to try to minimise the occurrence of collisions between simultaneously transmitted data. However, CSMA/CA is only effective when nodes can detect other transmitting nodes, which is not the case if a competing node is out of transmission range of the sender, but within the interference range of the receiver. Hence, in our model no signal will be detected before transmission and so if the other node is already transmitting then a collision will definitely occur. Once the collision is detected (through the lack of an acknowledgement) then the node will enter its backoff process in an attempt to avoid a repeated of the collision.

Clearly, if each transmitting node cannot sense the other then collisions are inevitable and consequently bandwidth is wasted and there is an impact on performance. The purpose of this chapter is to analyse the performance of IEEE 802.11b and 802.11g protocols subject to the hidden node problem by using PEPA. In this chapter, we will describe that faster transmission provide better maximum throughput and the slower the speed of transmission relative to the IFS duration, the greater the probability of collision in transmission. The model in each version of the protocol uses the same method but differs in its transmission rates and Inter-Frame Spacing. We have compared the obtained results from IEEE 802.11b protocol with those from IEEE 802.11g protocol and show some interesting similarities in performance profiles. Finally, we will illustrate the sensitivity of backoff rate for 802.11g protocol in this phenomenon.

3.2 PEPA models of IEEE 802.11b/g of the hidden node.

In this section, a specific scenario is presented to model the hidden node problem as illustrated in Figure 3.1, and collision rate for each of the IEEE 802.11b and IEEE 802.11g protocols. In this scenario, node `A1` is attempting to send to node `A2` and node `B1` is attempting to send to node `B2`. `A1` and `B1` are outside each other's transmission range, however `A2` and `B2` can both detect frames sent by both senders. Hence if both `A1` and `B1` send simultaneously neither receiver will be able to successfully receive the data. The same issue does not arise if `A2` and `B2` are sending as they sense transmission from all other nodes.

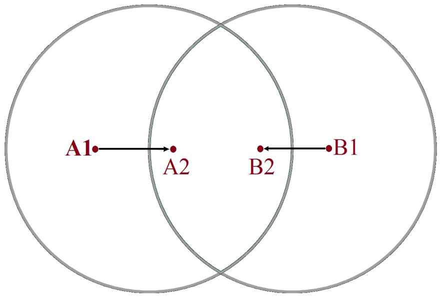


Fig. 3.1 The hidden node problem [70].

3.2.1 Hidden node problem with a PEPA model.

We modeled the hidden node scenario shown in Figure 3.1 as `PairA` and `PairB` can interact over a transmission medium called `MediumS`. An analytical study has been presented by Kloul and Valois [46] to better understand similar problem "the hidden nodes problem", as they have evaluated the behaviour of IEEE 802.11 standards in terms of channel utilisation and channel throughput for the pairs are attempting to access the medium. In this research, we have extended the performance study from one scenario to many scenarios in resent protocols. Kloul and Valois [46] only examined the 802.11b, but we are investigated 802.11g too, and compared the obtained results to 802.11b. Our study in 802.11g will show that the findings in 802.11b are still relevant to 802.11g. The issues in 802.11b can still be found in our analyses in 802.11g and new protocols, for instance changing speeds in 802.11g will impact on results in our scenarios, such as hidden node problem. We have interested on channel utilisation, throughput and probability of transmission as particular metrics for the pairs are attempting to access the medium. We have selected these metrics to study the performance of 802.11 protocols, as we have focused on these metrics to use the same approaches of [46]. We have examined the channel utilistion and throughput as well-known system metrics, which several studies and models were used the same metrics. We have used it as an abstract not details models. More details metrics might be useful by other methods. Other metrics could be examined, but for our abstract model the throughput and utilisation metrics are useful keys to study the performance of the system.

Our hidden node scenario is not free of collision and it happens when a pair attempts to transmit simultaneously (as they cannot sense each other). While the first node is "listening" on the network it can access the channel as it is free to send any frames, meanwhile, the second node cannot sense the medium is occupied by the first one as its "hidden". When `PairA` attempts to transmit and access the medium, the `PairB` is hidden from it, so `PairA` cannot receive an acknowledgement, in this situation `PairA` starts to retransmit the frames after resizing the contention window. When a collision occurs and `PairA` waits or resize the Contention Window (CW) for a period of time in case if the channel is busy till its free to be used.

In this scenario we can see, that if node `A2` sends any frame to node `A1`, and if `A1` and `B1` are the only hides then they can never detect transmission from each other, hence to each of them medium will appear to be free and they can therefore transmit. The hidden node will also be detected by the lack of acknowledgement.

The specifications of the hidden node presents in the following for `PairA`, `PairB` and `MediumS`. As, we have described in the above and in our model any pairs of nodes are attempting to transmit a frame and use the medium. The model in the following shows, if Pair A tries to use the medium or send any frames, firstly the `PairA` starts with a crucial action to backoff at the rate `r` to `PairA0`. Afterwards, the `PairA0` begins to count the *DIFS* at the rate μ_{difs} to `PairA1`. Then, `PairA1` has a choice of either start count backoff at the rate $p\mu_{bck}$ and stay at the `PairA1` or end the backoff to the `PairA2` at the rate $q\mu_{bck}$. If `PairA1` state has a choice to `PairA2`, then the frame transmits at the rate μ_{data} to `PairA3`, and `PairA3` will count *SIFS* at the rate μ_{sifs} to `PairA6`. Finally, after the frame is transmitted successfully, then an Aacknowledgement *ACK* will be received in `PairA6` at the rate μ_{ack} and the process will start again from `PairA`, in a case of collision then the `PairA6` proceeds the collision action or resize the action at the rate `s` to `PairA`. In this model, the second pair of node (`Pair B`) has similar process to the same mentioned pair of node (`Pair A`).

The specifications of sequential components process of Pair A and Pair B shows as follows:

$$
\begin{aligned}
PairA &\stackrel{def}{=} (draw\_backoff, r).PairA0\\
PairA0 &\stackrel{def}{=} (count\_difs, \mu_{difs}).PairA1\\
PairA1 &\stackrel{def}{=} (count\_backoff, p\mu_{bck}).PairA1 + (end\_backoff, q\mu_{bck}).PairA2\\
PairA2 &\stackrel{def}{=} (transmit, \mu_{data}).PairA3\\
PairA3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).PairA6\\
PairA6 &\stackrel{def}{=} (ack, \mu_{ack}).PairA + (collision, \top).(resize\_W, s).PairA
\end{aligned}
$$

$$
\begin{aligned}
PairB &\stackrel{def}{=} (draw\_backoff, r).PairB0\\
PairB0 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).PairB1\\
PairB1 &\stackrel{def}{=} (count\_backoffB, p\mu_{bck}).PairB1 + (end\_backoffB, q\mu_{bck}).PairB2\\
PairB2 &\stackrel{def}{=} (transmitB, \mu_{data}).PairB3\\
PairB3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).PairB6\\
PairB6 &\stackrel{def}{=} (ackB, \mu_{ack}).PairB + (collision, \top).(resize\_W, s).PairB
\end{aligned}
$$

Component (`MediumS`): The medium can be used by `Pair A` and/or `Pair B`. If both nodes are attempted to transmit a frame and occupy the medium simultaneously then collision occurs, because both nodes are out of range of each other. The medium specifications shows, that the `MediumS` represents the situation where the medium is unoccupied. `MediumS1` represents the medium being used by the `Pair A`, `MediumS2` represents the medium being used by the `Pair B` and `MediumS3` represents the collision occurs due to any interference at the rate `rc`. The medium specifications are shown in the following as it can be used by each pair.

$$\begin{aligned}
MediumS &\stackrel{def}{=} (transmit, \top).MediumS1 + (transmitB, \top).MediumS2 \\
MediumS1 &\stackrel{def}{=} (ack, \top).MediumS + (transmitB, \top).MediumS3 \\
MediumS2 &\stackrel{def}{=} (transmit, \top).MediumS3 + (ackB, \top).MediumS \\
MediumS3 &\stackrel{def}{=} (collision, rc).MediumS
\end{aligned}$$

The complete system: In this model all components are interacted with this cooperation sets by:

$$Set \stackrel{def}{=} ((PairA) \underset{K}{\bowtie} PairB) \underset{L}{\bowtie} MediumS$$

Where, $K = \{collision\}$
And, $L = \{transmit, ack, transmitB, ackB, collision\}$

3.3 Parameters

This section will present the parameters that have been used in this study to examine the model of the hidden node problem. Inter-frame spacing time is very specific in the IEEE 802.11 standards, as it coordinates access to the medium to transmit frames. According to the IEEE 802.11 definition, the data rate per stream are 1, 2, 5.5, and 11 Mbit/s in IEEE 802.11b and 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s in IEEE 802.11g standard (see [25, 45, 85] for more details). In this study, we have studied the 1, 2, 5.5, and 11 Mbit/s for 802.11b and considered the 6, 12, 36 and 54 Mbit/s as a sample of data rates for 802.11g. Once a pair attempts to transmit and if it senses that the channel is free to be used, then it will start to transmit with a probability of 'p'; in our research the values of 'p' and 'q' have assumed to 0.5, where (q=1-p). In our scenario, each pair has count backoff and end backoff actions with ($p \times \mu_{bck}$) and ($q \times \mu_{bck}$) rates respectively.

In IEEE 802.11b standard, the data rate per stream are 1, 2, 5.5, and 11 Mbit/s, which are equal to 125000, 250000, 687500 and 1375000 Bytes/s respectively. Moreover, in the current chapter and the Chapter 4 and 5, these rates have been applied with each of packet payload size 700, 900, 1000, 1200, 1400 and 1500 Bytes to analyse the models. Particularly, in our models, the packets per time unit for arrival and departure rates are λoc = 100000 and μ = 200000 respectively; these are the same values that have been used in [46].

Furthermore, the WLAN is use the CSMA/CA for collision avoidance, it has crucially been used for performance improvement and precisely for sharing the medium equally or other phenomena, such as hidden node problem. In the following sub sections, three techniques *(IFS, CW and ACK)* are presented which they are required to process transmitting and receiving frames.(for more details go back to the Chapter 2).

Inter-Frame Space (*IFS*). The IEEE 802.11 specifications are a giant system of timers. Before each frame transmits, the length of the Inter-Frame Space is dependent on the previous frame type, the require *IFS* is applied if noise occurs. Possibly, when transmitting of any particular frame ends and before another one starts, the *IFS* can apply a delay for the channel to stay clear as smallest number. It is an essential idle period of time needed to ensure that other nodes may access the channel. The main purpose of an *IFS* is to supply waiting time for each frame transmission in a particular node, to allow the transmitted signal to reach another node (essential for listening). IEEE 802.11 protocols have deal with several IFS: Short Inter-Frame Space *SIFS*, Distributed Inter-Frame Space *DIFS*, Extended Inter-Frame Space *EIFS* and slot time, see [22, 25, 40] and [84].

Short Inter-Frame Space (*SIFS*). *SIFS* in IEEE 802.11 protocols is an Interframe Spacing prior as a minimum *IFS* for highest priority transmissions used with DCF, measured by microseconds (μs). It is important in IEEE 802.11 networks as a fixed and shortest value to better process a received frame. *SIFS* is equal to $10\mu s$ in IEEE 802.11b/g/n protocols family.

***DCF* Inter-Frame Space (*DIFS*).** As an acronym of Distributed Coordination Function (DCF) Interframe Spacing time, 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 period of time (*backoff*).
DIFS = *SIFS* + (2 $\times$ (slot time = 20 μs in IEEE 802.11b/g/n protocols)).

Extended Inter-Frame Space (*EIFS*). When the node can detect the signal but the *DIFS* is not functioning for sending next frame during collision or erroneous frame transmission, the transmission node is using Extended Inter-Frame Space *EIFS* instead of *DIFS*, (used with erroneous frame transmission). It is the longest of the *IFS*, but has the lowest priority after *DIFS*. *EIFS* (in *DCF*) can derive by:
EIFS = *SIFS* $+$ *DIFS* $+$ transmission time of ACK frame at lowest basic rate.

Contention Window (*CW*). According to CSMA/CA mechanism (see Chapter 2 for more information), if a node wants to transmit any frame, it senses whether the channel is free or not. If it is free then the node transmits, if not the node waits for a random time backoff, it is selected by node from a Contention Window (*CW*), until it becomes free (the *CW* observes the backoff interval once channel is busy). The node waits to minimise any collision once it experiences an idle channel for an appropriate *IFS* (otherwise many waiting nodes might transmit simultaneously). The node needs less time to wait if there is a shorter backoff period, so transmission will be faster, unless there is a collision. Backoff is chosen over [0, *CW*], and *CW* = $CWmin$ for all station or nodes if a node successfully transmits a frame and then receives an *ACK*. In the non-transmission case, the node deals another backoff, with each unsuccessful transmission it increments exponentially by multiplication of 2 at every retransmission for the same frame, this attempt and *CW* increases exponentially until it reaches $CWmax$. Finally, the *CW* resets to $CWmin$ when the frame is received properly. *CW* and backoff can be found as follows:
In the IEEE 802.11b, the $CWmin$ = 31, but in 802.11g $CWmin$ = 15, and $CWmax$ = 1023. $CWmin$ augmented by 2n-1 on each retry.
Backoff Time = (Random () mod ($CW+1$)) $\times$ slot time, where the slot time = $20\mu s$
If Backoff Timer = b, where b is a random integer, also $CWmin \leq b \leq CWmax$

By using the mean of CW we can calculate μ_{bck}, where $\bar{CW} = 15.5$ in 802.11b and 7.5 in 802.11g:

$$\mu_{bck} = \frac{10^6}{\bar{CW} \times \text{ slot time}}$$

Data rates and ACK. An ACK as a precaution action that the frame has been received successfully sends by a receiver when it gets the frame. In the presented model, the ACK rate of each frame denoted by μack. The ACK in 802.11b is deal with data rate 1, 2, 5.5. and 11 Mbit/s, which each μ_{ack} is equal to 1644.74, 3289.5, 9046.125 and 18092.25 Bytes/s respectively. Similarly, the ACK in 802.11g deals with data rate 6, 12, 36 and 54 Mbit/s, If μ_{ack} = 1644.75 for 1 Mbit/s data rate then for 6 Mbit/s data rate is equal to 9868.5 (6 × 1644.75). Consequently, in 802.11g each μack is equal to 9868.44, 19736.88, 59210.64 and 88815.96 respectively. μ_{ack} can be obtained by:

$$\mu ack = \frac{\text{channel throughput}}{(ACK \text{ length})}$$

A rate of waiting action ($\mu data$) for frames can be found as follow if ACK length = 1 Byte:

$$\mu data = \frac{\text{data rate } \times \frac{10^6}{8}}{\text{packet payload size}}$$

3.4 Results and discussions of the hidden node problem in IEEE 802.11b/g.

The proposed PEPA model in the Section 3.2.1 for hidden node problem (in our mentioned scenario) has been applied for both IEEE 802.11b and IEEE 802.11g protocols. From this model we have obtained each of the channel utilisation rate, probability of transmission, channel throughput and collision probability in each case.

First, we analysed the channel utilisation rate in our PEPA model, as has been found in the both pairs (Pair A and Pair B) for each protocol by the following formula:

Channel utilisation= Pr[MediumS and (Pair A2 or Pair B2)] + Pr_1 + Pr_2 + Pr_3

Where Pr_1=Probability[MediumS1]

Pr_2=Probability[MediumS2] and

Pr_3=Probability[MediumS3]

Figure 3.2 shows the channel utilisation rate for IEEE the 802.11b protocol. The channel is almost completely saturated for slow transmission speeds, but for faster transmission speed there is a fair amount of unused capacity. This is because the Inter-Frame Spaces are fixed for all transmission speeds and they have to be long enough to cope with the slowest transmission rate. Therefore in our model, which aims to show maximum channel utilisation rate for two nodes, in the IEEE 802.11b protocol the 1 Mbps transmission speed is almost completely using the medium, whereas for faster transmission rates some capacity will be wasted due to the waiting set for slower transmission.

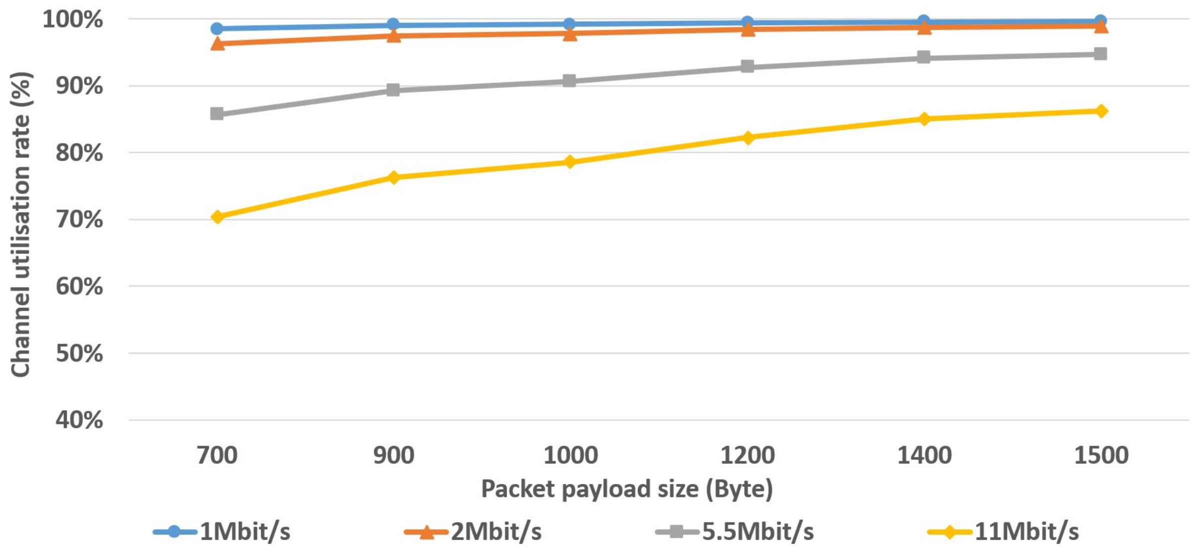


Fig. 3.2 Channel utilisation rate for both pairs in IEEE 802.11b.

Clearly, the results of the hidden node scenario shows that the channel utilisation rate will increase as the packet payload size increases. It is clear that this increase in the channel utilisation is simply because the ratio between transmitting and waiting reduces as each transmission takes longer. Moreover, a very similar profile is shown in Figure 3.3 for IEEE 802.11g protocol, although the channel utilisation rate here is not quite as high. Again the slower transmission rates and longer frame lengths create more channel utilisation as the ratio between transmitting and waiting is increased.

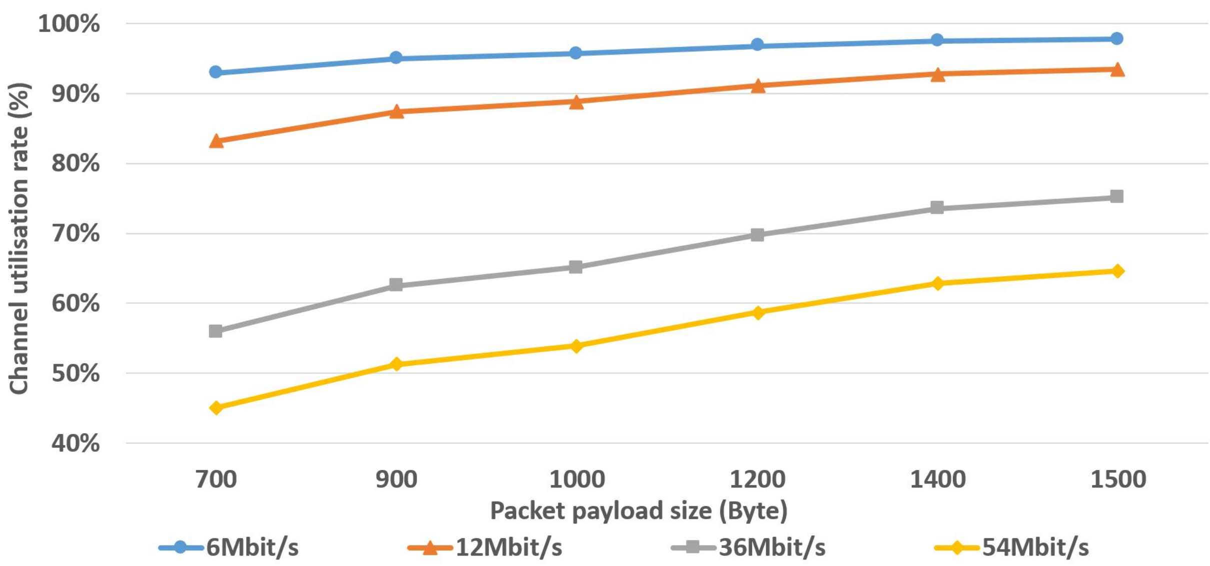


Fig. 3.3 Channel utilisation rate for both pairs in IEEE 802.11g.

Figures 3.4 and 3.5 present the probability of transmission for the IEEE 802.11b and IEEE 802.11g protocols respectively. As one would expect, each figure shows a similar profile to the channel utilisation rate, but slightly reduced as the transmission rate increases. What is slightly surprising in our obtained results is that for the fastest shorted frames in the IEEE 802.11g protocol, only around 36% of capacity is being used successfully in this protocol. This is due to the number of collisions experienced.

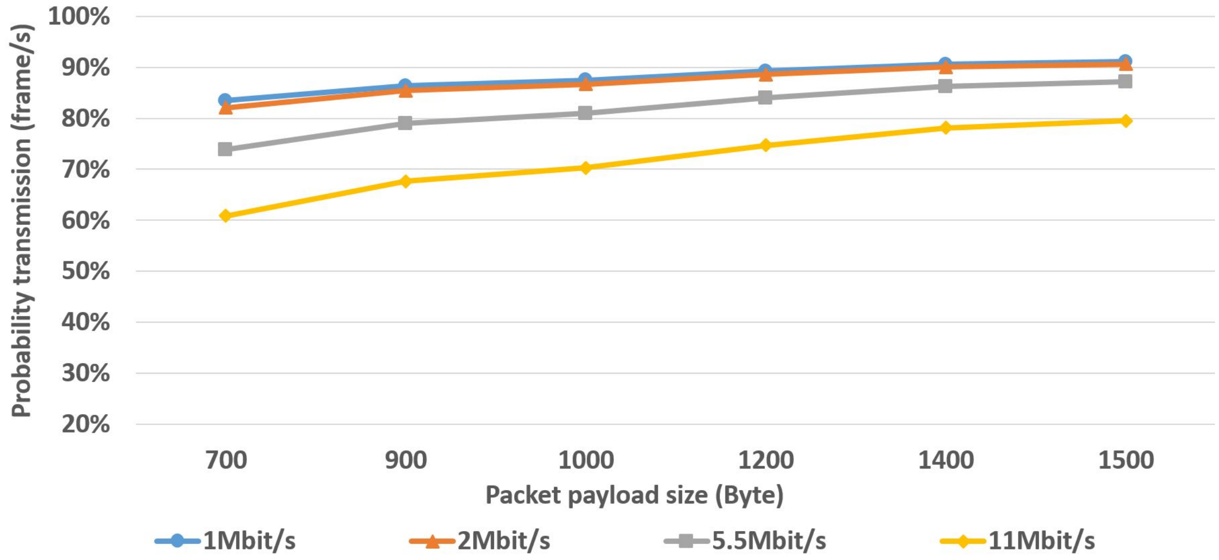


Fig. 3.4 Probability transmission for both pairs in IEEE 802.11b.

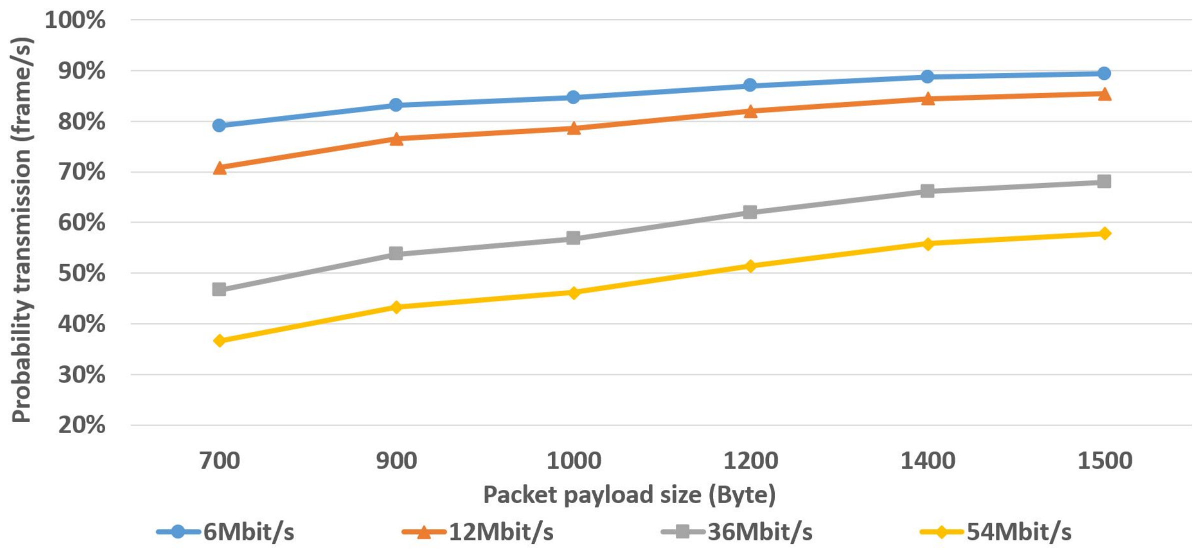


Fig. 3.5 Probability transmission for both pairs in IEEE 802.11g.

We have also examined the channel throughput, which decreases as the packet payload size increases. The channel throughout is shown in Figures 3.6 and 3.7 for the IEEE 802.11b and IEEE 802.11g protocols respectively. However, we can clearly see that the faster the transmission rate the higher the channel throughput, despite the lower transmission probability we have observed in Figures 3.4 and 3.5. Quite clearly the fast transmission rates allow more data to be sent in less time, despite the apparent inefficiencies of the Inter-Frame Space *IFS* at higher rates.

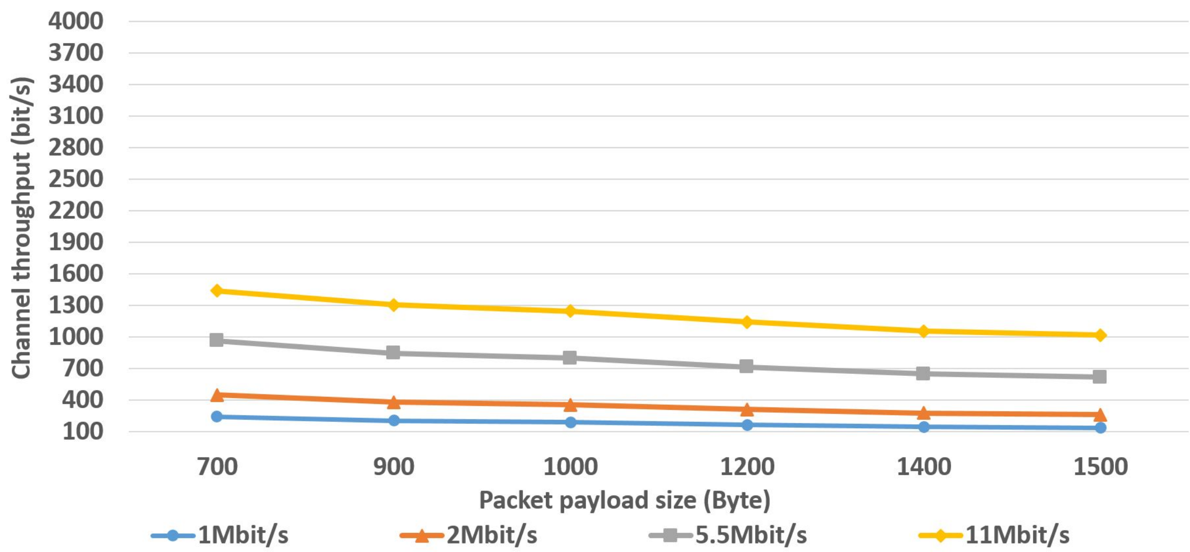


Fig. 3.6 Channel throughput rate for both pairs in IEEE 802.11b.

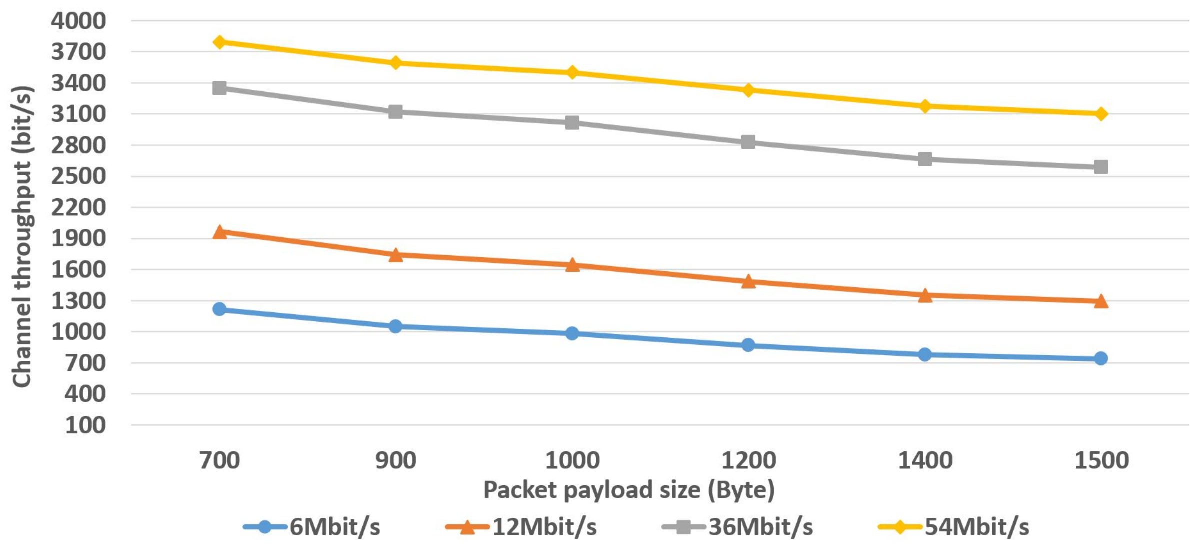


Fig. 3.7 Channel throughput rate for both pairs in IEEE 802.11g.

Finally, we studied the probability of collision in Figures 3.8 and 3.9. Again we can see very similar profiles for the IEEE 802.11b and 11g. Here, we observed that the probability of collision is much greater for slow transmission speeds, which also helps to explain some of the lower throughput shown in Figures 3.6 and 3.7. Slightly counter-intuitively the collision probability reduces as frame length increases. One might think that longer transmissions are more likely to be interrupted by a transmission from a hidden node, but this does not seem to be the case. One reason for this is that at this high load more short frames would be transmitted than long ones, so there are more frames which can collide. This effect is particularly noticeable when the transmission speed is relatively low. Thus, when the transmission speed is high the ratio between transmission and waiting (*IFS*) is relatively low (hence, the lower utilisation rate that we have already observed), as a consequence, there is more time when the other node is not transmitting and so the chance of collision is reduced. At higher transmission rates the difference between long and short frames makes much less difference than when the transmission rate is low.

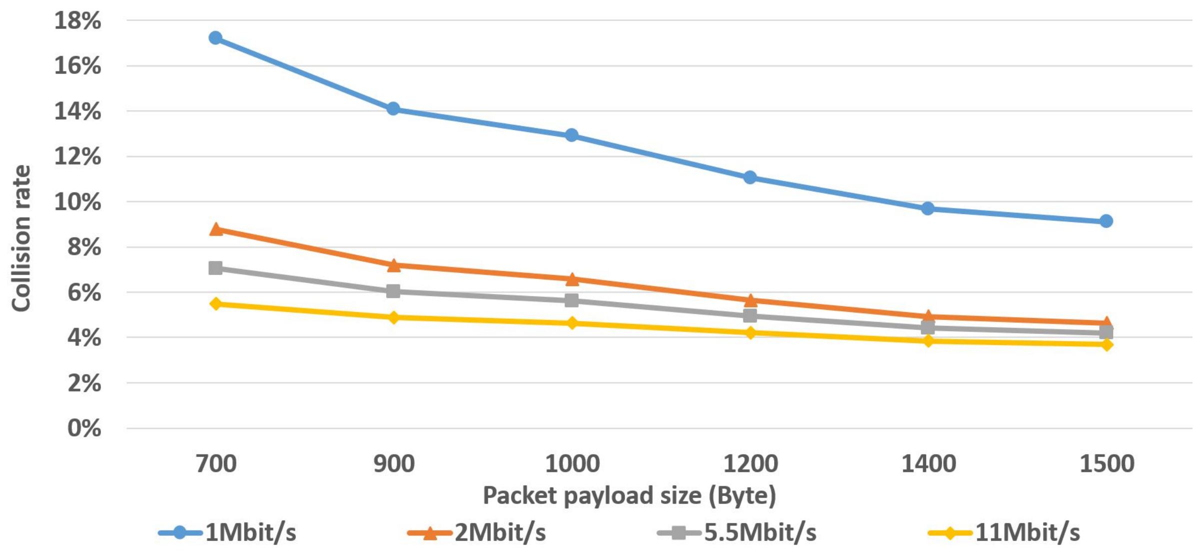


Fig. 3.8 Probability of collision of transmission in IEEE 802.11b.

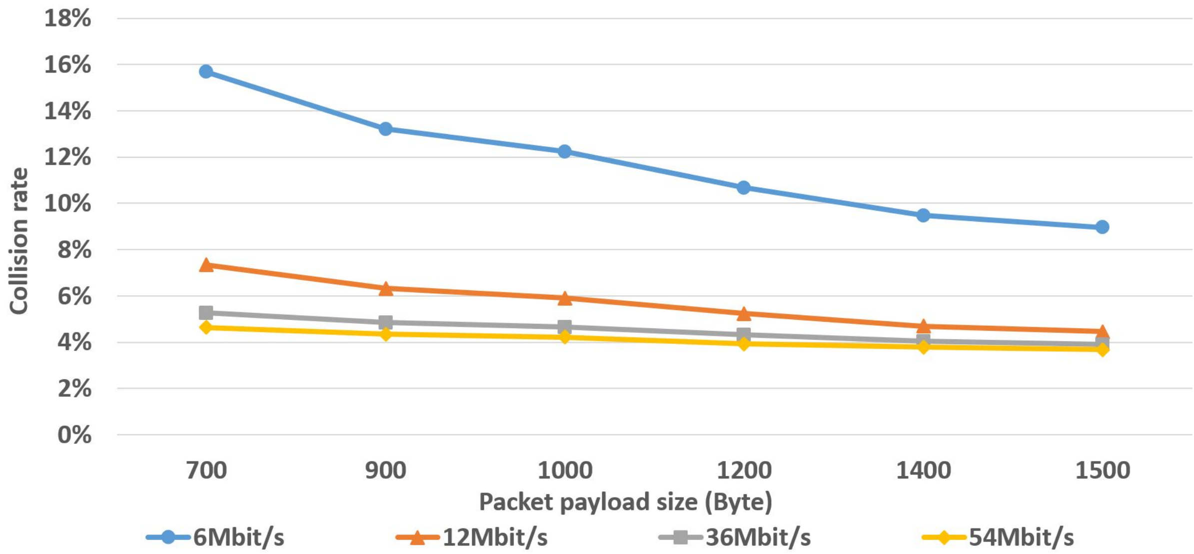


Fig. 3.9 Probability of collision of transmission in IEEE 802.11g.

3.5 Sensitivity to backoff rate at 20.

This section will present the performance results of the hidden node scenario in 802.11g, when backoff rate is 20. We examined the low load of backoff (r=20), to investigate how the low load will impact the channel utilisation, probability of transmission, channel throughput and probability of collision, see Figures 3.10 to 3.13. The sensitivity of backoff will affect the performance of 802.11g in this scenario, for instance the channel utilisation and channel throughput will be massively lower (when the load is low r=20) compared to the previous case (when the load is high r=200000).

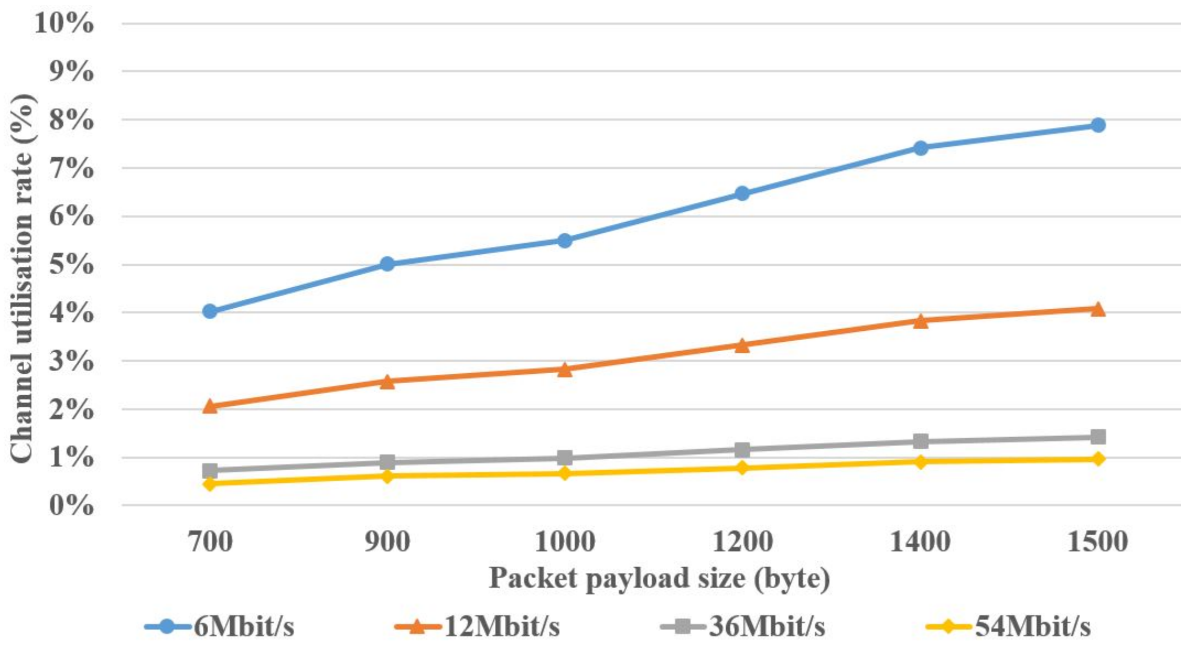


Fig. 3.10 Channel utilisation for both pairs in 802.11g, when backoff = 20.

Figure 3.10 shows the channel utilisation for both pairs in 802.11g, when backoff rate is 20. The channel utilisation will increase by increasing the packet payload size. The slow speed in transmission will present higher utilisation with longer frame lengths, as the proportion between transmitting and waiting is increased. The low load of backoff rate (r=20) slightly affects the utilisation, relatively to the transmission's speed. As, our new backoff is very low (r=20) then the affection of low load of backoff appeared on utilisation. If we compare the result of 6 Mbps when packet payload size is 700 and r is 20 to the same speed when r=200000, then we can see that it is 95.67% when r=200000. In general, the channel utilisation presents similar trend, but it is much lower when r=20 compared to the channel utilisation when r=200000.

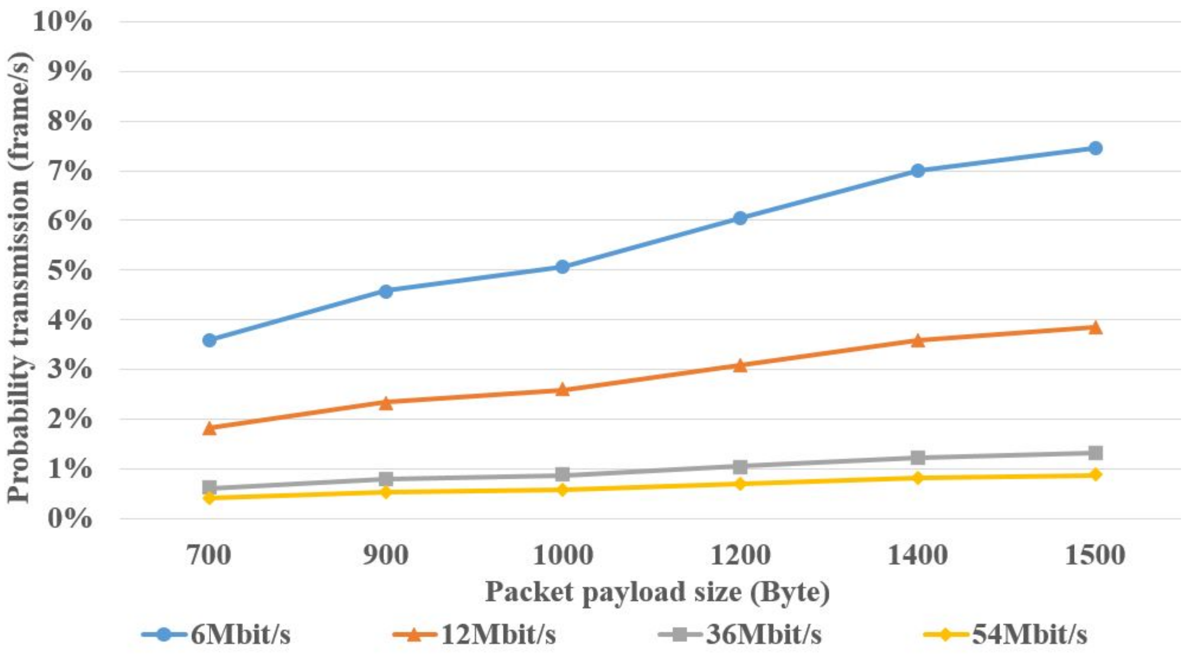


Fig. 3.11 Probability transmission for both pairs in 802.11g, when backoff = 20.

The probability of transmission in 802.11g when backoff is 20, has similar profile of the probability of transmission when backoff rate is 200000. But in this case when r=20, then the probability of transmission massively drops down. The probability of transmission in the slowest speed (6 Mbps) is less than 4%, when packet payload size is 700. Hence, the low rate of backoff will affect the probability of transmission. The experimental study of low load shows, that the collision will increase and the node will experience more waiting time and waste more of its capacity in the low load of backoff rate (r =20), see Figure 3.11.

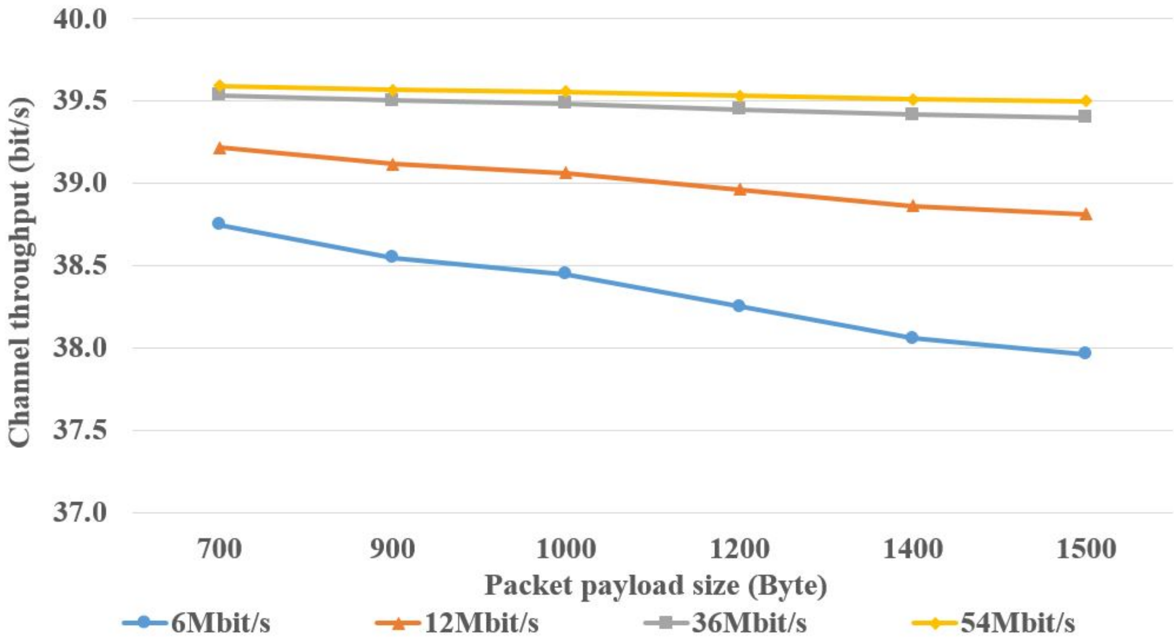


Fig. 3.12 Channel throughput rate for both pairs in 802.11g, when backoff = 20.

Figure 3.12 presents the total throughput of both pairs in 802.11g. It shows the throughput has significantly decreased, when r=20 compared to the throughput when r=200000. Thus, there would be less request in a low load case of backoff rate. As, we have obtained 5% reduction in 6 Mbps, when the packet payload size is 700. However, the affections of low load of backoff will slightly appear on 54 Mbps (fastest speed), when the packet payload size increases, because the transmission is very fast, which low rate will not massively impact in this speed.

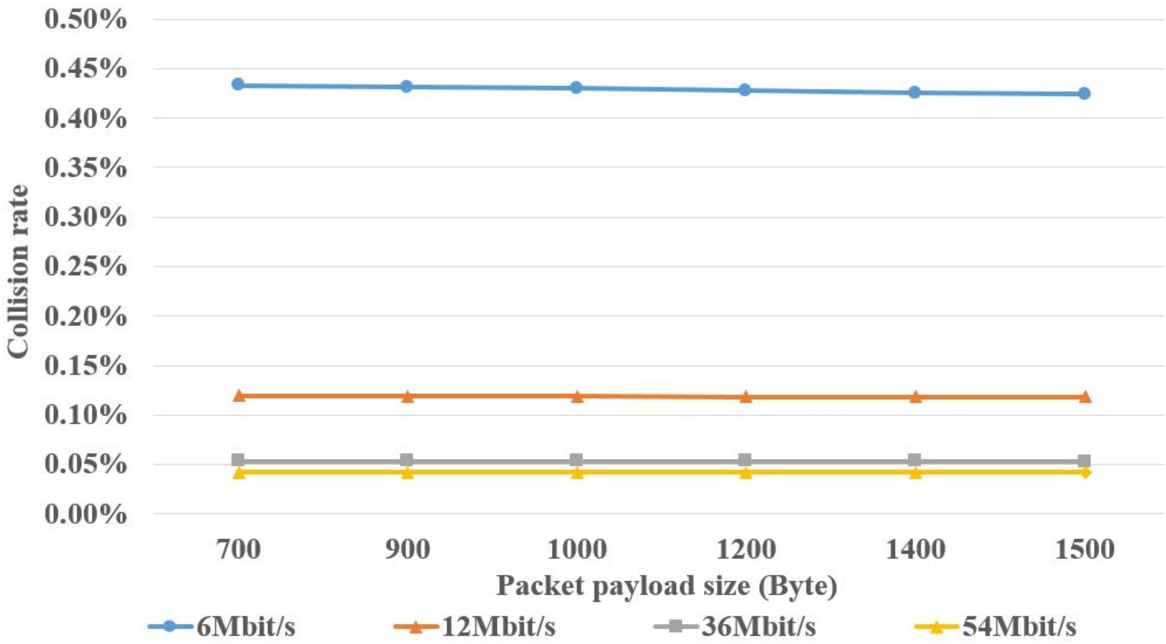


Fig. 3.13 Probability of collision of transmission in 802.11g, when backoff = 20.

Finally, the probability of collision is shown in Figure 3.13, and this collision is much higher in the slowest speed (6 Mbps). From this figure we can see that, everything happens in a very slow transmission, and the slow backoff rate will significantly affect the probability of collision. Also, the probability of collision at 34 and 56 Mbps are very similar, which is about 0.05% on both speeds. However, this figure shows the probability of collision will not be highly affected when the packet payload size increases, this is because the arrival rate is very small (r=20) and it will not have high affections on packet payload size.

3.6 Sensitivity to backoff at 20, 200, 2000 and 20000

In this section, we varied the backoff rate, from low to high rates. We investigated how the variability of backoff will impact the channel utilisation, probability of transmission, throughput and probability of collision. We have examined the backoff rate at 20, 200, 2000 and 20000 in 802.11g for 6 Mbps. From Figures 3.14 to 3.17 we can see that there is less change, when the backoff will increase from 20 to 2000. Also, the results of r=2000 are more similar to the results of r=200000 (see our experimental results in the Section 3.4). In this study, we specifically considered the very essential and very small rate in backoff rate r=20, in comparison to r=200000. We have obtained around 5% reduction of the channel utilisation in 6 Mbps, if the packet payload size is 700 and r=20, in comparison to the same speed when r=200000. But, we have obtained a massive dropping when r=200 compared to r=200000, which is around 40% (because there is less traffic in r=200). The following equation has used to find the relative utilisation, which is the same for relative throughput.

$$\text{Relative utilisation} = \frac{\text{Channel utilisation of r=200000 - Channel utilisation of r=ri}}{\text{Channel utilisation of r=200000}}$$

Where r_i = 20, 200, 2000 and 20000 .

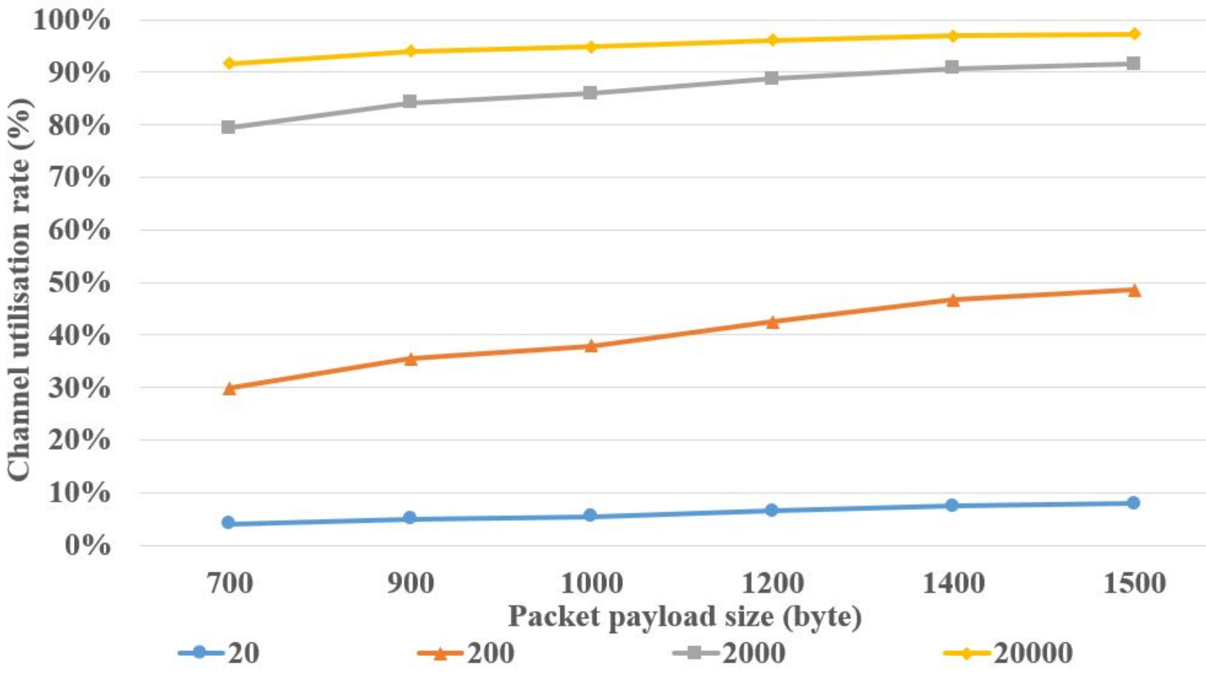


Fig. 3.14 Utilisation of both pairs in 802.11g for 6 Mbps (r=20, 200,2000 and 20000).

Figure 3.14 demonstrated the channel utilisation in IEEE 802.11g for the slower speed (6 Mbps), when the backoff rate has been varied, as we have studied r_i=20,200,2000, and 20000. This figure shows the channel utilisation will increase, when we increase the packet payload size by increasing the backoff from 20 to 20000. Here, we can understand if backoff rate r=20000, then the channel utilisation is almost present the same utilisation as r=200000 (as it has been presented it in 3.4).

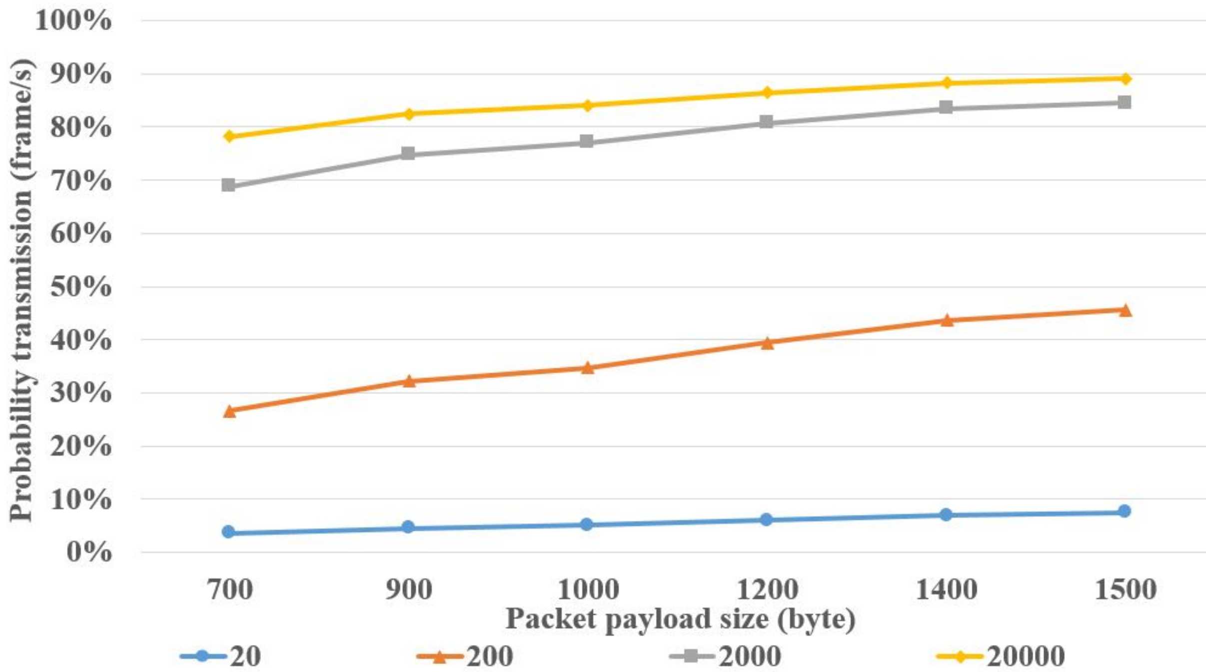


Fig. 3.15 Probability transmission of 2 pairs in 802.11g for 6 Mbps (r=20,200,2000 and 20000).

Figure 3.15 presents the probability transmission in 802.11g for the speed of 6 Mbps, when the backoff rate has been varied from 20 to 20000. The probability transmission will increase by increasing the packet payload size, when the backoff will increase too. This figure shows the backoff will be significantly affected the probability transmission in a low load of backoff (r=20). Thus, the probability transmission will increase by increasing the backoff. This increase in backoff have affected more in 6 Mbps compared to other speeds, as everything is happening slowly in this speed, and this backoff is very slow.

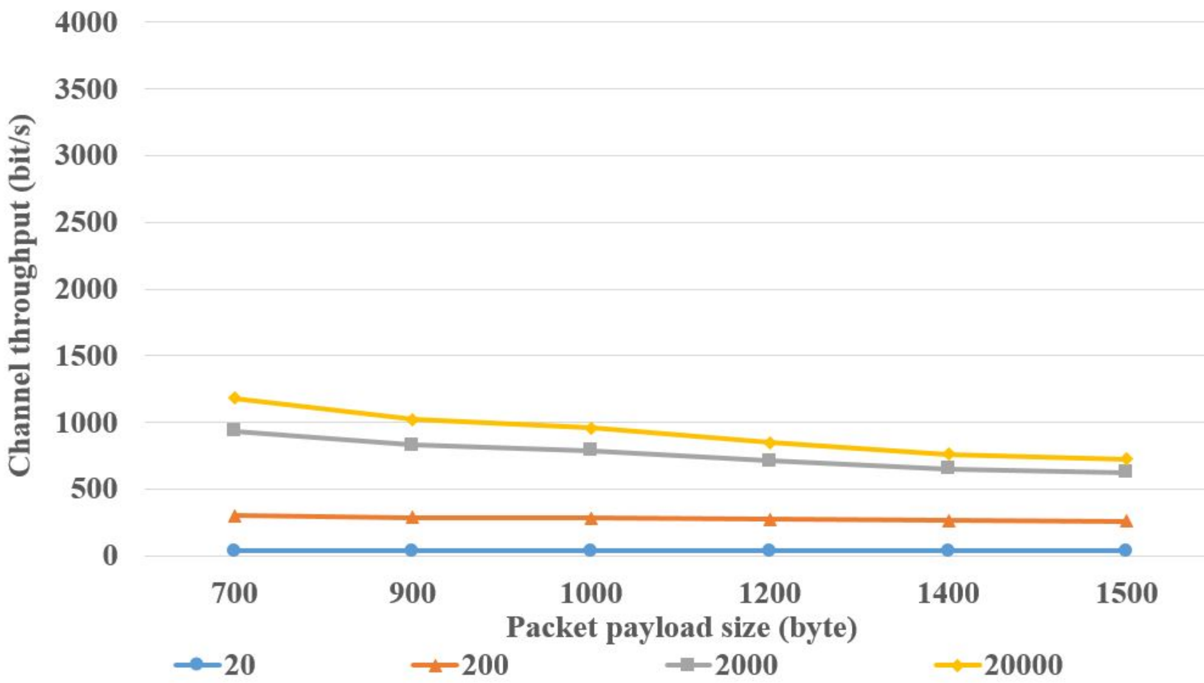


Fig. 3.16 Throughput in 802.11g for both pairs of 6 Mbps, when r=20,200,2000 and 20000.

Figure 3.16 illustrated the total throughput for both pairs in 802.11g for 6 Mbps. This figure presented the throughput when r=20,200,2000 and 20000. Generally, the throughput has decreased by increasing the packet payload size. Particularly, Figure 3.16 demonstrated that the total throughput for both pairs becomes lower in a low load, compared to the high load. Hence, we can obtain a high throughput by increasing the load of backoff rate from 20 to 20000. For instance, if r=20000 then more data will be allowed to be transmitted in a less time.

Finally, in this chapter we observed that the probability of collision is greater in a slowest speed. Particularly, in this experimental study and in Figure 3.17, we observed that the load of backoff will massively affect the collision. As, we obtained much lower collision if the backoff is very low. Figure 3.17 illustrates that the probability of collision is nearly 0.43% in the all packet payload sizes, when backoff is very low (r=20). However, the collision will be higher when we will increase the load of backoff rate from 20 to 20000 for the same speed of transmission.

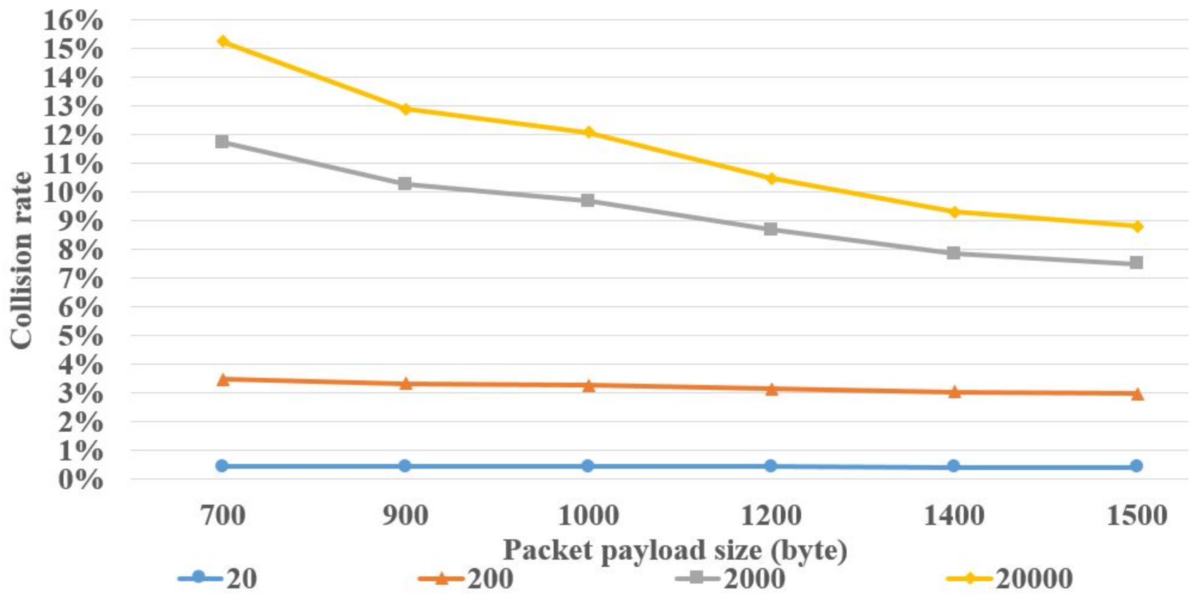


Fig. 3.17 Probability of collision of transmission in 802.11g for 2 pairs of 6 Mbps (r=20,200,2000 and 20000).

3.7 Chapter summary.

The hidden node problem is a well known phenomenon in wireless networks. It occurs when two nodes transmit which are out of range of each other, but both within range of at least one of the intended recipients. This chapter analysed and studied the performance modelling on this phenomenon in the IEEE 802.11b and 802.11g used PEPA. These results helped us to better understand the performance of these protocols while this problem occurs. In our scenario, each node attempts to transmit whenever it is able, but congestion occurs with a proportion of messages because the nodes are hidden from each other. Hence, the maximum throughput is limited by the occurrence of collisions, the efficiency of the backoff process and the need to retransmit data and acknowledgements. The waiting times introduced by the *IFS* are tuned to work for the slowest transmission speeds in each version of the protocol. As such the maximum utilisation rate is achieved when the transmission is slowest. However, we also observed that slow transmission results in more collisions and hence the maximum throughput is far greater when the transmission rate is faster. In essence, faster transmission allows more data to be transmitted in less time with fewer collisions. Faster transmission is also shown to be less susceptible to variation in the collision probability with frame size. This observation leads us to speculate whether a lower collision rate might be achieved for slow transmission rates if the Inter-Frame Space *IFS* periods were longer. This remains a question for future investigation. Finally, we investigated the sensitivity of backoff rate for 802.11g protocol in this scenario.

The next chapters will be considered a situation, where any node attempts to transmit might always be out competed by its neighbours, leading to an unfair sharing of network bandwidth. The main aim of the next chapter will be investigating the fairness performance modelling of the IEEE 802.11b protocol in terms of channel access.

Chapter 4

Frames property in IEEE 802.11b WLAN protocol

4.1 Introduction.

In this chapter we will introduce scenarios for modelling performance and fairness in IEEE 802.11 networks. In the first study we focus on IEEE 802.11b protocol; recreating and extending the results of Kloul and Valois [46].

This chapter will focus the investigation on the fairness properties of the IEEE 802.11b protocol, as many unfairness reported in terms of channel access in this protocol. This chapter presents our study performance modelling of the IEEE 802.11b protocol. When a wireless node competes to access the medium for sending a message, similarly, another one in the same transmission range might attempts to do so, consequently the traffic might occur. In the WLAN, dynamic topology will establish due to the nodes mobility. Thus, with the traffic occurrence or failure in transmission, the performance of WLAN is strongly affected. We aim to investigate the fairness of IEEE 802.11b protocol in terms of channel access in the three main scenarios used the stochastic process algebra PEPA. 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 they can compete to access the medium. In our study, we considered (single hop transmission on two pairs and three pairs scenarios, see our paper [4]) and four pairs scenarios, see [5]). Essentially, the approach of the three pairs scenario is based on the model of Kloul and Valois [46], extended to consider additional analysis that is available now in the latest tools for PEPA and in considering additional scenarios. Our 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 channel utilisation rate and channel throughput of each pair of nodes. We show that there are uncertainty of fairness to access the medium on the two pairs case and unfairness on the three and four pairs scenarios, in terms of channel utilisation and channel throughput. In addition, we will illustrate a fairness metric of channel utilisation for three and four pairs scenario with sensitivity of backoff rate. Finally, we will investigate the sensitivity to geometric assumption, where CW augmented.

4.2 Scenarios with a PEPA model.

This section presents the three PEPA models based on three main scenarios of the IEEE 802.11b wireless systems. Fundamentally, we investigated fairness issue in each scenario; each scenario at least has two or more nodes, which they are attempted to use the medium for transmitting a frame via a wireless medium. The following scenarios are used "listen before talk" approach; a particular node senses the medium in purpose of reducing any interferences or to avoid of any collisions might occur. For the given scenarios and PEPA models, we demonstrate the performance modelling of WLAN IEEE 802.11b protocol, as we have studied the two, three and four pairs scenarios in terms to investigate the fairness and how they compete to access the medium. Moreover, we built these scenarios and models, based the medium access timing mechanism in the IEEE 802.11 and DCF based CSMA/CA (the details have been highlighted in the Chapter 2). With presenting a PEPA model of IEEE 802.11b protocol and on each scenarios, which highlight different performance issues, we studied the channel access in terms of utilisation, throughput with fairness and unfairness issue in this chapter. In particular, we examine the fairness matter when there is a competition for accessing to the transmission channel.

4.2.1 The two pairs scenario (scenario 4.1).

A model of the two pairs case in 802.11b shows in this section. For convenience, this scenario (see Figure 4.1) directed our research to expand the model as a basic scenario to study further scenarios. We extended this scenario to examine three pairs scenario, see Figure 4.2 and four pairs scenario, see Figure 4.3. Fundamentally, the two pairs scenario contains two main components (Pair A and Pair B), which can be distinguished between an idle and a busy medium. Both pairs have been used as two symmetric and independent pairs, they can occupy a wireless medium. On this scenario, both nodes can listen the medium before sending any frame. If the medium is idle, then a specific node in a pair can attempt to transmit a frame, and its partner node waits to receive it and vice versa. But if the medium is busy then the node waits for a period of time till it is free to be use. Moreover, once the frame has been sent successfully, consequently after sensing the medium the other node will start to send an *ACK* (an acknowledgement mechanism is a technique that can be used to certify reception that the frame has been received successfully). Clearly, this scenario is fair, as each pair can access the medium equally.

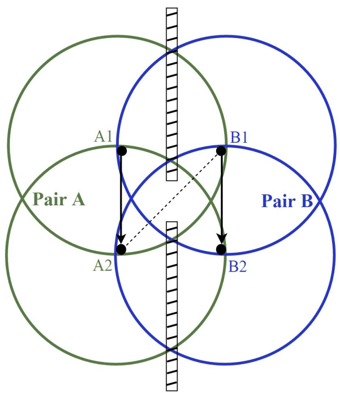


Fig. 4.1 The two pairs scenario (scenario 4.1).

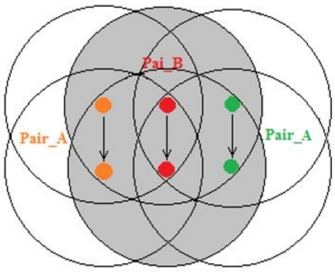


Fig. 4.2 The three pairs scenario (scenario 4.2).

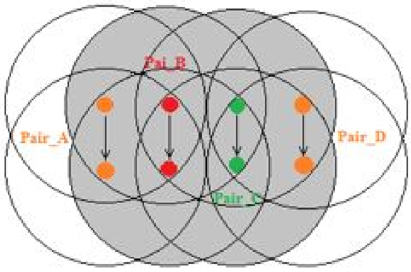


Fig. 4.3 The four pairs scenario (scenario 4.3).

The following specifications are shown, the model of the two pairs scenario (scenario 4.1) has an interaction between three components, which are denoted by (Pair A, Pair B, and Medium F). Precisely, `Pair_A` and `Pair_B` are having an equal chance to occupy the medium (`Medium_F`). According to the medium access control scheme, in this model if Pair A attempts to transmit any frame via `Medium_F`, firstly the `Pair_A` operates with an action 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` waits with `Pair_A4`. Similarly, all *SIFS* and *EIFS* will count till the backoff end, then the frame can transmit in `Pair_A2`. Finally, after the frame is transmitted successfully, then an *ACK* will be received in `Pair_A6`. Once the *ACK* has been received, the same process will start again to send another frame. This process is exactly the same for the second pair of nods (Pair B).

Sequential Component Process of Pair A and Pair B components:

The following model presents both components (Pair A and Pair B). When a particular pair is occupying the medium, then the other one waits until the medium will be free to be used.

$$
\begin{array}{rcl}
Pair\_A & \stackrel{def}{=} & (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 & \stackrel{def}{=} & (count\_difsA, \mu_{difs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A1 & \stackrel{def}{=} & (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
 & + & (queueA, \top).Pair\_A5 \\
Pair\_A2 & \stackrel{def}{=} & (transmitA, \mu_{data}).Pair\_A3 + (queueA, \top).Pair\_A5 \\
Pair\_A3 & \stackrel{def}{=} & (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A4 & \stackrel{def}{=} & (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_A4 \\
Pair\_A6 & \stackrel{def}{=} & (ackA, \mu_{ack}).Pair\_A
\end{array}
$$

$$
\begin{aligned}
Pair\_B &\stackrel{def}{=} (draw\_backoff, r).Pair\_B0\\
Pair\_B0 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).Pair\_B1 + (queueB, \top).Pair\_B5\\
Pair\_B1 &\stackrel{def}{=} (count\_backoffB, p\mu_{bck}).Pair\_B1 + (end\_backoffB, q\mu_{bck}).Pair\_B2\\
&+ (queueB, \top).Pair\_B5\\
Pair\_B2 &\stackrel{def}{=} (transmitB, \mu_{data}).Pair\_B3 + (queueB, \top).Pair\_B5\\
Pair\_B3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6\\
Pair\_B4 &\stackrel{def}{=} (count\_difsB, \mu difs).Pair\_B1 + (count\_eifsB, \mu_{eifs}).Pair\_B1 + (queueB, \top).Pair\_B5\\
Pair\_B5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_B4\\
Pair\_B6 &\stackrel{def}{=} (ackB, \mu_{ack}).Pair\_B
\end{aligned}
$$

The complete system: In this scenario to complete the system, the `Pair_A`, `Pair_B` and `Medium_F` components interact through the following cooperation sets:

$$
\text{Scenario 4.1} \stackrel{def}{=} (Pair\_A \underset{K}{\bowtie} Medium\_F) \underset{L}{\bowtie} Pair\_B
$$

Where $K = \{transmitA, ackA, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA\}$. $L = \{transmit, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

Component of Medium F: In this model, the medium is shared by both pairs (Pair A and Pair B). In the case of occupying the medium by any particular pair, then the other pair stops trying to transmit until the medium become an idle. The following specification shows the shared medium component (`Medium_F`), such that it can be used equally by both pairs. The specifications of medium in this scenario shows, that the `Medium_F` represents the situation where the medium is unoccupied. `Medium_F1` represents the medium being used by the pair A and `Medium_F2` represents the medium being used by the pair B.

$$
\begin{aligned}
Medium\_F &\stackrel{def}{=} (transmitA, \top).Medium\_F2 + (transmitB, \top).Medium\_F1\\
&+ (count\_difsA, \top).Medium\_F + (count\_backoffA, \top).Medium\_F\\
&+ (end\_backoffA, \top).Medium\_F + (count\_eifsA, \top).Medium\_F\\
&+ (count\_difsB, \top).Medium\_F + (count\_backoffB, \top).Medium\_F\\
&+ (end\_backoffB, \top).Medium\_F + (count\_eifsB, \top).Medium\_F\\
Medium\_F1 &\stackrel{def}{=} (ackB, \top).Medium\_F + (queueA, \lambda_{oc}).Medium\_F1\\
Medium\_F2 &\stackrel{def}{=} (ackA, \top).Medium\_F + (queueB, \lambda_{oc}).Medium\_F2
\end{aligned}
$$

4.2.2 The three pairs scenario (scenario 4.2).

After indicated the two pairs scenario, we modelled the three pairs case. This scenario contains four main components Pair A, Pair B, Pair A (as a second external pair) and the medium. These components are denoted by `Pair_A`, `Pair_B`, `Pair_A` (second external pair) and `Medium_F` respectively. Both external pairs which are denoted by `Pair_A` are two symmetric pairs. Both external pairs can access the medium equally, but the central one (`Pair_B`) has less chance to access it. The main principles in this scenario is that, both external pairs (`Pair_A` and `Pair_A`) cannot hear each other as they lie outside each others transmission range, but the central pair (Pair_B) can hear both of them. When either external pair is attempting to deliver a frame, then the central pair cannot do so; the central stays in a queue until the channel is idle. The central pair has to wait for either external pair, if they are trying to occupy the medium. But, the two external pairs can only be blocked by the central pair and not by each other. Hence if one external pair is transmitting, then the other one will be able to do so. As such the central pair has a far greater chance of being blocked. We will explain this phenomenon through numerical results in 4.4.

PEPA model: In this model, all pairs collaborate with the medium, either it is occupied by either externals or central pair. The specifications of the three pairs scenario is displayed below:

Sequential Component Process of both External Pairs (Pair_A).

In this scenario, if any external pair (Pair_A) attempts to use the medium, then it starts to operate in Pair_A with an action draw backoff to Pair_A0. Then Pair_A0 begins to count *DIFS* to Pair_A1 or stay in the queue in Pair_A5, while the state of Pair_A5 waits with Pair_A4. Moreover, the all *SIFS* and *EIFS* will count till the backoff end, then the frame can transmit in Pair_A2. Finally, after the frame is transmitted successfully, then an Acknowledgement ,*ACK*, will be received in Pair_A6. In this case when the *ACK* has been received, then the same process can be started again to send another frame. Both external pairs have similar process as they are symmetric, also Pair B (central pair) has exactly similar process.

$$\begin{aligned}
Pair_A &\stackrel{def}{=} (draw_backoff, r).Pair_A0 \\
Pair_A0 &\stackrel{def}{=} (count_difsA, \mu_{difs}).Pair_A1 + (queueA, \top).Pair_A5 \\
Pair_A1 &\stackrel{def}{=} (count_backoffA, p\mu_{bck}).Pair_A1 + (end_backoffA, q\mu_{bck}).Pair_A2 \\
&\quad + (queueA, \top).Pair_A5 \\
Pair_A2 &\stackrel{def}{=} (transmitA, \mu_{data}).Pair_A3 + (queueA, \top).Pair_A5 \\
Pair_A3 &\stackrel{def}{=} (count_sifs, \mu_{sifs}).Pair_A6 \\
Pair_A4 &\stackrel{def}{=} (count_difsA, \mu_{difs}).Pair_A1 + (count_eifsA, \mu_{eifs}).Pair_A1 + (queueA, \top).Pair_A5 \\
Pair_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair_A4 \\
Pair_A6 &\stackrel{def}{=} (ackA, \mu_{ack}).Pair_A
\end{aligned}$$

Sequential Component Process of Central Pair (Pair_B).

$$\begin{aligned}
Pair_B &\stackrel{def}{=} (draw_backoff, r).Pair_B0 \\
Pair_B0 &\stackrel{def}{=} (count_difsB, \mu_{difs}).Pair_B1 + (queueB, \top).Pair_B5 \\
Pair_B1 &\stackrel{def}{=} (count_backoffB, p\mu_{bck}).Pair_B1 + (end_backoffB, q\mu_{bck}).Pair_B2 \\
&\quad + (queueB, \top).Pair_B5 \\
Pair_B2 &\stackrel{def}{=} (transmitB, \mu_{data}).Pair_B3 + (queueB, \top).Pair_B5 \\
Pair_B3 &\stackrel{def}{=} (count_sifs, \mu_{sifs}).Pair_B6 \\
Pair_B4 &\stackrel{def}{=} (count_difsB, \mu_{difs}).Pair_B1 + (count_eifsB, \mu_{eifs}).Pair_B1 + (queueB, \top).Pair_B5 \\
Pair_B5 &\stackrel{def}{=} (wait, \mu_{data}).Pair_B4 \\
Pair_B6 &\stackrel{def}{=} (ackB, \mu_{ack}).Pair_B
\end{aligned}$$

The complete system: This system is completed when any external pairs compute to send any frame through the `Medium_F`, both external pairs attempts to access the medium, which this symbol $\|$ shows both external pairs can use the medium and they can interact the central pair through the `Medium_F`, here is the cooperation sets that are defined as:

$$\text{Scenario 4.2} \overset{def}{=} ((Pair\_A \| Pair\_A) \underset{K}{\bowtie} Medium\_F) \underset{L}{\bowtie} Pair\_B$$

Where $K = \{transmitA, ackA, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA\}$. $L = \{transmit, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

Component of Medium F: The shared medium in this scenario shows, that `Medium_F` represents the situation where the medium is unoccupied. `Medium_F1` represents the medium being used by the central pair. `Medium_F2` represents the medium being used by exactly one of the external pairs. Finally, `Medium_F3` represents the medium being used by both external pairs:

$$\begin{aligned}
Medium_F &\overset{def}{=} (transmitA, \top).Medium_F2 + (transmitB, \top).Medium_F1 \\
&+ (count_difsA, \top).Medium_F + (count_backoffA, \top).Medium_F \\
&+ (end_backoffA, \top).Medium_F + (count_eifsA, \top).Medium_F \\
&+ (count_difsB, \top).Medium_F + (count_backoffB, \top).Medium_F \\
&+ (end_backoffB, \top).Medium_F + (count_eifsB, \top).Medium_F \\
Medium_F1 &\overset{def}{=} (ackB, \top).Medium_F + (queueA, \lambda_{oc}).Medium_F1 \\
Medium_F2 &\overset{def}{=} (transmitA, \top).Medium_F3 + (ackA, \top).Medium_F \\
&+ (queueB, \lambda_{oc}).Medium_F2 + (count_difsA, \top).Medium_F2 \\
&+ (count_backoffA, \top).Medium_F2 + (end_backoffA, \top).Medium_F2 \\
&+ (count_eifsA, \top).Medium_F2 \\
Medium_F3 &\overset{def}{=} (ackA, \top).Medium_F2 + (queueB, \lambda_{oc}).Medium_F3 \\
&+ (count_difsA, \top).Medium_F3 + (count_backoffA, \top).Medium_F3 \\
&+ (end_backoffA, \top).Medium_F3 + (count_eifsA, \top).Medium_F3
\end{aligned}$$

4.2.3 The four pairs scenario (scenario 4.3).

The four pairs scenario contains two central pairs, two external pairs and a medium, see Figure 4.3. These components are denoted by (Pair A, Pair B, Pair C, Pair D and Medium). Both external pairs (Pair A and Pair D) are independent from each other and symmetric. In this scenario the pairs are arranged so that Pair B is affected by transmission from Pair A and Pair C, and Pair C is affected by Pair D. Clearly, each external pair is affected by only one of the internal pairs; i.e. Pair A is affected by transmission from Pair B and Pair D is affected by Pair C only. Here, we can understand that the both central pairs have less chance to access the medium rather than the external pairs. This scenario is not completely fair, because Pair B and Pair C are penalised. However, it is not as restrictive as the three pairs scenario, as if Pair A is transmitting (but not Pair D) then Pair C still has a chance to access the medium. Similarly, if Pair D is transmitting (but not Pair A) then Pair B has a chance to access the channel. By this approach the four pairs scenario is a fair case in comparison to the three pairs scenario.

PEPA model of four pairs scenario: In this scenario each pair attempts to access the medium and send the data. When any pair such as `Pair_A` attempts to use the medium, firstly the action of backoff will get started from this pair to `Pair_A0`. Afterwards `Pair_A0` starts to count *DIFS* to `Pair_A1` or stay in the queue in `Pair_A5`, if it has a choice to `Pair_A5` then it waits in this state to `Pair_A4`. But, if it has a choice to `Pair_A1` then either it counts backoff in `Pair_A1` or ends backoff in `Pair_A2` or stays in a queue in `Pair_A5`. Moreover, the all *SIFS* and *EIFS* will count till the backoff end, then the frame will transmit in `Pair_A2`. Finally, after the frame is transmitted successfully, then an *ACK* will be received in `Pair_A6`. In this case when the *ACK* has been received, then the same process can be started again for sending another frame if the pair senses that the medium is free to use. This process is similar in the other pairs.

$$
\begin{array}{rcl}
Pair\_A & \stackrel{def}{=} & (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 & \stackrel{def}{=} & (count\_difsA, \mu_{difs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A1 & \stackrel{def}{=} & (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
 & + & (queueA, \top).Pair\_A5 \\
Pair\_A2 & \stackrel{def}{=} & (transmitA, \mu_{data}).Pair\_A3 + (queueA, \top).Pair\_A5 \\
Pair\_A3 & \stackrel{def}{=} & (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A4 & \stackrel{def}{=} & (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 \\
 & + & (queueA, \top).Pair\_A5 \\
Pair\_A5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_A4 \\
Pair\_A6 & \stackrel{def}{=} & (ackA, \mu_{ack}).Pair\_A \\
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 \\
 & + & (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 \\
 & + & (queueB, \top).Pair\_B5 \\
Pair\_B5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_B4 \\
Pair\_B6 & \stackrel{def}{=} & (ackB, \mu_{ack}).Pair\_B \\
Pair\_C & \stackrel{def}{=} & (draw\_backoff, r).Pair\_C0 \\
Pair\_C0 & \stackrel{def}{=} & (count\_difsC, \mu_{difs}).Pair\_C1 + (queueC, \top).Pair\_C5 \\
Pair\_C1 & \stackrel{def}{=} & (count\_backoffC, p\mu_{bck}).Pair\_C1 + (end\_backoffC, q\mu_{bck}).Pair\_C2 \\
 & + & (queueC, \top).Pair\_C5 \\
Pair\_C2 & \stackrel{def}{=} & (transmitC, \mu_{data}).Pair\_C3 + (queueC, \top).Pair\_C5 \\
Pair\_C3 & \stackrel{def}{=} & (count\_sifs, \mu_{sifs}).Pair\_C6 \\
Pair\_C4 & \stackrel{def}{=} & count\_difsC, \mu_{difs}).Pair\_C1 + (count\_eifsC, \mu_{eifs}).Pair\_C1 \\
 & + & (queueC, \top).Pair\_C5 \\
Pair\_C5 & \stackrel{def}{=} & (wait, \mu_{data}).Pair\_C4 \\
Pair\_C6 & \stackrel{def}{=} & (ackC, \mu_{ack}).Pair\_C
\end{array}
$$

$$
\begin{aligned}
Pair\_D &\stackrel{def}{=} (draw\_backoff, r).Pair\_D0 \\
Pair\_D0 &\stackrel{def}{=} (count\_difsD, \mu_{difs}).Pair\_D1 + (queueD, \top).Pair\_D5 \\
Pair\_D1 &\stackrel{def}{=} (count\_backoffD, p\mu_{bck}).Pair\_D1 + (end\_backoffD, q\mu_{bck}).Pair\_D2 \\
&+ (queueD, \top).Pair\_D5 \\
Pair\_D2 &\stackrel{def}{=} (transmitD, \mu_{data}).Pair\_D3 + (queueD, \top).Pair\_D5 \\
Pair\_D3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_D6 \\
Pair\_D4 &\stackrel{def}{=} (count\_difsD, \mu_{difs}).Pair\_D1 + (count\_eifsD, \mu_{eifs}).Pair\_D1 \\
&+ (queueD, \top).Pair\_D5 \\
Pair\_D5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_D4 \\
Pair\_D6 &\stackrel{def}{=} (ackD, \mu_{ack}).Pair\_D
\end{aligned}
$$

Component of Medium F: In the four pairs case the shared medium (`Medium_F`) works much the same way in the previous cases, but in this case (see Figure 4.4) the `Medium_F` represents the situation where the medium is unoccupied. `Medium_A` represents the medium occupied by Pair A as it is succeeded transmission by Pair A. `Medium_D` represents the medium occupied by Pair D which the `Medium_D` is succeeded transmission by Pair D. `Medium_B` represents the medium occupied by Pair B which the `Medium_B` is succeeded transmission by Pair B. `Medium_C` represents the medium occupied by Pair C only. Similarly, `Medium_AD` represents the medium occupied by Pair A and Pair D. Also, `Medium_BD` represents the medium occupied by Pair B and Pair D. Finally, `Medium_AC` represents the medium occupied by Pair A and Pair C.

$$
\begin{aligned}
Medium\_F &\stackrel{def}{=} (transmitA, \top).Medium\_A + (transmitB, \top).Medium\_B \\
&+ (transmitC, \top).Medium\_C + (transmitD, \top).Medium\_D \\
&+ (count\_difsA, \top).Medium\_A + (count\_backoffA, \top).Medium\_A \\
&+ (end\_backoffA, \top).Medium\_A + (count\_eifsA, \top).Medium\_A \\
&+ (count\_difsB, \top).Medium\_B + (count\_backoffB, \top).Medium\_B \\
&+ (end\_backoffB, \top).Medium\_B + (count\_eifsB, \top).Medium\_B \\
&+ (count\_difsC, \top).Medium\_C + (count\_backoffC, \top).Medium\_C \\
&+ (end\_backoffC, \top).Medium\_C + (count\_eifsC, \top).Medium\_C \\
&+ (count\_difsD, \top).Medium\_D + (count\_backoffD, \top).Medium\_D \\
&+ (end\_backoffD, \top).Medium\_D + (count\_eifsD, \top).Medium\_D \\
Medium\_A &\stackrel{def}{=} (transmitC, \top).Medium\_AC + (transmitD, \top).Medium\_AD \\
&+ (ackA, \top).Medium\_F + (queueB, \lambda oc).Medium\_A \\
Medium\_D &\stackrel{def}{=} (transmitA, \top).Medium\_AD + (transmitB, \top).Medium\_BD \\
&+ (ackD, \top).Medium\_F + (queueC, \lambda oc).Medium\_D \\
Medium\_B &\stackrel{def}{=} (transmitD, \top).Medium\_BD + (ackB, \top).Medium\_F \\
&+ (queueA, \lambda oc).Medium\_B + (queueC, \lambda oc).Medium\_B \\
Medium\_C &\stackrel{def}{=} (transmitA, \top).Medium\_AC + (ackC, \top).Medium\_F + (queueB, \lambda oc).Medium\_C \\
&+ (queueD, \lambda oc).Medium_C
\end{aligned}
$$

$$\begin{aligned}
Medium_AD &\stackrel{def}{=} (ackA,\top).Medium_D + (ackD,\top).Medium_A \\
&+ (queueB,\lambda oc).Medium_AD + (queueC,\lambda oc).Medium_AD \\
Medium_BD &\stackrel{def}{=} (ackB,\top).Medium_D + (ackD,\top).Medium_B \\
&+ (queueA,\lambda oc).Medium_BD + (queueC,\lambda oc).Medium_BD \\
Medium_AC &\stackrel{def}{=} (ackA,\top).Medium_C + (ackC,\top).Medium_A \\
&+ (queueB,\lambda oc).Medium_AC + (queueC,\lambda oc).Medium_AC
\end{aligned}$$

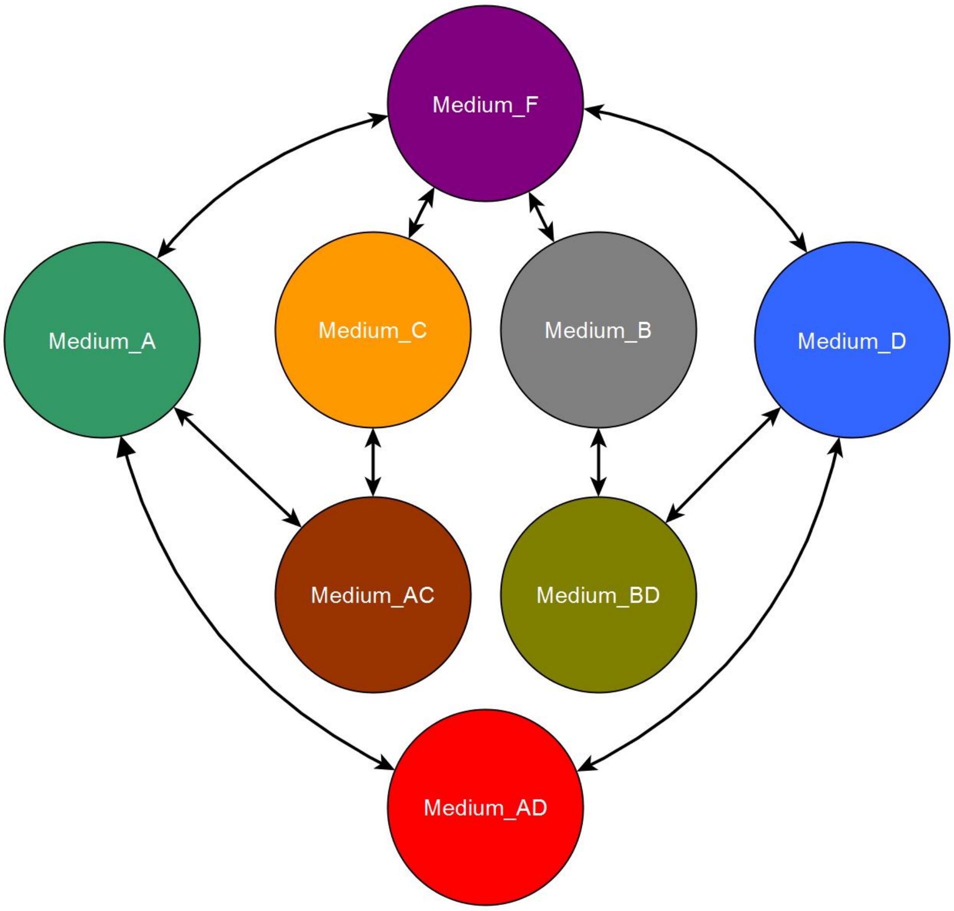


Fig. 4.4 The medium component in scenario 4.3.

The complete system: In this model, the pairs do not interact directly; however, each pair can interact with the medium to change is state, which is turn affects the subsequence behaviour of the other pairs. However, both external pairs cannot interact with each other, this symbol $||$ shows that, as it has been explained, this scenario is cooperated between all components that are defined as the following cooperation sets:

$$\text{Scenario 4.3} \stackrel{def}{=} (Pair\_A \parallel Pair\_B \parallel Pair\_C \parallel Pair\_D) \underset{L}{\bowtie} Medium\_F$$

Where $L = \{transmitA, ackA, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA, transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB, transmitC, ackC, queueC, count\_difsC, count\_backoffC, end\_backoffC, count\_eifsC, transmitD, ackD, queueD, count\_difsD, count\_backoffD, end\_backoffD, count\_eifsD\}$

4.3 Parameters.

This section contains the parameters that we used to analyse the models of each scenario. These parameters have been used in the next section to better understand the performance of the 802.11b protocol. Fundamentally, IEEE 802.11 protocol has a very specific Inter-Frame Spacing, which coordinates access to the medium to transmit frames. If any pair wants to transmit and if it senses that the channel is idle, then it transmits with the probability of 'p'. For convenience, each pair has count back-off and end back-off actions with ($p \times \mu bck$) and ($q \times \mu bck$) rates respectively; in our study we assume 0.5 as a value of p and q (q=1-p).

According to the IEEE 802.11b definition and PHY standards, the data rate per stream are 1, 2, 5.5, and 11 Mbps, equal to 125000, 250000, 687500 and 1375000 Bytes/s respectively (see [25, 85] for more details). These rates have been applied with each of packet payload size 700, 900, 1000, 1200, 1400 and 1500 Bytes to analyse the model. Particularly, in this model, the packets per time unit for arrival and departure rate are λoc = 100000 and μ = 200000 respectively; these are the same values that have been used in [46].

Inter-Frame Space (*IFS*). The 802.11 is a system of timers. Before each frame transmits, the length of the Inter-Frame Space (*IFS*) is dependent on the previous frame type, the required *IFS* is applied if noise occurs. After transmitting a frame and before another one starts, the *IFS* is applied to the channel to stay clear. This is an essential idle period of time needed to ensure that other nodes may access the channel, otherwise a sender could occupy the medium for a long period and starve other nodes. The main purpose of an *IFS* is to supply waiting time for each frame transmission in a particular node, to allows the transmitted signal to reach another node (essential for listening). IEEE 802.11 protocols have deal with several IFS: *SIFS*, *DIFS*, *EIFS* and slot time, see [22, 25, 40] and [84].

Short Inter-Frame Space (*SIFS*). *SIFS* in IEEE 802.11 protocol is an interframe spacing prior as a minimum *IFS* for highest priority transmissions used with Distributed Coordination Function (DCF), measured by microseconds (μs). It is important in IEEE 802.11 networks as a fixed and shortest value to better process a received frame. *SIFS* is equal to 10μs in IEEE 802.11b, 802.11g and 802.11n family.

***DCF* Inter-Frame Space (*DIFS*).** As an acronym of DCF Interframe spacing it 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 period of time (*backoff*).
DIFS = *SIFS* + (2 $\times$ (slot time =20 μs in 802.11b/g/n family)).

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

Contention Window (*CW*). According to the CSMA/CA mechanism (see Chapter 2), if a node wants to transmit any frame, it senses whether the channel is free or not. If it is free then the node transmits, otherwise, the node waits for a random time backoff selected from a Contention

Window (*CW*), until the medium becomes free (the *CW* observes the backoff interval once channel is busy). The node waits to minimise any collision once it experiences an idle channel for an appropriate *IFS* (otherwise many waiting nodes might transmit simultaneously). The node needs less time to wait if there is a shorter backoff period, so transmission will be faster, unless there is a collision. Backoff is chosen over [0, *CW*], and *CW* = *CWmin* for all station or nodes if a node successfully transmits a frame and then receives an *ACK*. In the non-transmission case, the node deals another backoff, with each unsuccessful transmission it increments exponentially by multiplication of 2 at every retransmission for the same frame, this attempt and *CW* increases exponentially until it reaches *CWmax*. Finally, the *CW* resets to *CWmin* when the frame is received properly. *CW* and backoff can be found as follows:
In the IEEE 802.11b protocol, the *CWmin* = 31, and *CWmax* = 1023. *CWmin* augmented by 2n-1 on each retry.
Backoff Time = (Random () mod ($CW+1$)) $\times$ slot time.
If Backoff Timer = b, where b is a random integer, also $CWmin \leq b \leq CWmax$
We are used $\bar{CW}$ as the mean of *CW* = 15.5 and the slot time = $20\mu s$, to calculate μ_{bck} by:

$$\mu_{bck} = \frac{10^6}{\bar{CW} \times \text{ slot time}}$$

Data rates and ACK. An *ACK* send by receiver when it gets the frame successfully, it is precautions action when collisions occur. The *ACK* in 802.11b protocol is deal with data rate 1, 2, 5.5 and 11 Mbps, each μack is equal to 1644.74, 3289.5, 9046.125 and 18092.25 Bytes/s respectively. In the presented model, the *ACK* rate of each frame has been denoted by (μack). For example, for 1 Mbps speed the μack = 1644.75, which it can be obtained by:

$$\mu_{ack} = \frac{\text{channel throughput}}{(\,ACK \text{ length= 1 Byte})}$$

Also, $\mu data$ is a rate of waiting action for frames, which it can be calculated as follows:

$$\mu_{data} = \frac{\text{data rate} \times \frac{10^6}{8}}{\text{packet payload size}}$$

4.4 Results and discussions of IEEE 802.11b protocol.

This section shows the obtained results of our experimental study on IEEE 802.11b protocol. In this section, the presented models has been used to measure the channel utilisation rate, channel throughput rate and probability of transmission, by demonstrating on PEPA to analyse the IEEE 802.11b performance of the (two pairs, three pairs and four pairs) scenarios.

4.4.1 Performance results of the two pairs scenario (scenario 4.1).

We analysed the performance of the two pairs scenario used (r, λoc, $\mu difs$, $\mu sifs$, $\mu eifs$) values, that they are (200000, 100000, 20000, 100000, 2747.3) respectively. We concentrated to measure the channel utilisation rate and channel throughput, towards a better understanding on the model behaviour. Firstly, we started to measure the channel utilisation in our experiment. The given formula can be used to obtain the channel utilisation rate.

Utilisation = Pr[Medium_F and (Pair_A2 or Pair_B2)] + Pr[Medium_F1]+ Pr[Medium_F2]

The channel utilisation rate increases if the payload size increases for the data rate 1, 2, 5.5, and 11 Mbps (see Figure 4.5). This is because the occupied channel time increases as the payload size increases. Hence, we can see the channel utilisation rate in 1 Mbps is increasing while the packet payload size is increasing for the same speed. Also, it is the same for all speeds, accordingly we can see that the data transmission rate will become faster. Likewise, we analysed the behaviour of the protocol by studying the interaction between both pairs in terms of the probability of transmission. The probability transmission for the channel utilisation on the two pairs case is increased as the payload size is increased, see Figure 4.6.

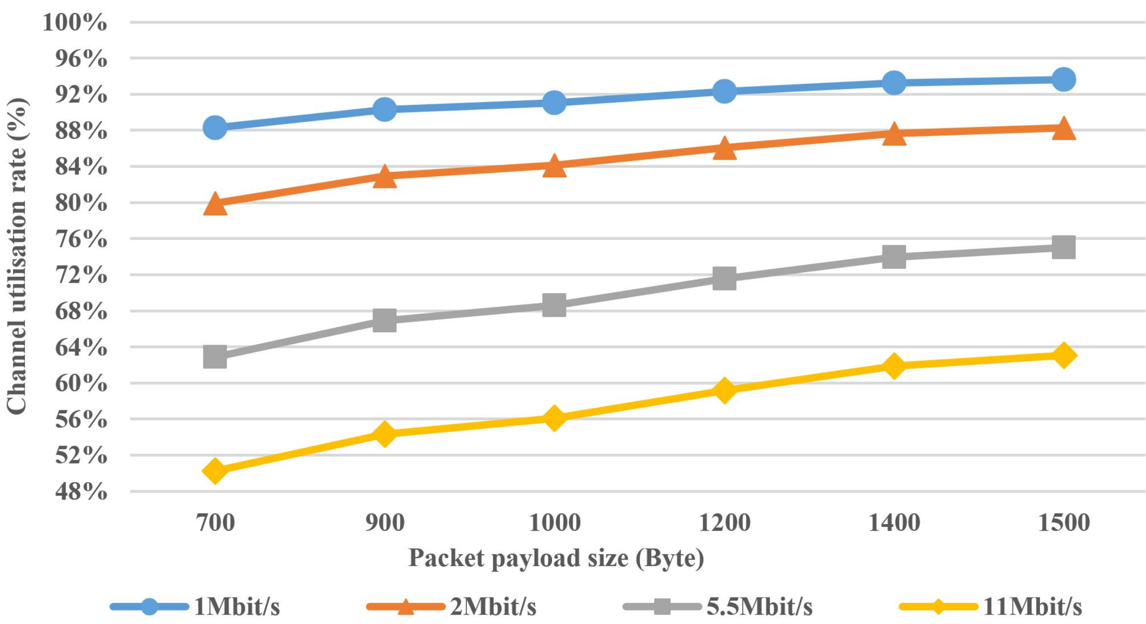


Fig. 4.5 Channel utilisation rate for the two pairs in scenario 4.1.

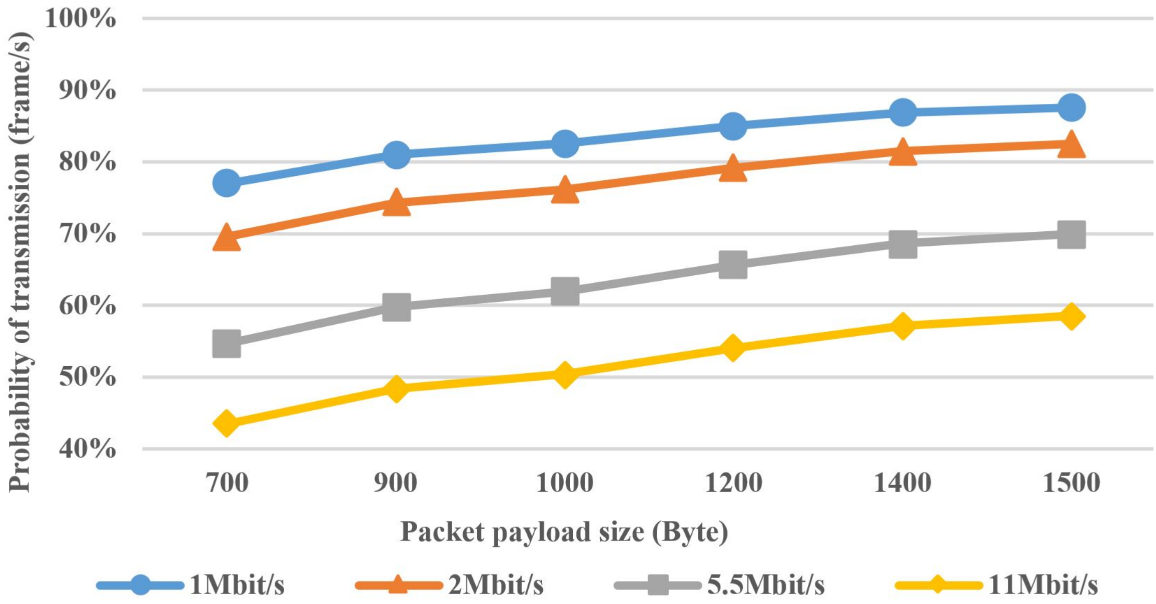


Fig. 4.6 Probability of transmission for the two pairs in scenario 4.1.

We also study channel throughput to better understand the IEEE 802.11b protocol. The channel throughput decreases when the packet payload size increases. This is because the channel occupancy time increases with increasing payload size from 700 to 1500 Bytes, see Figure 4.7. Finally, if we have faster backoff, then less time is required to transmit a frame. This means we will get faster transition in shorter time. Once, the backoff ends successfully, then the medium can be used equally for transmitting data by each (Pair A and Pair B) in this scenario.

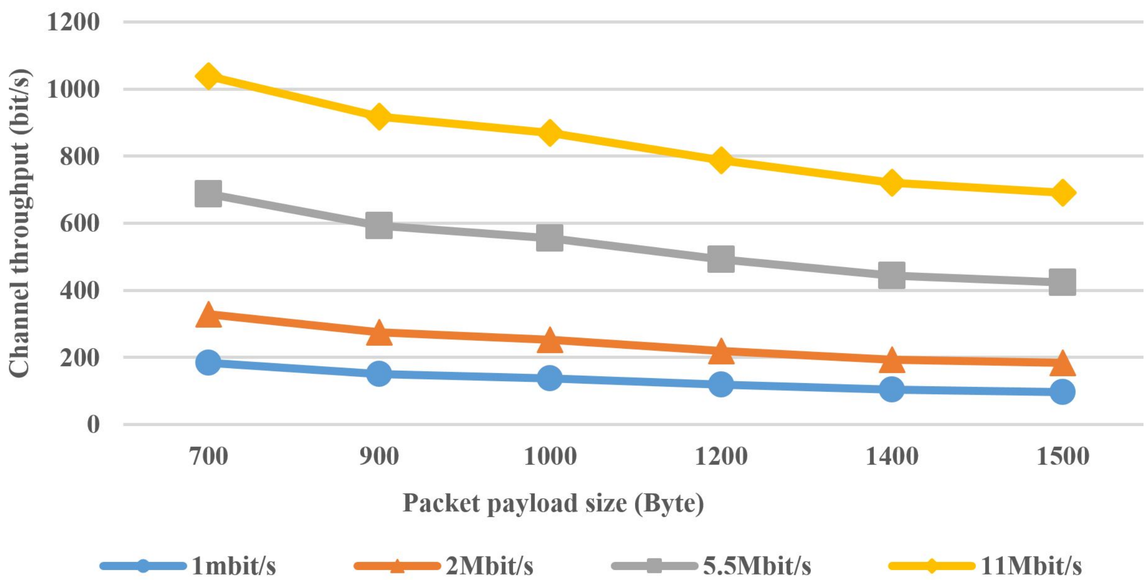


Fig. 4.7 Total throughput for both Pair A and Pair B in scenario 4.1.

In the two pairs scenario, the obtained results of each pair is equal as they are symmetric; both pairs are equally occupying the channel. Figure 4.8 shows the nodes channel utilisation rate for Pair A (which it is identical for Pair B). The channel utilisation rate is increasing in each speed as the payload size increases. Hence, each pair can access the medium equally and fairly, this is a fair scenario.

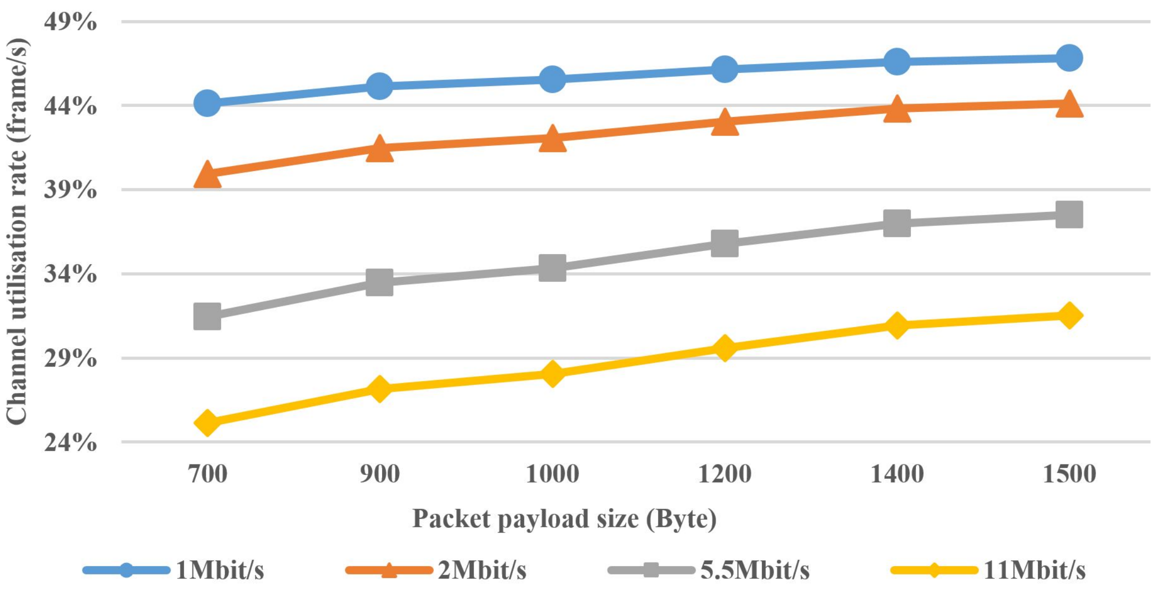


Fig. 4.8 Channel utilisation rate for the Pair A in scenario 4.1.

4.4.2 Performance results of the three pairs scenario (scenario 4.2).

The three pairs scenario demonstrates the effects of unfair access. In this system both external pairs (Pair A and Pair A) are fully independent. They have equal chance to access the medium, but, the behaviour of the central pair (Pair B) is not the same as the external pairs. The rate declarations and parameters in this scenario are the same as previous scenario.

Firstly, we studied the probability of transmission and it can be calculated by this formula: Probability of transmission = *Pr*[Medium_F and (Pair_A2 or Pair_B2 or Pair_A2)]
Figure 4.9 shows the probability of transmission in `Medium_F` with `Pair_A2` or `Pair_B2` or `Pair_A2`. In 1 Mbps and 700 payload size the probability of transmission approximately is 78% and it increases as the packet payload size increases. Here, we can understand that, the probability of transmission in a lower bandwidth is greater compared to the higher bandwidth.

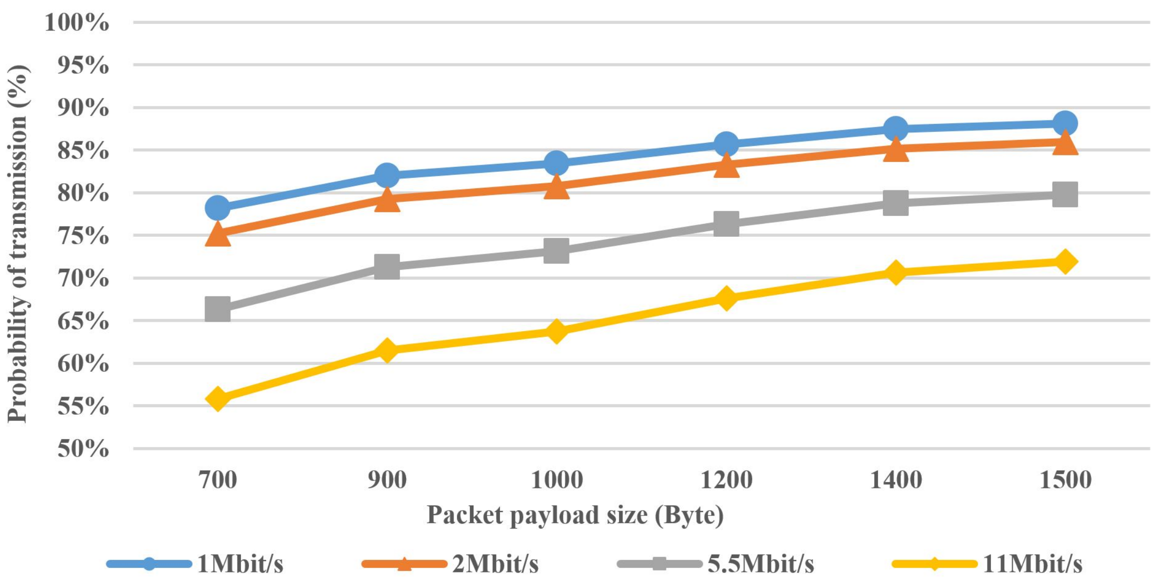


Fig. 4.9 Probability of transmission for the three pairs in scenario 4.2.

We examined the channel utilisation rate for both external pairs, which, it is increased as the packet payload size is increased. Both external pairs may transmit at the same time without collisions occurring This is causes the channel the use time to increase, because of the packet size is increasing at the same time and they can occupy the channel equally as two symmetric pairs. The following formula has been used to obtain of the presented results in Figure 4.10.

$$\text{Channel utilisation} = \text{ total utilisation} \times \frac{\text{throughput A}}{\text{total throughput (AckA and AckB)}}$$

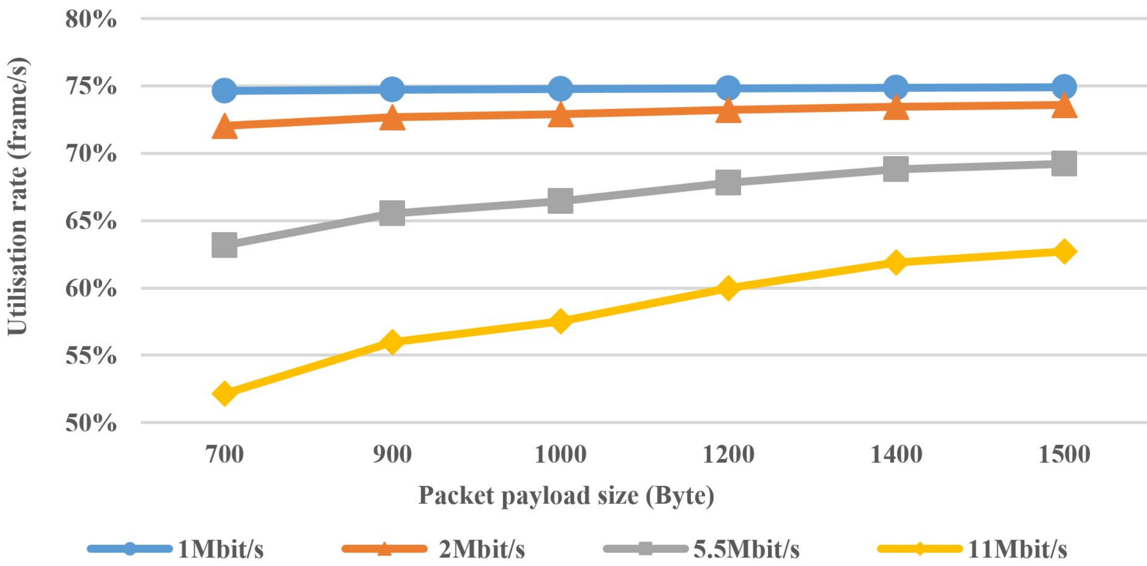


Fig. 4.10 Channel utilisation rate for the external pairs in scenario 4.2.

Moreover, the channel utilisation rate of the central pair, has a similarity to the channel utilisation rate of the external pairs. However, in the central pair it is much lower than the external pairs. Due to the central pair have very limited to access the channel, most of the time the channel is occupied by the external pairs, see Figure 4.11. Under this circumstance, this scenario is unfair for the central pair in terms of channel access.

$$\text{Channel utilisation} = \text{ total utilisation} \times \frac{\text{throughput B}}{\text{total throughput (AckA and AckB)}}$$

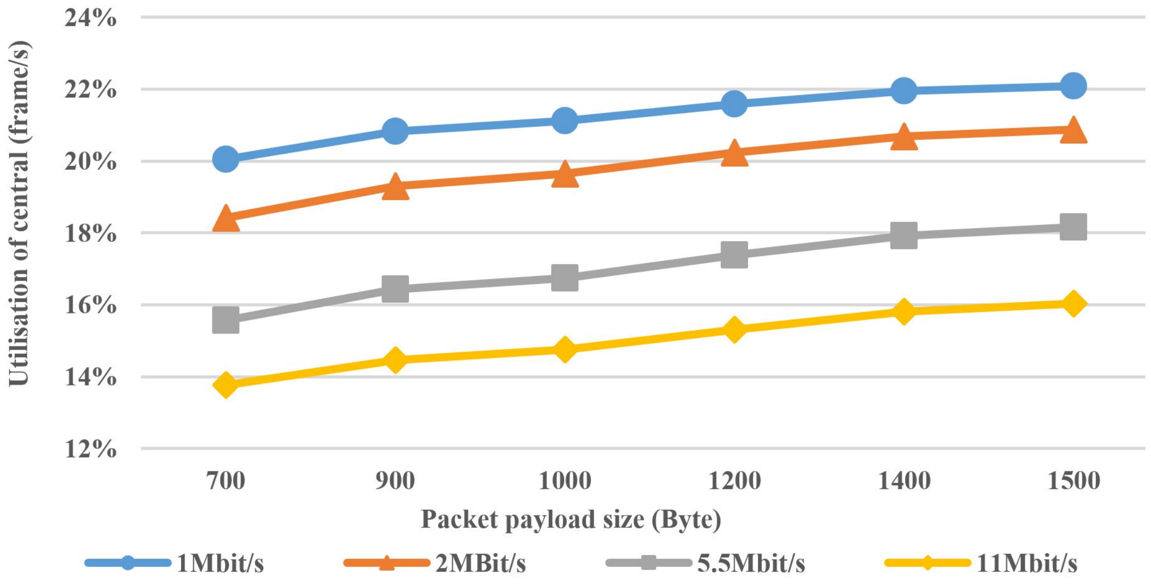


Fig. 4.11 Channel utilisation rate for the central pair in scenario 4.2.

We can see from Figure 4.10 and 4.11 that the channel utilisation rate increases as the packet payload size increases, but in a higher bandwidth it is lower compared to the slow bandwidth such as 1 Mbps speed, as the slow bandwidth stays longer in the medium during transmission.

Finally, the channel throughput decreases as the packet payload size increases. However, it is not similar to the channel utilisation rates, because of the channel occupancy time. The fastest channel in transmitting packet, will occupy less time in this channel, Figure 4.12 shows the channel throughput of external pairs and Figure 4.13 shows the channel throughput of central pair. However, accessing the channel by the central pair is limited compared to the external pairs. In term of throughput, this scenario is unfair. Clearly, the central pair is out competed by others and so it is unfairly disadvantaged.

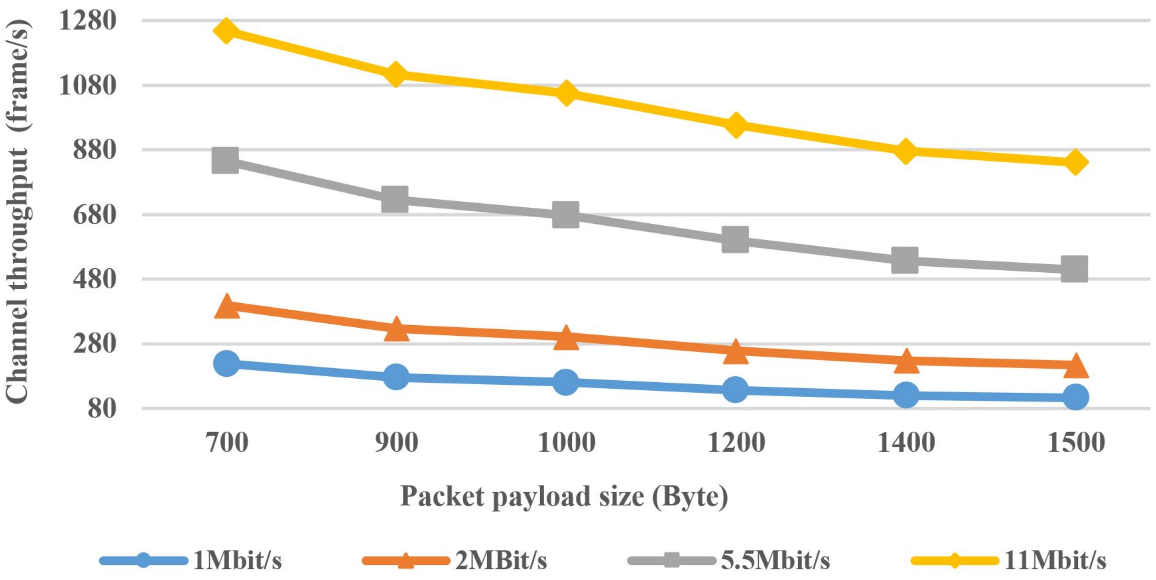


Fig. 4.12 Channel throughput rate for the external pairs in scenario 4.2.

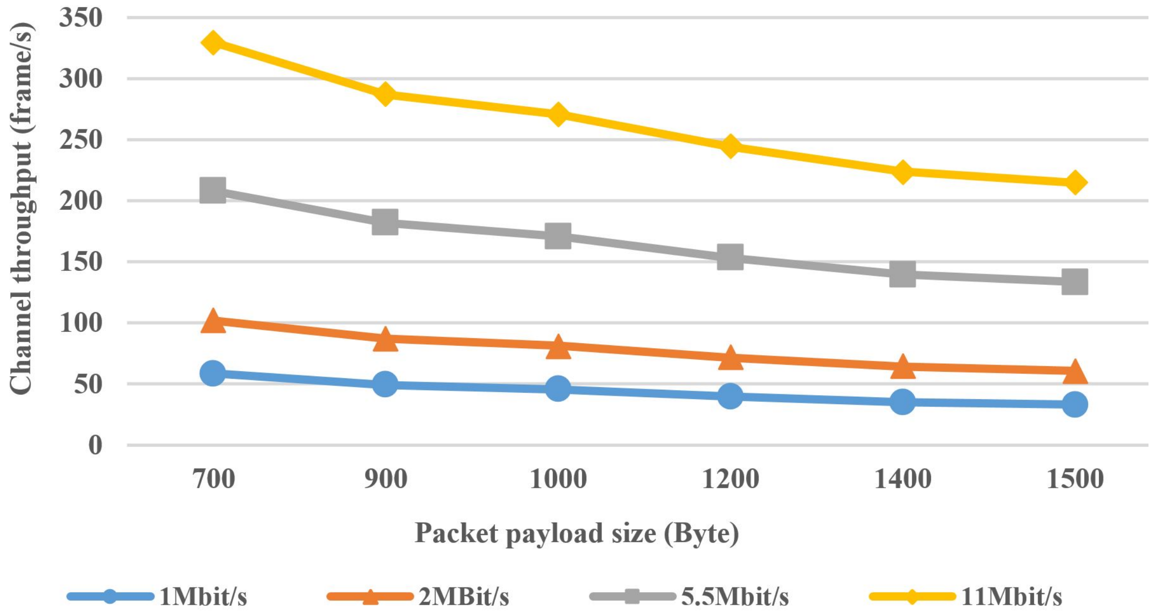


Fig. 4.13 Channel throughput rate for the central pair in scenario 4.2.

4.4.3 Performance results of the four pairs scenario (scenario 4.3).

In this scenario, we studied the probability of transmission, channel utilisation and channel throughput for all pairs. Firstly, we clarify the probability of transmission as it is shown in Figure 4.14. In the model of four pairs case the obtained results show that, the probability of transmission for 1 Mbps is 72%. It increases if the packet payload size increases too, but the probability of transmission decreases by increase of the speed of transmission (1, 2, 5.5, 11 Mbps respectively). All pairs are strongly in competition to access the medium.
Probability of transmission= *Pr*[Medium_F and (Pair_A2 or Pair_B2 or Pair_C2 or Pair_D2)]

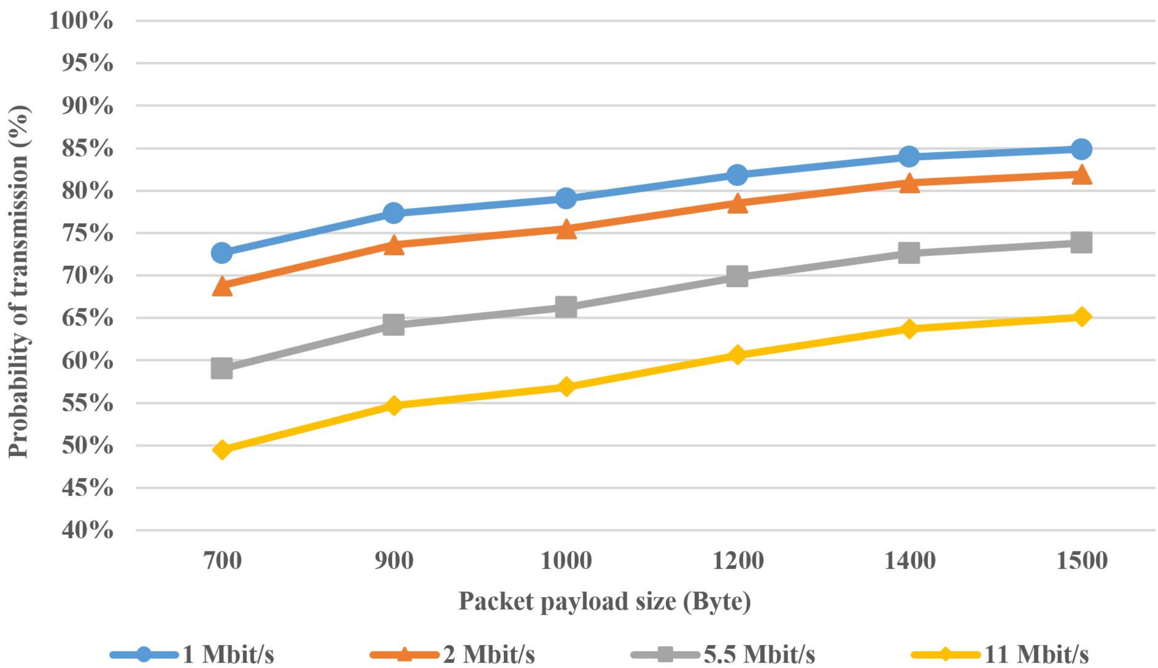


Fig. 4.14 Probability of transmission for the four pairs in scenario 4.3.

We examined the external pairs (Pair A and Pair D) and the central pairs (Pair B and Pair C) to analyse the channel utilisation rate. In our study, we calculated the total utilisation for all pairs, see Figure 4.15. The total utilisation rate increases as the packet payload size increases, this is because of the duration of occupant the channel is increasing by external pairs (Pair A and Pair D), as they can occupy the channel more.
Channel utilisation = $\sum$ channel utilisation + (1-Pr[Medium]).

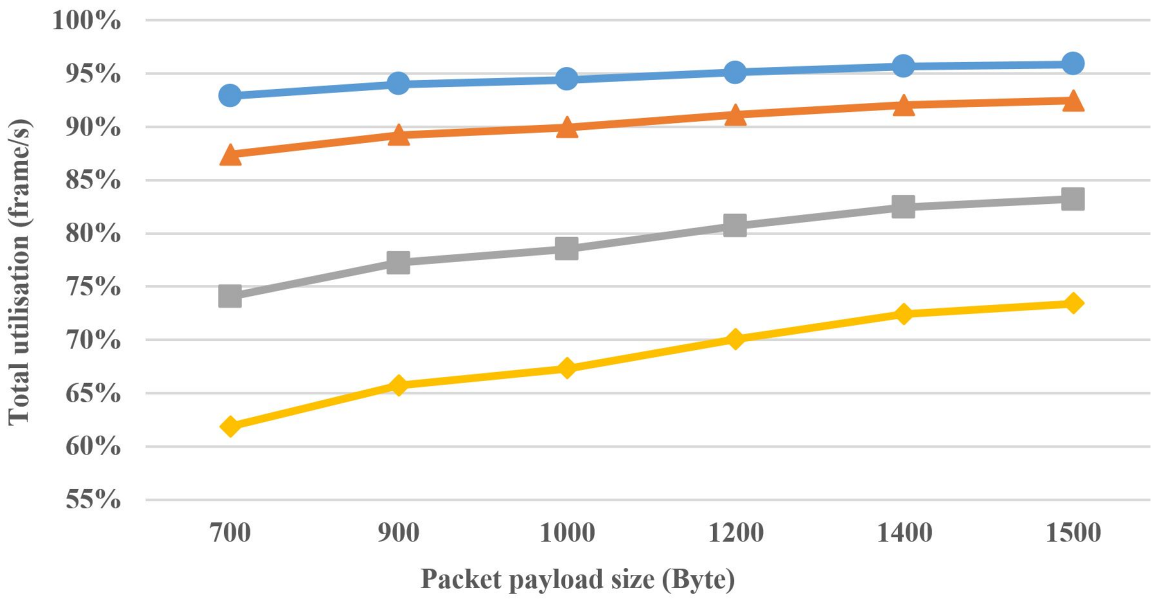


Fig. 4.15 Total utilisation for the four pairs in scenario 4.3.

The total channel utilisation rate on the four pairs scenario is less than the other scenarios. As seen in Figures 4.10 and 4.11, because there is more chance of collision. In the four pairs scenario, the channel utilisation rate is not as easily analysed in comparison to the others scenarios. This is because of one of the central pair and one of the external pair might be in transmission at the same time. The better way to analyse the channel utilisation rate, is to calculate it for external pairs and central pairs separately, as it further explains how much time is used in the medium by each central and external pairs fairly.

The following formula uses to measure the channel utilisation rate in external pairs, see Figure 4.16. The channel utilisation rate in a particular external pair is more similar to the total utilisation rate. It increases as the packet payload size increases, and it is similar in the second external pair, as they are symmetric.

$$\text{Utilisation of externals} = \text{ total utilisation} \times \frac{\text{throughput A}}{\text{total throughput (AckA, AckB, AckC and AckD)}}$$

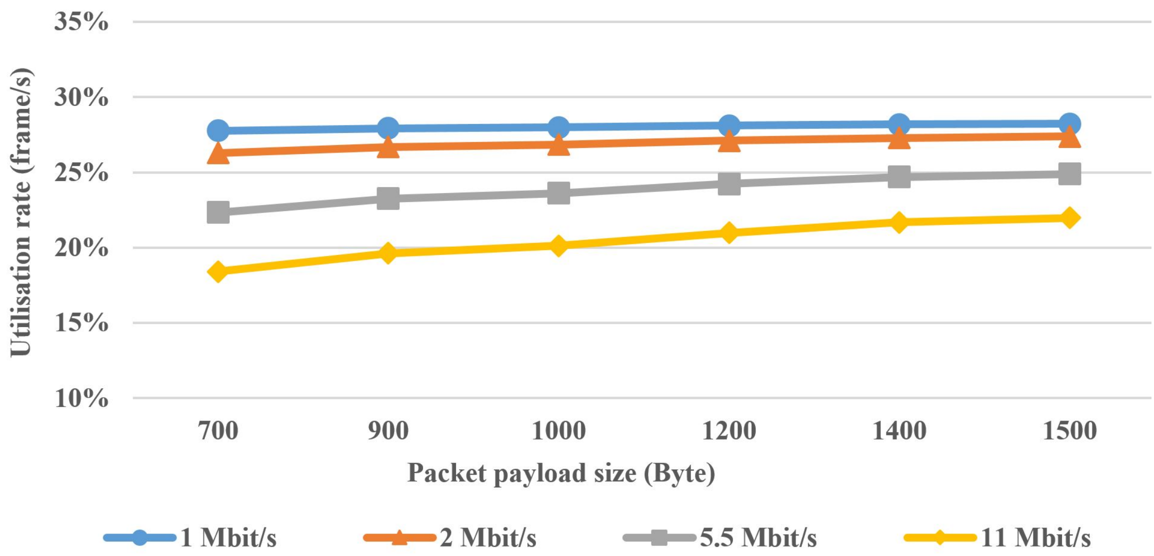


Fig. 4.16 Channel utilisation rate for one external pair in scenario 4.3.

The channel utilisation rate for central pairs increases as the packet payload size increases. Figure 4.17 shows the channel utilisation of a particular central pair. Any central pair might get congested, if one or both external pairs are occupying the channel. But, each central pair has a limited chance to access the medium, as most time the medium is occupied by the one or both external pairs. On the four pairs case, if either Pair A or Pair D (as an external pairs) attempts to send a frame (if the channel is free) then one of the central (Pair B or Pair C) is blocked. For example, if the Pair B (as one of central pair) is transmitting then Pair D (as one of external pair) can transmit too, then the other pairs (Pair A and Pair C) are blocked. Likewise, if the Pair A is transmitting (as one of external pair) and Pair C (as one of central pair) can transmit also, which means, the Pair B (as the central pair) and Pair D (an the external pair) are blocked. Hence, if Pair A is transmitting then Pair B can not do so as they can hear each other. Similarly, if Pair D is transmitting then Pair C is blocked (and vice versa). Here, we can understand that the both central pairs have less chance to access the medium rather than the external pairs.

The key point is both externals can transmit simultaneously, but both the central pairs cannot transmit simultaneously, the externals always have more chance to transmit. An external can only blocked by one central pair. However, each central pair can be blocked by the other central and one of the externals. Hence this is more chance that a central is blocked than an external.

Although, the advantage of this scenario is; only one of the central pairs (Pair B or Pair C) can use the channel at the same time. Moreover, each of them can hear each other and the external neighbour. In this case the channel utilisation rate in central pair(s) is lower than channel utilisation rate in external(s). In the four pairs scenario the channel utilisation rate for each pair is fairer compared to the three pairs scenario. It is calculated by the following formula, and see Figure 4.17.

$$\text{Utilisation of centrals} = \text{ total utilisation} \times \frac{\text{throughput B}}{\text{total throughput (AckA, AckB, AckC and AckD)}}$$

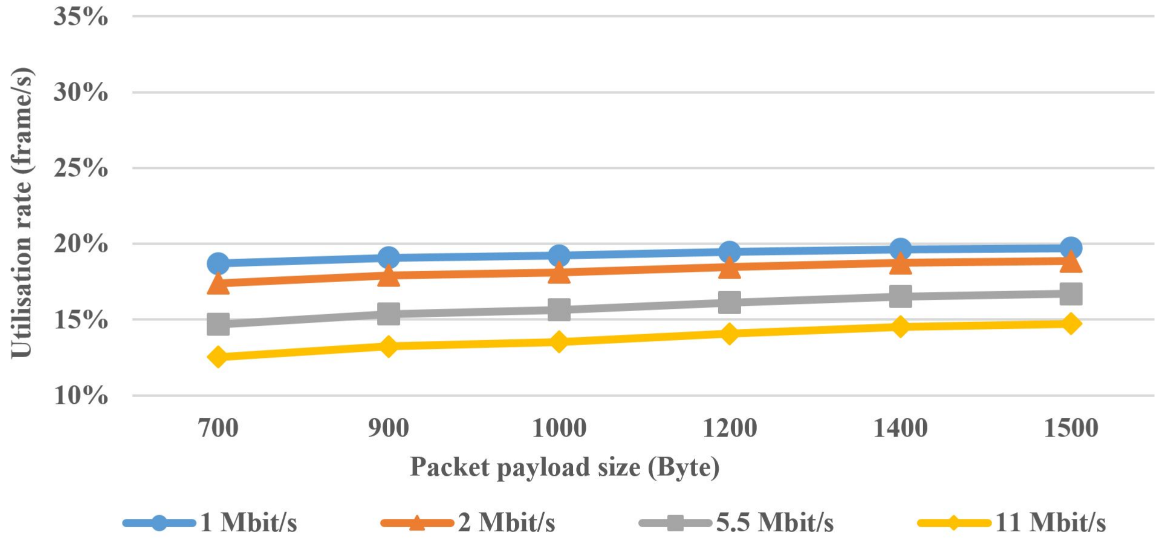


Fig. 4.17 Channel utilisation rate for the central pair in scenario 4.3.

Finally, we examined the channel throughput on this scenario. The channel throughput is decreased as the packet payload size is increased. But in comparison to the three pairs case it is lower, because of the channel occupancy time channel throughput is different to the channel utilisation rate for both external and central pairs. This means the highest bandwidth obtains higher throughput in transmission compared to the lower speed. Figure 4.18 and 4.19 are shown the channel throughput for externals and both central perspectively. As we can see in these figures, the channel throughput decreases when packet payload size increases. However, in the central pairs, the channel throughput is lower compared to the external pairs. This scenario is unfair as each central pair is out competed by others and it is unfairly disadvantaged.

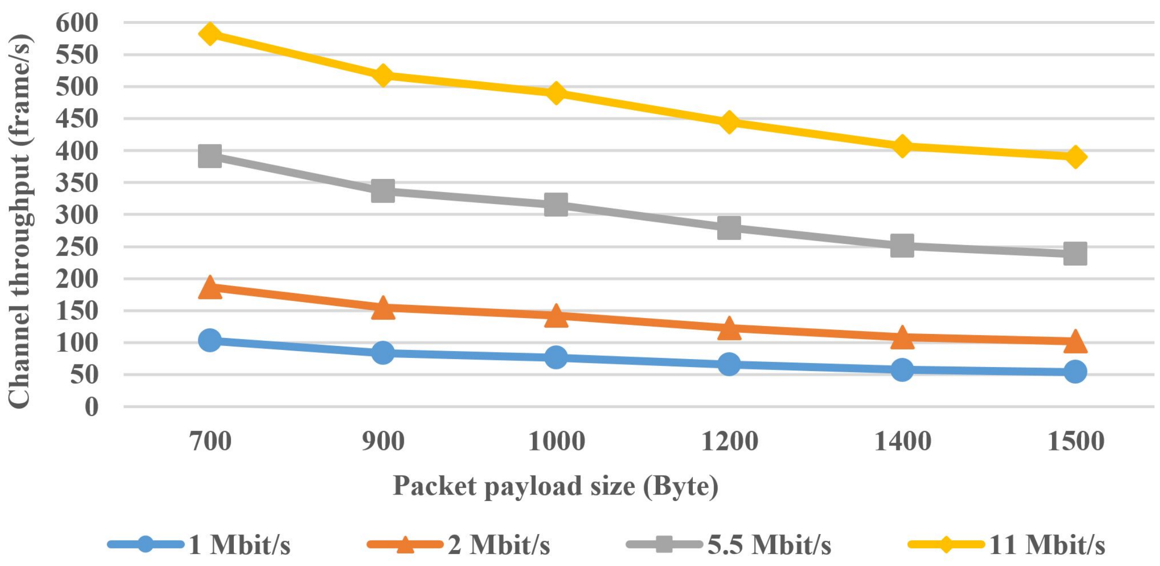


Fig. 4.18 Channel throughput rate for the external pairs in scenario 4.3.

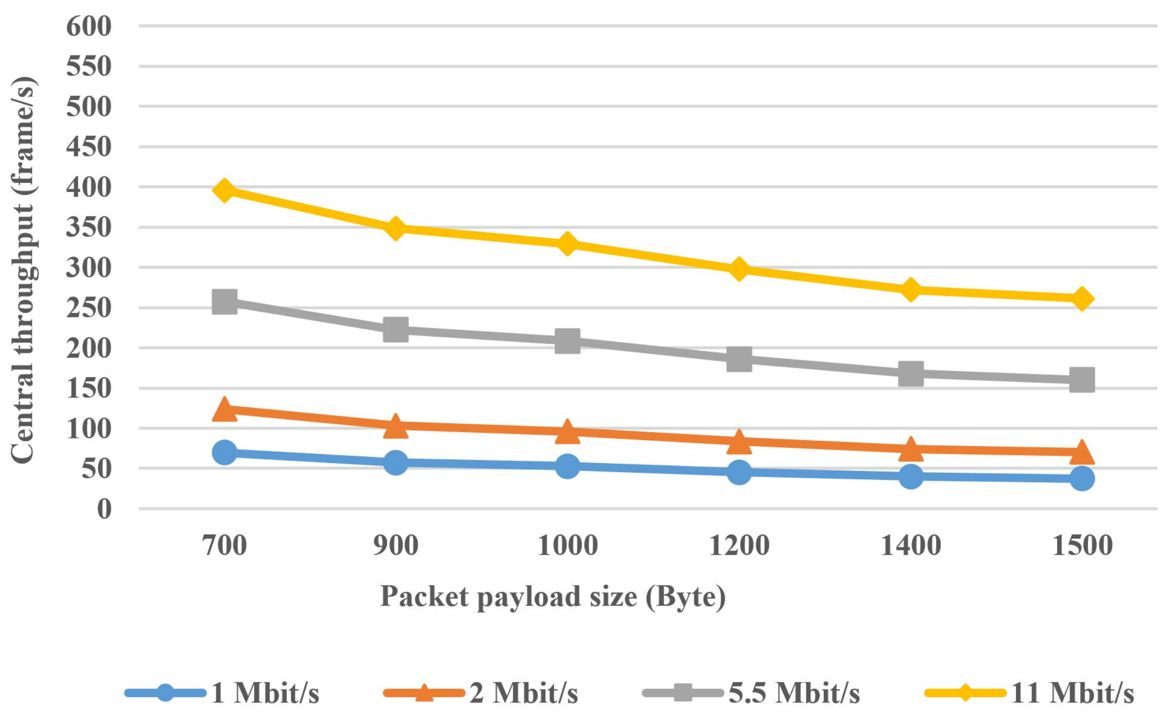


Fig. 4.19 Channel throughput rate for the central pair in scenario 4.3.

4.4.4 Fairness metric of utilisation in 3 and 4 pairs scenarios (r=200000).

In this section, we examined how fairness develops based on the load of backoff rate. We studied the fairness metric of channel utilisation in three pairs and four pairs scenarios, when backoff rate is 200000. Figure 4.20 presents the fairness metric of channel utilisation in the three pairs scenario. This figure shows, that the slowest speed of transmission (1 Mbps) will present a better fairness compared to other speeds. However, the highest speed (11 Mbps) can demonstrate a better performance compared to 2 and 5.5 Mbps speeds, when a packet payload size is 700. The following equation can be used to find the fairness metric of utilisation.

$$\text{Fairness metric of channel utilisation} = \frac{\text{Channel utilisation of one Internal pair}}{\text{Channel utilisation of one External pair}}$$

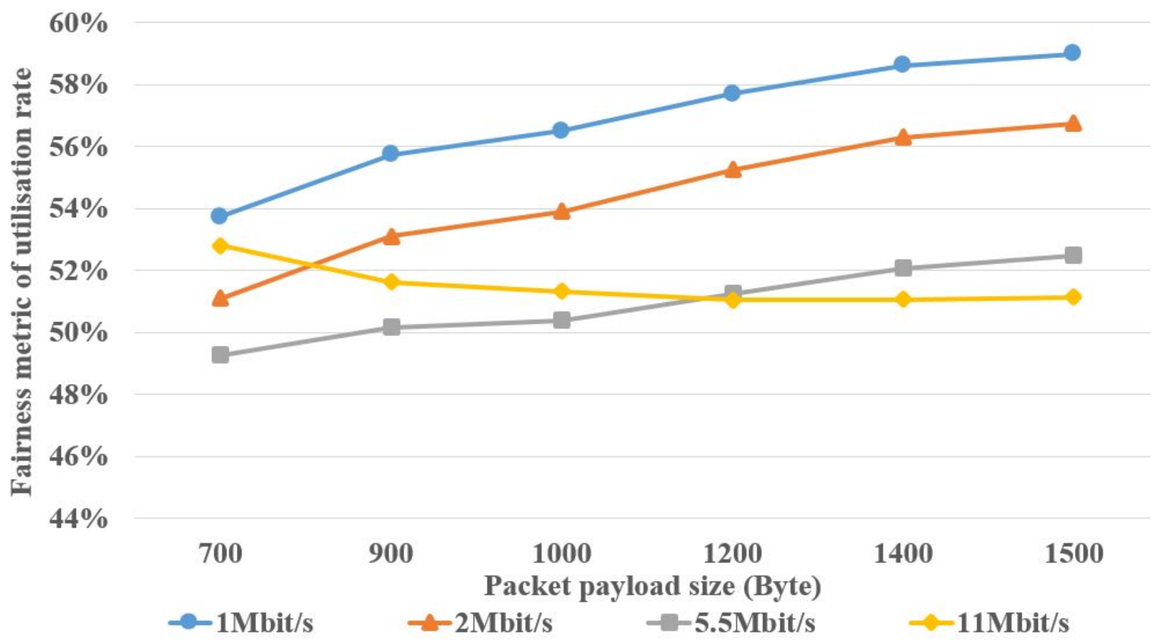


Fig. 4.20 The fairness metric of channel utilisation for three pairs in 802.11b (r=200000).

Moreover, we have used the similar method as it is presented above to examine the fairness metric of channel utilisation for the four pairs scenario. Figure 4.21 illustrates our fairness metric of channel utilisation for the four pairs scenario, when backoff r=200000. Here, we can observe that 11 Mbps speed will demonstrate a better fairness compared to 1, 2 and 5.5 Mbps speeds, when a packet payload size is 700. However, the slowest speed of transmission in this case study (1 Mbps) will significantly perform better fairness compared to the other speeds, specifically when we increase the packet payload size from 700 to 1500.

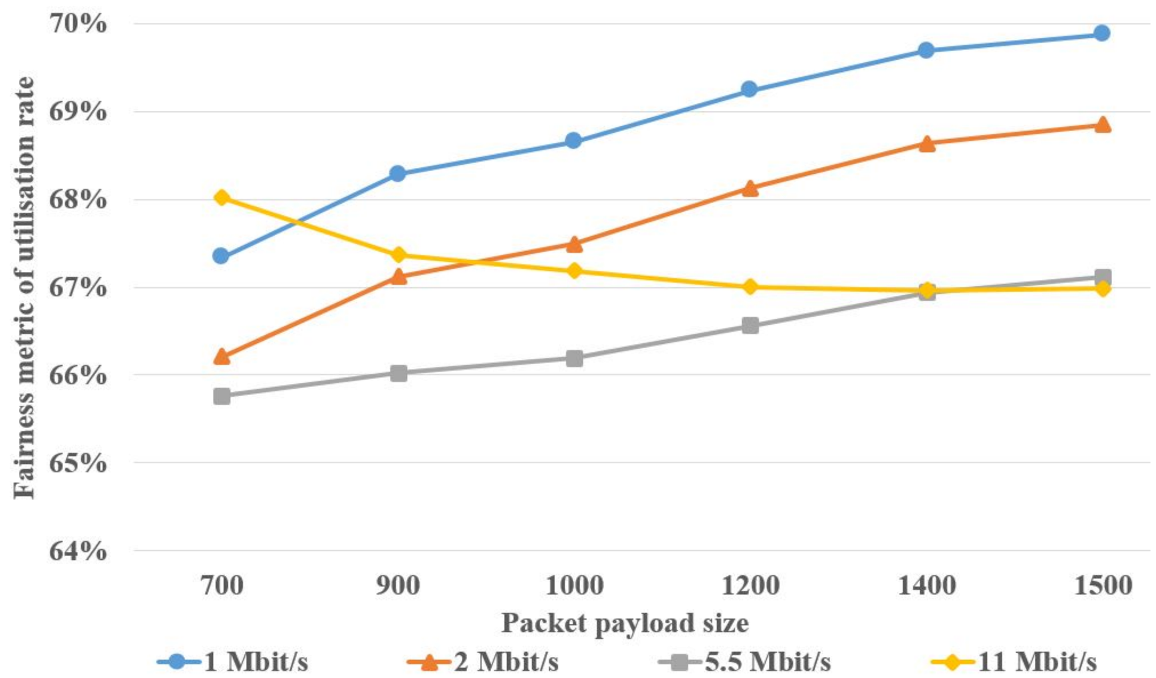


Fig. 4.21 The fairness metric of channel utilisation for four pairs in 802.11b (r= 200000).

4.4.5 Fairness metric of utilisation in 3 and 4 pairs scenarios (r=20).

In this section, we extend our analysis to consider the sensitivity of backoff rate, when r=20 for the three and four pairs scenario. Figure 4.22 shows the fairness metric of channel utilisation for the three pairs scansion in 802.11b, when r=20. This figure shows that the system is almost completely fair when the speed is 11 Mbps, but it will droops down when speed decreases. Clearly, it decreases massively in 1 Mbps when the packet payload size increases from 700 to 1500. The slowest speed presents poor fairness compared to the highest speed, see Figure 4.22. Also, a very low backoff will provide a lower probability of the contentions, and if there is no contention then it is fair for the scenario; fairness is relative with the contention if we have decreased the speed of transmission, which means the transmission will take longer for sending any frame.

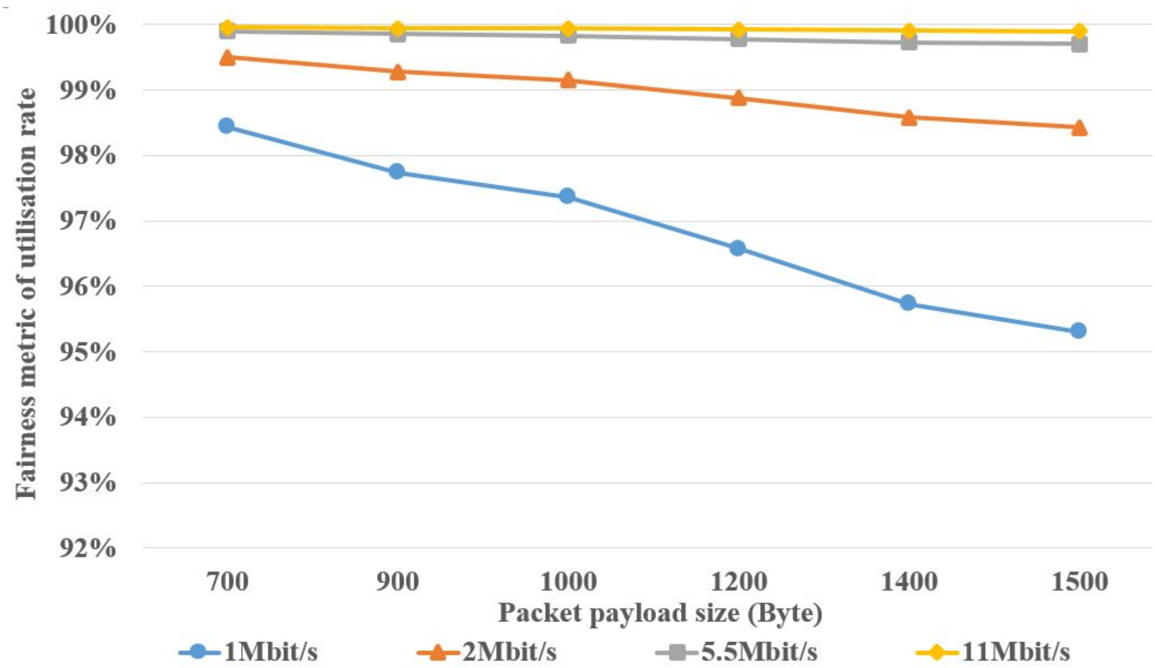


Fig. 4.22 The fairness metric of channel utilisation for three pairs in 802.11b (r=20).

Finally, the profile of sensitivity of the backoff in the four pairs scenario, when r=20 is similar to the three pairs scenario. Figure 4.23 shows the fairness metric of channel utilisation for the four pairs scansion in 802.11b, when r=20. Similarly, this figure shows the fairness metric is nearly saturated in 11 Mbps as the three pairs scenario, also it decreases by reducing the transmission speed. In a slowest speed of transmission (1 Mbps), this decrease has significantly occurred. Moreover, the fairness metric of channel utilisation in 1 Mbps decreases more compared to the three pairs case, by increasing the packet payload size; as we have two external and two central pairs in the four pairs case, which means the slowest speed is very slow to be used by all the pairs. Thus, the low backoff will affect more in a slow speed compared to high speed.

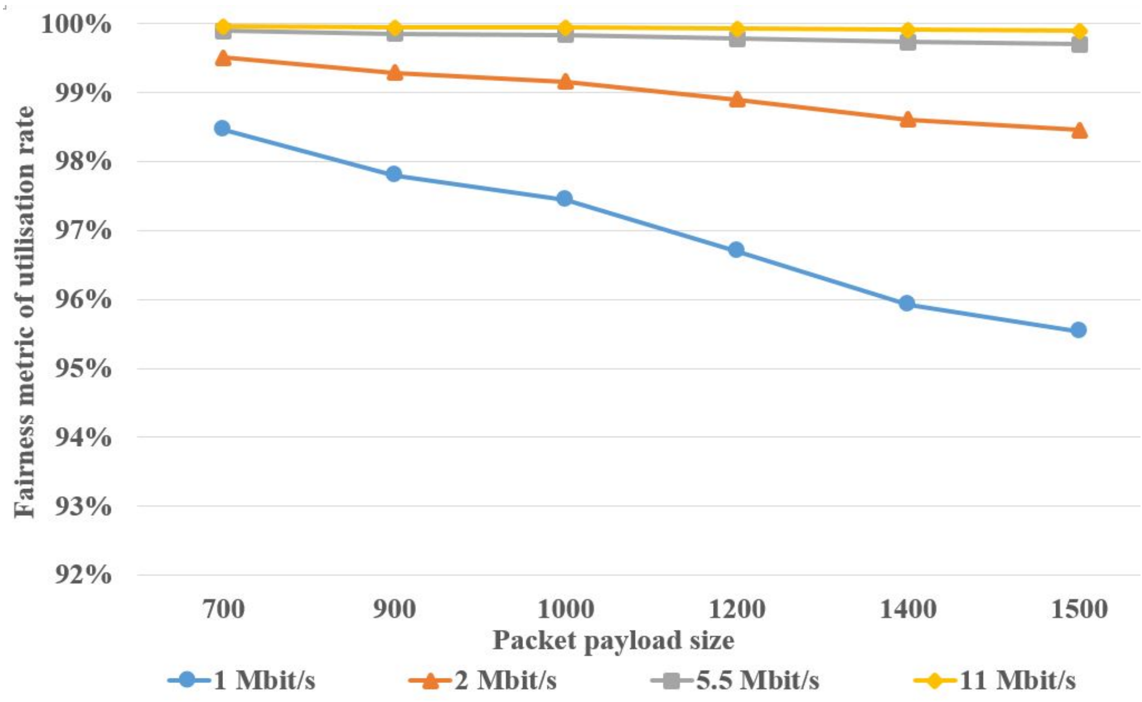


Fig. 4.23 The fairness metric of channel utilisation for four pairs in 802.11b (r=20).

4.4.6 Sensitivity to geometric assumption.

In our previous models, backoff and CW were set at a constant average value and were not doubled with every unsuccessful transmission. But, in this section we examined a model of two pairs scenario, when backoff will double based on CW, due to any interference occurs. In this study, we will answer the main critical question, which is how much difference does it make, if we introduce long count backoff (when backoff value is doubling depends on CW augments from CWmin 63 to CWmax 1023).

The sequential components and process of two pairs and medium in this scenario are similar to our previous models, except that we have amended the (`Pair_A1`) in this model. `Pair_A1` attempts to count backoff at $p\mu_{bck}$ to `Pair_A1b`, or end backoff at the rate $q\mu_{bck}$ to `Pair_A2` or it stays in a queue in `Pair_A5`. If it has a choice to `Pair_A1b`, then CW will double and it will count backoff again in a new $p\mu_{bck}$, which is called $p\mu_{bck2}$ to `Pair_A1c`, or it will end backoff at the rate $q\mu_{bck}$ to `Pair_A2`, or stay in the queue in `Pair_A5`. Similarly, the state of `Pair_A1c` will have the same action as `Pair_A1b`, and it will be continued until the CW will reach its maximum value. The central pair (Pair B) has exactly similar process. The sequential component process of external Pair A presents as follows, which is similar in all pairs:

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1b + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A1b &\stackrel{def}{=} (count\_backoffA, p\mu_{bck2}).Pair\_A1c + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A1c &\stackrel{def}{=} (count\_backoffA, p\mu_{bck3}).Pair\_A1c + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
&+ (queueA, \top).Pair\_A5
\end{aligned}
$$

$$
\begin{aligned}
Pair\_A2 &\stackrel{def}{=} (transmitA, \mu_{data}).Pair\_A3 + (queueA, \top).Pair\_A5 \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4 \\
Pair\_A6 &\stackrel{def}{=} (ackA, \mu_{ack}).Pair\_A
\end{aligned}
$$

The following figures will explain the relative difference of our new mode (when the backoff time becomes double) compared to our previous model (where the backoff was fixed and CW was not augmented). Here, we examined the sensitivity to geometric assumption of 5.5 Mbps.

We have presented the sensitivity to geometric assumption in channel utilisation in Figure 4.24 compared to our new model (deterministic model). The following equation used to find the relative accuracy of geometric approximation of channel utilisation:

$$
\text{Relative accuracy of geometric} = \left| \frac{\text{Utilisation of Geometric - Utilisation of Deterministic}}{\text{Channel utilisation of Geometric}} \right|
$$

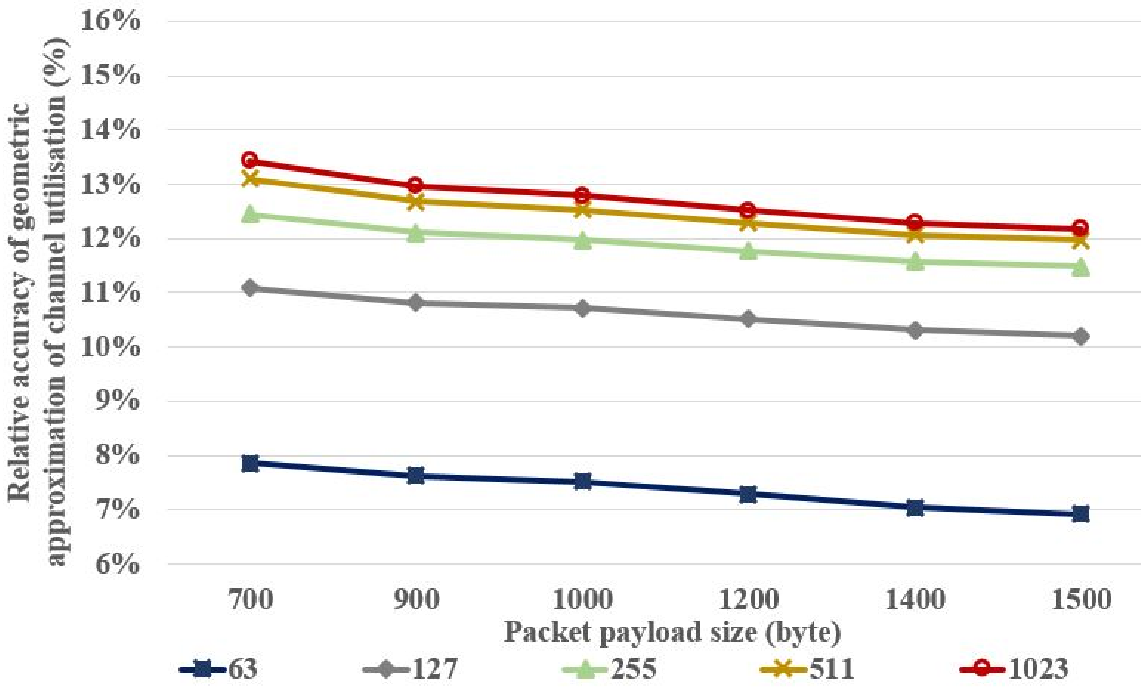


Fig. 4.24 Relative accuracy of geometric approximation of utilisation in 2 pairs of 5.5 Mbps.

Figure 4.24 presented the relative accuracy of geometric approximation of channel utilisation for 5.5 Mbps on two pairs scenario, when the backoff is doubled and CW augmented. The relative accuracy of geometric approximation of channel utilisation will be higher, if the CW will increase as it has augmented from 63 to 1023. But, the relative differences between these models when the CW augmented from 127 to 1023 are not massive. Here, we obtained nearly 5% difference between CW=63 to maximum CW=1023. We can see that the relative accuracy of geometric approximation of channel utilisation in CW=511 and CW=1023 are very similar with having a faint differences.

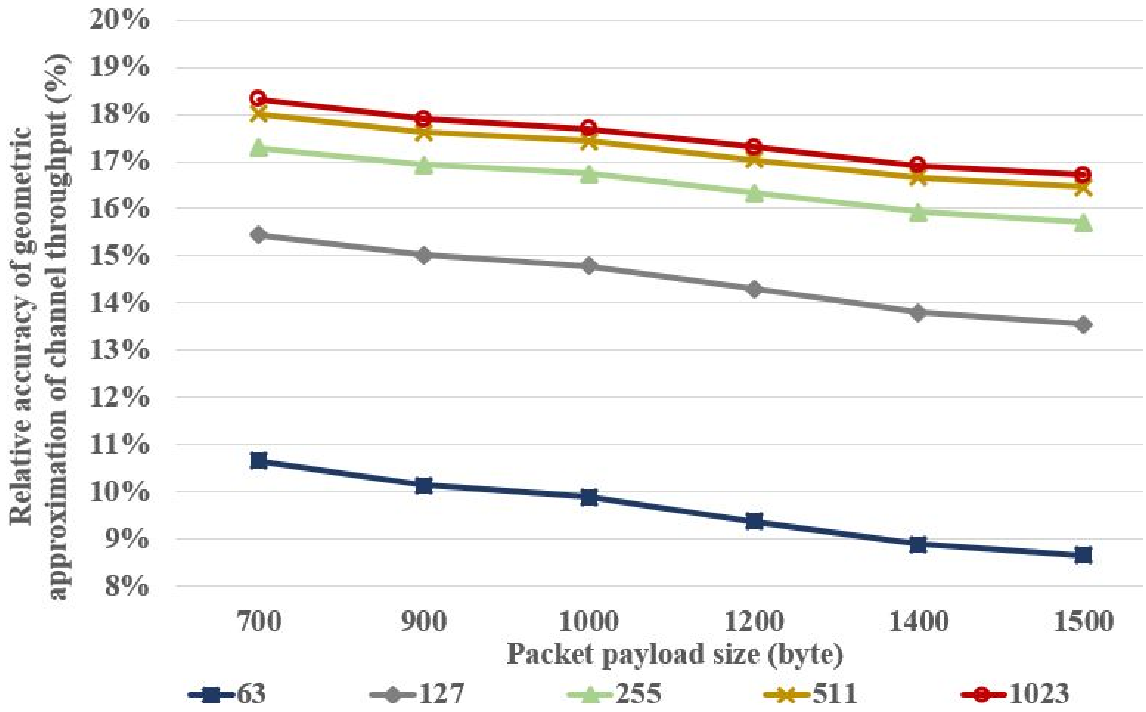


Fig. 4.25 Relative accuracy of geometric approximation of throughput in 2 pairs of 5.5 Mbps.

Figure 4.25 illustrated a relative accuracy of geometric approximation of channel throughput. As, it will decrease by increasing the packet payload size, which the profile of this figure is similar to Figure 4.24. Thus, we can see the relative accuracy of geometric approximation of channel throughput will be increased by doubling the CW from 63 to 1023, see Figure 4.25. Here, there is not much difference from the 63 to 1023, which we obtained approximately 8% differences. Here, we can understand that the augmented of CW will affect the channel utilisation and throughput, but it will not impact the fairness in this scenario as both pairs are symmetric.

4.4.7 Fairness metric of channel utilisation in 3 pairs scenario.

In the previous section, we examined the case where the speed is 5.5 Mbps on the two pairs scenario when backoff doubled depends on CW augments. We presented that the CW will affect the channel utilisation and throughput, when CW doubled during any unsuccessful transmissions. Clearly the changes to the behaviour of the contention window will not affect the fairness in the two pairs case, as both pairs are symmetric. For that purpose, we are interested to examine the three pairs scenario to show how fairness develops, if the backoff doubled due to interferences. In this case study, we have examined the fairness metric of channel utilisation in 5.5 Mbps for the three pairs scenario, when the backoff rate is 200000, and CW doubled in any failure of transmission. Figure 4.26 shows the fairness metric of channel utilisation in the three pairs case, which the fairness has been impacted if we increase CW-1 from 63 to 1023. This figure illustrates that the channel utilisation will decrease when the packet payload size increases. Hence, we can understand that the fairness metric of channel utilisation will be affected by CW, as it will be higher when the CW will increase. Thus, the fairness becomes poor when CW increases, as the central pair will be blocked more by both external pairs. The longer backoff based on

CW increases will affect the fairness in this scenario, as it presents a poor fairness. The fairness metric is better when CW is minimum (CWmin) compared to the other cases. Particularly, this figure demonstrates poor fairness when CW increases to the maximum (CWmax), see Figure 4.26. The fairness metric of utilisation in this scenario can be found as follows.

$$\text{Fairness metric of channel utilisation} = \frac{\text{Channel utilisation of one Internal pair}}{\text{Channel utilisation of one External pair}}$$

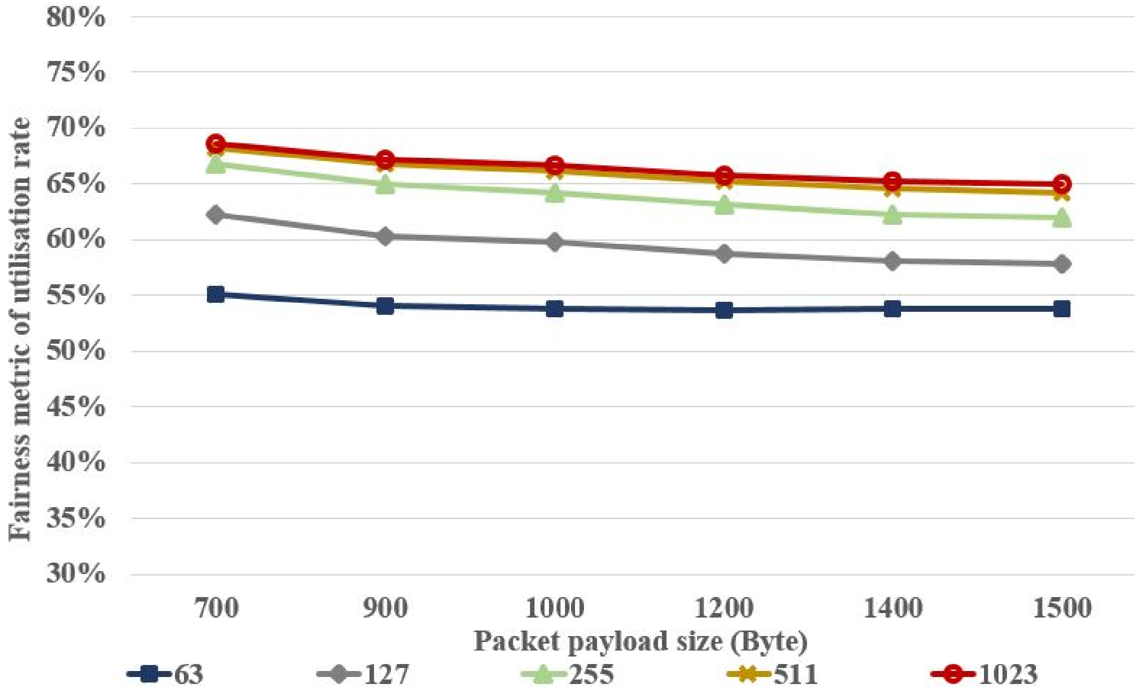


Fig. 4.26 Fairness metric of utilisation for 5.5 Mbps in 3 pairs, when CW doubled (r=200000).

4.5 Chapter summary.

In this chapter we explored three simple scenarios in 802.11b protocol to observe their relative fairness in terms of channel utilisation and throughput. From these results it is clearly seen that the arrangement of nodes within a network can have a profound effect of the performance obtained. Furthermore, we can see that this performance is not uniform across the nodes as those with more neighbours are subject to more competition for channel access. This is particularly evident in the three pairs scenario, where the central node receives a much reduced service. Such a scenario could easily arise in mobile network, where one pair of nodes from a link between two groups. As nodes in WLANs act as routers, the poor performance on this link may affect the performance of the entire network. The effect is less pronounced in the four pairs case, demonstrating that the more connected a network evenly distributed its performance should be. In addition, we studied the fairness metric of channel utilisation on three and four pairs scenario with sensitivity of backoff rate. Finally, we investigated the sensitivity to geometric assumption, where CW augmented.

The next chapter will present our efforts in considering to the IEEE 802.11g performance modelling and modelling unfairness with variable frame length on different pairs of scenarios (one pair, two pairs, three pairs and four pairs scenarios).

Chapter 5

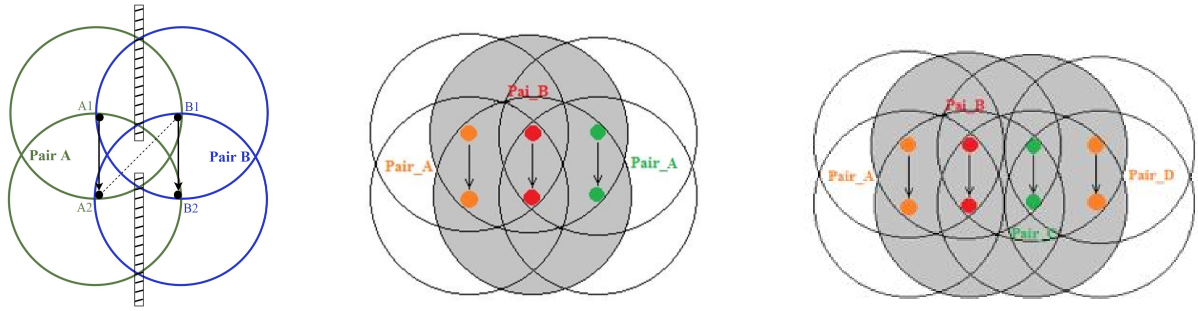
IEEE 802.11g performance modelling and fairness issue with variable frame length

5.1 Introduction.

This chapter will focus on evaluating the channel access and fairness issue due to topographic effects in the layout of communicating nodes under IEEE 802.11g protocol. The IEEE 802.11g is a very similar protocol to the IEEE 802.11b protocol, although the transmission ranges, transmission rates, frame lengths and other Timing Inter-Frame are different.

This chapter expands the model introduced in Chapter 4 to consider the different transmission rates and Inter-Frame Spacing (*IFS*) used in 802.11g. The results shows some interesting variation in fairness between longer and shorter frame length. This leads us to consider whether variation in frame length can impact on fairness. We therefore develop a model where pairs of nodes communicate with either an exponentially or a hyper-exponentially distributed frame length.

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 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) neighbouring nodes need to be able to ‘sense’ the medium before the transmission in order to minimise and detect interference. WLAN protocols provides 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 its operating environment. We seek to relax these conditions in our model to explore the effect of frame length variability on the fairness of network access. The proposed model has many of the features of IEEE 802.11g protocol, including the same average frame lengths. But, by introducing greater variability to the frame lengths we allow 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 WLAN with highly variable frame lengths, including frame bursting provision, considered in IEEE 802.11n protocol in the Chapter 6.



(a) Two pairs scenario. (b) Three pairs scenario. (c) Four pairs scenario.

Fig. 5.1 The two pairs, three pairs and four pairs scenarios.

5.2 Performance modelling of IEEE 802.11g protocol.

The channel utilisation, channel throughput with fairness and unfairness are studied in this section for IEEE 802.11g used PEPA. In this section we revisit the three scenarios introduced in the previous chapter. The models we analyse are structurally the same as in IEEE 802.11b protocol, but the rates are altered to reflect the different parameters by IEEE 802.11g protocol. Results are derived which demonstrate when and how unfairness might occur, leading to the penalisation of some nodes in a network. The pair components have identical behaviour in each case, but the medium is different. We consider three models corresponding to the three topological scenarios shown in Figure 5.1

Note 1: All pairs in these scenarios have similar behaviour as Pair A in scenario 5.1.

5.2.1 The two pairs scenario (scenario 5.1).

This section shows, the investigation of fairness issue in the 802.11g protocol with the two pairs scenario. This scenario has three components which are `Pair_A`, `Pair_B` as two symmetric and independent pairs and the medium component as denoted by `Med_F`. Once, any node in a pair attempts to transmit, then its partner node waits to receive an *ACK*. `Pair_A` and `Pair_B` are equally occupying the channel (`Med_F`). To transmit, `Pair_A` draws a backoff and becomes `Pair_A0`, then `Pair_A0` starts to count the *DIFS* to become `Pair_A1` or stays in the queue as `Pair_A5`. As `Pair_A5` it waits before becoming `Pair_A4`. All *SIFS* and *EIFS* will count until the backoff end, then the frame can transmit in `Pair_A2` finally the *ACK* will be received in `Pair_A6`. The second pair of node (Pair B) has similar process as it shows in the following specifications. Clearly, this scenario is fair, as each pair can access the medium fairly and equally.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0\\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (queueA, \top).Pair\_A5\\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2 + (queueA, \top).Pair\_A5\\
Pair\_A2 &\stackrel{def}{=} (transmitA, \mu_{data}).Pair\_A3 + (queueA, \top).Pair\_A5\\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6\\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 + (queueA, \top).Pair\_A5\\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4\\
Pair\_A6 &\stackrel{def}{=} (ackA, \mu_{ack}).Pair\_A
\end{aligned}
$$

$$\begin{aligned}
Pair_B &\stackrel{def}{=} (draw_backoff, r).Pair_B0\\
Pair_B0 &\stackrel{def}{=} (count_difsB, \mu_{difs}).Pair_B1 + (queueB, \top).Pair_B5\\
Pair_B1 &\stackrel{def}{=} (count_backoffB, p\mu_{bck}).Pair_B1 + (end_backoffB, q\mu_{bck}).Pair_B2 + (queueB, \top).Pair_B5\\
Pair_B2 &\stackrel{def}{=} (transmitB, \mu_{data}).Pair_B3 + (queueB, \top).Pair_B5\\
Pair_B3 &\stackrel{def}{=} (count_sifs, \mu_{sifs}).Pair_B6\\
Pair_B4 &\stackrel{def}{=} (count_difsB, \mu_{difs}).Pair_B1 + (count_eifsB, \mu_{eifs}).Pair_B1 + (queueB, \top).Pair_B5\\
Pair_B5 &\stackrel{def}{=} (wait, \mu_{data}).Pair_B4\\
Pair_B6 &\stackrel{def}{=} (ackB, \mu_{ack}).Pair_B
\end{aligned}$$

Component (`Med_F`): Pair A and Pair B uses the medium component by the following cooperation set. When a specific pair starts to occupy the medium then the other one stops to transmit. In this model, the specifications of shared medium by both pairs (Pair A and Pair B) shows, that the `Med_F` represents the situation where the medium is unoccupied. `Med_F1` represents the medium being used by the pair B and `Med_F2` represents the medium being used by the pair A.

$$\begin{aligned}
Med_F &\stackrel{def}{=} (transmitA, \top).Med_F2 + (transmitB, \top).Med_F1 + (count_difsA, \top).Med_F\\
&+ (count_backoffA, \top).Med_F + (end_backoffA, \top).Med_F\\
&+ (count_eifsA, \top).Med_F + (count_difsB, \top).Med_F + (count_backoffB, \top).Med_F\\
&+ (end_backoffB, \top).Med_F + (count_eifsB, \top).Med_F\\
Med_F1 &\stackrel{def}{=} (ackB, \top).Med_F + (queueA, \lambda oc).Med_F1\\
Med_F2 &\stackrel{def}{=} (ackA, \top).Med_F + (queueB, \lambda oc).Med_F2
\end{aligned}$$

$$\text{Scenario 5.1} \stackrel{def}{=} (Pair\_A \underset{K}{\bowtie} Med\_F) \underset{L}{\bowtie} Pair\_B$$

Where the sets K and L are:
$K = \{transmitA, ackA, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA\}$.
$L = \{transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

5.2.2 The three pairs scenario (scenario 5.2).

In this study we have expanded the experiment of the performance fairness from the two pairs scenario to the three pairs scenario. We have examined the behaviour of IEEE 802.11g protocol, in each of the channel utilisation, channel throughput and response time matters. The four components have been used in this scenario, which contains two external pairs (which they are denoted by Pair A as they are symmetric and cannot hear each other), a central pair (Pair B) can hear the both external pairs and a medium (`Med_F`). If, any external pair uses the medium then the central one (Pair B) is waiting and staying in the queue, until the channel is free to use. Consequently, the central pair has less chance to access the medium over both external pairs. Thus, this scenario demonstrates unfairness. Moreover, the central pair has been unfairly disadvantaged as it is been out competed by external pairs. On the other hand, external pairs have an unfair advantaged because they have more chance to access the medium.

PEPA model of scenario 5.2: All pairs cooperate with the medium, it is either free or it is occupied by central or external pair(s). The following cooperation sets shows the interaction between the pairs and the medium. The medium (`Med_F`) in this scenario is identical to the medium component in the two pairs scenario.

Component of Medium F: The shared medium component in this scenario shows, that the `Med_F` represents the situation where the medium is unoccupied. `Med_F1` represents the medium being used by the central pair (Pair B). Also, `Med_F2` represents the medium being used by exactly one of the external pairs (Pair A). Finally, `Med_F3` represents the medium being used by both external pairs. The shared medium in the three pairs model is given as follow:

$$\begin{aligned}
Med_F &\stackrel{def}{=} (transmitA,\top).Med_F2 + (transmitB,\top).Med_F1 + (count_difsA,\top).Med_F \\
&+ (count_backoffA,\top).Med_F + (end_backoffA,\top).Med_F \\
&+ (count_eifsA,\top).Med_F + (count_difsB,\top).Med_F + (count_backoffB,\top).Med_F \\
&+ (end_backoffB,\top).Med_F + (count_eifsB,\top).Med_F \\
Med_F1 &\stackrel{def}{=} (ackB,\top).Med_F + (queueA,\lambda oc).Med_F1 \\
Med_F2 &\stackrel{def}{=} (transmitA,\top).Med_F3 + (ackA,\top).Med_F + (queueB,\lambda oc).Med_F2 \\
&+ (count_difsA,\top).Med_F2 + (count_backoffA,\top).Med_F2 \\
&+ (end_backoffA,\top).Med_F2 + (count_eifsA,\top).Med_F2 \\
Med_F3 &\stackrel{def}{=} (ackA,\top).Med_F2 + (queueB,\lambda oc).Med_F3 + (count_difsA,\top).Med_F3 \\
&+ (count_backoffA,\top).Med_F3 + (end_backoffA,\top).Med_F3 + (count_eifsA,\top).Med_F3
\end{aligned}$$

$$\text{Scenario 5.2} \stackrel{def}{=} ((Pair\_A \| Pair\_A) \underset{K}{\bowtie} Med\_F) \underset{L}{\bowtie} Pair\_B$$

Where $K = \{transmitA, ackA, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA\}$. $L = \{transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

5.2.3 The four pairs scenario (scenario 5.3).

This scenario has two central pairs (B and C), two external pairs (A and D) and Medium F. Both external pairs are independent and symmetric. If Pair A is transmitting then Pair B is blocked and similarly if Pair D is transmitting then Pair C is blocked (and vice versa). Further more transmission from either central pair (B or C) will block transmission by the other central pair. Here, we can understand that both central pairs have less chance to access the medium compared with the external pairs. The situation is not completely fair, because Pair B and Pair C are penalised, however it is not as restrictive as the three pairs scenario; as if Pair A is transmitting (but not Pair D) then Pair C still has a chance to access the channel. Similarly, if Pair D is transmitting (but not Pair A) then Pair B has a chance to access the channel. By this approach, if we will compare the four pairs case to three pairs scenario, then we can see it is a relatively fairer scenario.

PEPA model of scenario 5.3: The medium has collaboration with all pairs as they are symmetric. The medium is either occupied by any external pairs or any central pairs. Pair A can interact indirectly with Pair B only through the medium F, but both external pairs do not interact with each other. For instance, if `Pair_A` senses the medium is idle then it attempts to use the medium. The backoff action begins from this pair to `Pair_A0`. Then `Pair_A0` starts to count *DIFS* to `Pair_A1` or stay in the queue in `Pair_A5`, if it has a choice to `Pair_A5` then it waits in this state to `Pair_A4`. But, if it has a choice to `Pair_A1` then either it counts backoff in `Pair_A1` or ends backoff in `Pair_A2` or stays in a queue in `Pair_A5`. Also, the all *SIFS* and *EIFS* will count till the backoff end, then the frame will transmit in `Pair_A2`. Finally, after the frame is transmitted successfully, then an *ACK* will be received in `Pair_A6`. In this case when the *ACK* has been received, then the same process can be started again for sending another frame if the pair senses that the medium is free to use. This process is similar in the other pairs.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0\\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1\\
&+ (queueA, \top).Pair\_A5\\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1\\
&+ (end\_backoffA, q\mu_{bck}).Pair\_A2\\
&+ (queueA, \top).Pair\_A5\\
Pair\_A2 &\stackrel{def}{=} (transmitA, \mu_{data}).Pair\_A3\\
&+ (queueA, \top).Pair\_A5\\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6\\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1\\
&+ (count\_eifsA, \mu_{eifs}).Pair\_A1\\
&+ (queueA, \top).Pair\_A5\\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4\\
Pair\_A6 &\stackrel{def}{=} (ackA, \mu_{ack}).Pair\_A
\end{aligned}
$$

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

$$
\begin{aligned}
Pair\_C &\stackrel{def}{=} (draw\_backoff, r).Pair\_C0\\
Pair\_C0 &\stackrel{def}{=} (count\_difsC, \mu_{difs}).Pair\_C1 + (queueC, \top).Pair\_C5\\
Pair\_C1 &\stackrel{def}{=} (count\_backoffC, p\mu_{bck}).Pair\_C1 + (end\_backoffC, q\mu_{bck}).Pair\_C2\\
&+ (queueC, \top).Pair\_C5\\
Pair\_C2 &\stackrel{def}{=} (transmitC, \mu_{data}).Pair\_C3 + (queueC, \top).Pair\_C5\\
Pair\_C3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_C6\\
Pair\_C4 &\stackrel{def}{=} (count\_difsC, \mu_{difs}).Pair\_C1 + (count\_eifsC, \mu_{eifs}).Pair\_C1\\
&+ (queueC, \top).Pair\_C5\\
Pair\_C5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_C4\\
Pair\_C6 &\stackrel{def}{=} (ackC, \mu_{ack}).Pair\_C
\end{aligned}
$$

$$
\begin{aligned}
Pair\_D &\overset{def}{=} (draw\_backoff, r).Pair\_D0 \\
Pair\_D0 &\overset{def}{=} (count\_difsD, \mu_{difs}).Pair\_D1 + (queueD, \top).Pair\_D5 \\
Pair\_D1 &\overset{def}{=} (count\_backoffD, p\mu_{bck}).Pair\_D1 + (end\_backoffD, q\mu_{bck}).Pair\_D2 \\
&+ (queueD, \top).Pair\_D5 \\
Pair\_D2 &\overset{def}{=} (transmitD, \mu_{data}).Pair\_D3 + (queueD, \top).Pair\_D5 \\
Pair\_D3 &\overset{def}{=} (count\_sifs, \mu_{sifs}).Pair\_D6 \\
Pair\_D4 &\overset{def}{=} (count\_difsD, \mu_{difs}).Pair\_D1 + (count\_eifsD, \mu_{eifs}).Pair\_D1 \\
&+ (queueD, \top).Pair\_D5 \\
Pair\_D5 &\overset{def}{=} (wait, \mu_{data}).Pair\_D4 \\
Pair\_D6 &\overset{def}{=} (ackD, \mu_{ack}).Pair\_D
\end{aligned}
$$

Component of Medium F: In this scenario the derivative `Medium_F` represents the unoccupied medium. `Medium_A`, `Medium_B`, `Medium_C` and `Medium_D` represent the situation where the medium is being used by exactly one pair of nodes. `Medium_AD`, `Medium_BD` and `Medium_AC` represent the use of the medium by two pairs of nodes. Where medium is free of transmission can start at any of the nodes, leading to one of the behaviours `Medium_A`, `Medium_B`, `Medium_C` or `Medium_D`. From these behaviours communication can be completed with an `ACK` resulting in the medium becoming free once again, or another non-neighbouring pair can being transmitting.

$$
\begin{aligned}
Medium\_F &\overset{def}{=} (transmitA, \top).Medium\_A + (transmitB, \top).Medium\_B \\
&+ (transmitC, \top).Medium\_C + (transmitD, \top).Medium\_D \\
&+ (count\_difsA, \top).Medium\_A + (count\_backoffA, \top).Medium\_A \\
&+ (end\_backoffA, \top).Medium\_A + (count\_eifsA, \top).Medium\_A \\
&+ (count\_difsB, \top).Medium\_B + (count\_backoffB, \top).Medium\_B \\
&+ (end\_backoffB, \top).Medium\_B + (count\_eifsB, \top).Medium\_B \\
&+ (count\_difsC, \top).Medium\_C + (count\_backoffC, \top).Medium\_C \\
&+ (end\_backoffC, \top).Medium\_C + (count\_eifsC, \top).Medium\_C \\
&+ (count\_difsD, \top).Medium\_D + (count\_backoffD, \top).Medium\_D \\
&+ (end\_backoffD, \top).Medium\_D + (count\_eifsD, \top).Medium\_D \\
Medium\_A &\overset{def}{=} (transmitC, \top).Medium\_AC + (transmitD, \top).Medium\_AD \\
&+ (ackA, \top).Medium\_F + (queueB, \lambda oc).Medium\_A \\
Medium\_D &\overset{def}{=} (transmitA, \top).Medium\_AD + (transmitB, \top).Medium\_BD \\
&+ (ackD, \top).Medium\_F + (queueC, \lambda oc).Medium\_D \\
Medium\_B &\overset{def}{=} (transmitD, \top).Medium\_BD + (ackB, \top).Medium\_F \\
&+ (queueA, \lambda oc).Medium\_B + (queueC, \lambda oc).Medium\_B \\
Medium\_C &\overset{def}{=} (transmitA, \top).Medium\_AC + (ackC, \top).Medium\_F \\
&+ (queueB, \lambda oc).Medium\_C + (queueD, \lambda oc).Medium_C \\
Medium\_AD &\overset{def}{=} (ackA, \top).Medium\_D + (ackD, \top).Medium\_A \\
&+ (queueB, \lambda oc).Medium\_AD + (queueC, \lambda oc).Medium\_AD \\
Medium\_BD &\overset{def}{=} (ackB, \top).Medium\_D + (ackD, \top).Medium\_B \\
&+ (queueA, \lambda oc).Medium\_BD + (queueC, \lambda oc).Medium\_BD \\
Medium\_AC &\overset{def}{=} (ackA, \top).Medium\_C + (ackC, \top).Medium\_A \\
&+ (queueB, \lambda oc).Medium\_AC + (queueC, \lambda oc).Medium\_AC
\end{aligned}
$$

The complete system: In this model, the pairs interact indirectly through the medium. This scenario has the following cooperation between all components that is defined as:

$$\text{Scenario 5.3} \stackrel{def}{=} (Pair\_A \parallel Pair\_B \parallel Pair\_C \parallel Pair\_D) \underset{L}{\bowtie} Medium\_F$$

Where the value of $L = \{transmitA, ackA, queueA, count\_difsA, count_backoffA, end\_backoffA, count\_eifsA, transmitB, ackB, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB, transmitC, ackC, queueC, count\_difsC, count\_backoffC, end\_backoffC, count\_eifsC, transmitD, ackD, queueD, count\_difsD, count\_backoffD, end\_backoffD, count\_eifsD\}$

5.3 Parameters.

IEEE 802.11 has a very specific Inter-Frame Spacing, which coordinates access to the medium to transmit frames. If any pair wants to transmit and if it senses the channel is idle then it transmits with the probability of 'p'. For convenience, each pair in this study 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 IEEE 802.11g protocol and PHY standards, the possible data rate per stream are 6, 9, 12, 18, 24, 36, 48, and 54 Mbits/s [25, 45]. In this study, we have 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 μ_{ack} shows as a rate of *ACK*, for instance, for 1 Mbit/s bandwidth the μack = 1644.75 then for 6 Mbit/s bandwidth it is 9868.5 (6 $\times$ 1644.75), as μ_{ack} can be found as follow:

$$\mu_{ack} = \frac{\text{channel throughput}}{(ACK \text{ length= 1 Byte})}$$

Inter-Frame Space (*IFS*). IEEE 802.11 is a large system of timers. Before each frame can transmit, the length of the IFS is dependant on the previous frame type, if any noise will occur, 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 main purpose of an *IFS* is to supply a waiting time for each frame transmission in a particular node, to allow the transmitted signal to reach another node (essential for listening). IEEE 802.11 protocol has several IFS and the main parameter of IFS in the IEEE 802.11g shows in the following that have been used in our models which are: *SIFS*, *DIFS*, *EIFS* and slot time, see [22, 25] and [40].

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

***DCF* Inter-Frame Space (*DIFS*).** It is a medium priority waiting time and longer after *SIFS* 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 $\times$ (slot time =20 μs in IEEE 802.11b, 802.11g and 802.11n)).

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

Contention Window (*CW*). In CSMA/CA, if a node wants to transmit any frame, it senses whether the channel whether is free or not. If it is free then the node transmits, if not the node waits for a random backoff, selected by node from a Contention Window (*CW*), until it becomes free. The node waits to minimise any collision once it experiences an idle channel for an appropriate *IFS*, otherwise many waiting nodes might transmit simultaneously. The node needs less time to wait if there is a shorter backoff period, so transmission will be faster, unless there is a collision. Backoff is chosen in [0, *CW*]. *CW=CWmin* for all nodes if a node successfully transmits a frame and then receives an *ACK*. Otherwise, the node draws another *backoff* and the *CW* increases exponentially, until it reaches *CWmax*. Finally, when the backoff reaches 0, the node starts to transmit and the *CW* resets to *CWmin* when the frame is received.
CWmin = 15, *CWmax* = 1023. *CWmin* augmented by 2n-1 on each retry.
Backoff Time = (Random () mod (CW+1)) $\times$ slot time.
If Backoff Timer = b, where *b* is a random integer, also $CWmin \leq b \leq CWmax$
By using the $C\bar{W}min$ and slot time then we can obtain the μ_{bck}, where $C\bar{W}min$ = 7.5 and slot time = 20μs:

$$\mu_{bck} = \frac{10^6}{\bar{CW} \times \text{ slot time}}$$

The receiver sends an Acknowledgement (*ACK*) if it gets a frame successfully also, $\mu data$ is a rate of waiting action for frames, which can be calculated as follow:

$$\mu_{data} = \frac{\text{data rate } \times \frac{10^6}{8}}{\text{packet payload size}}$$

5.4 Results and discussions.

This section will present the results and discussions of the performance of IEEE 802.11g protocol. Particullarly, the channel utilisation and channel throughput will illustrate in each scenario as we have presented in the previous sections.

5.4.1 Performance results of the two pairs scenario (scenario 5.1).

We investigated the performance of the two pairs scenario by considered the rates of (r, λoc, $\mu difs$, $\mu sifs$, $\mu eifs$) which they are (200000, 100000, 20000, 100000, 2747.3) respectively. These parameters have been used in all our scenarios to measure the channel utilisation and channel throughput. In this scenario Pair A can receive an Acknowledgement (*ACK*) during its transmitting via medium F. This case is fairness on each of the medium utilisation and throughput, by using the above parameters and the given formula as follow:
Utilisation = Pr[Medium_F and (Pair_A2 or Pair_B2)] + Pr[Medium_F1]+ Pr[Medium_F2]

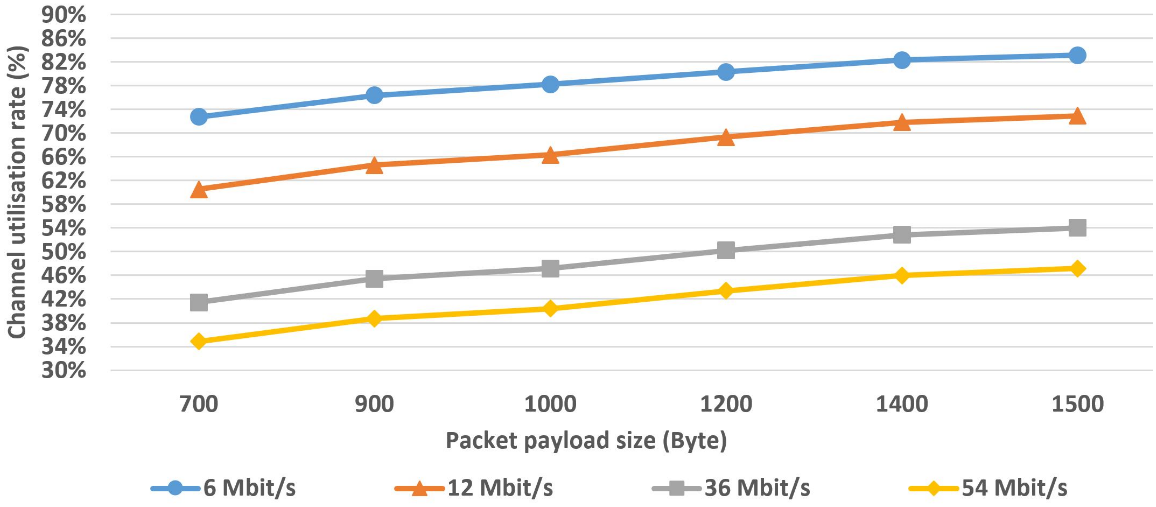


Fig. 5.2 Channel utilisation rate in scenario 5.1.

In Figure 5.2 the channel utilisation rate will increase as the packet payload size increases. This increase is because of the occupied channel time which has increased as the packet payload size increased (as there is more data to be transmitted). In 54 Mbit/s bandwidth any frame can be sent faster relative to other delays. We can see that channel utilisation rate in 6 Mbit/s is increasing while the packet payload size is increasing for the same speed. Accordingly, the actual transmission rate will be faster and the channel utilisation rate for each pairs is exactly half of the total channel utilisation. Hence, each pair can access the medium equally. However, the channel throughput decreases when the packet payload size increases. This is because the channel occupancy time is always increasing with increasing the packet payload size from 700 to 1500 bytes, see Figure 5.3. Finally, in throughput if we have faster backoff, we need less time to transmit, which means we will obtain faster transition in shorter less time. Once the backoff ends successfully, then each pairs can use the medium equally, then the sender receives an Acknowledgement (*ACK*). Hence, we can see that this scenario is totally fair.

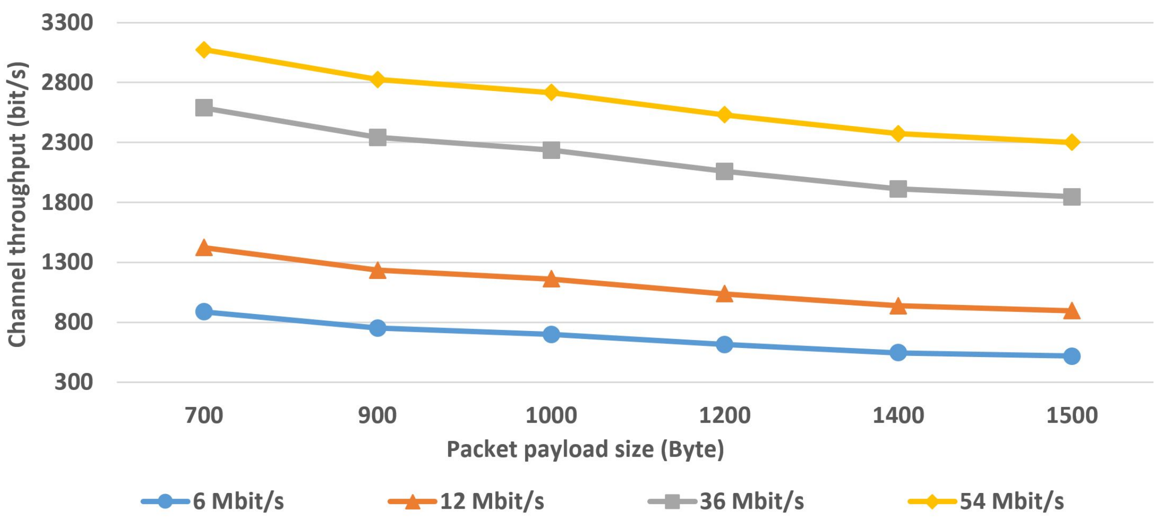


Fig. 5.3 Total throughput for both pairs in scenario 5.1.

5.4.2 Performance results of the three pairs scenario (scenario 5.2).

In the three pairs scenario both external pairs are using the channel equally. However, the behaviour of the central pair is not the same as the external pairs. The channel utilisation rate for external pairs increases as the packet payload size increases (the same as the previous scenario). Both external pairs are able to transmit at the same time without collisions. This is caused by the external pairs as the packet payload size is increasing at the same time, they can occupy the channel equally as two symmetric pairs, see Figure 5.4. The following formula has been used to obtain the channel utilisation.

$$\text{Channel utilisation} = \text{ total utilisation} \times \frac{\text{throughput A}}{\text{total throughput (AckA and AckB)}}$$

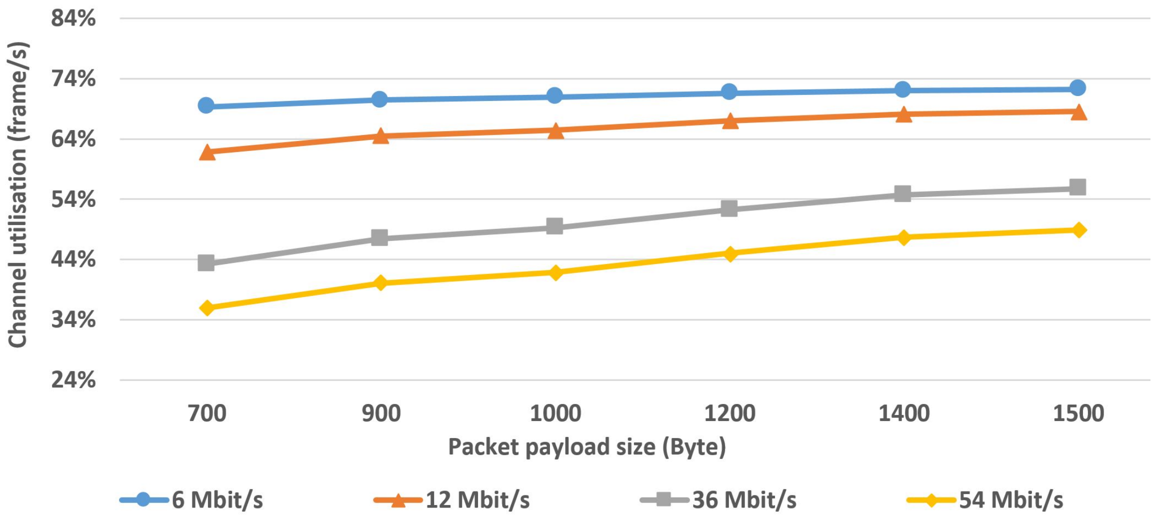


Fig. 5.4 Channel utilisation rate for the external pairs in scenario 5.2.

The channel utilisation rate of the central pair has a similar profile to the external pairs, but it is much lower because the central pair has very limited access the channel, as most of the time the channel is occupied by the external pairs, see Figure 5.5. The following formula has been used to find the channel utilisation of the central pair (Pair B) in this scenario.

$$\text{Channel utilisation} = \text{ total utilisation} \times \frac{\text{throughput B}}{\text{total throughput (AckA and AckB)}}$$

As the channel utilisation rate increases we understand that the three pairs scenario is unfair. For the faster transmission we need to increase the packet payload size or transmit at a lower throughput. Finally, the channel throughput decreases as the packet payload size increases. But, it is not like the channel utilisation, due to the channel occupancy time. The fastest channel in transmitting packet will occupy less time in this channel, Figure 5.6 shows the channel throughput in external pairs and Figure 5.7 presents the channel throughput in the central pair. However, accessing the channel by the central pair is limited compared to the external pairs. Additionally, in terms of channel throughput, this scenario is unfairness and it is not significant for all pairs. Thus, the central pair is out competed by both external pairs and it is unfairly disadvantaged, but

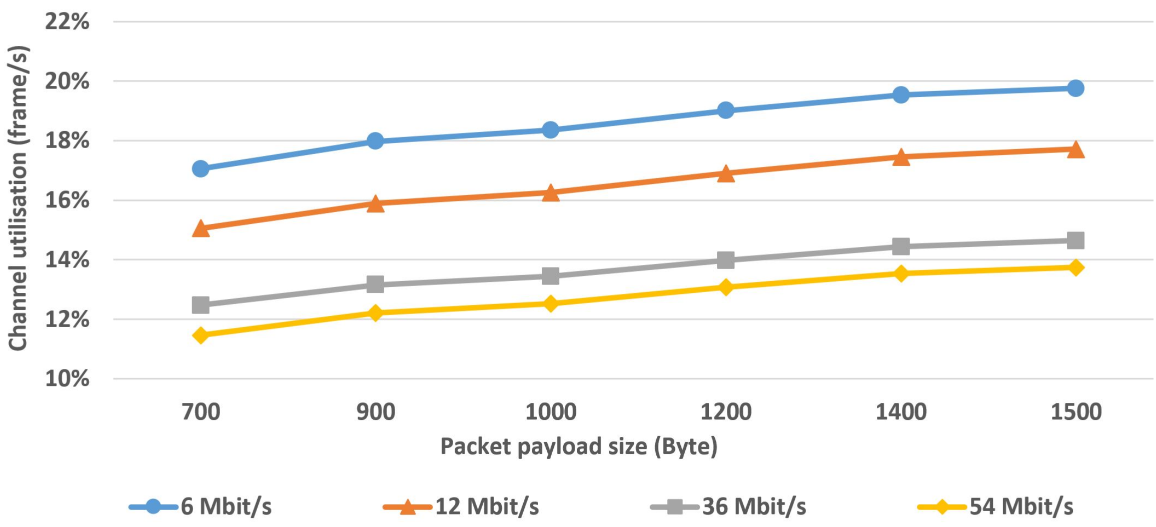


Fig. 5.5 Channel utilisation rate for the central pair in scenario 5.2.

the external pairs are unfairly advantaged as both pairs are able to access the channel when the central pair is blocked.

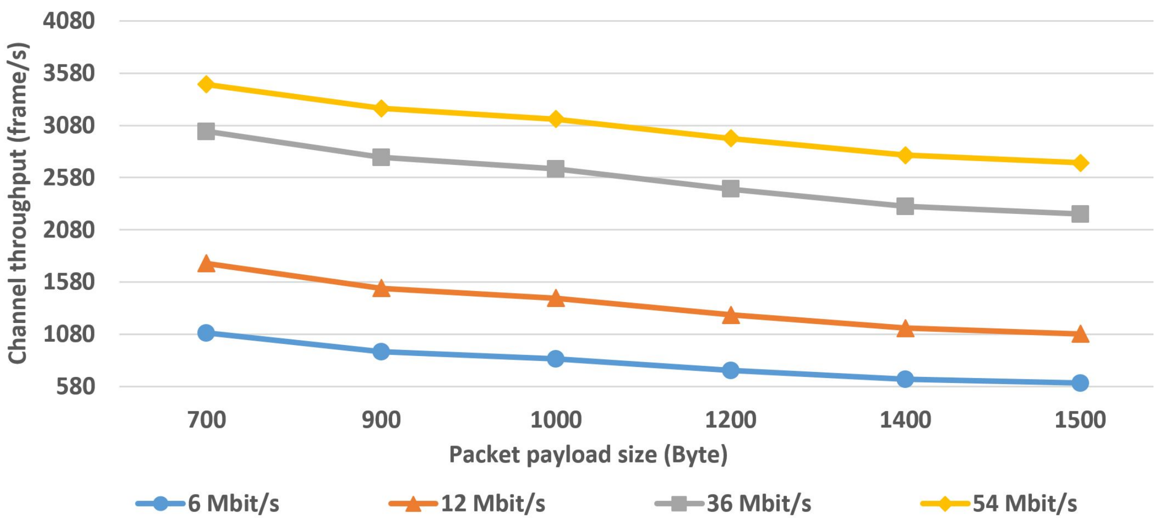


Fig. 5.6 Channel throughput rate for the external pairs in scenario 5.2.

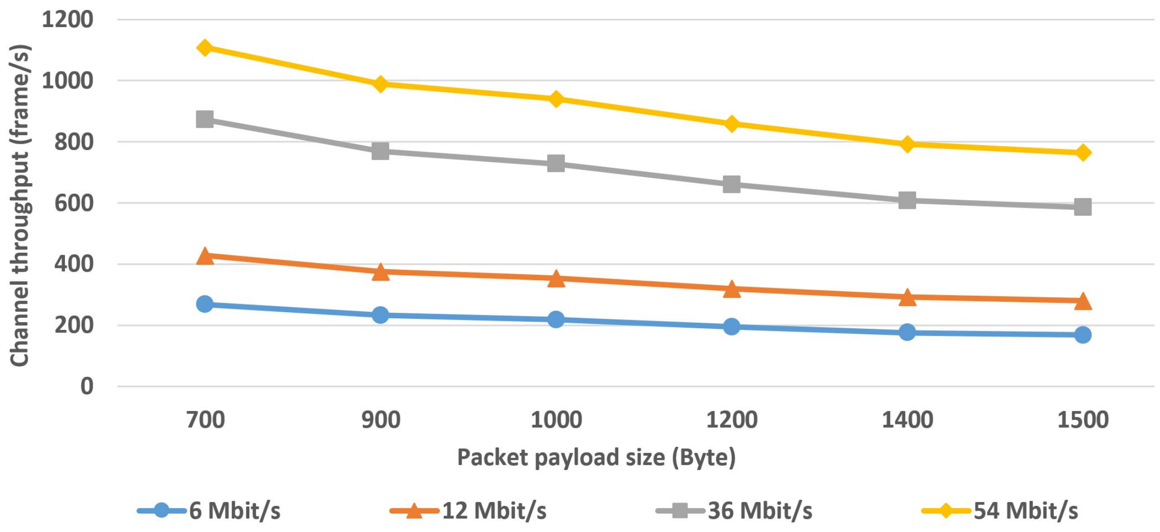


Fig. 5.7 Channel throughput rate for the central pairs in scenario 5.2.

5.4.3 Performance results of the four pairs scenario (scenario 5.3).

In the previous scenario the unfairness has been reported. Hence, the four pairs scenario has been considered to investigate the fairness issue in more details with a different topology. Figure 5.8 shows the channel utilisation rate for external pairs in this scenario. In the four pairs scenario the channel utilisation for external pairs increases as the packet payload size are increased.

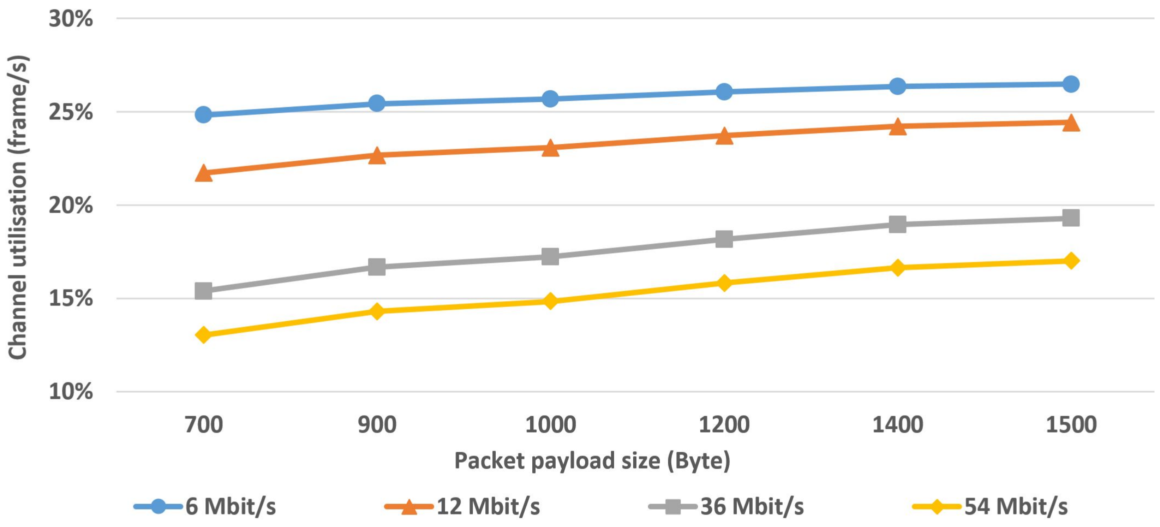


Fig. 5.8 Channel utilisation rate for the external pairs in scenario 5.3.

The channel utilisation rate for central pairs will increase if the packet payload size will increase too. In this case, each central pair has a more limited access to the medium, as the medium is occupied by the external pairs much of the time. In this scenario, the central pairs cannot use the channel at the same time. Each of them can hear each other and the nearest external neighbour. In addition, in the four pairs scenario, the channel utilisation rate for each pair is higher compared to the channel utilisation in the three pairs scenario, see Figure 5.9.

Channel utilisation (external pairs)= $\sum$ Channel utilisation + (1-Pr[Medium]).

$$\text{Channel utilisation (central pairs)} = \text{total utilisation} \times Y$$

Where

$$\text{Y} = \frac{\text{throughput B}}{\text{total throughput (AckA, AckB, AckC and AckD)}}$$

We calculate the channel utilisation for the external and central pairs separately. Figure 5.10 shows how much time is used in the medium in total by all pairs. We have used the following formula for measuring the channel utilisation for the external in this scenario. Here, both external pairs and the central pairs occupy the channel equally as they are symmetric.

$$\text{Channel utilisation (external pairs)} = \text{total utilisation} \times Z$$

Where

$$\text{Z} = \frac{\text{throughput A}}{\text{total throughput (AckA, AckB, AckC and AckD)}}$$

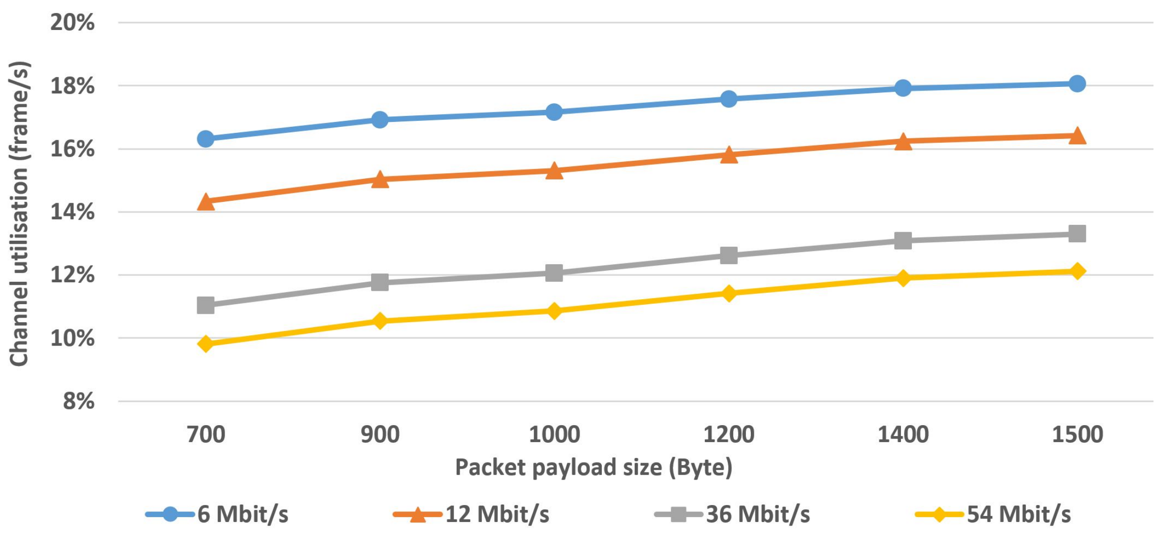


Fig. 5.9 Channel utilisation rate for the central pairs in scenario 5.3.

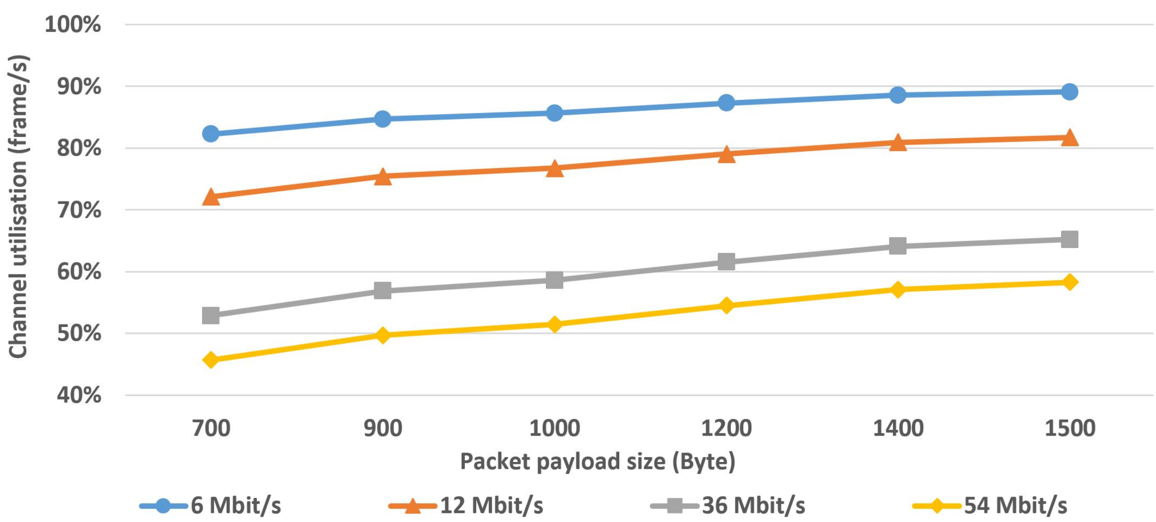


Fig. 5.10 Channel utilisation rate for all pairs in scenario 5.3.

Finally, the channel throughput in the four pairs scenario is decreased as the packet payload size is increased. In the three pairs case it is lower because of the channel occupancy time, which means the fastest channel in transmitting packet will occupy less time. In terms of channel throughput this scenario is unfair. The central pairs are out competed by other pairs and are unfairly disadvantaged, see Figures 5.11 and 5.12.

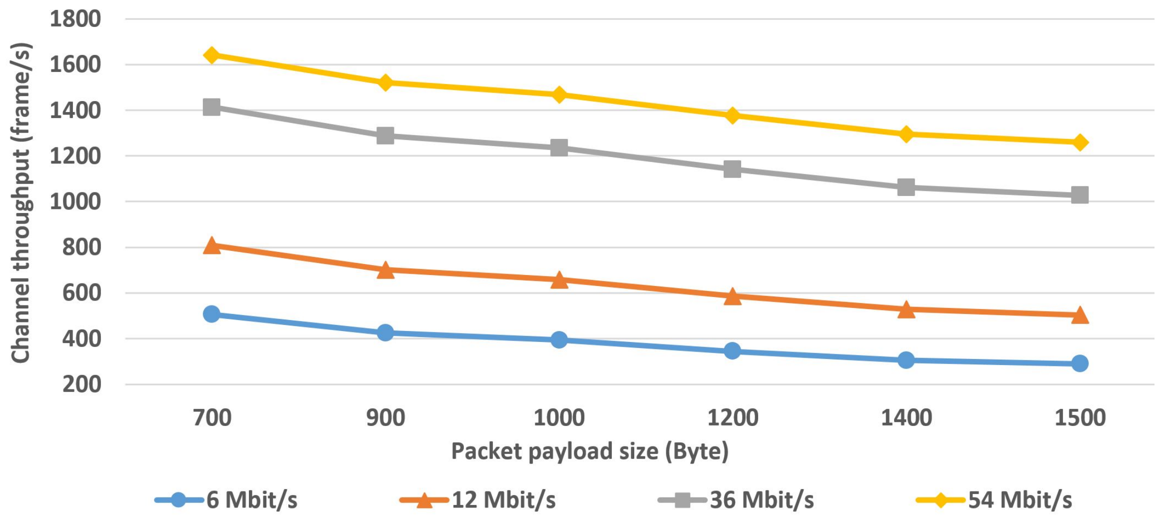


Fig. 5.11 Channel throughput rate for the external pairs in scenario 5.3.

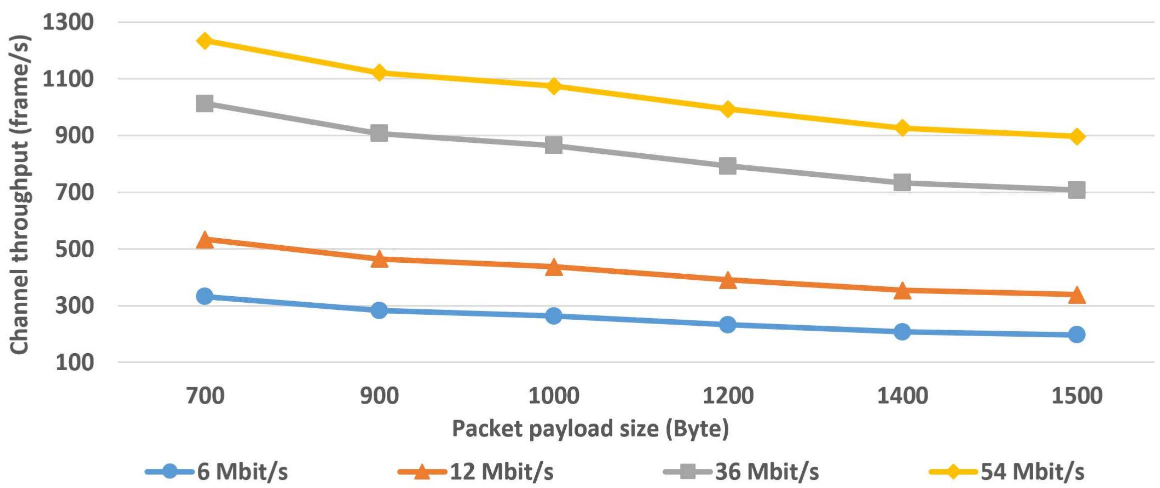


Fig. 5.12 Channel throughput rate for the central pairs in scenario 5.3.

5.4.4 Fairness metric of utilisation in 3 and 4 pairs scenarios (r=200000)

This section explore the fairness metric of channel utilisation in the three and four pairs scenarios, see Figure 5.13. The investigation of the fairness metric in 802.11g is shown in this section, when the node has backoff 200000. Figure 5.13 presents, the high speed of transmission (54 Mbit/s) has better fairness compared to other speeds. The fairness metric in 54 Mbps decreases by increasing the packet payload size, when the packet payload size increases. However, fairness metric of channel utilisation will increase in a slowest speed (6 Mbps) by increasing the packet payload size. Hence, the speed of transmission in this protocol will affect the fairness metric.

The fairness metric can be obtained as follows:

$$\text{Fairness metric of channel utilisation} = \frac{\text{Channel utilisation of one Internal pair}}{\text{Channel utilisation of one External pair}}$$

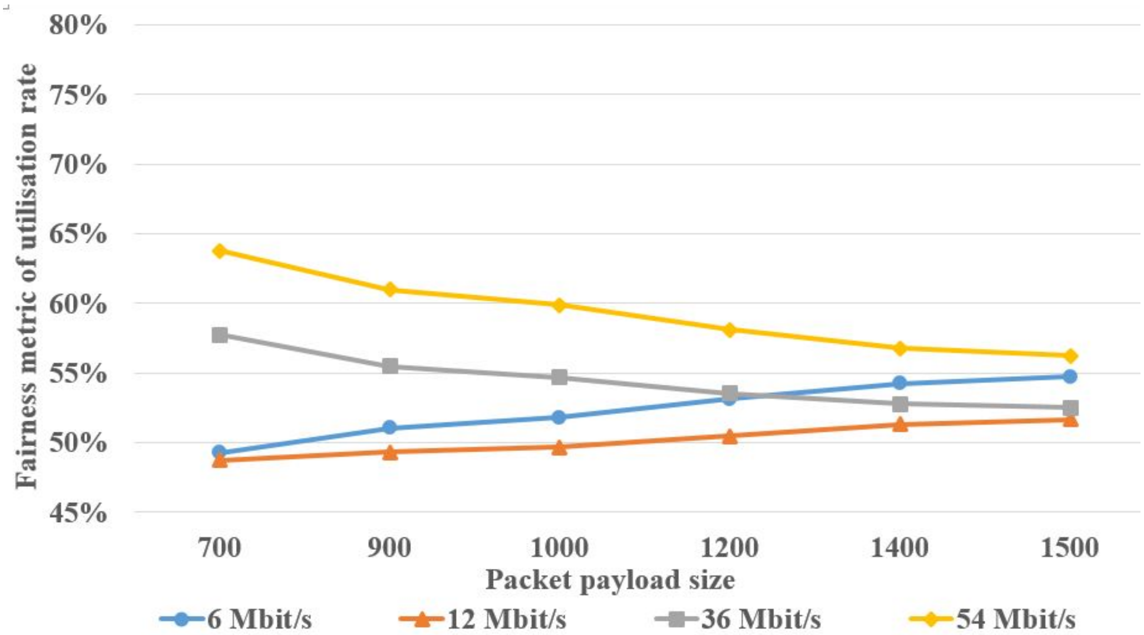


Fig. 5.13 Fairness metric of utilisation for all speeds in 3 pairs, when CW doubled (r=200000).

Figure 5.14 illustrates the fairness metric of channel utilisation in the four pairs scenario, when r=200000. The four pairs scenario has similar profile to the fairness metric of channel utilisation in the three pairs case. However, the fairness metric of channel utilisation in the four pairs scenario is nearly 10% higher than the fairness metric of channel utilisation in three pairs scenario. As the four pairs scenario has two central and two external nodes. The number of nodes in any scenario will affect the fairness metric. In this case study when r=200000 for 54 Mbps speed, then the fairness metric will decrease when the packet payload size increases. However, in a slowest speed (6 Mbps) the fairness metric of utilisation will increase. Here, when we increase the packet payload size to 1500, then the all speeds does not show too much differences in terms of fairness. In a small packet payload size the backoff illustrates significant difference, when the speed of transmission increases from 6 to 54 Mbps. Clearly, the small packet payload size presents very poor fairness in this scenario for all speeds. Because the outer pairs have more chances to resend, but the central pair will have less chance to access the medium and send frames, as it will only send very less compared to the outer pairs.

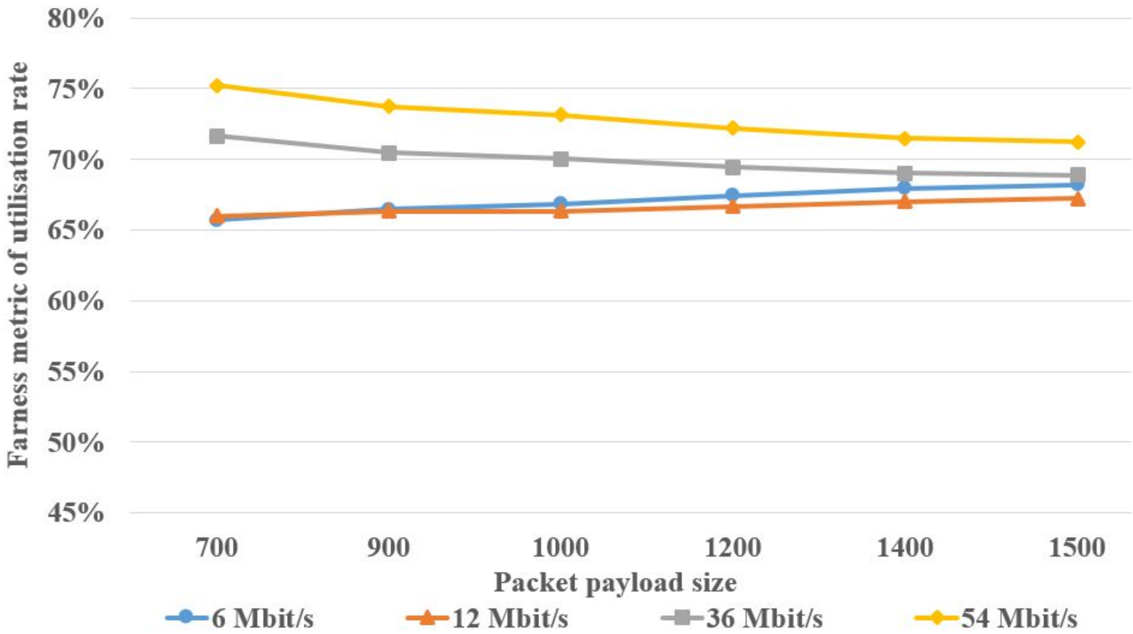


Fig. 5.14 Fairness metric of utilisation for all speeds in 4 pairs, when CW doubled (r=200000).

5.4.5 Sensitivity to value of backoff with fairness metric (r=20)

In this section, we studied the backoff rate (when r=20) to examine the fairness metric in three and four pairs scenarios. Figure 5.15 and 5.16 shows the fairness metric of channel utilisation for three and four pairs case in 802.11g respectively, when r=20. These Figures illustrate that the system is almost completely fair in the high speed (54 Mbps), and the packet payload size will not affect the fairness metric in this speed. However, fairness will significantly decrease when the packet payload size increases in a slow speed of transmission, we mainly see this decrease in 6 Mbps. From these figures we can see that the number of pairs will slightly affect the fairness metric of channel utilisation. In both scenarios, the pair will have more chance to transmit if the backoff is low and transmission speed is fast (it has less chance to transmit in a slower speed). This case shows the pair spends lots of its time in backoff, and it has very short time for transmitting. The amount space available for the central pair becomes smaller, hence there is less space for the central pair to occupy the medium compared with the outer pairs. But, they are still fair in the slowest speed, which is about 99%

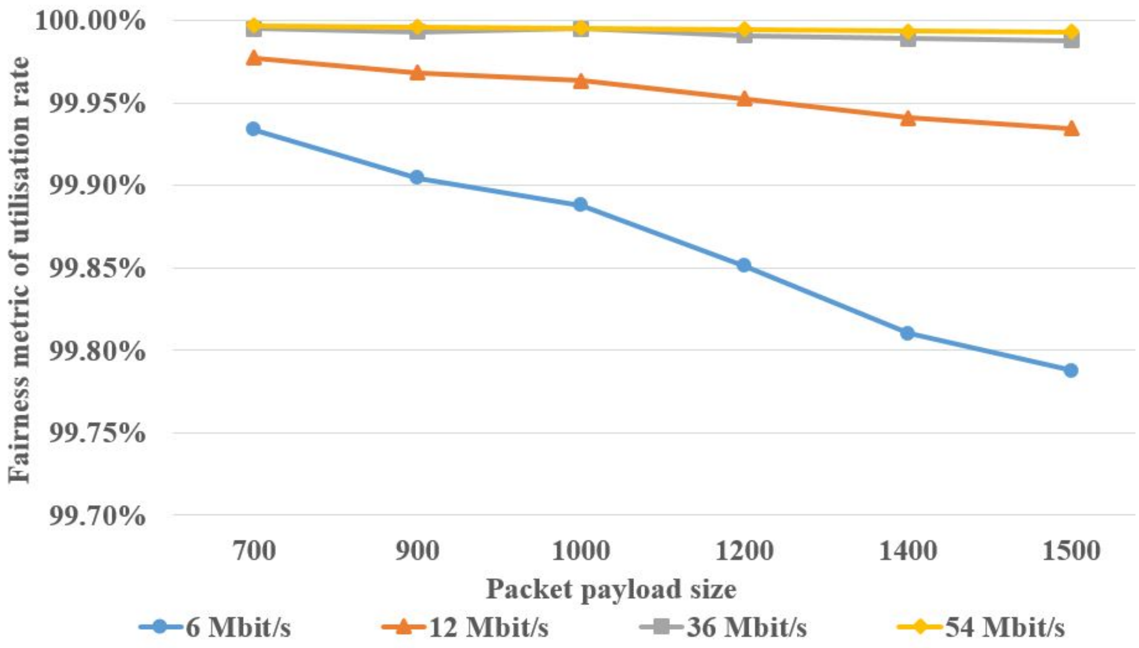


Fig. 5.15 Fairness metric of utilisation for all speeds in 3 pairs, when CW doubled (r=20).

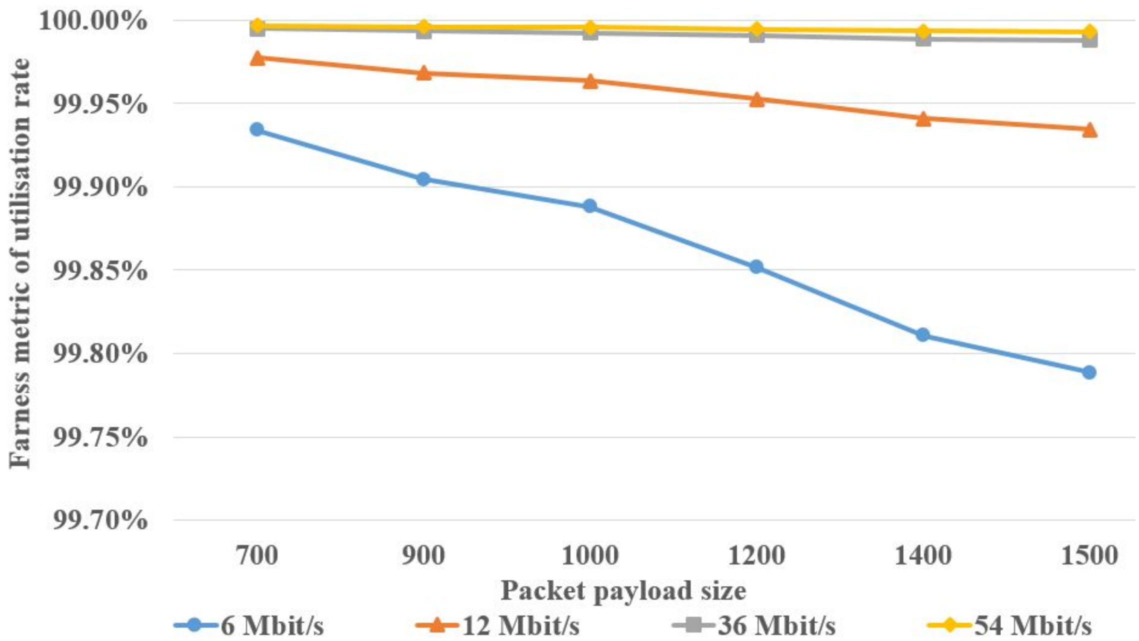


Fig. 5.16 Fairness metric of utilisation for all speeds in 4 pairs, when CW doubled (r=20).

5.5 Variable frame length.

In the previous section we have seen how the performance and fairness is affected by frame length. We now consider whether variation in frame length can also affect performance and fairness. The previous models all assumed that the frame transmission duration was an exponentially distributed random variable. Clearly sampling from the exponential distribution causes some variation, however the variance of the exponential distribution is relatively limited.

In this section we therefore consider transmission delays and which are hyper-exponentially distributed. The hyper-exponential distribution has the advantage that we can increase the variance to a much greater degree, independently from the mean, thus allowing us to consider the impact of frame length variability. A basic model, which is one pair scenario (scenario 5.4) is used to derive a baseline throughput when there is no contention. Two other models, which are two pairs scenario (scenario 5.5) and three pairs scenarios (scenario 5.6) are used to explore how competition to access the medium affects throughput and channel utilisation. If the system is fair then all nodes should experience the same throughput and utilisation (when all nodes have the same demand). But, we already know that 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. By examining on the variable frame length in this study, we seek to explore how it affects the fairness in each scenario in the IEEE 802.11g protocol, using two transmission rates, one for "normal" short frames and one for "occasional" long frames.

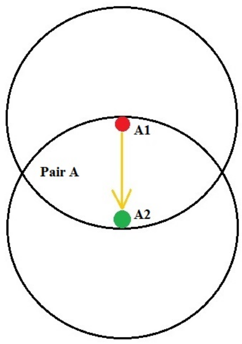


Fig. 5.17 The one pair scenario.

The same parameters have been used in the following models that presented in Section 5.3 but, the different values of μ_{data} are used from "long" and "short" frames. The value of μ_{data} can be obtained as follow:

$$\mu_{data} = \frac{\text{data rate } \times \frac{10^6}{8}}{\text{packet payload size}}$$

We denoted μ_{data1} for the transmission of the short frames (proportion α) and μ_{data2} for the long frames (proportion $1-\alpha$). In this experiment, we assumed that the average frame length is the same in all cases:

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

If we assume that $\mu_{data1} = a\mu_{data2}$, where $a > 1$, then μ_{data2} can be found as follow:

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

In the following experiments we have fixed $a = 100$ and vary the proportion of short frames, α, in order to change the variance of the frame transmission.

5.5.1 The one pair scenario (scenario 5.4).

This scenario is used to illustrate the behaviour of the transmitting pair and to provide a baseline performance. There is no fairness matter in this scenario, because a pair has no competitor as it is a single pair. This model is a baseline for other scenarios. The model of one pair scenario consists of two components; a Pair depicts of communicating nodes and `Med_F` depicts of the transmission medium. Firstly, `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 $1-\alpha$). `Pair2a` depicts transmission of short frames, whereas `Pair2b` specifies transmission of long frames ($\mu_{data1} > \mu_{data2}$). `Pair3` counts the *SIFS* period, then an *ACK* is received in `Pair4`.

$$
\begin{aligned}
Pair &\stackrel{def}{=} (draw\_backoff, r).Pair0\\
Pair0 &\stackrel{def}{=} (count\_difs, \mu_{difs}).Pair1\\
Pair1 &\stackrel{def}{=} (count\_backoff, p\mu_{bck}).Pair1 + (end\_backoff, \alpha q\mu_{bck}).Pair2a\\
&\quad +(end\_backoff, (1-\alpha)q\mu_{bck}).Pair2b\\
Pair2a &\stackrel{def}{=} (transmit, \mu_{data1}).Pair3\\
Pair2b &\stackrel{def}{=} (transmit, \mu_{data2}).Pair3\\
Pair3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair4\\
Pair4 &\stackrel{def}{=} (ack, \mu_{ack}).Pair
\end{aligned}
$$

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

$$\text{Scenario 5.4} \stackrel{def}{=} Pair \underset{K}{\bowtie} Med\_F$$

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

5.5.2 The two pairs scenario (scenario 5.5).

This scenario contains the two asymmetric pairs, interacting with a shared medium. In this scenario, if any node in a pair attempts to transmit, then its partner node waits to receive an Acknowledgement (*ACK*). Generally, Pair A behaves as in the previous model in Section 5.5.1, having hyper-exponentially distributed frame lengths, whereas Pair B exponentially distributed frame lengths. Unlike the previous case we also need to consider contention and subsequent waiting for access, which adds additional behaviours to both model components (as in Section 5.2.2). For this reason we modelled the choice of long frame 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` in the Pair A or `queueB` in the Pair B and subsequent `wait` (`waitS` or `waitL` for short frames or long frames at `Pair_A`) before reattempting to transmit.

For instance, `Pair_A` draws backoff (with probability $\alpha \times r$) becomes `Pair_A0S` for the short frame or it has a choice to backoff (with probability $(1-\alpha) \times r$) to the state of `Pair_A0L` for a long frame. `Pair_A0S` starts count *difs* to `Pair_A1S` or stays at the queue to `Pair_A5S`. Similarly, `Pair_A0L` starts count *difs* to `Pair_A1L`, or stays at the queue to `Pair_A5L`. If it has a choice to the `Pair_A5S` then it waits in this state to `Pair_A4S`, but if it has a choice to the `Pair_A5L` then it waits in this state to `Pair_A4L`. Also, the all *SIFS* and *EIFS* will count until the backoff end for each long and short frames, then the short frame will transmit in `Pair_A2S` with μ_{data1} and the long frame will transmit in `Pair_A2L` with μ_{data2}. Finally, after the frame (either short or long frame) is transmitted successfully, then an *ACK* will be received in `Pair_A6`.

$$
\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\_A3 + (queue, \top).Pair\_A5S \\
Pair\_A2L &\stackrel{def}{=} (transmit, \mu_{data2}).Pair\_A3 + (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 \\
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}
$$

Component of Medium F: The specifications of the shared medium in the two pairs scenario in the following shows, that the `Med_F` represents the situation where the medium is unoccupied.

`Med_F1` represents the medium being used by the central pair (Pair B). Also, `Med_F2` represents the medium being used by the other pair (Pair A).

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

The complete system: In this model, both pairs interact indirectly through the medium. This scenario has the following cooperation between all components that is defined as:

$$\text{Scenario 5.5} \stackrel{def}{=} (Pair\_A \underset{K}{\bowtie} Med\_F) \underset{L}{\bowtie} Pair\_B$$

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

5.5.3 The three pairs scenario (scenario 5.6).

This final scenario (three pairs scenario) has two symmetric outer pairs which are denoted by (`Pair_A` and `Pair_A`), one inner (`Pair_B`) and a shared medium (`Med_F`). The outer pairs cannot hear one another and so may transmit independently. But, 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 for this case study the outer pairs have hyper-exponentially distributed frame lengths (as `Pair_A` in the previous scenario), whereas the inner pair has exponentially distributed frame lengths (as `Pair_B` in the previous scenario). The model therefore only differs from the previous scenario is having two instances of `Pair_A` (the second external pair has similar name as it is presented by `Pair_A` for clarity) and having a modified cooperation set.

Component of Medium F: The shared medium component in this scenario shows, that the `Med_F` represents the situation where the medium is unoccupied. `Med_F1` represents the medium being used by the central pair (Pair B). Also, `Med_F2` represents the medium being used by exactly one of the external pairs (Pair A). Finally, `Med_F3` represents the medium being used by both external pairs. The shared medium in the three pairs model is given as follow:

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

The complete system: This scenario has cooperation between all components as follow:

$$\text{Scenario 5.6} \stackrel{def}{=} ((Pair\_A||Pair\_A) \underset{K}{\bowtie} Med\_F) \underset{L}{\bowtie} Pair\_B$$

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

5.6 Results of IEEE 802.11g with variable frame length.

5.6.1 Performance results of the one pair scenario (scenario 5.4).

Figures 5.18 and 5.19 shows the average utilisation and throughput respectively for this scenario for different average frame lengths and transmission rates. This scenario has 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 average frame length; the utilisation increases slightly and throughput decreases slightly as the packet size increases.

5.6.2 Performance results of the two pairs scenario (scenario 5.5).

In this scenario, the frame length variance is greater at Pair A compared to Pair B (if $0 < \alpha < 1$). From the Figures 5.20, 5.21, 5.22 and 5.23, we can determine that the medium utilisation rate is greater by Pair B than Pair A. However, this effect is less when the proportion of long frames is reduced. Furthermore, we also determine where α is equal to 0.89, then the Pair B will gain around a 15% utilisation advantage over Pair A. Whereas, when $\alpha = 0.99$ (fewer long frames) this advantage is only around 8%, despite the long frames being transmitted in this case. This effect is fairly consistent regardless of the transmission rate in this case scenario.

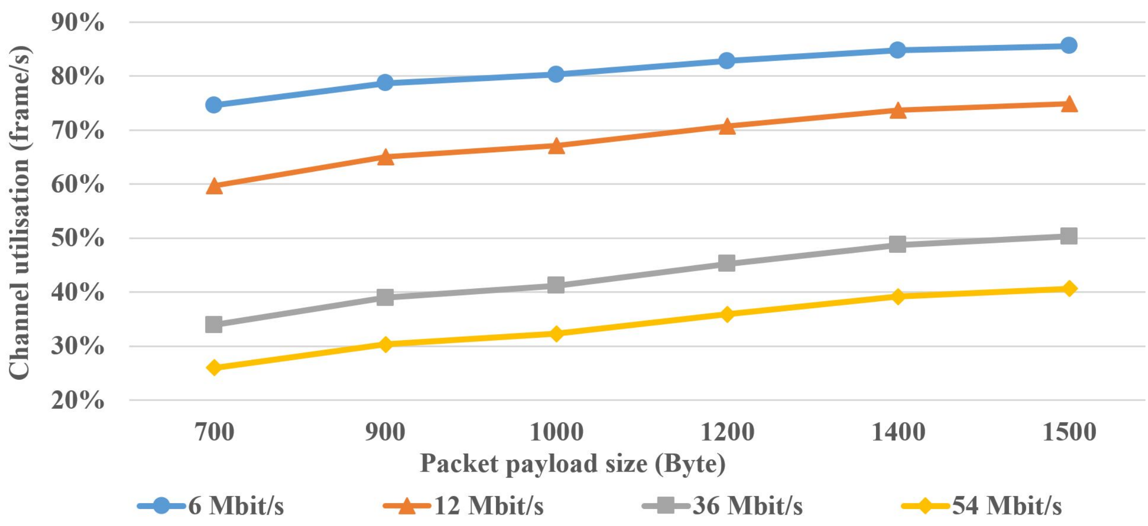


Fig. 5.18 Channel utilisation rate for the one pair scenario in scenario 5.4.

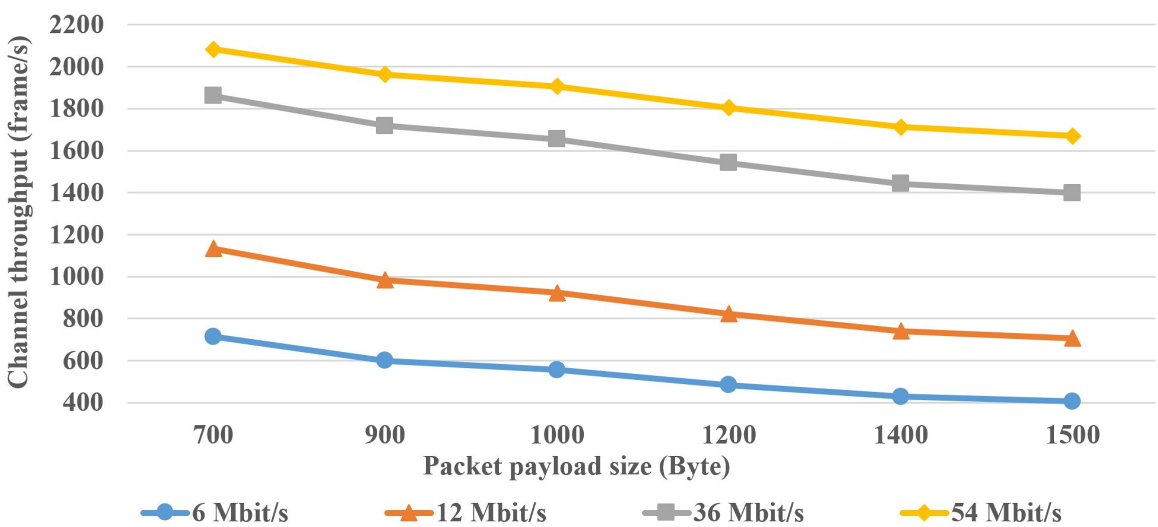


Fig. 5.19 Channel throughput rate for the one pair scenario in scenario 5.4.

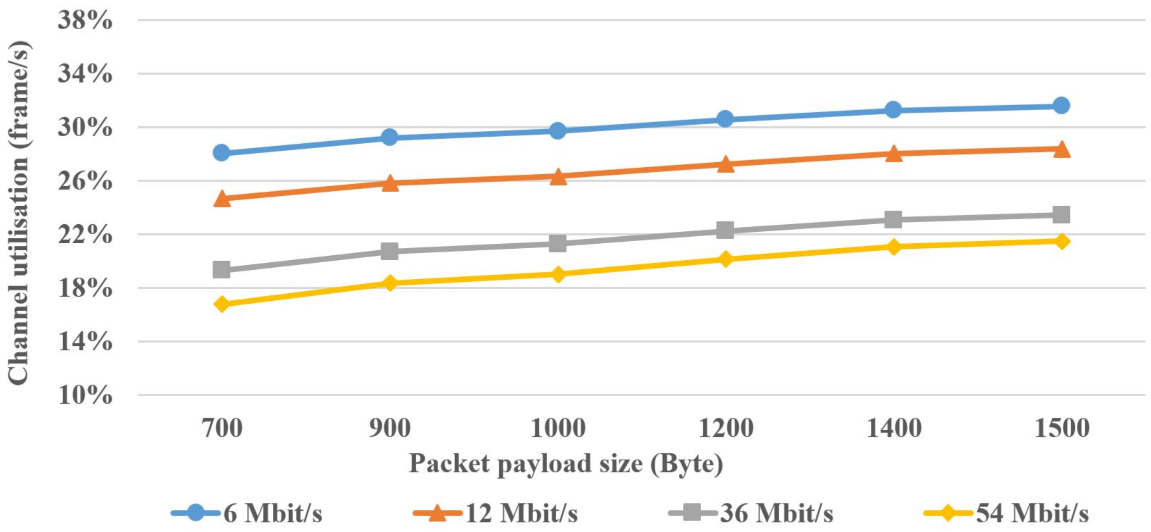


Fig. 5.20 Channel utilisation rate for the Pair A, where $\alpha = 0.89$ in scenario 5.5.

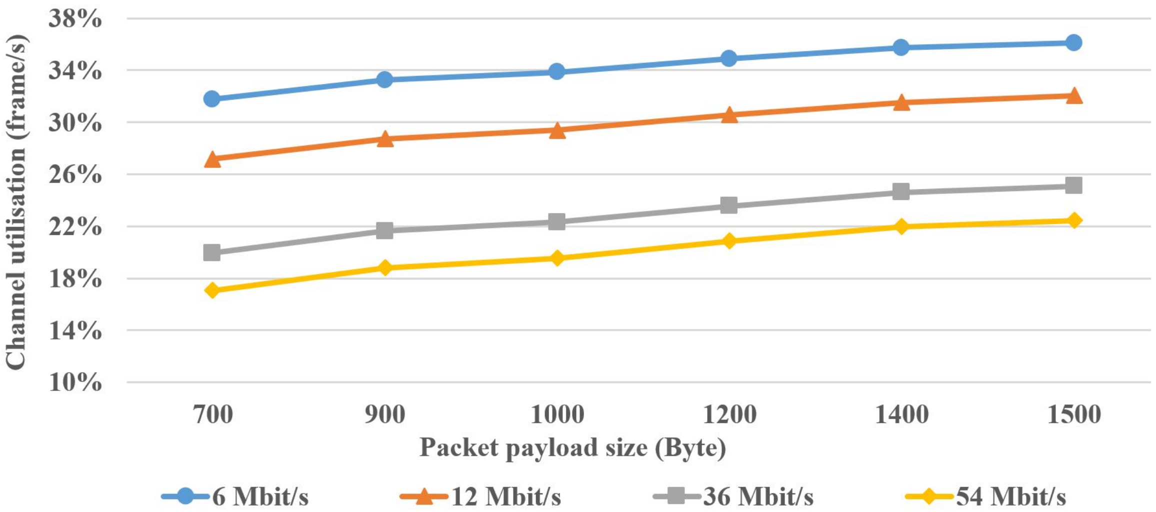


Fig. 5.21 Channel utilisation rate for the Pair A, where $\alpha = 0.99$ in scenario 5.5.

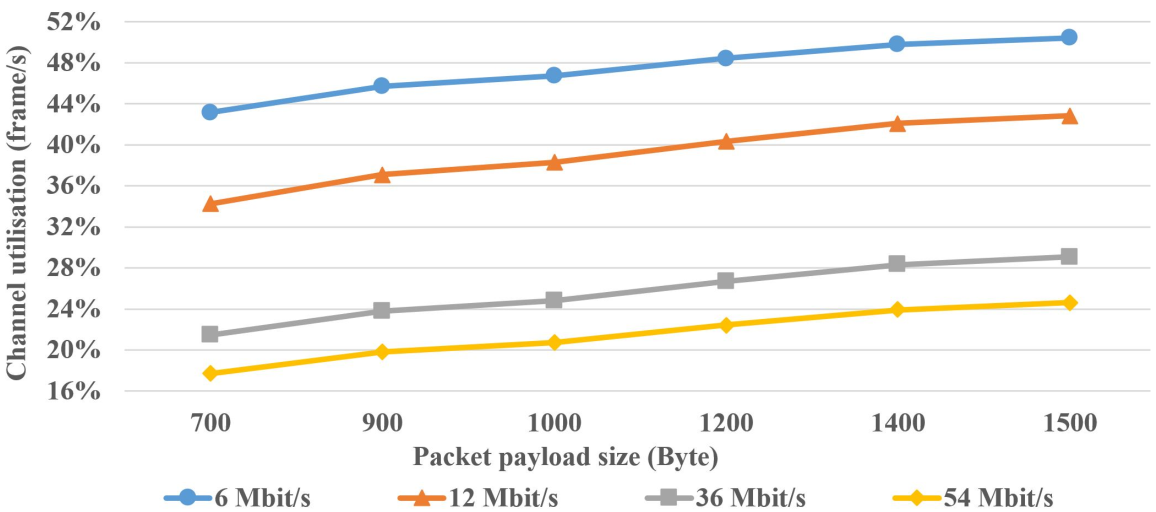


Fig. 5.22 Channel utilisation rate for the Pair B, where $\alpha = 0.89$ in scenario 5.5.

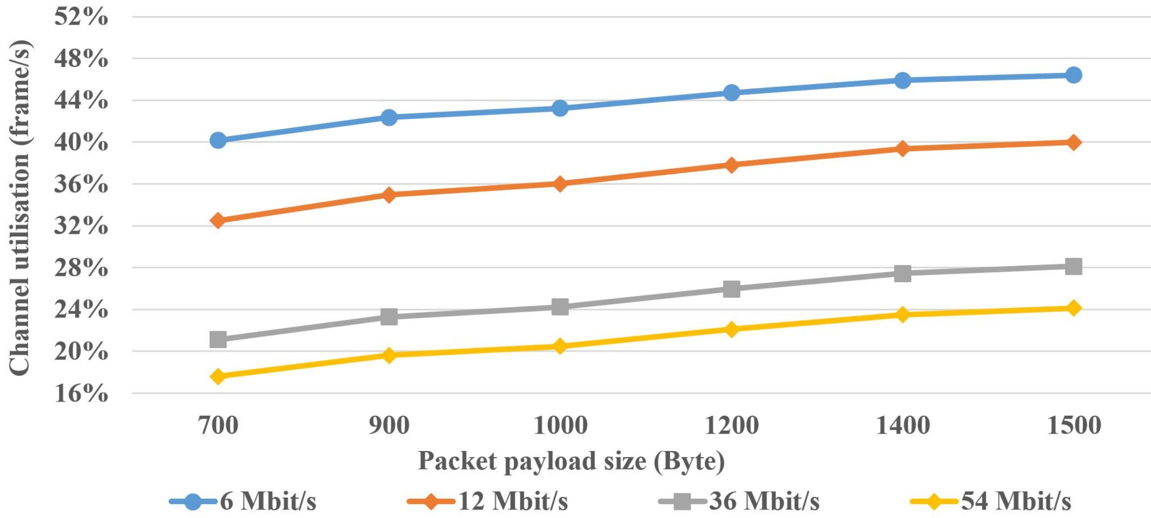


Fig. 5.23 Channel utilisation rate for the Pair B, where $\alpha = 0.99$ in scenario 5.5.

Moreover, Figures 5.24 and 5.25 show the channel throughput in both Pair A and Pair B when $\alpha = 0.89$. It is clear that the Pair B has significantly better performance than Pair A under these conditions. If $\alpha = 0.99$, then there is only a slight difference between the throughput in Pair A and Pair B, as it show in Figures 5.26 and 5.27. In the each presented case, the general trends of channel utilisation and channel throughput are consistent with the non-competitive case in scenario 5.1. However, it is clear that variance in frame length is having a significant impact on the share of resources available to each pair.

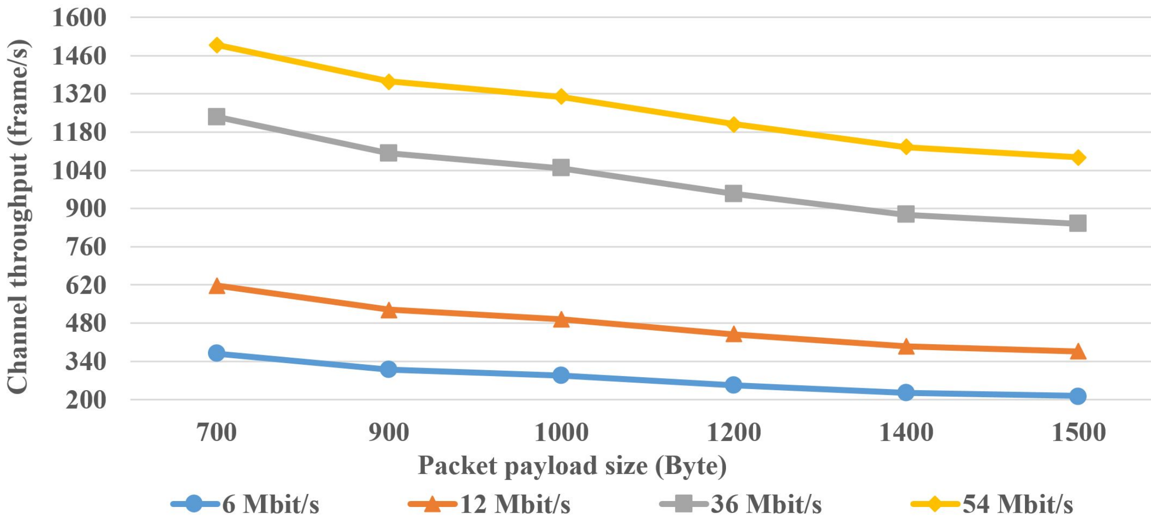


Fig. 5.24 Channel throughput rate for the Pair A, where $\alpha = 0.89$ in scenario 5.5.

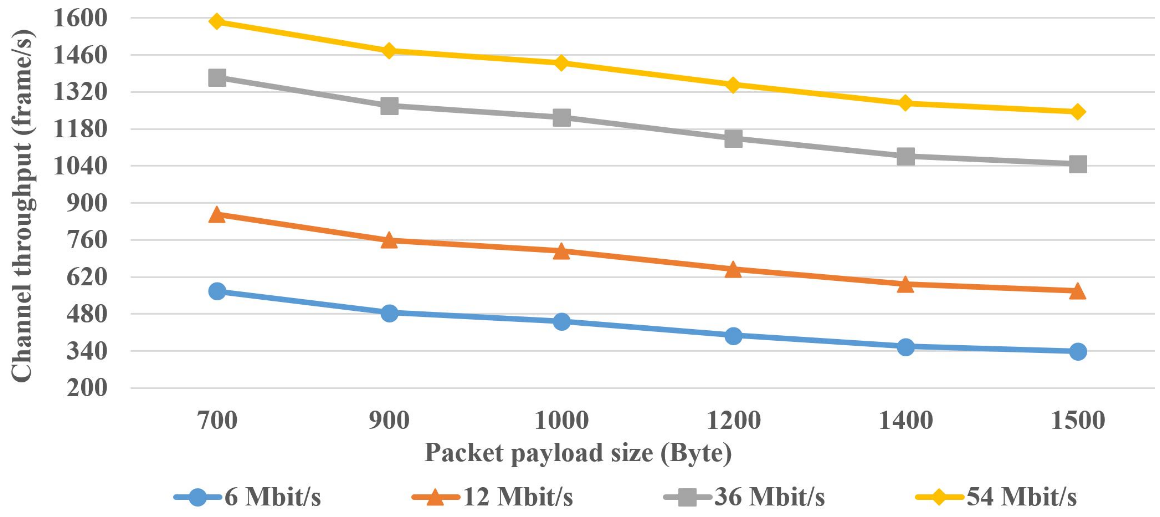


Fig. 5.25 Channel throughput rate for the Pair B, where $\alpha = 0.89$ in scenario 5.5.

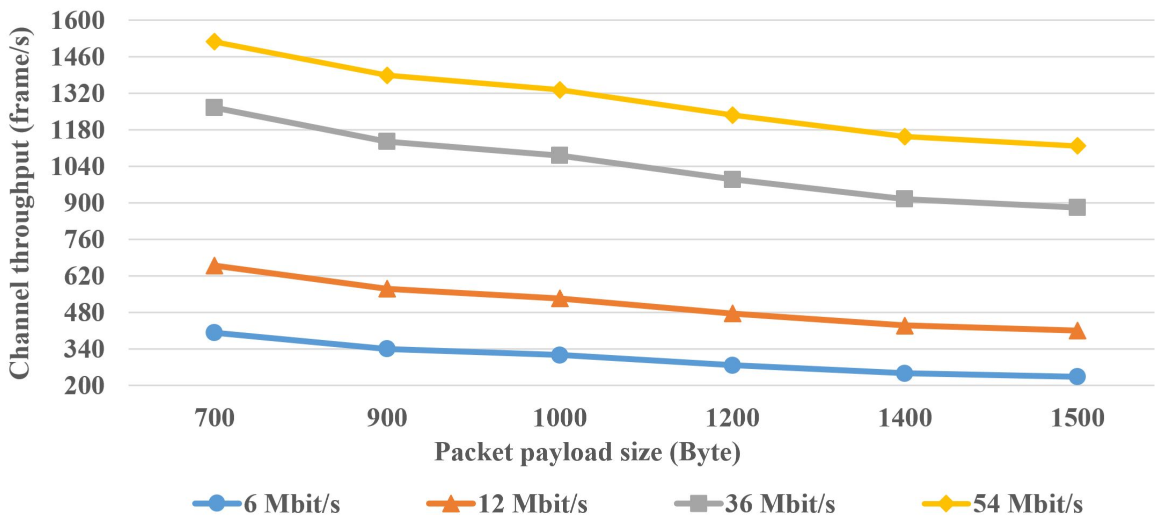


Fig. 5.26 Channel throughput rate for the Pair A, where $\alpha = 0.99$ in scenario 5.5.

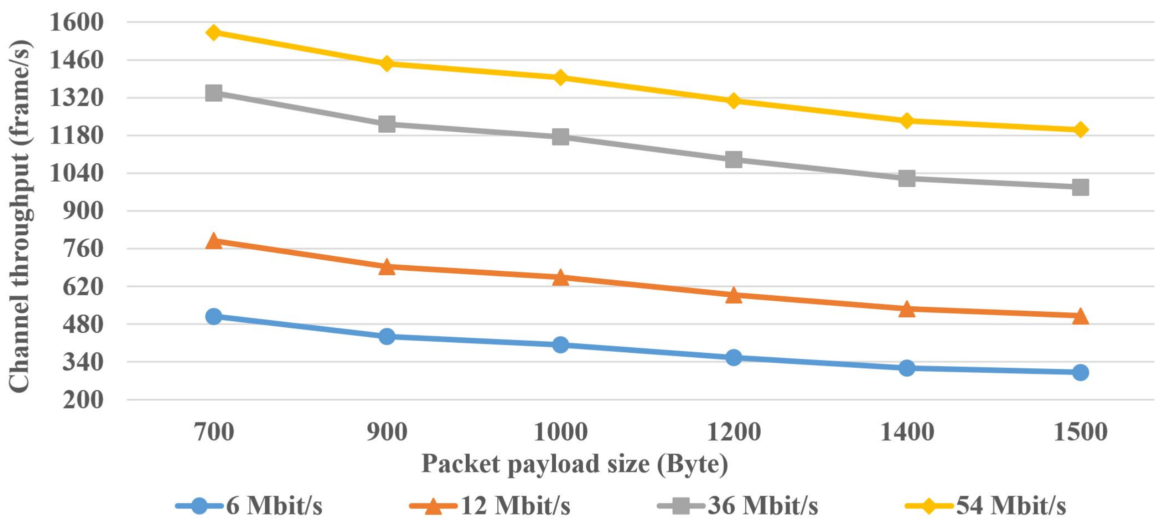


Fig. 5.27 Channel throughput rate for the Pair B, where $\alpha = 0.99$ in scenario 5.5.

Toward a better understanding what is causing this imbalance in performance, we also studied the throughput of the *wait* action. In Pair A waiting to transmit for a long frame is denoted by *WaitL* and *WaitS* for a short frames. Figures 5.28 and 5.29 show that the throughput of *wait* in Pair B is slightly increased between $\alpha = 0.89$ and 0.99. This shows that the transmission is more likely to be delayed when $\alpha = 0.99$. Also, we see that waiting is much more likely to occur when the transmission rate is high and the payload size is small, simply because there are more occasions when a delay may happen.

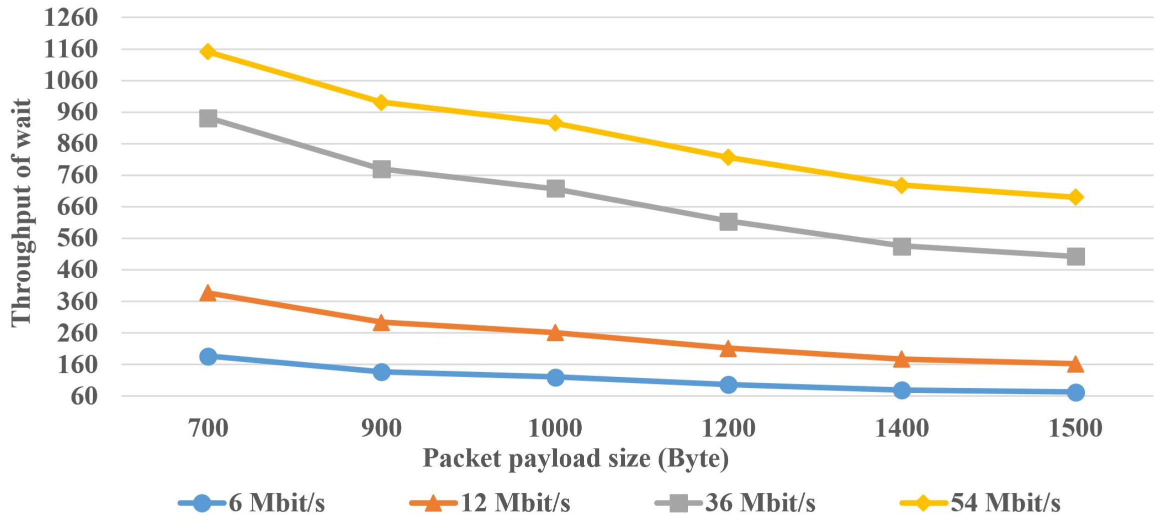


Fig. 5.28 Throughput of Wait, where $\alpha = 0.89$ in scenario 5.5.

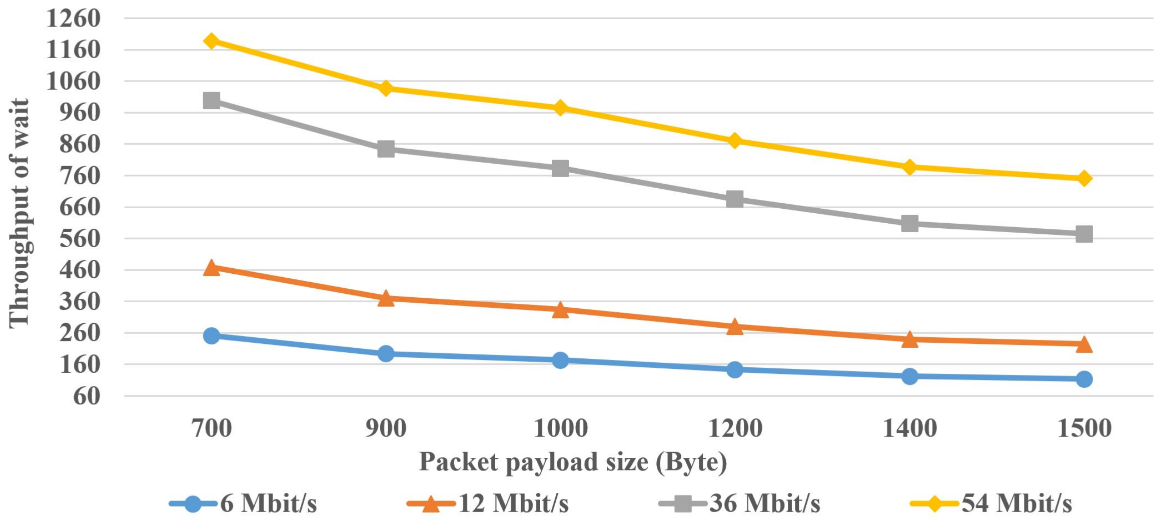


Fig. 5.29 Throughput of Wait, where $\alpha = 0.99$ in scenario 5.5.

The throughput of *waitS* in Pair A is show in Figure 5.30 for $\alpha = 0.89$ and the throughput of *waitS*, where $\alpha = 0.99$ as shown in Figure 5.31. The throughput of *waitL* as shown in Figure 5.32, where $\alpha = 0.89$ and the throughput of *waitL*, where $\alpha = 0.99$ as shown in Figure 5.33. We can see that the throughput of *waitS* at Pair A is significantly increased, where α has increased 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 $\alpha = 0.99$.

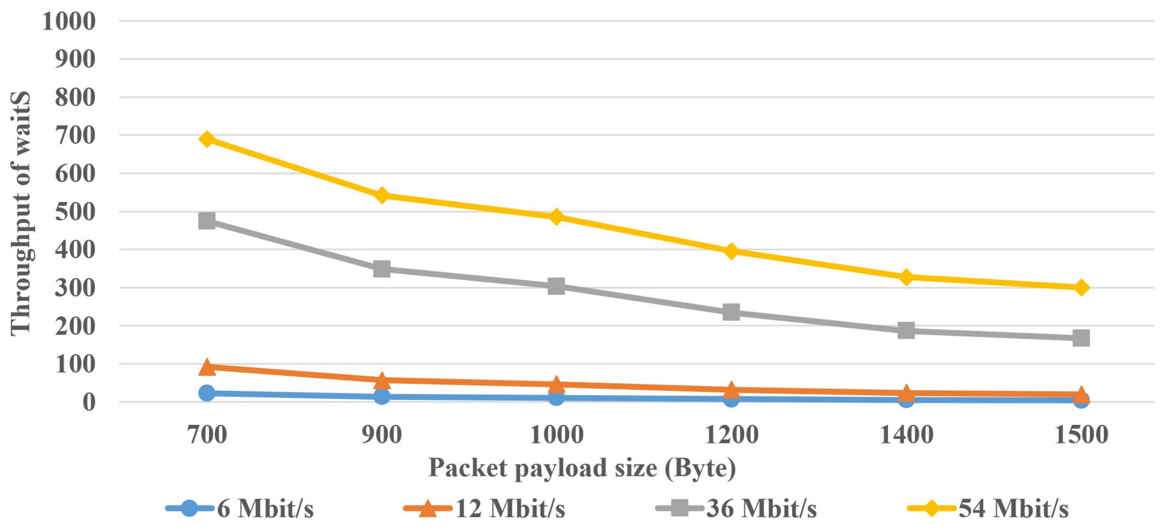


Fig. 5.30 Throughput of WaitS, where α = 0.89 in scenario 5.5.

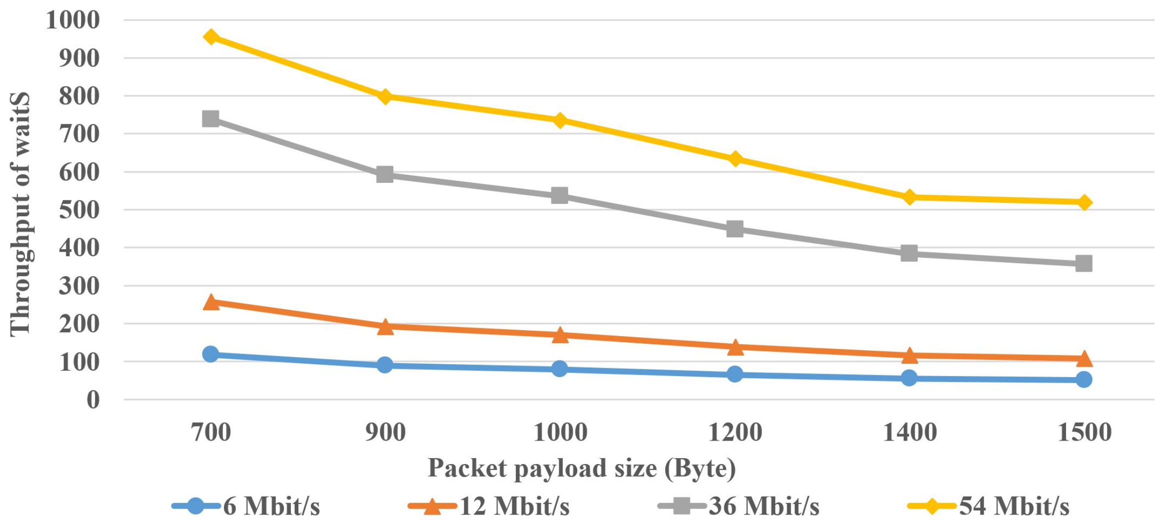


Fig. 5.31 Throughput of WaitS, where α = 0.99 in scenario 5.5.

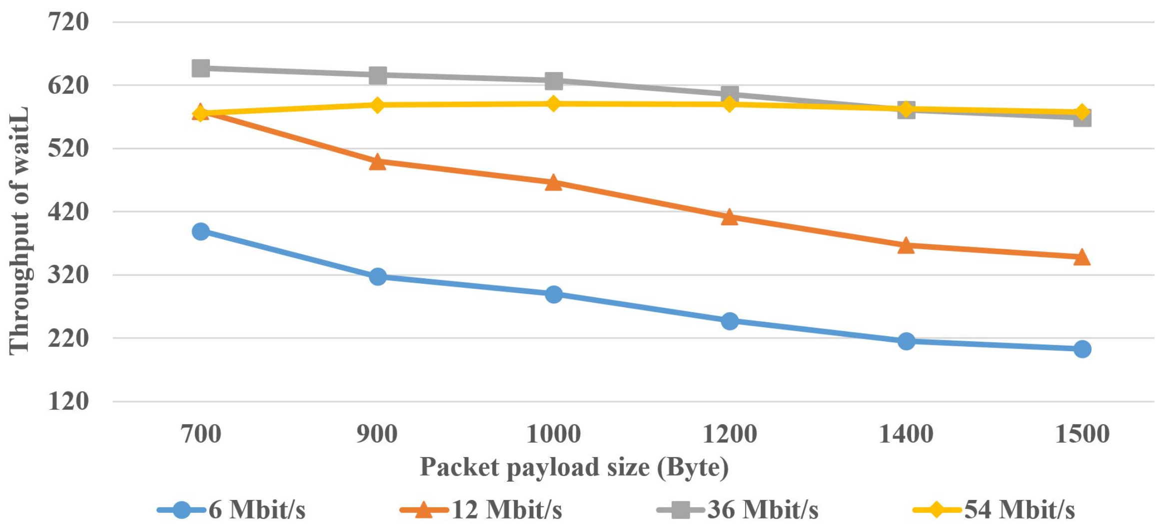


Fig. 5.32 Throughput of WaitL, where α = 0.89 in scenario 5.5.

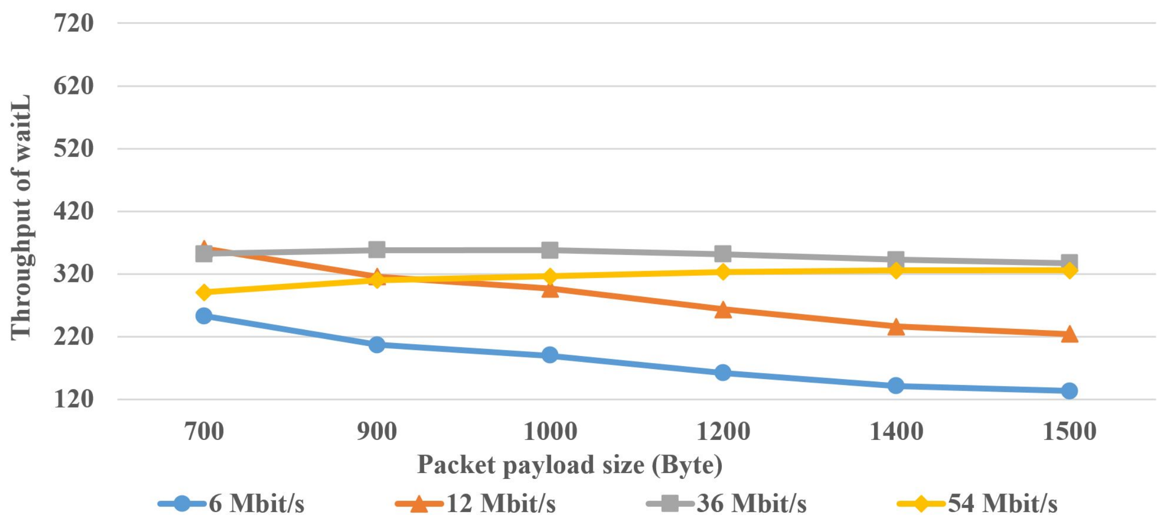


Fig. 5.33 Throughput of WaitL, where $\alpha = 0.99$ in scenario 5.5.

The cumulative throughput of *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 5.20 to 5.27. But, if $\alpha = 0.99$ the cumulative throughput of wait actions at Pair A is only slightly higher than Pair B, leading to the much closer performance noted earlier. Clearly, *waitL* has a significant impact on the fairness exhibited in this scenario.

5.6.3 Performance results of the three pairs scenario (scenario 5.6).

This section shows the results of the three pairs case. This scenario shows how altering tuning the frame length variation with α will affect performance. In Section 5.6.2, 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. By causing the outer pairs to have a higher variance we aim to reduce their topological advantage over the inner pair. Figures 5.34 and 5.35 show the combined utilisation of the outer pairs when $\alpha = 0.89$ and 0.99. When the transmission rate is low then there is little variation with payload size, but greater variation as transmission rate increases. In this scenario, we have also observed that the utilisation by the outer pairs will increase by around 8% as α is increased from 0.89 to 0.99.

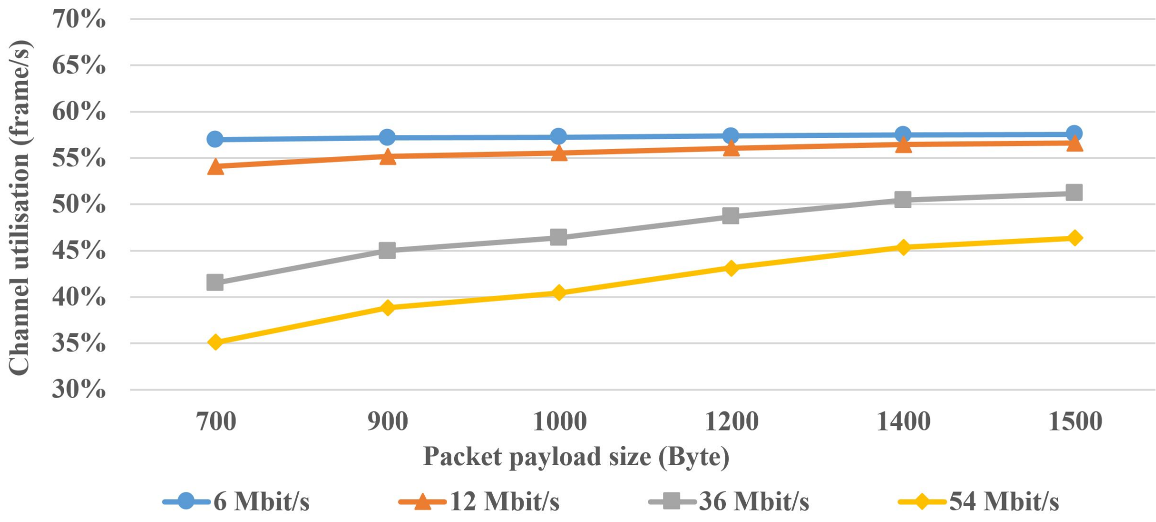


Fig. 5.34 Channel utilisation rate for the outer pairs, where $\alpha = 0.89$ in scenario 5.6.

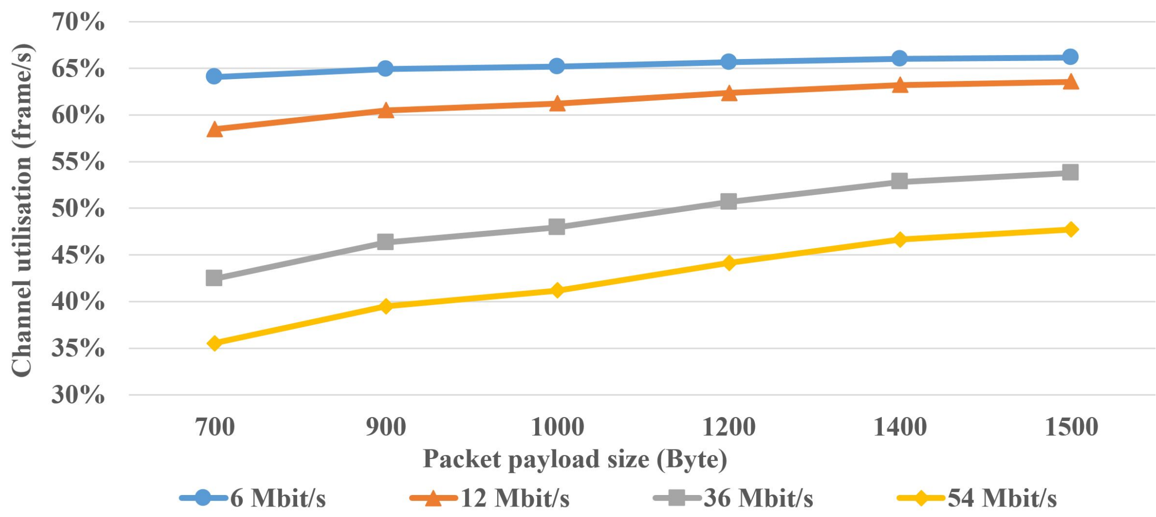


Fig. 5.35 Channel utilisation rate for the outer pair, where $\alpha = 0.99$ in scenario 5.6.

Similarly, Figures 5.36 and 5.37 present the corresponding channel utilisation by the inner pair. As expected, when $\alpha = 0.99$ then in all cases the outer pairs significantly outperform the inner pair. However, if $\alpha = 0.89$ 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 packet payload size is very small.

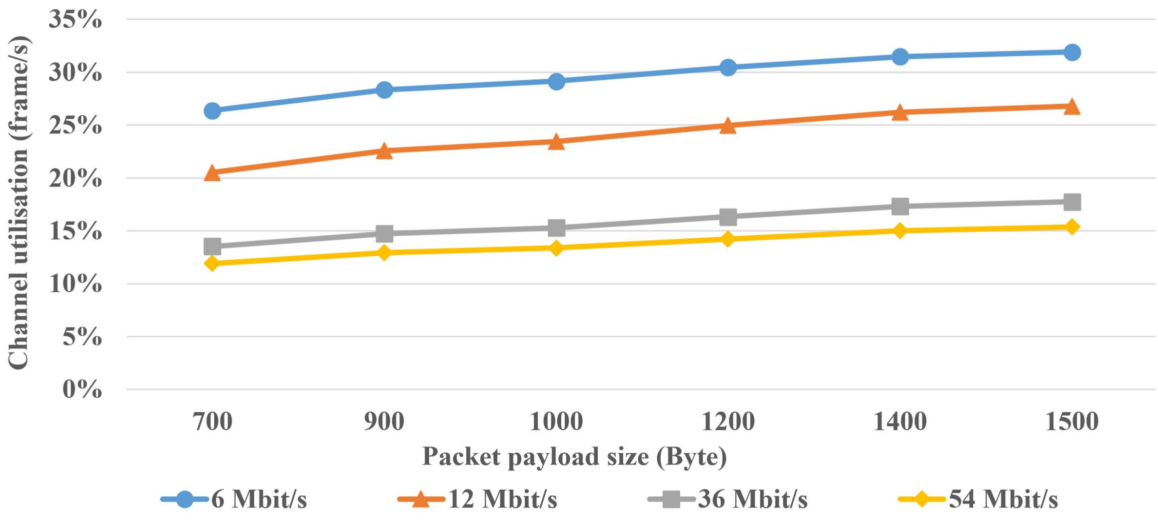


Fig. 5.36 Channel utilisation rate for the inner pair where, $\alpha = 0.89$ in scenario 5.6.

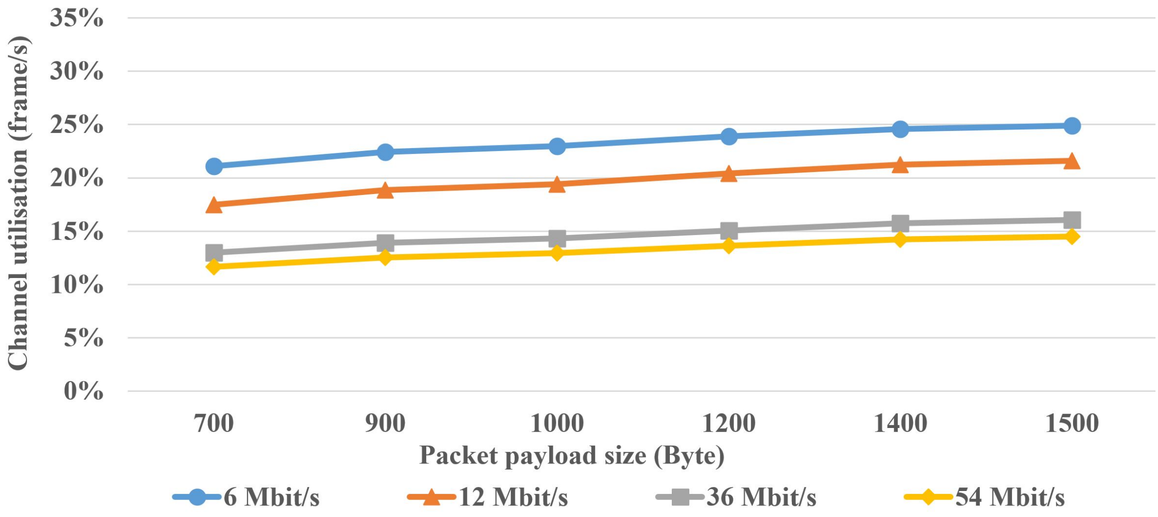


Fig. 5.37 Channel utilisation rate for the inner pair, where $\alpha = 0.99$ in scenario 5.6.

In all other cases the outer pairs still outperform the inner pairs, although the unfairness is clearly reduced compared with $\alpha = 0.99$. The corresponding of channel throughput results are shown in Figures 5.38, 5.39, 5.40 and 5.41. If $\alpha = 0.89$ and the transmission rate is 6 Mbit/s then the small advantage in channel utilisation rate when the packet payload size is larger, leads to a significant advantage in channel 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.

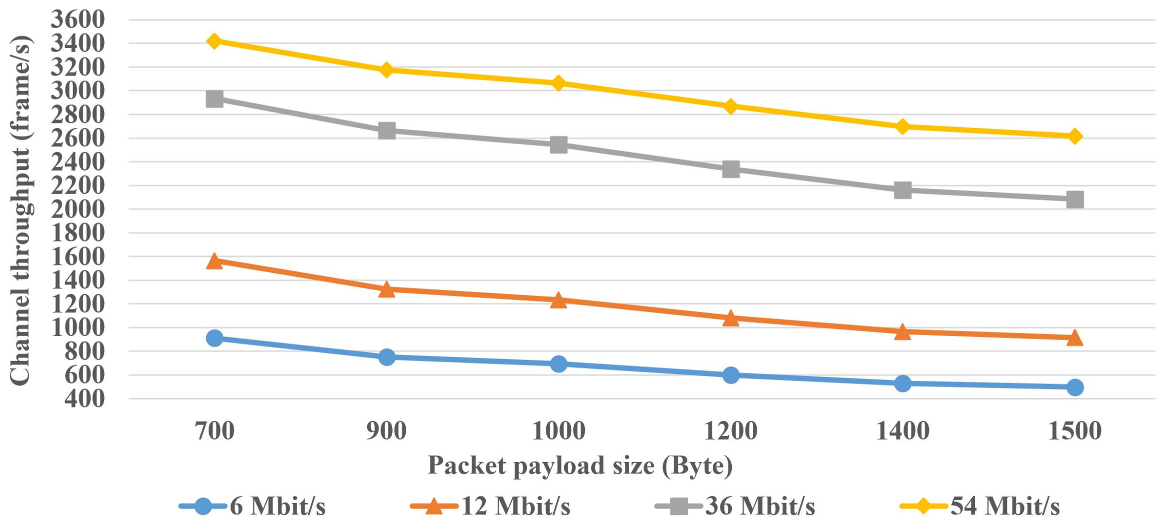


Fig. 5.38 Channel throughput rate for the outer pairs, where α = 0.89 in scenario 5.6.

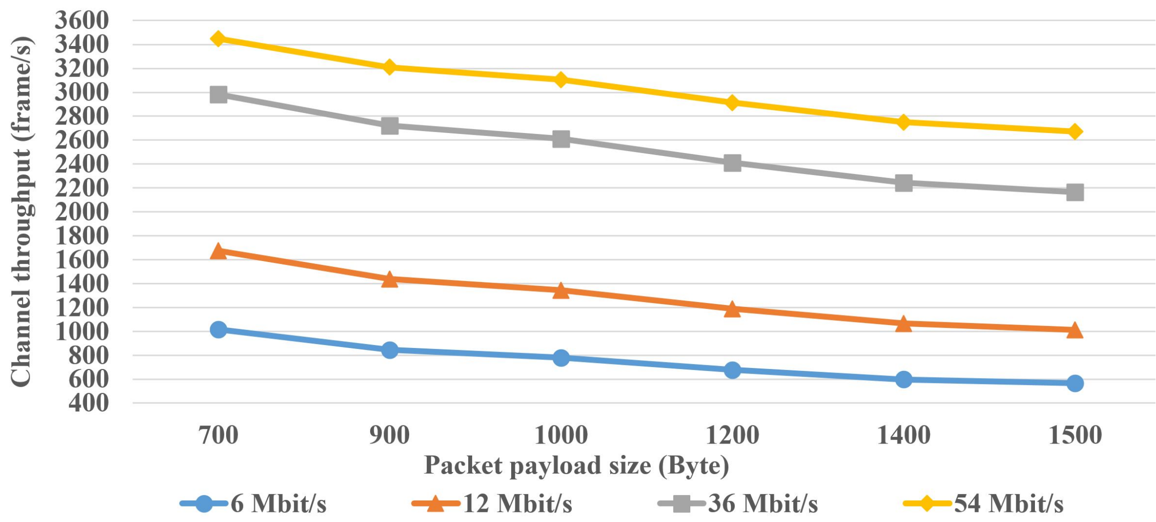


Fig. 5.39 Channel throughput rate for the outer pairs, where α = 0.99 in scenario 5.6.

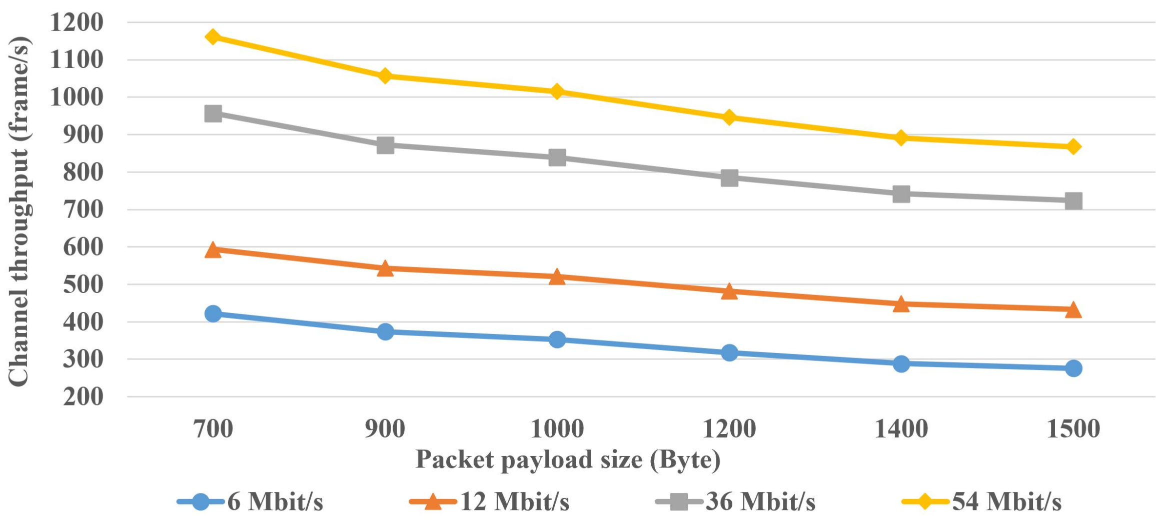


Fig. 5.40 Channel throughput rate for the inner pair, where α =0.89 in scenario 5.6.

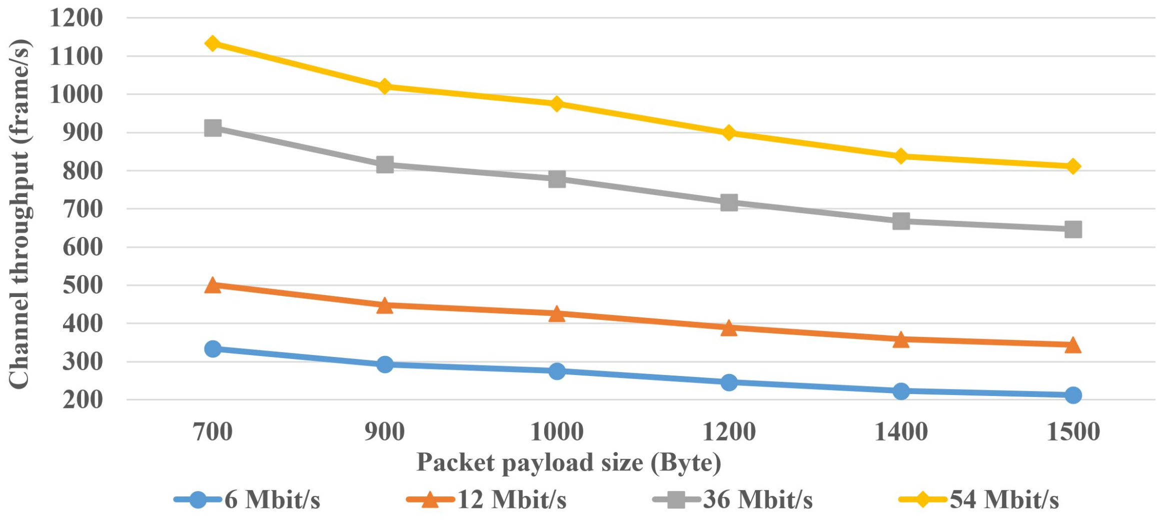


Fig. 5.41 Channel throughput rate for the inner pair, where $\alpha = 0.99$ in scenario 5.6.

We now consider the throughput of the various wait actions in order to better understand the observed behaviour. Figures 5.42 and 5.43 show the throughput of the *wait* action at the inner pair. The throughput of *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 shows that very few transmissions are being queued.

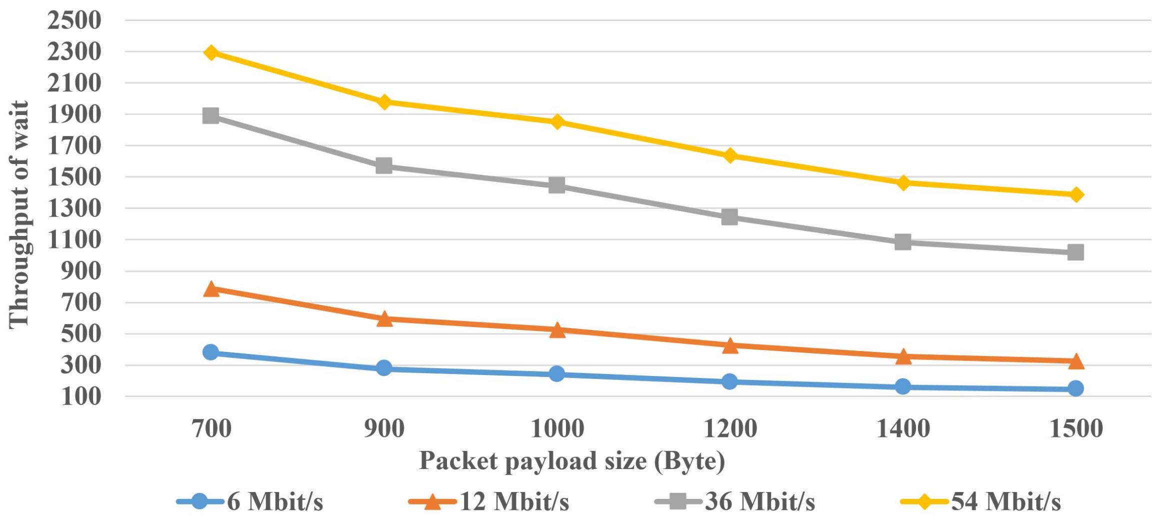


Fig. 5.42 Throughput of Wait, where $\alpha = 0.89$ in scenario 5.6.

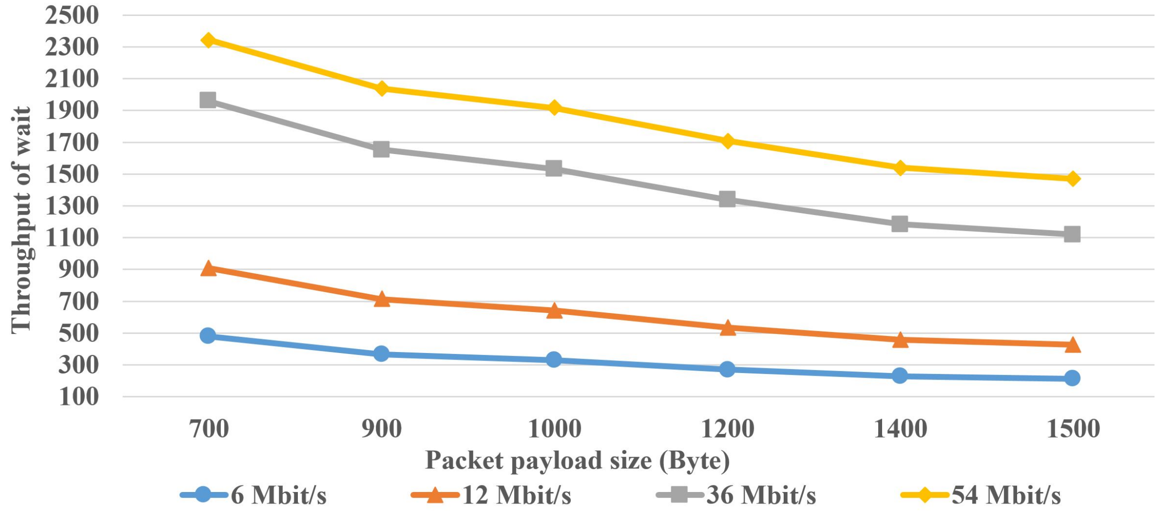


Fig. 5.43 Throughput of Wait, where $\alpha = 0.99$ in scenario 5.6.

Likewise, Figures 5.44 and 5.45 show the throughput of `WaitL` in the Pair A when $\alpha = 0.89$ and $\alpha = 0.99$ respectively. Similarly, the Figures 5.46 and 5.47 present the corresponding throughput for *waitS* when $\alpha = 0.89$ and $\alpha = 0.99$ respectively, at the outer pairs.

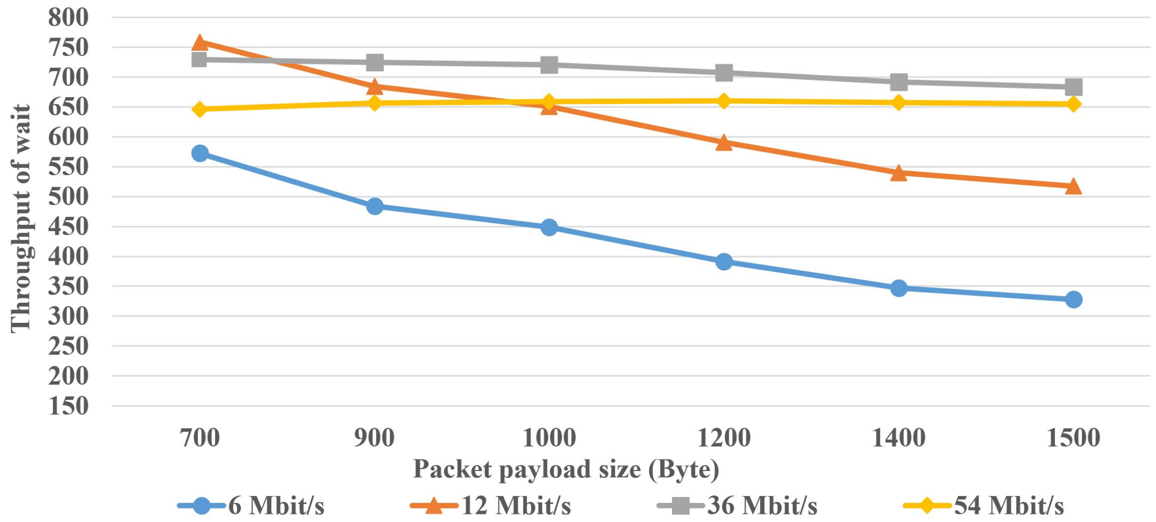


Fig. 5.44 Throughput of WaitL, where $\alpha = 0.89$ in scenario 5.6.

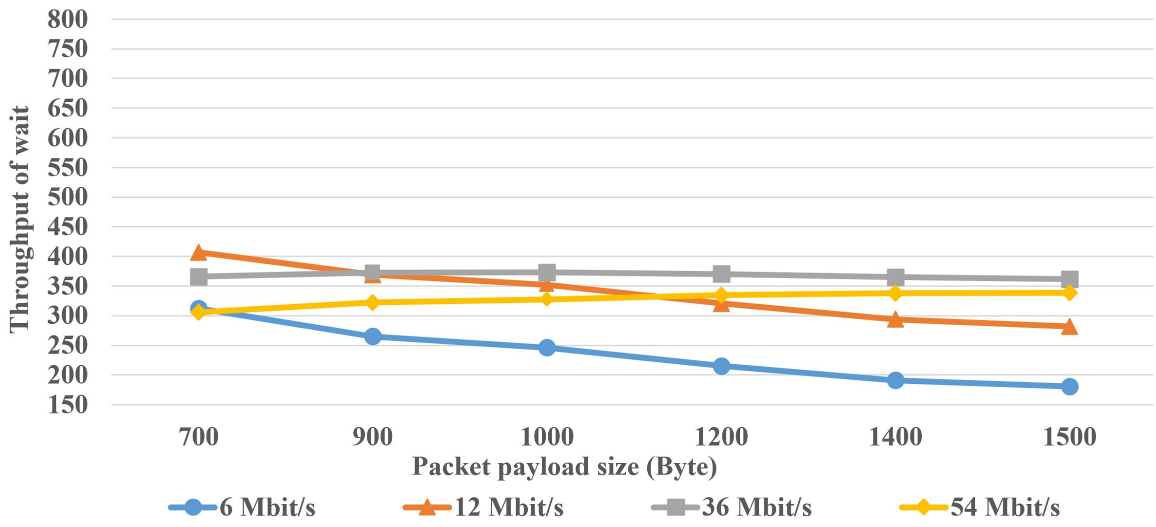


Fig. 5.45 Throughput of WaitL, where $\alpha = 0.99$ in scenario 5.6.

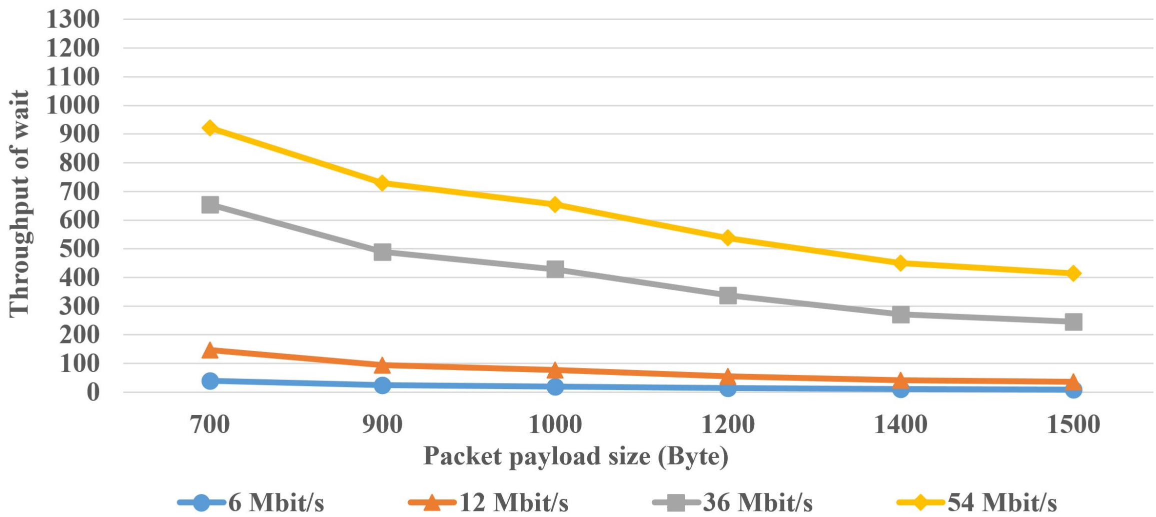


Fig. 5.46 Throughput of WaitS, where $\alpha = 0.89$ in scenario 5.6.

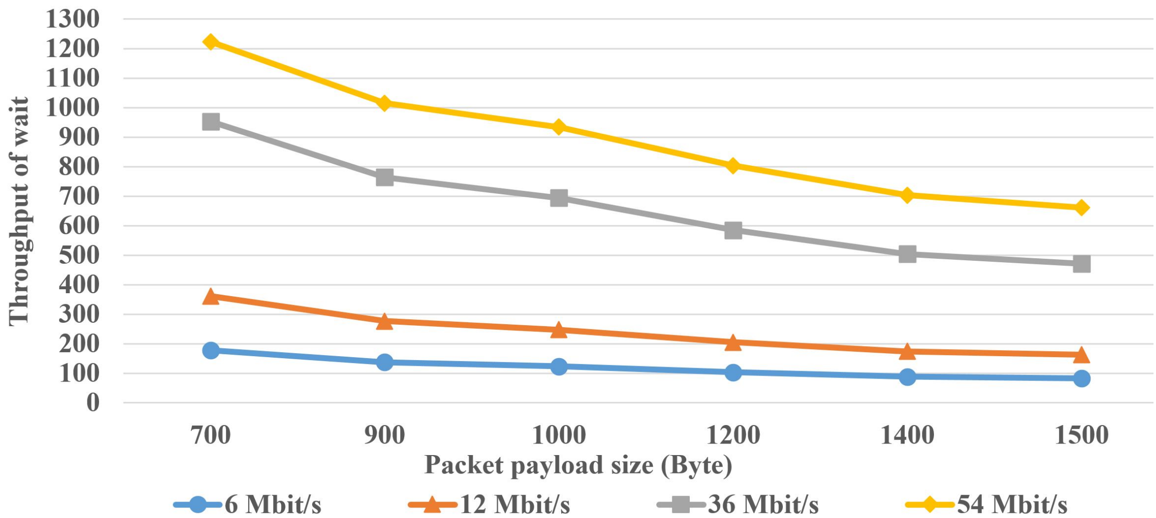


Fig. 5.47 Throughput of WaitS, where $\alpha = 0.99$ in scenario 5.6.

We can see that the throughput of *waitS* in Figures 5.46 and 5.47 increases significantly as α is increased from 0.89 to 0.99. Moreover, we can see that the throughput of *waitS* is very low when the transmission rate is 6 Mbit/s. The throughput of *waitL* in the Figures 5.44 and 5.45 is substantially higher. This is not surprising given that long frames are much more likely to be delayed under competition. Again, we can 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. As in Scenario 5.5 has illustrated, 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 packet payload size 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, if the transmission rate is faster or the packet payload size is less, then the effect of variance is clearly greater.

5.6.4 Fairness metric of utilisation in three pairs case (r=200000)

This section presented the fairness metric of channel utilisation for the three pairs case with having variable frame length in 802.11g, when r=200000 and α=0.8, see Figure 5.48. This figure shows the slow speed will present higher fairness metric compared to the faster speed, when the packet payload size increases. The fairness metric will be affected more in slow speed of transmission, when the backoff rate is high (r=200000) and α=0.89.

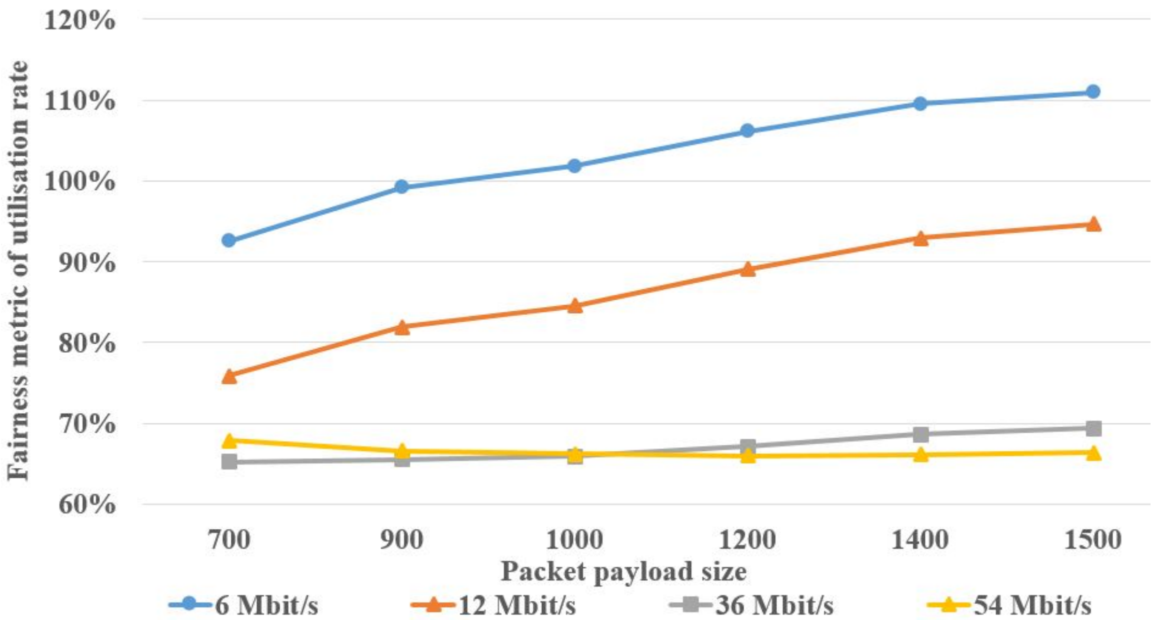


Fig. 5.48 Fairness metric of utilisation for 3 pairs in 802.11g, when r=200000 and α=0.89.

However, the fairness metric of channel utilisation will present poor fairness, when α=0.99 and r=200000 compared to the previous case (when α is 0.89), see Figure 5.49. From this figure we understand that all speed of transmission (from slow to high) will have nearly the same fairness metric, when packet payload size is 700. But, by increasing the packet payload size then the slow speed will present better fairness metric.

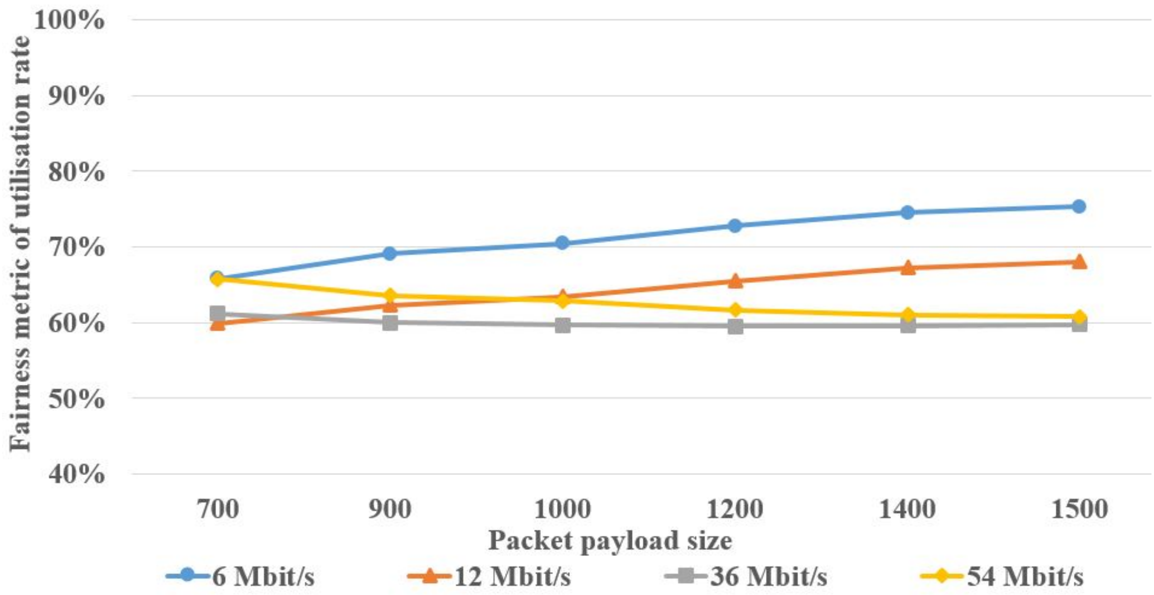


Fig. 5.49 Fairness metric of utilisation for 3 pairs in 802.11g, when r=200000 and α=0.99.

5.6.5 Sensitivity to backoff rate at 20 with fairness metric.

In this section, we investigated the fairness metric of channel utilisation in 802.11g for 3 pairs scenario, when the node has variable frame lengths (α=0.89 and 0.99) and backoff rate (r=20). Figure 5.50 and 5.51 shows the fairness metric of channel utilisation in this scenario of backoff rate at 20, when α=0.89 and α=0.99 respectively. These figures have similar profile of fairness metric of channel utilisation, when the node in the three pairs scenario has no variable frame lengths (see Figure 5.15). In this study, from Figures 5.50 and 5.51 we can understand that the fairness metric is nearly saturated in 54 Mbps speed, and the packet payload size will not affect the fairness metric in this high speed. However, in a slow speed of transmission the fairness metric of utilisation will decrease, when the packet payload size increases. Thus, the variable frame lengths will not affect the fairness metric of channel utilisation, also the number of pairs in this scenario will slightly affect the fairness metric too.

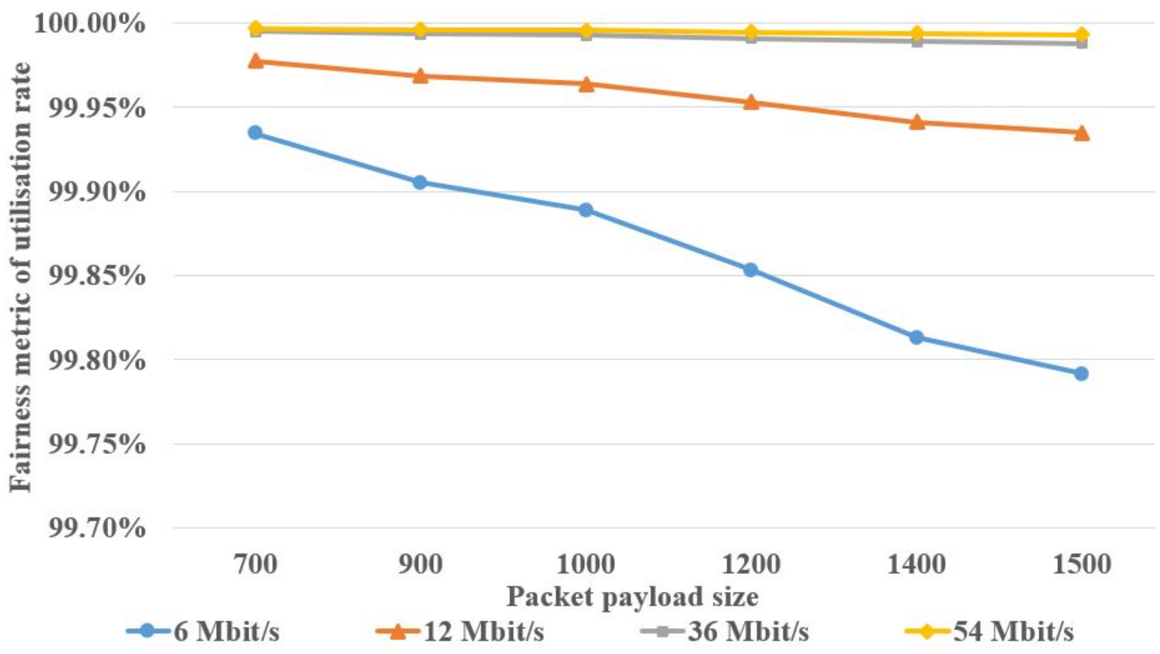


Fig. 5.50 Fairness metric of utilisation for 3 pairs in 802.11g, when r=20 and α=0.89.

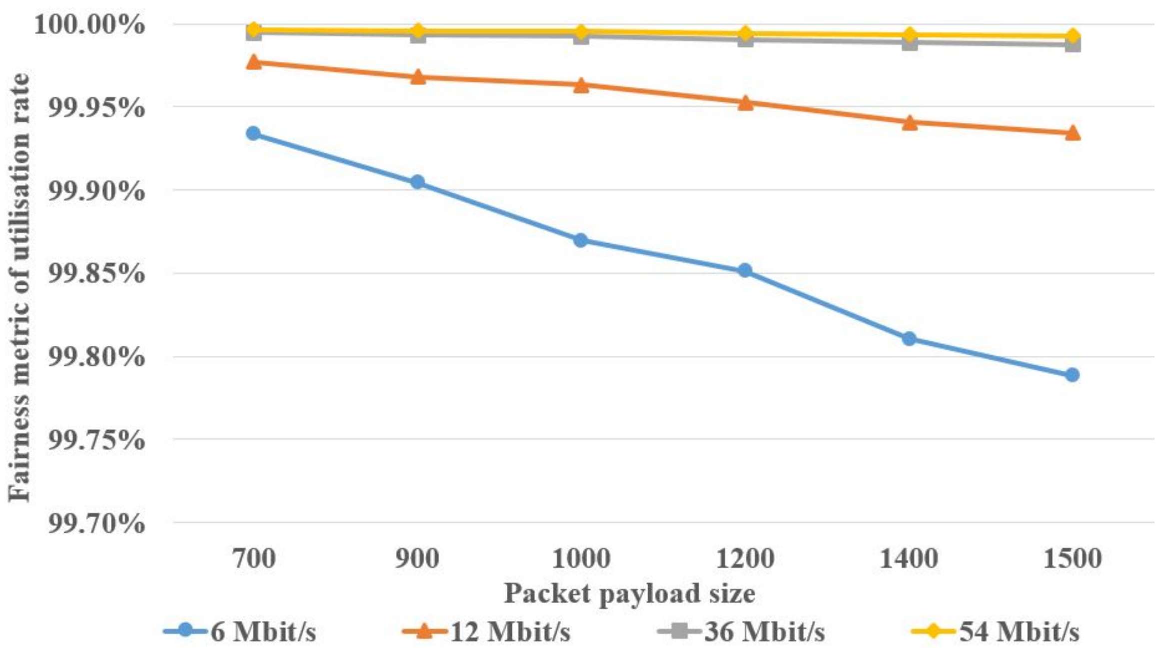


Fig. 5.51 Fairness metric of utilisation for 3 pairs in 802.11g, when r=20 and α=0.99.

5.6.6 Variable frame length with a range of α from 0.99 to 0.64.

In our previous case study and in Section 5.5, we considered the variable frame lengths. As a specific node had hyper-exponential distribution, and we examined the variable frame length on 0.89 and 0.99. However, in this section, we investigate the range of variable frame lengths (α) from 0.99 to 0.64, as we have initiated α at 0.99 and examined it by reducing in steps of 0.05 till 0.64. In this experimental study, the proportion of average message lengths are the same and r=200000, but we have varied the length of long and short messages. This section presents our investigation study on α (0.99, 0.94, 0.89, 0.84, 0.79, 0.74, 0.69, 0.64) by examining the channel utilisation, which we have only examined one speed (6 Mbps) for the two pairs scenario (scenario 5.5). In this scenario, pair A has hyper-exponential distributed frame lengths, while pair B has exponentially distributed frame lengths.

Generally, in this scenario the channel utilisation increases when packet payload size increases too. Figure 5.52 shows the channel utilisation of Pair A for 6 Mbps, when α is varied from 0.99 to 0.64. This figure illustrates that the channel utilisation will reduce from 31% to 28%, when we reduce the α from 0.99 to 0.89. As there is more efficient in 0.99 which there is fewer long frames in a system. However, when α is 0.89 it presents less efficient as there is more long frames in a system to be sent. But, surprisingly when we decrease the α from 0.89 to 0.64 then the channel utilisation becomes higher. Due to coefficient of variation not being directly proportional to α.

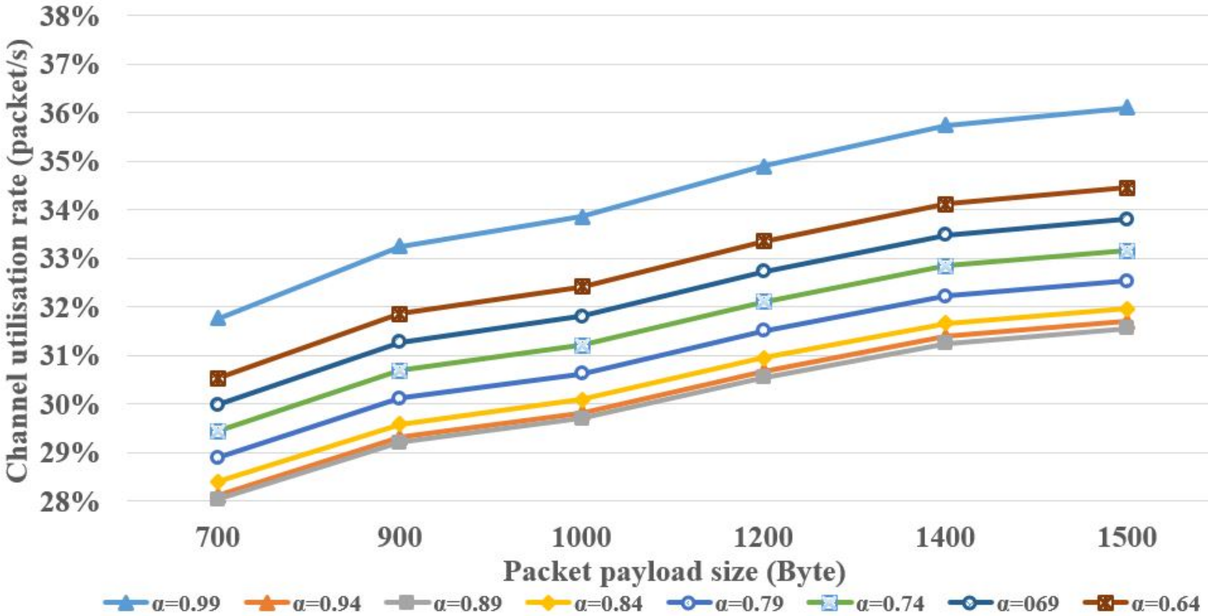


Fig. 5.52 Utilisation rate of Pair A for 6 Mbps in 2 pairs case within the range of α.

Moreover, α is one parameter in a system for the short and long frames, as we have different μ_{data}. Thus, the channel utilisation will not present as a linear when α decreases. The most frames are short in a very large α. But, the long frames are very long frames, as α decreases which we will proportionally obtain long frame (but not very long frame). This is due to the coefficient of variation which does not change as linear.

Likewise, Figure 5.53 shows the channel utilisation in Pair B for the speed of 6 Mbps, when α is varied from 0.99 to 0.64. The channel utilisation will increase from 40% to 43% in this study, when α is 0.99 and 0.89. But, when we decrease α from 0.89 to 0.64 then the channel utilisation drops down, see Figure 5.53. This is due to the complexity of a model and the interactions between different parameters in this model; there is a race condition between the different parameters in a complex model.

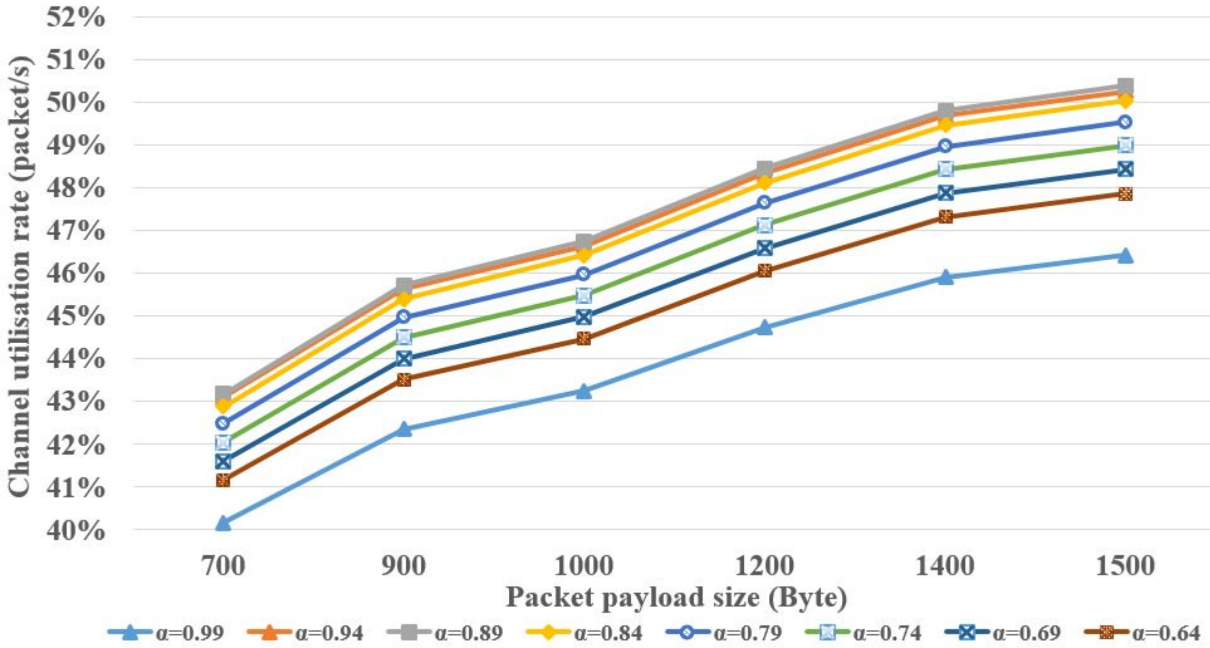


Fig. 5.53 Utilisation rate of Pair B for 6 Mbps in 2 pairs case within the range of α.

5.7 Chapter summary.

The presented results shows that the network topology may have a profound effect on the obtained performance for individual nodes, which may deviate considerably from the average. Network topology is an arrangement of elements in any network, including any node and connection links, which the link could be wire, wireless or both, and how these elements connect to each other via a specific link. Therefore performance studies which ignore topological effects may be seriously misleading. The first set of models confirm that the same fairness issues exist in 802.11g as in 802.11b. In practical we see that the higher transmission rates can lead to a relatively low access rate by the disadvantaged central pair.

In the second part of this chapter,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, as expected. 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 pairs scenario demonstrates a topologically unfair situation which has previously shown to massively hinder the performance of the inner pair. 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 of frame length in order to increase its performance. In addition, in this chapter we illustrated fairness metric of utilisation on three and four pairs scenario, and sensitivity of backoff. Finally, we considered to investigate the range of variable frame lengths.

These results show that the duration of channel occupancy (determined by the transmission rate and frame length) has a profound effect on performance and fairness. In practical varying this duration can alter the expected performance significantly. This leads us on to consider the effect of feature of IEEE 802.11n protocol. We will therefore present and analyse models of frame bursting in IEEE 802.11n in the next chapter.

Chapter 6

Performance modelling of IEEE 802.11n with frame bursting

6.1 Introduction.

The achievable capacity has increased significantly in IEEE 802.11n protocol, with the data rate reaching up to 600 Mbps (it is therefore over 10 times faster than 802.11g). This protocol has five main technical improvements; MIMO, Spatial Multiplexing, Channel Bonding, Short Guard Interval and MAC layer Enhancements. The technology of MIMO stands for "Multiple Input and Multiple Output" used in IEEE 802.11n to increase speed and data rates by using multiple transmitters and receivers at the same time by both the sender and the receiver. Spatial Multiplexing transmission technique in MIMO technology, has been employed the use of multiple antennas to transmit and receive independent and multiple data streams simultaneously, which support users to obtain the maximum use of the available bandwidth. Another technical improvement that increases throughput in IEEE 802.11n is channel bonding. This is a combination two or more communication links or adjacent channels in which to increase the amount of data that can be transmitted. Generally, Guard Interval (GI) is used in communications to avoid interference among symbol transmissions (the space between characters being transmitted) from multipath effect. Most IEEE 802.11 protocols use 800 *ns* as a guard interval. But in IEEE 802.11n, the interval time becomes 400 *ns* as a Short Guard Interval (SGI); this shorter period of time for symbol transmission can be used to improve the throughput. Practically in this chapter, we concentrate on MAC layer enhancements, as we are interested in modelling and investigating the MAC layer performance. In this chapter, the performance demonstrated by IEEE 802.11n MAC layer attributes frame aggregation and block acknowledgement. It also presents a novel model of frame bursting in IEEE 802.11n. As in the preceding chapters, we presented models of restricted network topologies and studied their performance and fairness, by varying the burst length to determine its effect.

6.2 IEEE 802.11n frame bursting.

Different enhancements have been introduced in IEEE 802.11 protocols, including the MAC layer enhancements. The main achievable enhancements in the IEEE 802.11n standard are MAC layer improvement and frame bursting, that helps the sender to transmit several frames simultaneously, during a limited duration called Transmission Opportunity (TXOP). In IEEE 802.11n protocol, the large number of frames can be sent through the medium by reducing the Inter-Frame Spacing time, in which the throughput performance and efficiency of this protocol are significantly enhanced by frame bursting method. In IEEE 802.11n, when a node attempts to use the medium for sending frames, then it sends a burst of frames rather than a single frame (multiple frames have been merged into one aggregation). Hence, the medium will be occupied for longer. An Acknowledgement (*ACK*) technique replaced by a Block Acknowledgement (*BACK* or *BA*) to acknowledge many received frames and reverse direction mechanism rather than individual acknowledge following every single frame of sequences. The Block Acknowledgement, *BA*, technique allows transmission in both directions and acknowledge multiple frames. This MAC layer enhancement with the frame aggregation mechanism improved the throughput of this protocol by reducing the overheads over a larger number of frame bursting. In our study, we considered these enhancements to analyse the performance of this protocol, Figure 6.1 shows the MAC enhancements (for more information see [47, 79]).

In IEEE 802.11n protocol, the frame bursting is improved step by step as shown in five separate rows in Figure 6.1. Basically, the frame transmission in row 1 is similar to the frame transmission in the previous protocols, such as IEEE 802.11g. In this row, a single frame is sent by the sender and waits to receive a single Acknowledgement (*ACK*) to acknowledge each individual frames. While in row 2, a Block Acknowledgement Request, *BAR*, and Block Acknowledgement, *BA*, are functioning after several frames being transmitted. This will improve the protocol to reduce the number of *ACK*. Likewise, in row 3, the Inter-Frame Spacing time is slightly changed, and a period of time *SIFS* is replaced by *RIFS* between each frame. But in row 4 the waiting time (*RIFS* and *SIFS*) are removed between the frames, and the main enhancement in this row is the concatenation of frames into frame bursting by aggregating multiple frames together; in order to achieve higher throughput. Also in the row 4, the *RIFS* is functioning after sending all frames and before *BAR*. Moreover, when the Block Acknowledgement Request *BAR* is requested and after a period of time (*SIFS*), the *BA* will be received. Finally, the last improvement in row 5, shows the *BAR* removed, and a multiple of frames transmitted as block frames. The Block Acknowledgement (*BA*) technique will acknowledge several received frames after a period of time *SIFS*. The improvements in this row will lead to the higher throughput by transmitting a frame bursting with less waiting time.

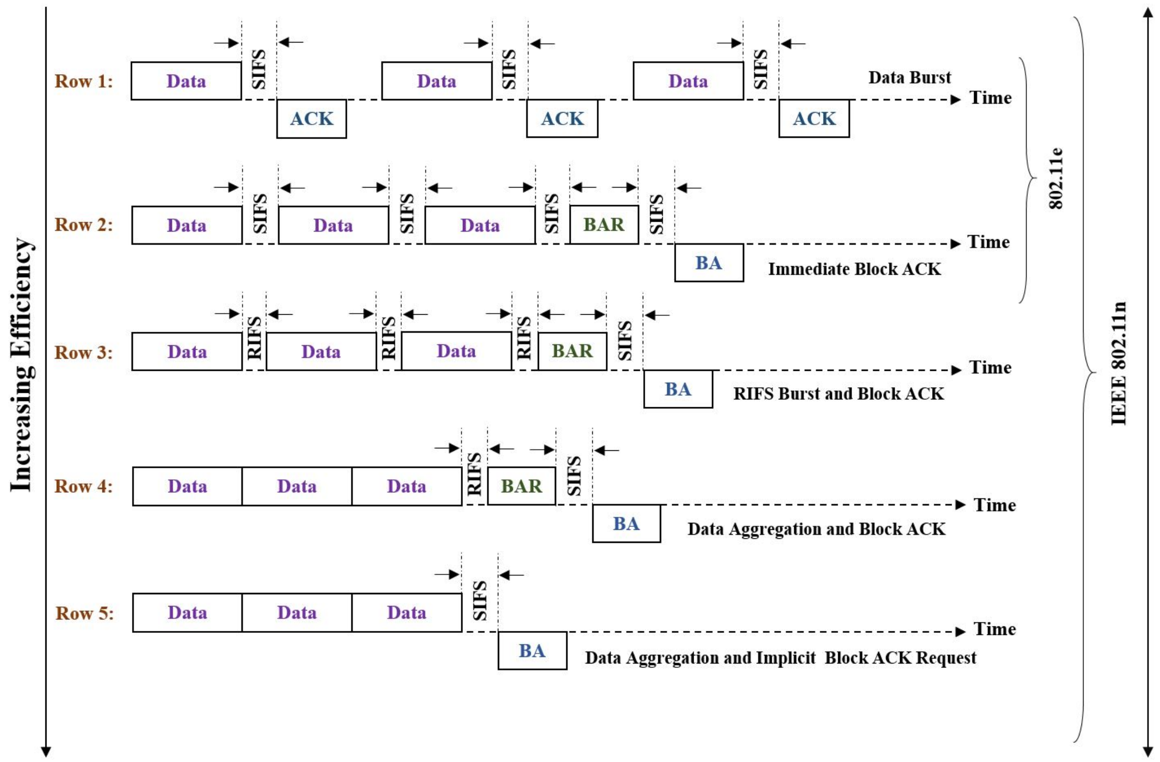
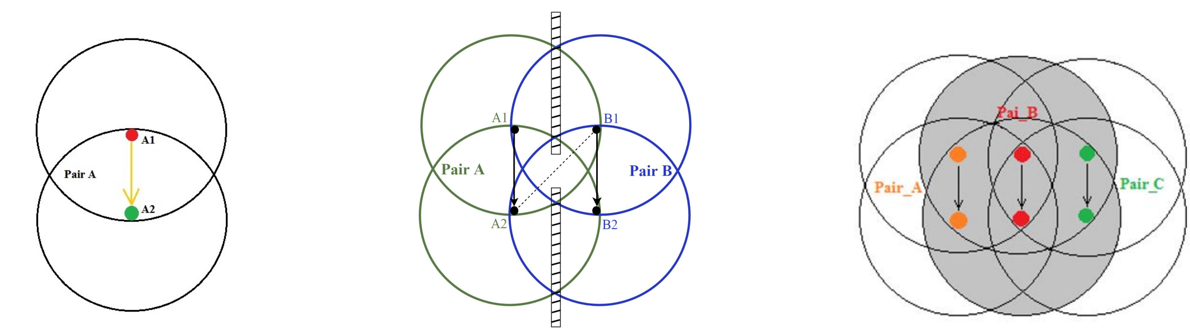


Fig. 6.1 IEEE 802.11n MAC layer enhancements [47, 79].

6.3 PEPA models.

In this chapter, we have used PEPA to investigate the highlighted different performance issues by studying the medium access in terms of channel utilisation and throughput. Three main scenarios are presented to investigate fairness in IEEE 802.11n. The following scenarios are used "listen before talk" approach; in each scenario a particular node senses the medium (attempts to transmit a frame(s) via a wireless media) for the purpose of reducing any interferences or in order to avoid collisions that might occur. Moreover, we created these scenarios based on the medium access mechanism in IEEE 802.11 and DCF based CSMA/CA (more details have been highlighted in Chapter 2). In this chapter, we firstly modelled the one pair scenario, shown in Figure 6.2a, then we created a model for the two pairs scenario, shown in Figure 6.2b. Finally, three pairs scenario (see Figure 6.2c) considered for comparison purposes with other protocol (802.11b/g).



(a) One pair scenario. (b) Two pairs scenario. (c) Three pairs scenario.

Fig. 6.2 The one pair, two pairs and three pairs scenarios.

6.3.1 The one pair scenario (scenario 6.1).

Firstly, we investigate the one pair scenario shown in Figure 6.2a in PEPA by examining five different models based on the IEEE 802.11n MAC layer enhancements shown in Figure 6.1. The one pair scenario is useful to illustrate the behaviour of the transmitting pair, to provide a baseline performance and to show how performance is affected by frame bursting. All five models of the one pair scenario are shown as follows:

Model one based on row 1 on MAC layer enhancements in IEEE 802.11n protocol.

This model presents an essential model in our study that is based on row 1 on the IEEE 802.11n MAC enhancements, as it is shown in Figure 6.1. It is structurally more similar to the models in IEEE 802.11b and IEEE 802.11g protocols in Chapter 4 and 5. A node can transmit a frame at a time and it waits to receive a single *ACK* after every single transmitted frame. But, the rates and parameters are slightly modified in the IEEE 802.11n protocol compared to the IEEE 802.11g based on the modifications of IEEE organisation. Another difference in this model is the probability of subsequence frame, that is denoted by p_1 and Intermediate ACK (*iack*). The average frame burst length, as denoted by n where $2 \leq n \leq 10$, and the probability of subsequent frames, as denoted by $p_{\ 1}$, are used in this model, more details are shown in Section 6.4.

This model consists of two main components, which are Pair_A and Medium_F. Firstly, `Pair_A` draws backoff and becomes `Pair_A0` at a rate r. Then `Pair_A0` starts to count *DIFS* to `Pair_A1`. Also, `Pair_A1` starts count `backoff` with a rate of $p\mu_{bck}$ in the `Pair_A1` or it ends `backoff` with a rate of $q\mu_{bck}$ in the `Pair_A2`. If `Pair_A1` has a choice to `Pair_A2` then a frame will transmit in `Pair_A2` to `Pair_A3`. The state `Pair_A3` counts a *SIFS* period of time (with probability $p_1\mu_{sifs}$) to request an *iack* with rate μ_{ack} in `Pair_A2` to make a different path for an *ACK* to return in transmission (it interviews an *ACK* for doing an *ACK* at the end), or it is counting *SIFS* period of time (with probability (1-p_1)μ_{sifs}) to state `Pair_A6`. Finally, `Pair_A6` will receive the *ACK* to `Pair_A` to acknowledge the frame that received, see the following specifications of the one pair scenario based on the row 1 in 802.11n MAC enhancements, shown in Figure 6.1.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{def}{=} (count\_difs, \mu_{difs}).Pair\_A1 \\
Pair\_A1 &\stackrel{def}{=} (count\_backoff, p\mu_{bck}).Pair\_A1 + (end\_backoff, q\mu_{bck}).Pair\_A2 \\
Pair\_A2 &\stackrel{def}{=} (transmit, \mu_{data}).Pair\_A3 \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, p_1\mu_{sifs}).(iack, \mu_{ack})Pair\_A2 \\
&\ \ + \ (count\_sifs, (1-p_1)\mu_{sifs}).Pair\_A6 \\
Pair\_A6 &\stackrel{def}{=} (ack, \mu_{ack}).Pair\_A
\end{aligned}
$$

Component of Medium_F: The medium component is totally occupied by Pair_A in this model. The operation in this medium is very similar to the operation medium, presented in the previous protocols, such as IEEE 802.11g. Here, `Medium_F` represents the situation where the medium is unoccupied; once the frame transmitted, it goes to `Medium_F1`. `Medium_F1` represents that the medium is being used by `Pair_A` as *ACK* will acknowledge to `Medium_F`.

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

The complete system: In this scenario, `Pair_A` as the only pair in the model is trying to occupy the `Medium_F` entirely, and the system will complete via the following cooperation sets:

$$\text{Scenario 6.1} \stackrel{def}{=} Pair\_A \underset{K}{\bowtie} Medium\_F$$

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

Model two based on row 2 on MAC layer enhancements in IEEE 802.11n.

In this section, we present our second mode that is based on row 2 on the MAC layer enhancement, as it is shown in Figure 6.1. This model is similar to the previous model (model one), but in this case we introduce a Block Acknowledgement, *BA*, instead of a single frame Acknowledgement (*ACK*). In this model, the *BA* will reduce the number of *ACK* when Block Acknowledgement Request, *BAR*, has requested with two extra states. In this scenario, several frames can be transmitted, then *BA* will acknowledge all the frames, also the *iack* feature is removed in this model. `Pair_A` draws backoff to `Pair_A0` at a rate *r*. Then `Pair_A0` starts to count *DIFS* to `Pair_A1`. The state `Pair_A1` starts count `backoff` with the rate of $p\mu_{bck}$ in the `Pair_A1` or it ends `backoff` with the rate of $q\mu_{bck}$ in the `Pair_A2`. In the state `Pair_A2` a frame will transmit to `Pair_A3`. `Pair_A3` counts a *SIFS* (with probability $p_1\mu_{sifs}$) to `Pair_A2`, or counts the *SIFS* with the probability of (1-p_1)μ_{sifs} to *Pair_A3b*. *Pair_A3b* does *BAR* with the rate of μ_{BAR} to *Pair_A3c*. The *Pair_A3c* counts *SIFS* with the rate of μ_{sifs} to `Pair_A6`. Finally, `Pair_A6` will receive the Block Acknowledgement (*BA*) to acknowledge all frames to `Pair_A`. The following specifications shows the one pair scenario based on the row 2 in Figure 6.1.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{def}{=} (count\_difs, \mu_{difs}).Pair\_A1 \\
Pair\_A1 &\stackrel{def}{=} (count\_backoff, p\mu_{bck}).Pair\_A1 + (end\_backoff, q\mu_{bck}).Pair\_A2 \\
Pair\_A2 &\stackrel{def}{=} (transmit, \mu_{data}).Pair\_A3 \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, p_1\mu_{sifs}).Pair\_A2 + (count\_sifs, (1-p_1)\mu sifs).Pair\_A3b \\
Pair\_A3b &\stackrel{def}{=} (BAR, \mu_{BAR}).Pair\_A3c \\
Pair\_A3c &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A6 &\stackrel{def}{=} (BA, \mu_{ack}).Pair\_A
\end{aligned}
$$

Component of Medium_F: In this model, the medium component is similar to the medium component in the model one. The only difference is the Block Acknowledgement (*BA*) in a `Medium_F1` instead of *ACK*. When `Medium_F1` shows the medium being used by the `Pair_A` *BA* that will acknowledge all frames been transmitted to `Medium_F`. This medium component shows as the following specification.

$$\begin{aligned}
Medium_F &\overset{def}{=} (transmit, \top).Medium_F1 + (count_difs, \top).Medium_F \\
&\quad +(count_backoff, \top).Medium_F + (end_backoff, \top).Medium_F \\
Medium_F1 &\overset{def}{=} (BA, \top).Medium_F
\end{aligned}$$

The complete system: In this scenario we can see that the `Pair_A` interacts through the `Medium_F` due to this cooperation sets:

$$\text{Scenario 6.1} \overset{def}{=} Pair\_A \underset{K}{\bowtie} Medium\_F$$

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

Model three based on row 3 on MAC layer enhancements in IEEE 802.11n.

This model is based on row 3 on the MAC layer enhancements, as shown in Figure 6.1. This model has a similarity to the previous model (model two), as the only difference is *RIFS* between the frames instead of *SIFS* as a smaller Inter-Frame Spacing time. This improvement is aimed to reduce the Inter-Frame Spacing time between each successive transmissions, while the *BAR* and *BA* are not been changed in this model. When the state has a choice to transmit frame `Pair_A2` to `Pair_A3`, then `Pair_A3` counts a *RIFS* (with probability $p_1\mu_{rifs}$) to `Pair_A2` or it counts the *RIFS* with the probability of (1-p_1)μ_{rifs} to *Pair_A3b*. And the other states have similar features until the *BA* will receive to acknowledge all frames from `Pair_A6` to `Pair_A`. The specifications of the one pair scenario based on row 3 on MAC layer enhancements shown as follow.

$$\begin{aligned}
Pair_A &\overset{def}{=} (draw_backoff, r).Pair_A0 \\
Pair_A0 &\overset{def}{=} (count_difs, \mu_{difs}).Pair_A1 \\
Pair_A1 &\overset{def}{=} (count_backoff, p\mu_{bck}).Pair_A1 + (end_backoff, q\mu_{bck}).Pair_A2 \\
Pair_A2 &\overset{def}{=} (transmit, \mu_{data}).Pair_A3 \\
Pair_A3 &\overset{def}{=} (count_rifs, p_1\mu_{rifs}).Pair_A2 + (count_rifs, (1-p_1)\mu_{rifs}).Pair_A3b \\
Pair_A3b &\overset{def}{=} (BAR, \mu_{BAR}).Pair_A3c \\
Pair_A3c &\overset{def}{=} (count_sifs, \mu_{sifs}).Pair_A6 \\
Pair_A6 &\overset{def}{=} (BA, \mu_{ack}).Pair_A
\end{aligned}$$

Component of Medium_F and cooperation sets: The medium component and cooperation sets in this model are similar to the component of `Medium_F` and cooperation sets in the model 2, see the Medium_F and cooperation sets in the model 2.

Model four based on row 4 on MAC layer enhancements in IEEE 802.11n.

The fourth model will show in this section that is based on row 4 on MAC layer enhancements in IEEE 802.11n protocol shown in Figure 6.1. In this model the frame has concatenated into frame bursting by aggregating multiple frames together; this enhancement from model 3 to model 4 is a well-known improvement in IEEE 802.11n standard that can improve the data throughput aiming to achieve higher throughput. Model 4 has no gap between the frames, whether each transmit will follow by another transmit or it goes to the count *RIFS* at the end. This model carries out looping to transmit multiple frames. The only difference between model 3 and model 4, is the state `Pair_A2` has a choice to transmit a frame from `Pair_A2` at the rate $p_1\mu_{data}$ to `Pair_A2` or it will transmit a frame at the rate (1-p_1)μ_{rifs} to `Pair_A3`. Then `Pair_A3` counts a *RIFS* with the rate μ_{rifs} to `Pair_A3b`, and the *Pair_A3b* does *BAR* with the rate of μ_{BAR} to *Pair_A3c*. The state of *Pair_A3c* counts *SIFS* with the rate of μ_{sifs} to `Pair_A6`. Finally, `Pair_A6` will receive Block Acknowledgement (*BA*) to `Pair_A` to acknowledge all frames that have been transmitted. The fourth model shows as follow.

$$
\begin{aligned}
Pair\_A &\stackrel{\text{def}}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{\text{def}}{=} (count\_difs, \mu_{difs}).Pair\_A1 \\
Pair\_A1 &\stackrel{\text{def}}{=} (count\_backoff, p\mu_{bck}).Pair\_A1 + (end\_backoff, q\mu_{bck}).Pair\_A2 \\
Pair\_A2 &\stackrel{\text{def}}{=} (transmit, p_1\mu_{data}).Pair\_A2 + (transmit, (1-p_1)\mu_{data}).Pair\_A3 \\
Pair\_A3 &\stackrel{\text{def}}{=} (count\_rifs, \mu_{rifs}).Pair\_A3b \\
Pair\_A3b &\stackrel{\text{def}}{=} (BAR, \mu_{BAR}).Pair\_A3c \\
Pair\_A3c &\stackrel{\text{def}}{=} (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A6 &\stackrel{\text{def}}{=} (BA, \mu_{ack}).Pair\_A
\end{aligned}
$$

Component of Medium_F and cooperation sets: The medium and cooperation sets in model 4 are similar to the `Medium_F` and cooperation sets in model 2 and model 3, see the component of `Medium_F` and cooperation sets in the model 2.

Model five based on row 5 on MAC layer enhancements in IEEE 802.11n.

The fifth model in this study is based on row 5 on the IEEE 802.11n MAC layer enhancements, shown in Figure 6.1. This model has a frame bursting feature to be sent, which has a benefit for the node to obtain higher throughput. The data acknowledgement is improved in this model in comparison to model 4, by removing the redundant Block Acknowledgement Request ,*BAR*, after all frame bursting has completely sent during the transmission. It is aimed to reduce the gap between multi-frames and Block Acknowledgement ,*BA*, scheme (the node is considered to be sent a sequence of frames repeatedly over and over again or it ends sending frames then obtains the *BA*). In model 5, the waiting time *SIFS* operates before the *BA* to acknowledge the entire block frames. The main difference from model 5 to model 4 is the state has a choice to transmit frame from `Pair_A2` at the rate $p_1\mu_{data}$ to `Pair_A2` or it transmit frame at the rate (1-p_1)μ_{data} to `Pair_A3`. Then `Pair_A3` counts a *SIFS* with the rate μ_{sifs} to `Pair_A6`. Finally, `Pair_A6` will receive *BA* to the state of `Pair_A` to acknowledge the entire block of frames that have been transmitted. The MAC enhancements in this model show significant improvements in this protocol, clearly the impact of the entire improvements appeared in model 5. Hence, this model becomes a baseline to study our next scenarios in this chapter. The following specifications show model 5 for the one pair scenario.

$$\begin{aligned}
Pair_A &\stackrel{def}{=} (draw_backoff, r).Pair_A0 \\
Pair_A0 &\stackrel{def}{=} (count_difs, \mu_{difs}).Pair_A1 \\
Pair_A1 &\stackrel{def}{=} (count_backoff, p\mu_{bck}).Pair_A1 + (end_backoff, q\mu_{bck}).Pair_A2 \\
Pair_A2 &\stackrel{def}{=} (transmit, p_1\mu_{data}).Pair_A2 + (transmit, (1-p_1)\mu_{data}).Pair_A3 \\
Pair_A3 &\stackrel{def}{=} (count_sifs, \mu_{sifs}).Pair_A6 \\
Pair_A6 &\stackrel{def}{=} (BA, \mu_{ack}).Pair_A
\end{aligned}$$

Component of Medium_F and cooperation sets: The medium component and cooperation sets in model 5 are similar to the `Medium_F` and cooperation sets in models 4, 3 and 2, as the medium component (`Medium_F`) is shown in the model 2.

6.3.2 The two pairs scenario (scenario 6.2).

In this section, we present the two pairs scenario (see Figure 6.2b) as we examined the same scenario in Chapter 3 and 4, but our model of two pairs scenario in this chapter is based on the last case study in model 5 in scenario 6.1. Similar structure of a pair in model 5 will apply to both pairs in the two pairs case in this scenario. In the two pairs scenario, we focused on transferring block frames without repeated waiting time to send another frame, and with a single Block Acknowledgement *BA* to acknowledge the entire frame burst. The purpose of the two pairs scenario is to investigate how the performance will be affected by the frame bursting when there is a competition without interference.

This scenario is consists of two main components, that are *Pair_A* and *Pair_B*. These pairs are able to interact due to a wireless medium (*Medium_F*). Both pairs are symmetric, independent and may listen to the medium simultaneously before sending any frames. If the medium is not free, then the node waits for a period of time until the medium becomes idle again. Once the medium becomes idle, a node may start to transmit a sequence of frames. After each frame, a probabilistic choice is made to send a subsequent frame. Once the frame bursting is delivered successfully, a Block Acknowledgement, *BA*, will acknowledge all the frames that have been sent. This scenario is fair in terms of channel access, as both pairs can hear each other and they can occupy the medium equally, but under the condition that both pairs are synchronised and have the same probability of sending successive frames.

We examined two case studies in this scenario by observing the number of frame bursting sent by both pairs. In our first case study, both pairs are symmetric and can use the medium equally, in which the average frame burst length n where $2 \leq n \leq 10$ for both pairs are similar. The probability of subsequent frames in *Pair_A* is denoted by p_1 and in *Pair_B* is denoted by p_2 i. e. $p_1 = p_2$. But in our second case study, we concentrated on the effect of frame bursting in more details, which p_1 in *Pair_A* is similar to p_1 in the first case study, but *Pair_B* has a fixed number of the average frame burst length (p_2), i. e. $p_1 \neq p_2$.

In this model, `Pair_A` attempts to transmit after sensing the medium at the initial stage to implement the transferring. `Pair_A` draws a backoff to `Pair_A0`, then `Pair_A0` counts *DIFS* to `Pair_A1` or it waits in the queue as `Pair_A5`. A node waits at rate μ_{data} in `Pair_A5` before reaches to `Pair_A4`. In `Pair_A4` the node has choices either counts *DIFS* to `Pair_A1` or *EIFS* to `Pair_A1` or waits in the `queue` at `Pair_A5`. `Pair_A1` starts count `backoff` to stay at `Pair_A1` or ends `backoff` to `Pair_A2` or stays in the `queue` to `Pair_A5`. When it has selected to go to `Pair_A2`, then it starts to transmit a frame with a probability of p_1 to send a subsequent frame (consequently staying in `Pair_A2`) or it ends the transmission, by going to `Pair_A3` with a probability of (1-p_1). If any node occupies the medium then the other node may `queue` at `Pair_A5`. When it stops transmitting, then in `Pair_A3` *SIFS* counts to `Pair_A6`. Finally, `Pair_A6` sends a *BA* to acknowledge that all the fames have been received successfully. The same process will apply to the second pair (`Pair_B`).

The system will be fair if $p_1 = p_2$, i. e. that the frame burst lengths at each pair are identically distributed. In our experimental results we will also explore the case study, where $p_1 \neq p_2$. The model of the two pairs scenario shows as the following specifications.

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A2 &\stackrel{def}{=} (transmitA, p_1\mu_{data}).Pair\_A2 + (transmitA, (1-p_1)\mu_{data}).Pair\_A3 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4 \\
Pair\_A6 &\stackrel{def}{=} (BA\_A, \mu_{ack}).Pair\_A
\end{aligned}
$$

$$
\begin{aligned}
Pair\_B &\stackrel{def}{=} (draw\_backoff, r).Pair\_B0 \\
Pair\_B0 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).Pair\_B1 + (queueB, \top).Pair\_B5 \\
Pair\_B1 &\stackrel{def}{=} (count\_backoffB, p\mu_{bck}).Pair\_B1 + (end\_backoffB, q\mu_{bck}).Pair\_B2 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B2 &\stackrel{def}{=} (transmitB, p_2\mu_{data}).Pair\_B2 + (transmitB, (1-p_2)\mu_{data}).Pair\_B3 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_B6 \\
Pair\_B4 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).Pair\_B1 + (count\_eifsB, \mu_{eifs}).Pair\_B1 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_B4 \\
Pair\_B6 &\stackrel{def}{=} (BA\_B, \mu_{ack}).Pair\_B
\end{aligned}
$$

The Medium_F component shows the situations, where the medium is unoccupied, but `Medium_F1` shows the medium being used by the `Pair_B` and `Medium_F2` shows the medium being used by the `Pair_A`. The medium component between both pairs is presented as follows:

$$
\begin{aligned}
Medium\_F &\stackrel{def}{=} (transmitA,\top).Medium\_F2 + (transmitB,\top).Medium\_F1\\
&+ (count\_difsA,\top).Medium\_F + (count\_backoffA,\top).Medium\_F\\
&+ (end\_backoffA,\top).Medium\_F + (count\_eifsA,\top).Medium\_F\\
&+ (count\_difsB,\top).Medium\_F + (count\_backoffB,\top).Medium\_F\\
&+ (end\_backoffB,\top).Medium\_F + (count\_eifsB,\top).Medium\_F\\
Medium\_F1 &\stackrel{def}{=} (transmitB,\top).Medium\_F1 + (BA\_B,\top).Medium\_F\\
&+ (queueA,\lambda oc).Medium\_F1\\
Medium\_F2 &\stackrel{def}{=} (transmitA,\top).Medium\_F2 + (BA\_A,\top).Medium\_F\\
&+ (queueB,\lambda oc).Medium\_F2
\end{aligned}
$$

The complete system: In this model, the `Pair_A`, `Pair_B` and `Medium_F` are interacting through the following cooperation sets:

$$\text{Scenario 6.2} \stackrel{def}{=} (Pair\_A \underset{K}{\bowtie} Medium\_F) \underset{L}{\bowtie} Pair\_B$$

Where the values of K and L are:
$K = \{transmitA, BA\_A, queueA, count\_difsA, count\_backoffA, end\_backoffA, count\_eifsA\}$
$L = \{transmitB, BA\_B, queueB, count\_difsB, count\_backoffB, end\_backoffB, count\_eifsB\}$.

6.3.3 The three pairs scenario (scenario 6.3).

In this section, we present three pairs scenario to study topographic unfairness in IEEE 802.11n protocol. Once again, we model central pair in competition with the two external pairs (Figure 6.2c). As in the two pair scenario, we model the most optimistic frame bursting option (row 5 in Figure 6.1). The following specifies the behaviour of the three pairs (`Pair_A`, `Pair_B` and `Pair_C`) and the medium (`Medium_F`). We assume that the external pairs (`Pair_A` and `Pair_C`) have the same frame burst probability (p_1), but that may be different for the central pair (`Pair_B`) as we denoted by p_2,

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0\\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu difs).Pair\_A1 + (queueA,\top).Pair\_A5\\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2\\
&+ (queueA,\top).Pair\_A5\\
Pair\_A2 &\stackrel{def}{=} (transmitA, p_1\mu_{data}).Pair\_A2 + (transmitA,(1-p_1)\mu_{data}).Pair\_A3\\
&+ (queueA,\top).Pair\_A5\\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6\\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1\\
&+ (queueA,\top).Pair\_A5\\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4\\
Pair\_A6 &\stackrel{def}{=} (BA\_A, \mu_{ack}).Pair\_A
\end{aligned}
$$

$$
\begin{aligned}
Pair\_B &\stackrel{def}{=} (draw\_backoff, r).Pair\_B0 \\
Pair\_B0 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).Pair\_B1 + (queueB, \top).Pair\_B5 \\
Pair\_B1 &\stackrel{def}{=} (count\_backoffB, p\mu_{bck}).Pair\_B1 + (end\_backoffB, q\mu_{bck}).Pair\_B2 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B2 &\stackrel{def}{=} (transmitB, p_2\mu_{data}).Pair\_B2 + (transmitB, (1-p_2)\mu_{data}).Pair\_B3 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_B6 \\
Pair\_B4 &\stackrel{def}{=} (count\_difsB, \mu_{difs}).Pair\_B1 + (count\_eifsB, \mu_{eifs}).Pair\_B1 \\
&+ (queueB, \top).Pair\_B5 \\
Pair\_B5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_B4 \\
Pair\_B6 &\stackrel{def}{=} (BA\_B, \mu_{ack}).Pair\_B
\end{aligned}
$$

$$
\begin{aligned}
Pair\_C &\stackrel{def}{=} (draw\_backoff, r).Pair\_C0 \\
Pair\_C0 &\stackrel{def}{=} (count\_difsC, \mu_{difs}).Pair\_C1 + (queueC, \top).Pair\_C5 \\
Pair\_C1 &\stackrel{def}{=} (count\_backoffC, p\mu_{bck}).Pair\_C1 + (end\_backoffC, q\mu_{bck}).Pair\_C2 \\
&+ (queueC, \top).Pair\_C5 \\
Pair\_C2 &\stackrel{def}{=} (transmitC, p_1\mu_{data}).Pair\_C2 + (transmitC, (1-p_1)\mu_{data}).Pair\_C3 \\
&+ (queueC, \top).Pair\_C5 \\
Pair\_C3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_C6 \\
Pair\_C4 &\stackrel{def}{=} (count\_difsC, \mu_{difs}).Pair\_C1 + (count\_eifsC, \mu_{eifs}).Pair\_C1 \\
&+ (queueC, \top).Pair\_C5 \\
Pair\_C5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_C4 \\
Pair\_C6 &\stackrel{def}{=} (BA\_C, \mu_{ack}).Pair\_C
\end{aligned}
$$

Component of Medium F: The shared medium component in the three pairs scenario shows, that the `Medium_F` represents the situation where the medium is unoccupied. `Medium_F1` represents the medium being used by the central pair (Pair_B). `Medium_F2` represents the medium being used by the external pair (Pair_A). Also, `Medium_F3` represents the medium being used by the external pair (Pair_C). Finally, `Medium_F4` represents the medium being used by both external pairs (Pair_A and Pair_C). The availability of all pairs to transmit interacts with the shared actions of the medium component as follows:

$$
\begin{aligned}
Medium\_F &\stackrel{def}{=} (transmitC, \top).Medium\_F3 + (transmitA, \top).Medium\_F2 \\
&+ (transmitB, \top).Medium\_F1 \\
&+ (count\_difsC, \top).Medium\_F + (count\_backoffC, \top).Medium\_F \\
&+ (end\_backoffC, \top).Medium\_F + (count\_eifsC, \top).Medium\_F \\
&+ (count\_difsA, \top).Medium\_F + (count\_backoffA, \top).Medium\_F \\
&+ (end\_backoffA, \top).Medium\_F + (count\_eifsA, \top).Medium\_F \\
&+ (count\_difsB, \top).Medium\_F + (count\_backoffB, \top).Medium\_F \\
&+ (end\_backoffB, \top).Medium\_F + (count\_eifsB, \top).Medium\_F \\
Medium\_F1 &\stackrel{def}{=} (transmitB, \top).Medium\_F1 + (BA\_B, \top).Medium\_F \\
&+ (queueA, \lambda oc).Medium\_F1 + (queueC, \lambda oc).Medium\_F1
\end{aligned}
$$

$$\begin{aligned}
Medium_F2 &\stackrel{def}{=} (transmitA, \top).Medium_F2 + (transmitC, \top).Medium_F4 \\
&+ (BA_A, \top).Medium_F + (count_difsC, \top).Medium_F2 \\
&+ (count_backoffC, \top).Medium_F2 + (end_backoffC, \top).Medium_F2 \\
&+ (count_eifsC, \top).Medium_F2 + (queueB, \lambda oc).Medium_F2 \\
Medium_F3 &\stackrel{def}{=} (transmitC, \top).Medium_F3 + (transmitA, \top).Medium_F4 \\
&+ (BA_C, \top).Medium_F + (count_difsC, \top).Medium_F3 \\
&+ (count_backoffC, \top).Medium_F3 + (end_backoffC, \top).Medium_F3 \\
&+ (count_eifsC, \top).Medium_F3 + (queueB, \lambda oc).Medium_F3 \\
Medium_F4 &\stackrel{def}{=} (BA_A, \top).Medium_F3 + (BA_C, \top).Medium_F2 \\
&+ (transmitA, \top).Medium_F4 + (transmitC, \top).Medium_F4 \\
&+ (queueB, \lambda oc).Medium_F4
\end{aligned}$$

The complete system: In this model all components interact through this cooperation sets:

$$\text{Scenario 6.3} \stackrel{def}{=} ((Pair\_A \| Pair\_C) \underset{K}{\bowtie} Medium\_F) \underset{L}{\bowtie} Pair\_B$$

Where the values of K and L are:
K ={transmitA, BA_A, queueA, count_difsA, count_backoffA, end_backoffA, count_eifsA, transmitC, BA_C, queueC, count_difsC, count_backoffC ,end_backoffC, count_eifsC}.
L ={transmitB, BA_B, queueB, count_difsB, count_backoffB, end_backoffB, count_eifsB}.

6.4 Parameters.

This section presents the main parameters in the IEEE 802.11n standard, see Table 6.1. Some parameters were shown in the previous chapters, and here we present these parameters that we used in 802.11n. The IEEE 802.11 protocols have very specific Inter-Frame Spacing, as they coordinate access to the medium for transmitting frames. When any pair wants to transmit, firstly it senses the channel to be used if it is idle, once silence is detected, then the node transmits with the probability of 'p'. For convenience, in our scenarios each pair has count back-off and end back-off actions with ($p\times$ μ_{bck}) and ($q\times$ μ_{bck}) rates respectively. We have assumed p and q= 0.5 (where, q=1-p). According to the definition of 802.11n protocol and PHY standards, a Short Guard Interval (SGI) is enabled to 400, and the possible data rate per stream are 15, 30, 45, 60, 90, 120, 135 and 150 Mbps [76]. In this study, we considered 150 Mbps as a sample of data rates, as we have studied on this speed. This data rate 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 rates are λoc = 100000 and μ = 200000 respectively. In our model μ_{ack} shows as a rate of ACK. If μ_{ack} = 1644.75 for 1 Mbps then for 150 Mbps speed the μ_{ack} = 246712.5 (150 $\times$ 1644.75).

$$\mu_{ack} = \frac{\text{channel throughput}}{ACK \text{ length}}$$

Where the value of ACK length = 1 byte.

Inter-Frame Space (*IFS*): A small amount of time is required in the IEEE 802.11 families to generate a successful transmission for interface protocol. At the beginning, the length of the *IFS* is dependent on the previous frame type, if any noise occurs, the *IFS* is used. Possibly, if transmission of a particular frame ends and before another one starts, the *IFS* applies a delay to the channel to stay clear. It is an essential idle period of time needed to ensure that other nodes may access the channel. The aim of the *IFS* is to supply a waiting time for each frame transmission in a specific node, allowing the transmitted signal to reach another node (essential for listening) that it is measured in microseconds [34, 64, 75].

Short Inter-Frame Space (*SIFS*): *SIFS* is the shortest IFS for highest priority transmissions used with DCF, that it aims to process a received frame; for instance, *SIFS* is applied between a data frame and the *ACK*. Additionally, *SIFS* can be used to separate single frames in a back-to-back frame burst, and the value of *SIFS* time in IEEE 802.11n protocol is 16 μs.

Slot time: A slot time is an integral required number if node attempts to send a data with the beginning of the transmission slot boundary. The duration of slot time is designed to provide sufficient space of the variability and sufficient required time to transmit a node's preamble to be detected by other nodes before the next slot boundary. The value of the slot time in the IEEE 802.11n PHYs is 9 μs (for 5 GHz).

DCF Inter-Frame Space (*DIFS*): *DIFS* is a medium priority waiting time used by nodes, that operates under the DCF to send and manage the data frames. The *DIFS* can be used to monitor the medium for a longer period of time than *SIFS*. If the channel is idle, the node waits for the *DIFS* to determine that the channel is not being used, and it waits for another period of time (*backoff*). The following formula shows the definition of *DIFS*.
DIFS = *SIFS* + (2 $\times$ (slot time = 9 μs in IEEE 802.11n standard)).

Extended Inter-Frame Space (*EIFS*): If the node detects a signal and a frame is not correctly received, the transmission node uses *EIFS* instead of *DIFS* (used with erroneous frame transmission) while an *ACK* might not be detected. *EIFS* is the longest of *IFS*, but it has the lowest priority after *DIFS*. It can be derived by:
EIFS = *SIFS* $+$ *DIFS* $+$ transmission time (*ACK*-lowest basic rate). Where lowest basic rate *ACK* is the time required to transmit an *ACK* frame at the lowest mandatory PHY data rate. The *EIFS* in IEEE 802.11n devices using OFDM is 160μs.

Contention Window (*CW*): In Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), if a node tries to send any frame, firstly it senses whether the channel is free or not. If it is free, the node transmits; if not, the node waits for a random backoff, and an integer value selected by the node from a Contention Window (*CW*), until it becomes free. If the states of medium transition is changed from busy to free, multi nodes might attempt to occupy the medium for sending data. In this case, collision might occur in transmission, and to minimise this negative impact on the medium, the node waits with a random backoff count and defer for that number of slot times. This is the main intention to minimise any collision once it experiences an idle channel for an appropriate *IFS*, otherwise many waiting nodes might transmit simultaneously. The node needs less time to wait if there is a shorter backoff period, so transmission will be faster, unless there is a collision. The random backoff count is selected as an integer drawn from a uniform distribution that is chosen in [0, *CW*] interval. *CW* = *CWmin* for all nodes if a node

successfully transmits a packet and receives an *ACK*. Otherwise, the node draws another *backoff* and the *CW* increases exponentially, until it reaches *CW* = *CWmax*. Finally, when the backoff reaches 0, the node starts to transmit and the value of *CW* resets to the initial value of *CW* = *CWmin* when the frame is received. In the IEEE 802.11n, if *CWmin* = 15 then *CWmax* = 1023 by augmented the *CWmin* to 2n-1 on each retry.
Backoff Time = (Random () mod (CW+1)) × slot time.
If BackoffTimer = b, where b is a random integer, also *CWmin* ≤b≤ *CWmax*
By using the mean of *CWmin* and if slot time = 9 μs, then we can calculate the μbck as follows:

$$\mu_{bck} = \frac{10^6}{\bar{CW} \times \text{slot time}}$$

Accordingly, if the mean of minimum contention windows *CWmin* = 7.5 then μbck = 14814.81481. Additionally, if p = 0.5 then $p\mu bck$ = 7407.407407. Likewise, when *DIFS* = 34 and *SIFS* = 16, then we can find the $\mu difs$ and $\mu sifs$ as follow:

$$\mu_{difs} = \frac{10^6}{34}, \text{ and } \mu_{eifs} = \frac{10^6}{16}$$

Finally, the receiver will send an *ACK* if it obtains a frame successfully. Similarly, $\mu data$ can be found as shows in the following. For example, the $\mu data$ is equal to 26785.71428 for 700 packet payload size in 150 Mbps data rate:

$$\mu_{data} = \frac{\text{data rate} \times \frac{10^6}{8}}{\text{packet payload size}}$$

Probability of subsequent frames p_1 and p_2: In our study, we have observed the number of frame bursting to be sent by pair(s). Initially, the average frame burst length is denoted by n, where 2 $\leq n \leq$ 10 for one pair and two pairs scenario, however 3 $\leq n \leq$ 10 for three pairs scenario. Also, the probability of subsequent frames to be sent is denoted by p_1, where $0 \leq p_1 \leq 1$. Thus, we can do the following to calculate p_1 and n, where $n \in \{2,3,4,5,7,8,9,10\}$:

$$n = \frac{1}{1-p_1}, \text{ hence } p_1 = \frac{(n-1)}{n}$$

In our experiment study, we demonstrated analytically the effect of frame bursting, that a pair(s) has a variation of frame burst to be sent per time interval, in a specific pair is denoted by p_1. In our scenario(s), if two or more pairs have the same behaviour, then they all have the same probability of subsequent frames. But, if any pair has no variation of frame bursting, then the probability of subsequent frames is fixed, which can be shown as p_2. In two pairs scenario, if both pairs are asymmetric then *P*air_A has p_1 and *P*air_B has p_2 (where n = 2 then p_2 = 0.5) i. e. $p_1 \neq p_2$, but in the three pairs scenario p_2 for the central pair (*P*air_B) is equal to 0.66, where n = 3. Further details are shown in Sections 6.5.2 and 6.5.3.

Table 6.1 Parameter values of IEEE 802.11n.

Attribut	Typical vale in 802.11n
CWmin, and CWmax	15 (mean=7.5), and 1023
Slot time	20{μs} or 9{μs} ms
SIFS	16{μs} ms
DIFS	34{μs} ms
EIFS	160{μs} ms
p , q (q=1-p)	0.5
λoc	100000
μ	200000
μack (for 150 Mbps)	246712.5
$\mu data$ (for 700 packet)	26785.71428
μbck (if CW mean=7.5)	14814.81481
pμbck (if p=0.5)	7407.407407

6.5 Results and discussions.

This section shows the obtained results of our experimental study on the IEEE 802.11n protocol, as we considered 150 Mbps data rates. The specification in our PEPA models with the presented parameters in the previous sections are used to measure the channel utilisation rate and channel throughput, to analyse the performance fairness of this protocol. This section will present the results of the one pair, two pairs and three pairs scenarios in terms of channel access.

6.5.1 Performance results of the one pair scenario (scenario 6.1).

In this scenario, we have studied the enhancements of IEEE 802.11n MAC layer to evaluate the protocol by examining five models (see Section 6.3.1). Results are presented in this section for each model, although, we have concentrated on the first model (that single frame has considered to be sent) and the last model (the more form compact).

Firstly, we investigated the channel utilisation rate and channel throughput in model 1. The behaviour of this model is similar to the model of IEEE 802.11g, although the rates are increased. This model used to understand the behaviour of MAC enhancements in IEEE 802.11n protocol. Figure 6.3 shows that the channel utilisation increases as the packet payload size increases. Since the pair sends more data, it therefore occupies the channel longer. The channel utilisation has obtained by the following formula:

Channel utilisation = (Pr[Medium_F] and (Pair_A2)) + (1-Pr[Medium_F]).

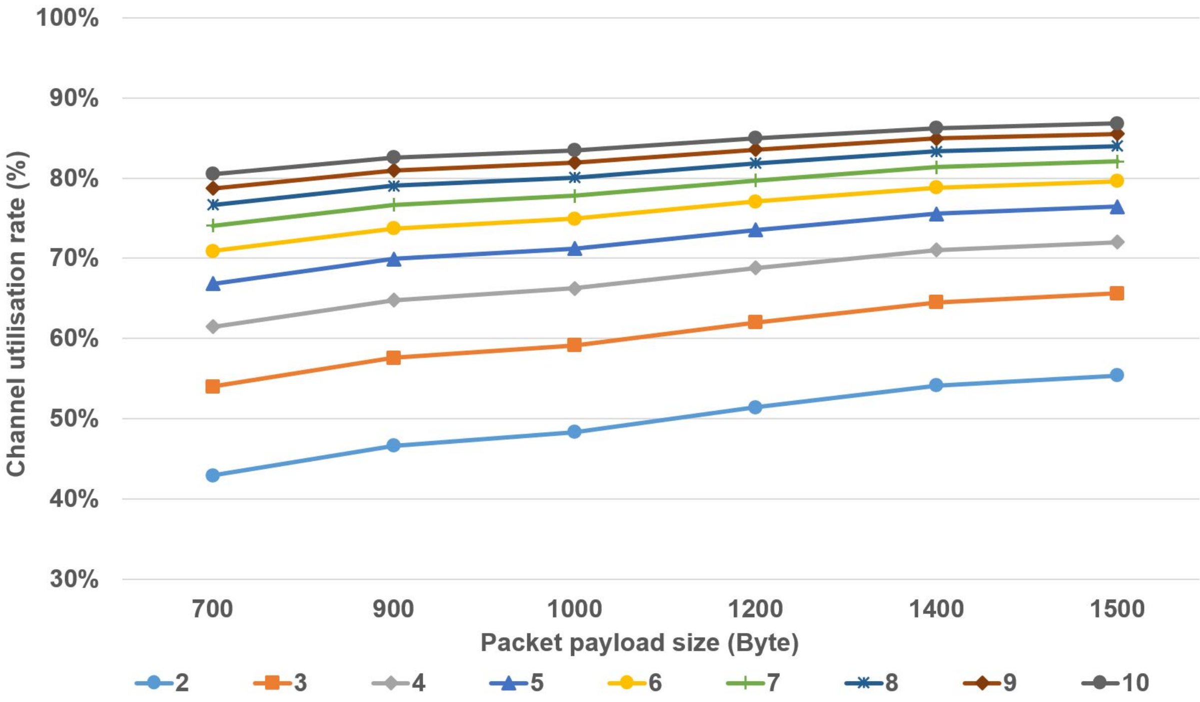


Fig. 6.3 Channel utilisation rate for the one pair scenario in model 1.

Figure 6.4 shows the channel throughput rate in the one pair scenario in model 1. The channel throughput in this model decreases as the packet payload size increases. This pair obtains the highest throughput by sending the shortest packet payload size.

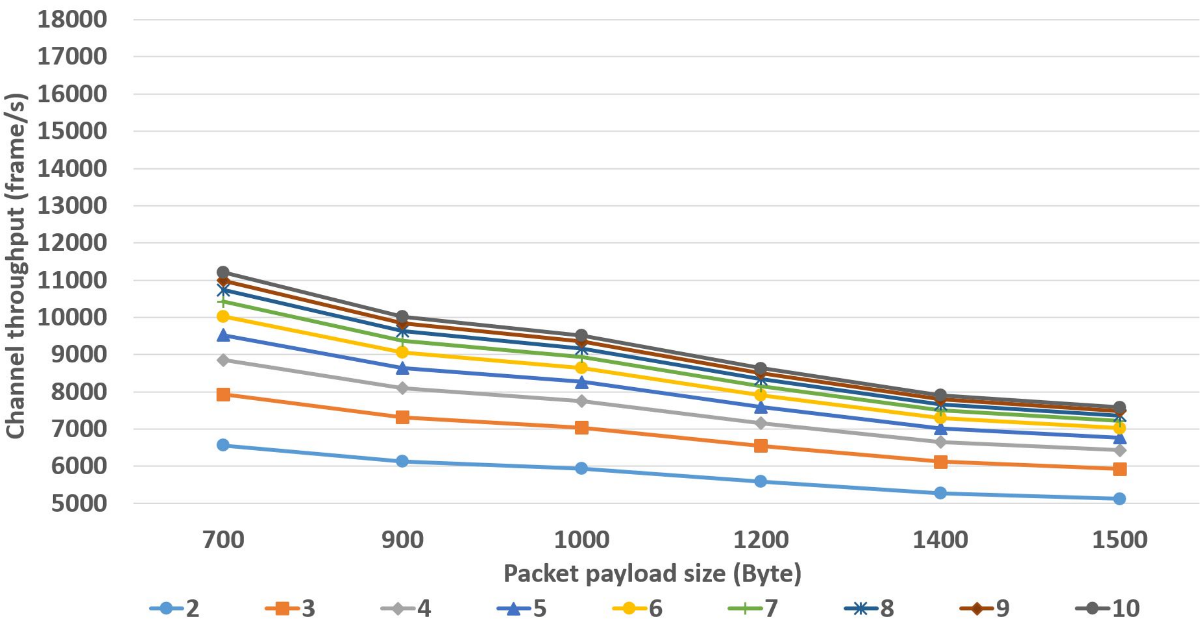


Fig. 6.4 Channel throughput rate for the one pair scenario in model 1.

Figures 6.5 to 6.10 show the channel utilisation rate and channel throughput from models 2 to 4 respectively. These figures show that the channel utilisation rate and channel throughput have similar profile to the channel utilisation and channel throughput in the model 1. In this case, the channel utilisation rate increases, but the channel throughput decreases as the packet payload size increases and the pair transfers more frames. Here, we can understand that the MAC layer improvements significantly impacts these results, as the channel utilisation rate becomes lower and channel throughput becomes higher from model 2 to model 4 in comparison to the channel utilisation and channel throughput in the model 1.

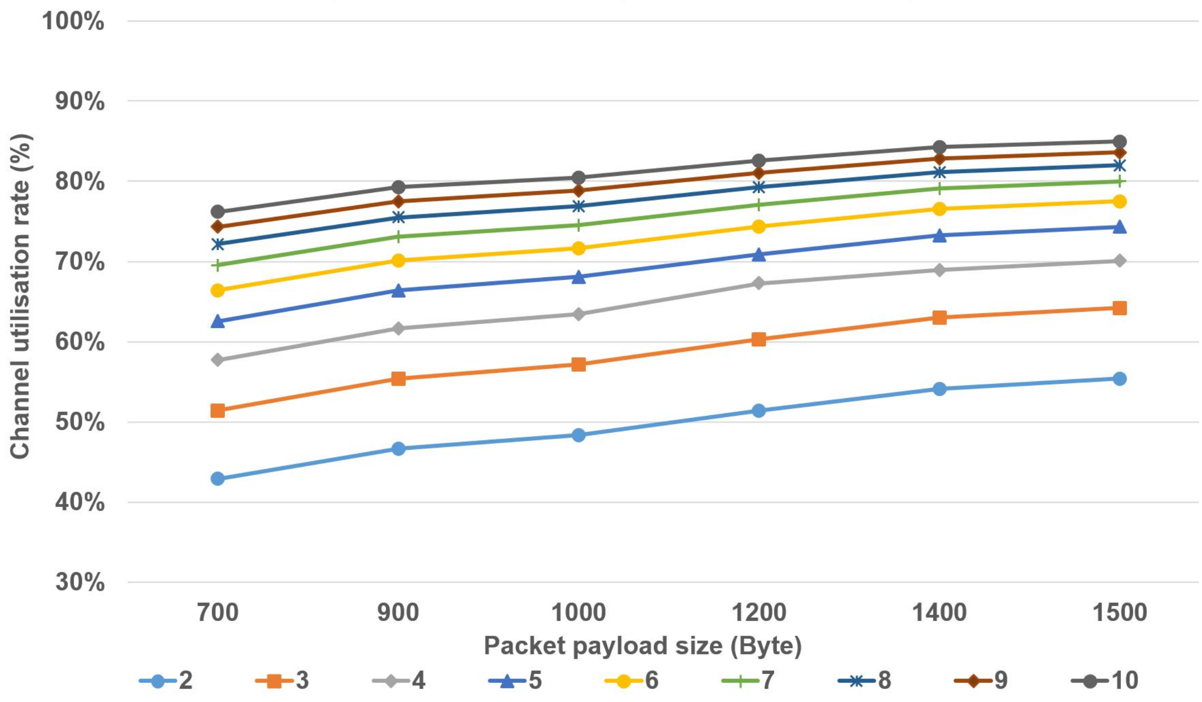


Fig. 6.5 Channel utilisation rate for the one pair scenario in model 2.

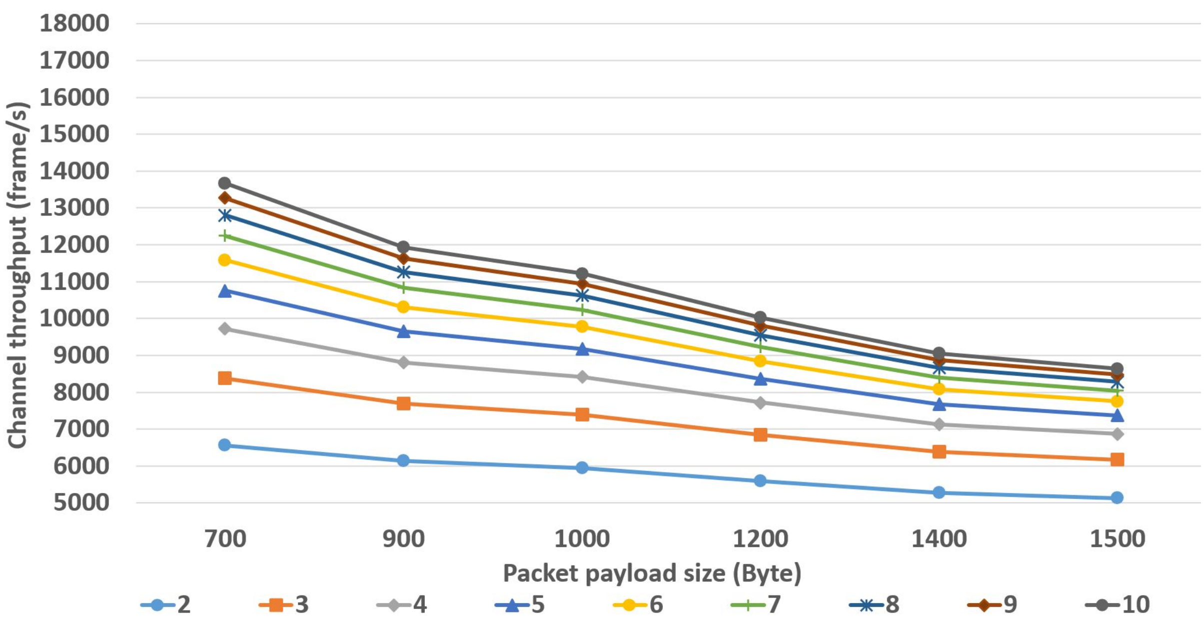


Fig. 6.6 Channel throughput rate in the one pair scenario in model 2.

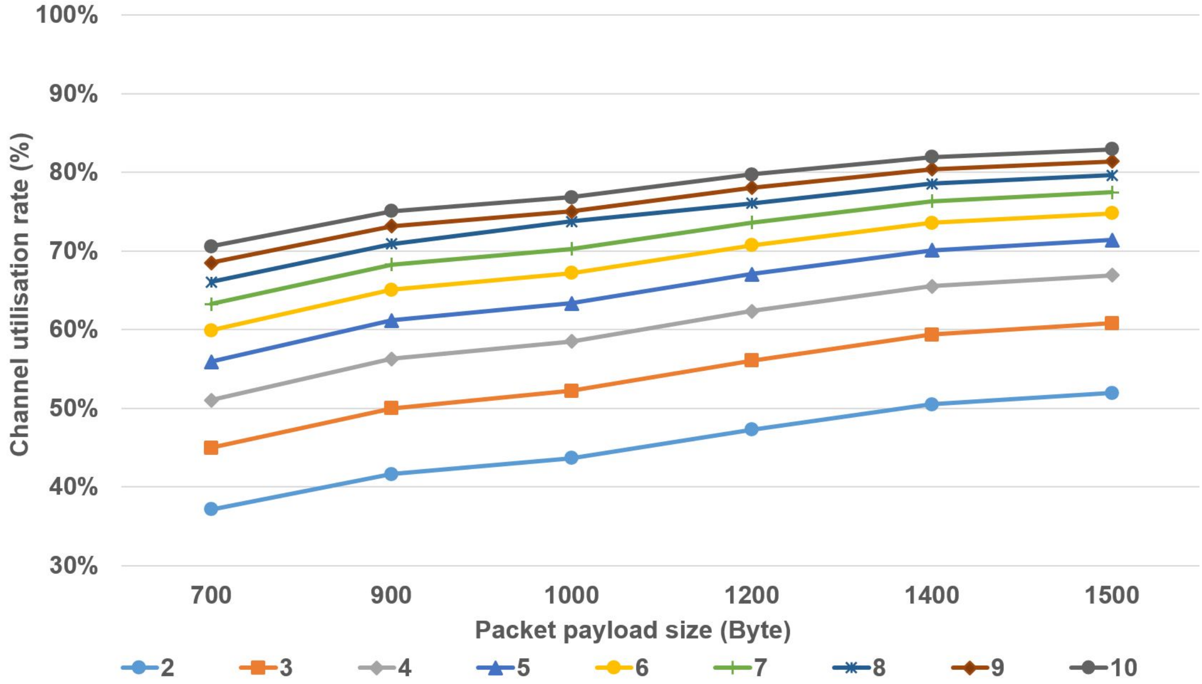


Fig. 6.7 Channel utilisation rate for the one pair scenario in model 3.

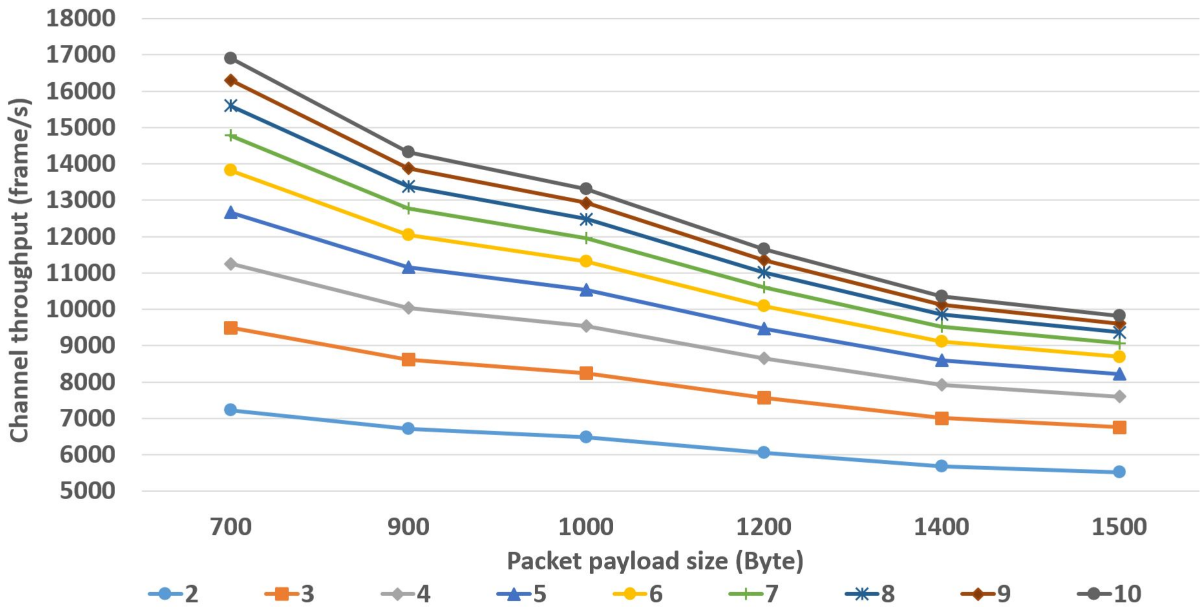


Fig. 6.8 Channel throughput rate for the one pair scenario in model 3.

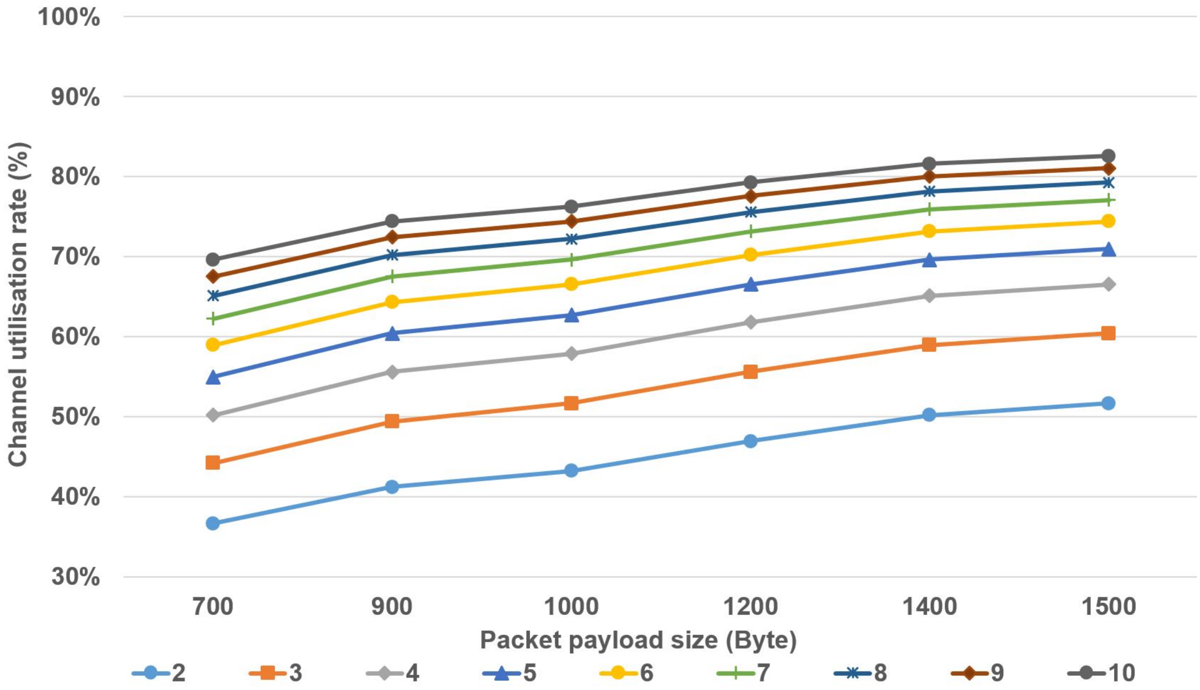


Fig. 6.9 Channel utilisation rate for the one pair scenario in model 4.

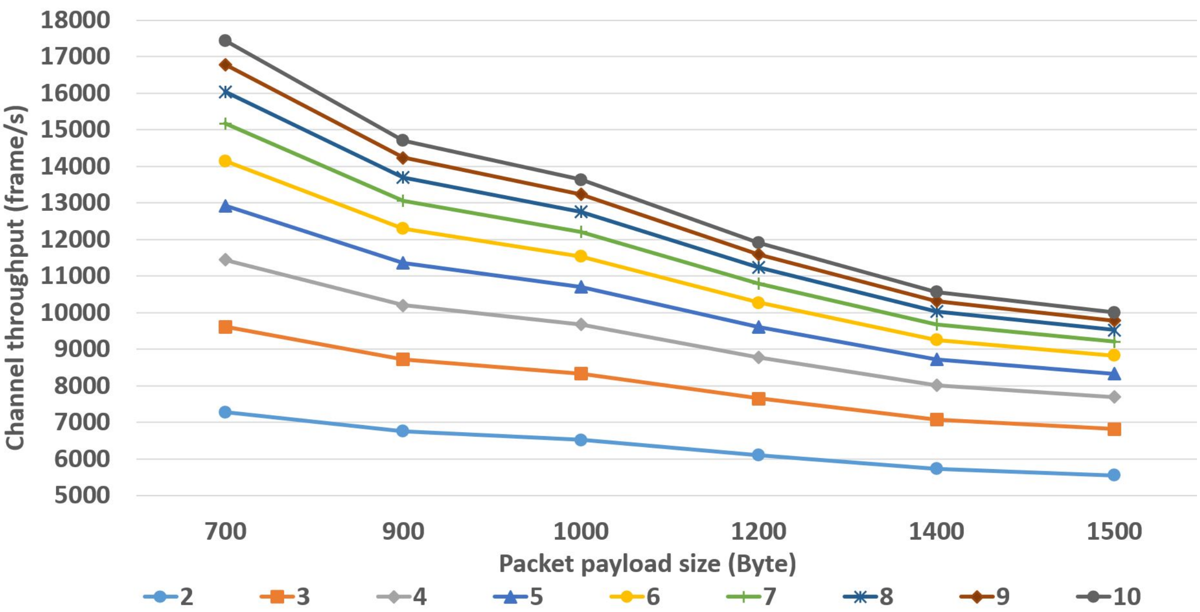


Fig. 6.10 Channel throughput rate for the one pair scenario in model 4.

In model 5 (scenario 6.1) for the one pair scenario, we have considered the frame bursting in every single transmission to be sent with a receiving *BA*. Figure 6.11 shows the channel utilisation in the model 5 for the one pair case. Here, we can understand that lower utilisation can be obtained in this model. Thus, we can address that the node could stay far longer in the transmission to transfer more frame bursting. It consumes less time in waiting to acknowledge that the frames are received. This is because the Block Acknowledgement, *BA*, will acknowledge the entire block frames. Hence, the channel utilisation becomes lower in this model than the channel utilisation in the other models. The impact of MAC layer enhancements can appear if we compare the utilisation in model 5 to the utilisation in model 1.

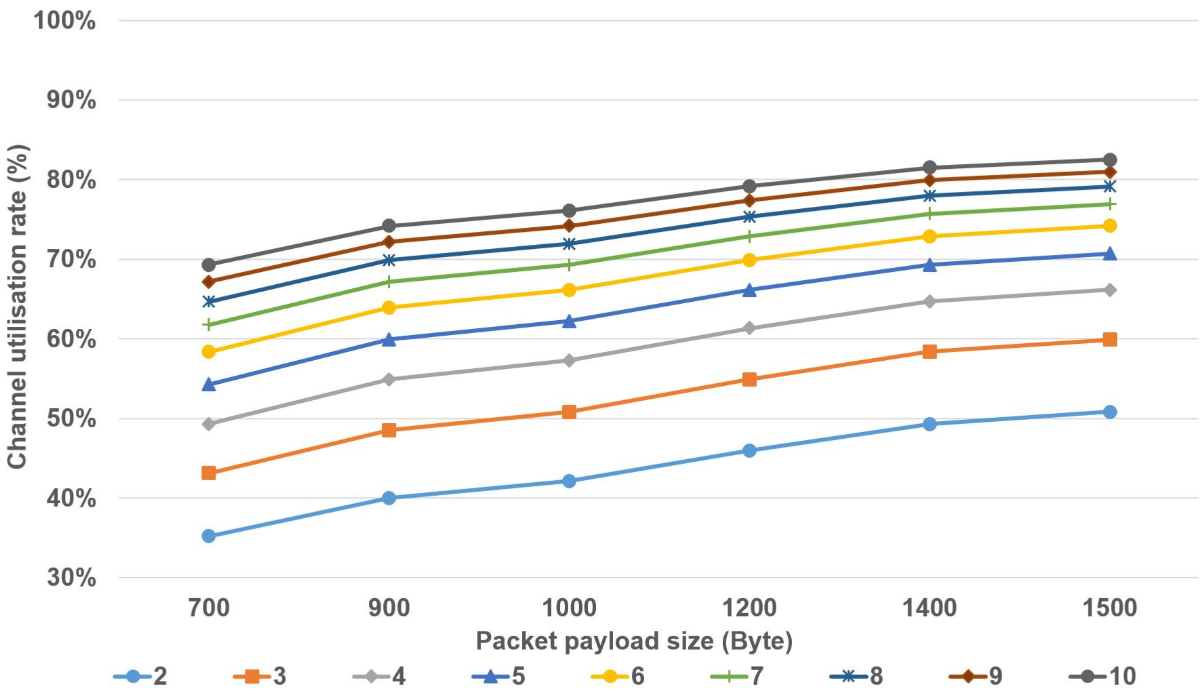


Fig. 6.11 Channel utilisation rate for the one pair scenario in model 5.

Finally, Figure 6.12 shows the channel throughput rate for the one pair scenario in model 5. The channel throughput rate decreases as the packet payload size increases. However, the channel throughput rate in model 5 is significantly higher and more efficient compared to the channel throughput in the previous models, especially if we compare it to the throughput in model 1. This is related to the improvement of the pair structure to concatenate the frame bursting, while the node can transmit a number of frame sequences at the same time (by increasing the average frame burst length n, from 2 to 10, then the higher throughput can be obtained relatively to the packet payload size). Consequently, we can understand that model 5 is more efficient to achieve the higher throughput. The data throughput can be increased, based on this model. This is due to the structure of node; it sends frame bursting and waiting for Block Acknowledgement (*BA*), which *BA* acknowledge entire frame bursting. These improvements of the frame aggregation mechanism and *BA*, have achieved the highest throughput in IEEE 802.11n compared to the previous protocols, such as IEEE 802.11g. Therefore, these enhancements in model 5 are considered in this experiment to examine further scenarios. The next section will show the results of the two pairs scenario.

6.5.2 Performance results of the two pairs scenario (scenario 6.2).

This section shows the results of the two pairs scenario. In this scenario we have examined the effect of the average frame bursting length in two case studies. Firstly, we investigated both pairs that have the same number of frame bursting, where $p_1 = p_2$. Then, we analysed the model if a particular pair has several frame bursting to be sent during transmission, but the second pair `Pair_B` has a fixed number of frame bursting to be sent, i. e. $p_1 \neq p_2$. The results of both case studies present as follow.

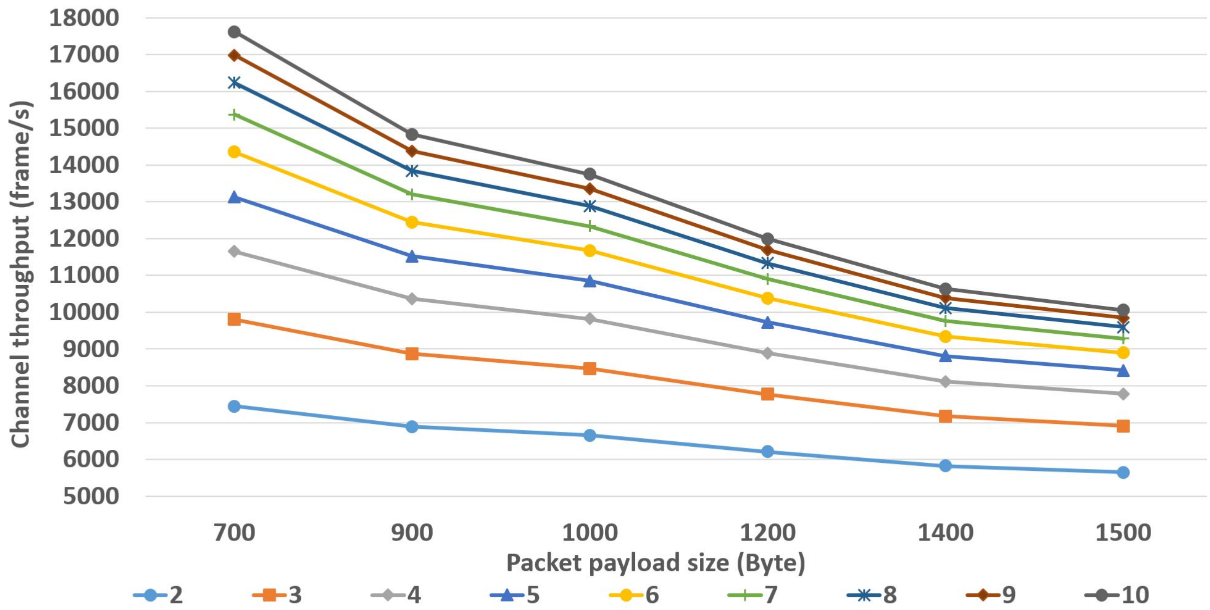


Fig. 6.12 Channel throughput rate for the one pair scenario in model 5.

Figure 6.13 shows the channel utilisation rate for a particular pair (`Pair_A`) in the two pairs scenario, where both pairs are symmetric and can send the same block of frames in transmission, i. e. $p_1 = p_2$. The channel utilisation rate in `Pair_A` increases as the packet payload size increases. When the node sends a large number of frame bursting, it obtains the highest utilisation, therefore the node will occupy the medium for longer. The channel utilisation in the second pair (`Pair_B`) is similar to the channel utilisation in the first pair (`Pair_A`) as they are symmetric and sharing the medium equally.

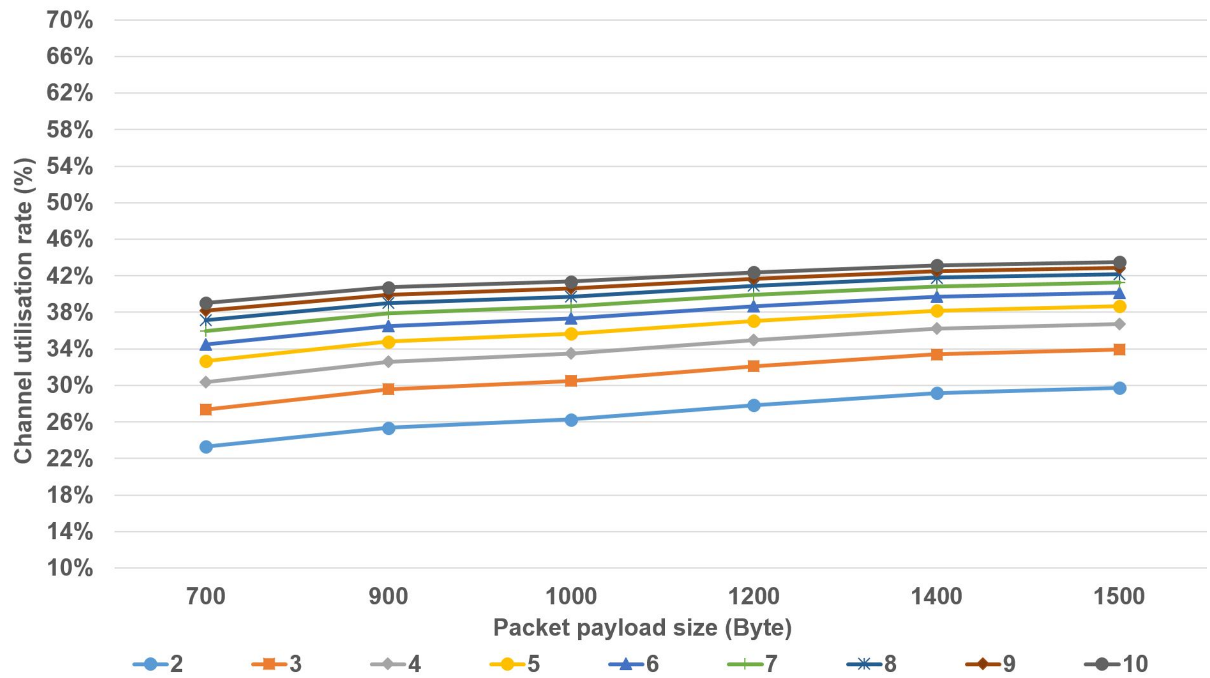


Fig. 6.13 Channel utilisation for the two pairs scenario for pair A/B, where $p_1 = p_2$.

Figure 6.14 shows that the channel throughput rate decreases for a particular pair (such as `Pair_A`) as the packet payload size increases. In this scenario, if the medium is free to be used then both pairs have the same chance to occupy it, as they have the same number of frames to be sent, where $p_1 = p_2$. Also, the channel throughput decreases in each node if they send larger packets with a larger number of frame bursting. Hence, less time is needed to transmit smaller packet payload for smaller block of frames (it is similar in Pair_B).

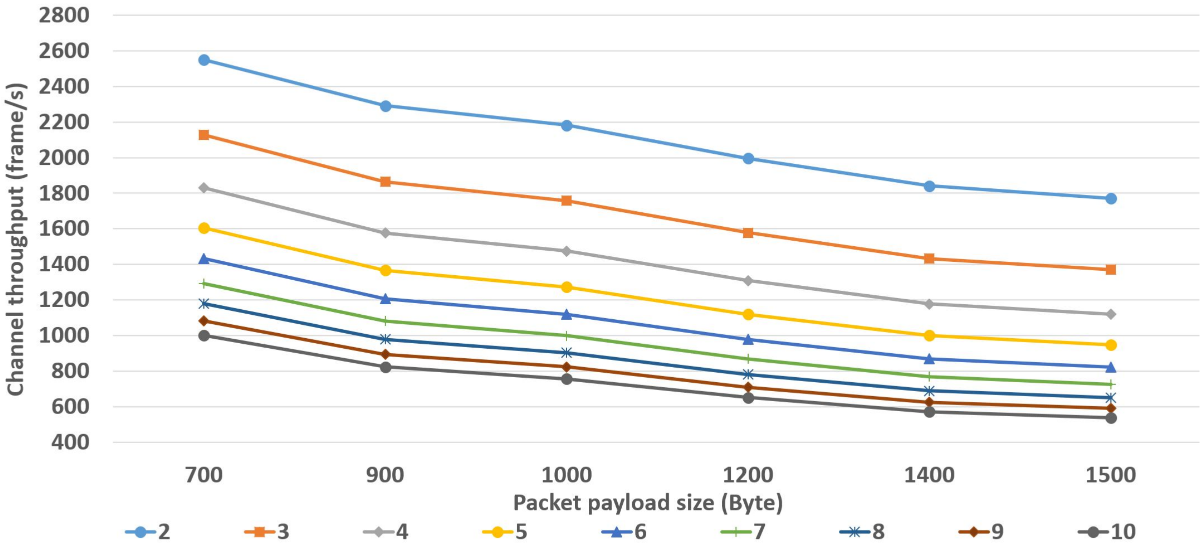


Fig. 6.14 Channel throughput for the two pairs scenario for pairs A/B, where $p_1 = p_2$.

However, in the second case study we analysed the channel utilisation rate, where $p_1 \neq p_2$. Figure 6.15 shows that the channel utilisation rate in the first pair (Pair_A) increases as the packet payload size increases, while this pair sends several frame bursting by increasing the probability of sequence frame bursting, i. e. the medium will be occupied longer by this pair as the average frame burst length n increases from 2 to 10.

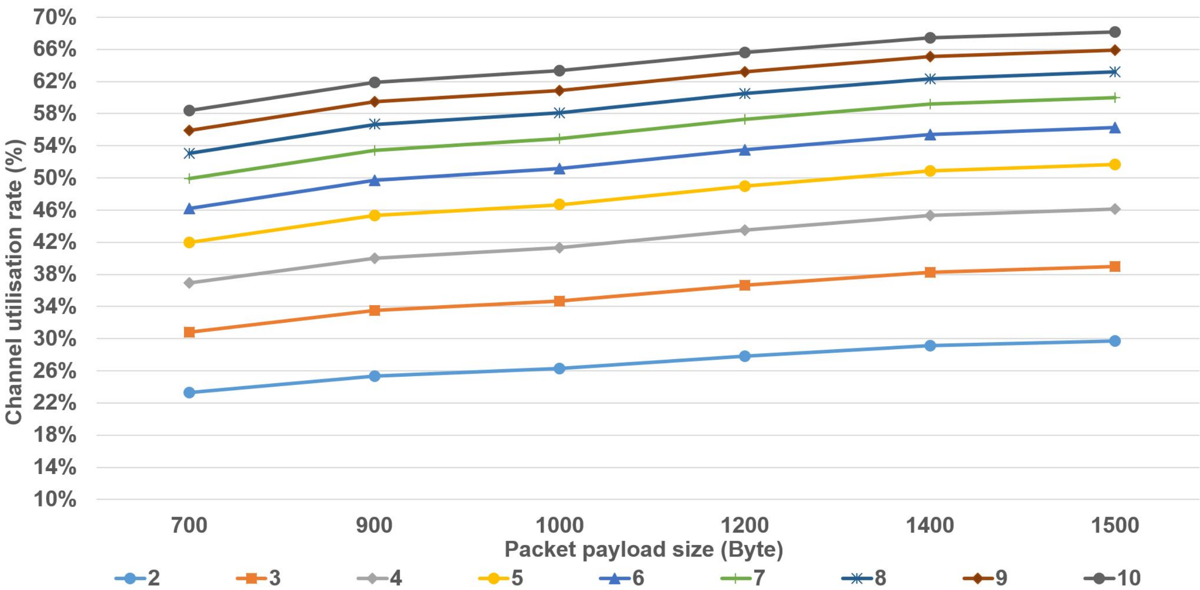


Fig. 6.15 Channel utilisation for the two pairs scenario for pair A, where $p_1 \neq p_2$.

Figure 6.16 shows that the channel utilisation rate in the second pair (Pair_B) increases as the packet payload size increases, where this pair has a fixed frame burst n=2, while in Pair_A n increases from 2 to 10. However, if we compare the channel utilisation in this pair (Pair_B) to the channel utilisation in the first pair (`Pair_A`), then we can understand that the utilisation in `Pair_B` is significantly lower than the utilisation in the `Pair_A` as the number of frame bursting to be sent is increased in `Pair_A`. When the average frame burst length n increases from 2 to 10 in `Pair_A`, `Pair_B` will be completely prevented from transmitting, because the `Pair_A` can send larger frame bursting and uses the medium longer, while `Pair_B` has less chance to use the medium. This increase of the average frame burst length n in `Pair_A` affect the channel utilisation in `Pair_B`, that decreases the channel utilisation in `Pair_B` rather than increasing it.

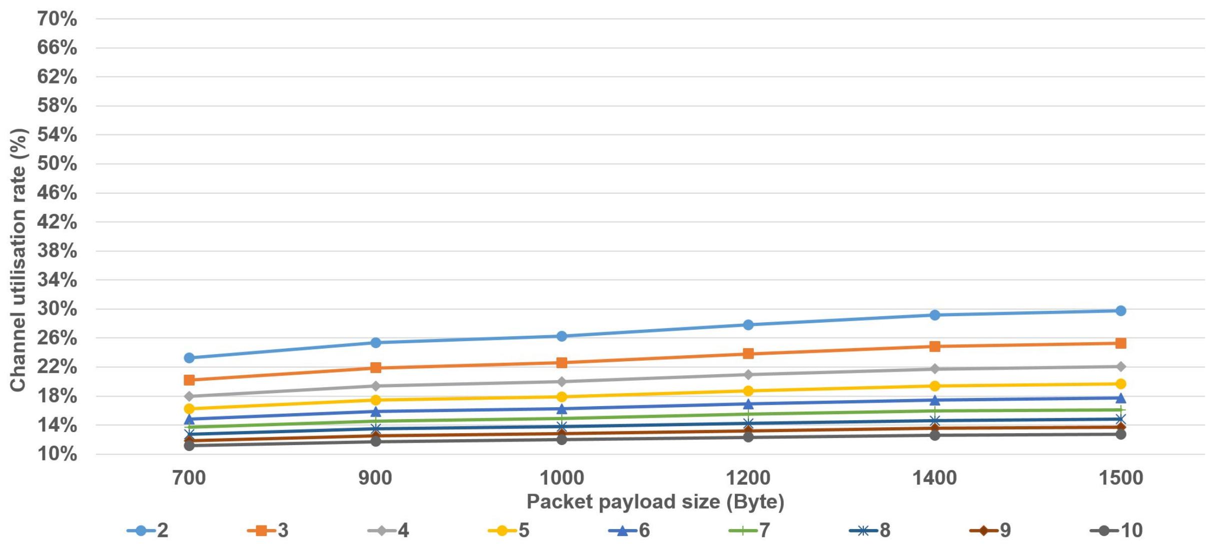


Fig. 6.16 Channel utilisation for the two pairs scenario for pair B, where $p_1 \neq p_2$.

In second case study, the transmission of larger frames in `Pair_A` and fixed frames in `Pair_B` have pros and cons. The channel throughput rate decreases for both pairs as the package payload size increases, as shown the channel throughput in `Pair_A` in Figure 6.17. But, when the second pair (`Pair_B`) has no variation of frame bursting to be sent (it sends two frames in per circle of transmission) then the channel throughput decreases more when the average frame burst length n is larger in `Pair_A`, as shown in Figure 6.18. In this case, `Pair_A` will stay longer in the medium and `Pair_B` has less chance to access the medium (`Pair_A` will send frames for much longer than `Pair_B`, and `Pair_B` waits for much longer in the queue than `Pair_A`). `Pair_A` will gain more advantages as it transmits more frames than `Pair_B`. This reduction in `Pair_B` has affected the efficient usage of the wireless medium in this study for such scenarios and in terms of channel access and sending a block frames approaches.

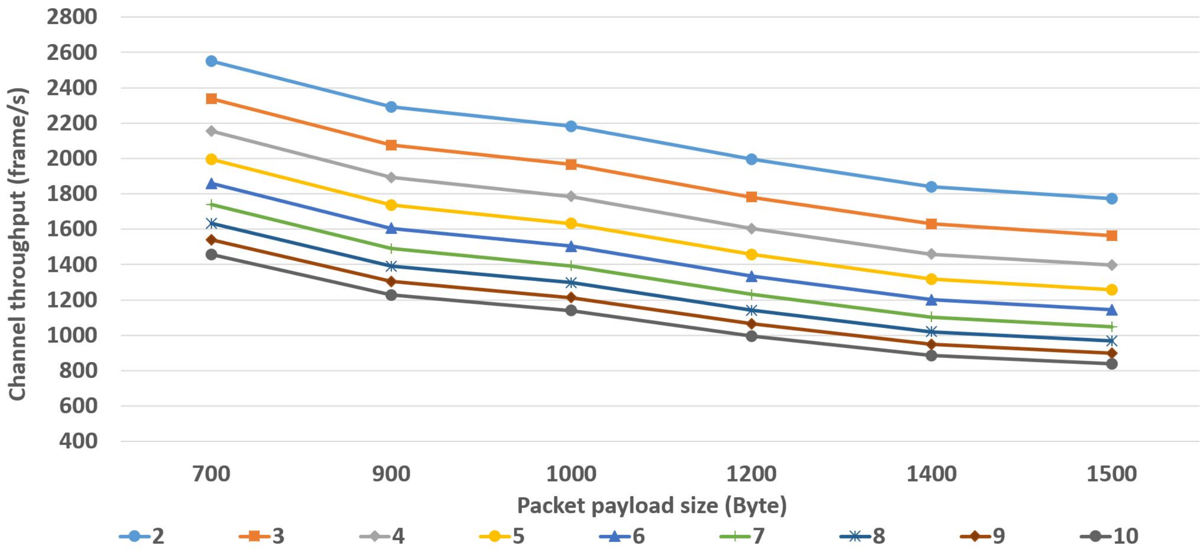


Fig. 6.17 Channel throughput rate in the two pairs scenario for pair A, where $p_1 \neq p_2$.

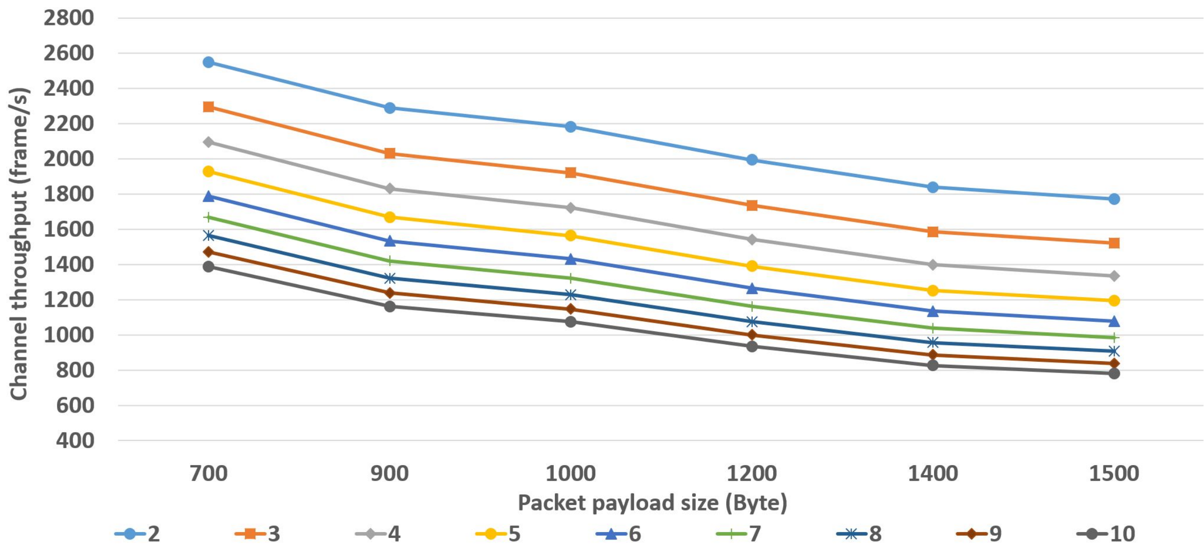


Fig. 6.18 Channel throughput rate in the two pairs scenario for pair B, where $p_1 \neq p_2$.

6.5.3 Performance results of the three pairs scenario (scenario 6.3).

This section shows the results of the three pairs scenario, as we initially considered this scenario for the purpose of reducing the unfairness in a particular pair (the inner pair) and investigate the outer pairs, while many unfairness has been reported in our previous chapters for IEEE 802.11b and 802.11g. We modelled the two case studies in this scenario as shown in Section 6.3.3. Due to these case studies, we investigated how the performance of IEEE 802.11n protocol changes by concentrating on the frame bursting to improve the efficiency of the protocol and channel throughput. The results of each case shows as follow.

All pairs in the three pairs scenario compete to use the medium. If the medium is free to be used, then any pair can attempt to transmit. If the inner pair uses the medium, then both outer pairs will wait until the medium becomes idle. But, if the medium is being in use by one of the outer pairs, only the other outer pair can transmit and the inner pair will be penalised.

In the first case study in this scenario, once all pairs have the same number of frame bursting to be sent at the same time, where $p_1 = p_2$, then the channel utilisation of outer pairs increases as the packet payload size increases. Because both outer pairs cannot hear each other, they have a higher chance to use the medium to send more frames. Hence, the channel utilisation in the outer pairs will be higher as the average length of frame bursting n becomes higher, in this scenario the value of n assumed to be 3 as an initial value, see Figure 6.19.

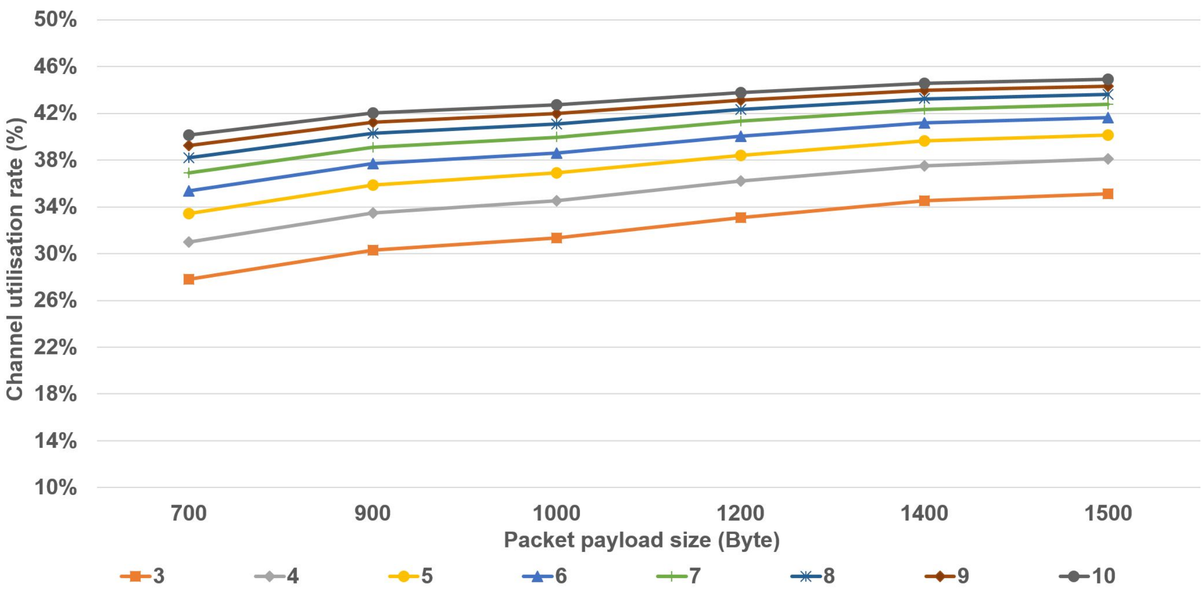


Fig. 6.19 Channel utilisation for the outer pairs in the three pair scenario, where $p_1 = p_2$.

The channel utilisation in the inner pair is different to the channel utilisation in the outer pairs. In the first case study, as the average frame burst length n increases from 3 to 10 and the package payload size increases as well, the inner pair will have less opportunity to access the medium. In this circumstance the channel utilisation in the inner pair is completely congested. Hence, when the frame intensity becomes less (the average frame burst length n decreases) then there is more opportunity for the inner pair to access the medium. In this case the inner pair might be affected less and the proportional for using the medium will be greater, see Figure 6.20.

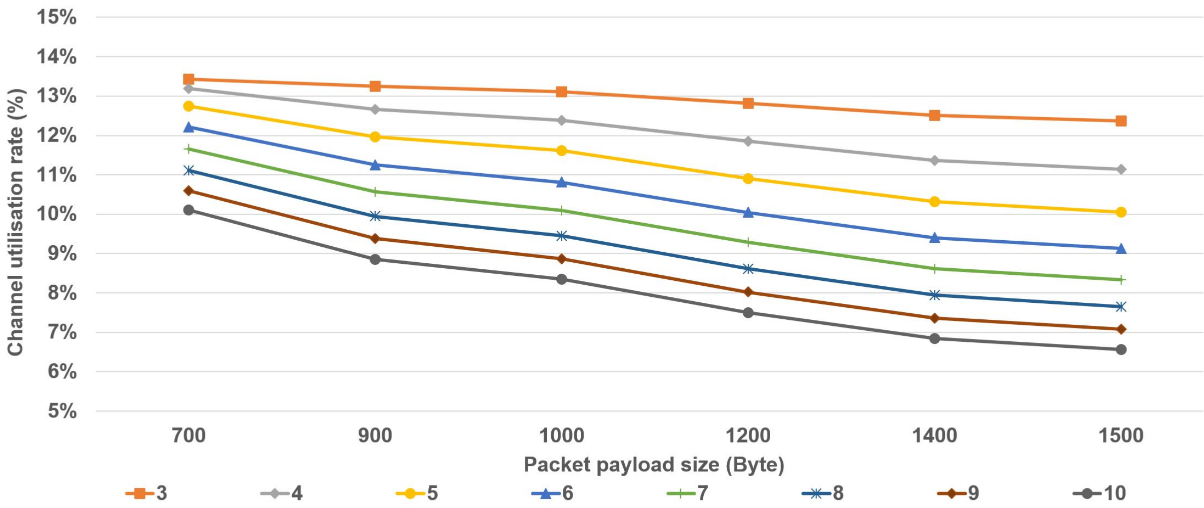


Fig. 6.20 Channel utilisation for the inner pair in the three pair scenario, where $p_1 = p_2$.

Likewise, in our first case study in this scenario, we also examined the channel throughput. It decreases in all pairs as the packet payload size increases, because of the channel occupancy time. The outer pairs have higher throughput relative to packet payload size with the number of frame bursting. When any outer pairs are sending larger packets with a larger average frame burst length n, the throughput decreases as it sends more and sends larger frame bursting, see Figure 6.21. The smaller frames occupy less time in this channel. However, the channel throughput of the inner pair decreases more as the packet payload size increases compared to the throughput of the outer pairs, see Figure 6.22. Hence, the inner pair can hear both outer pairs and will be blocked more the outer pairs. Therefore, both outer pairs have more chance to occupy the medium (with the longer sequence of frames in the inner pair, which we can understand that the worst throughput will obtain). This scenario is unfair in terms of channel throughput, as it is not significant for all pairs. Thus, the inner pair is out computed by both outer pairs and it is unfairly disadvantaged but the outer pairs are fairly advantaged. Hence, we have studied more details on the inner pair in our second case study, as we have increased the number of frame bursting to be sent by the inner pair, in order to increase the fairness issue in this scenario.

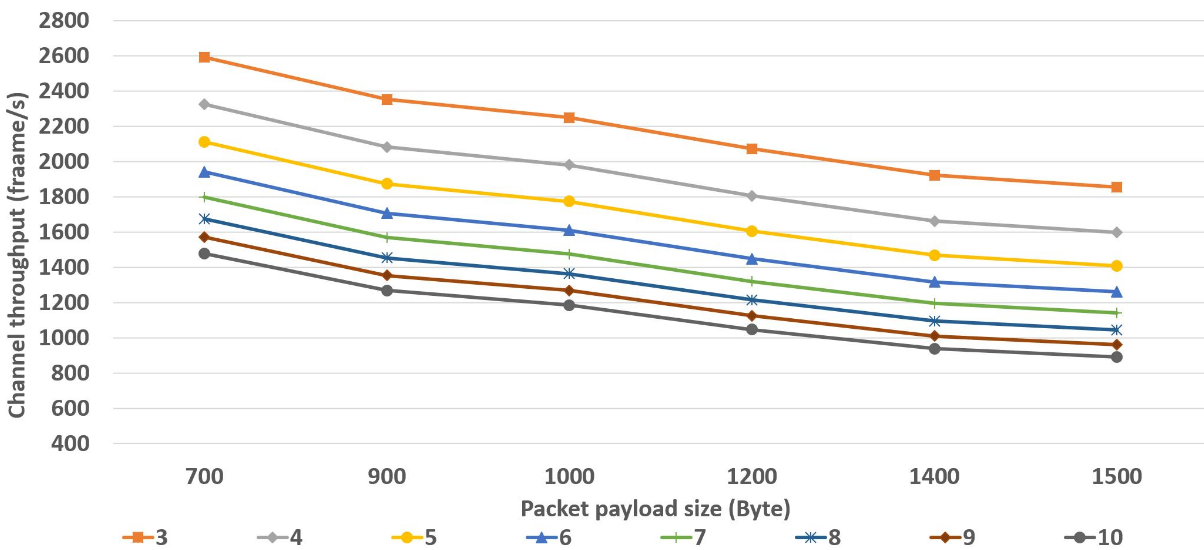


Fig. 6.21 Channel throughput for the outer pairs in the three pair scenario, where $p_1 = p_2$.

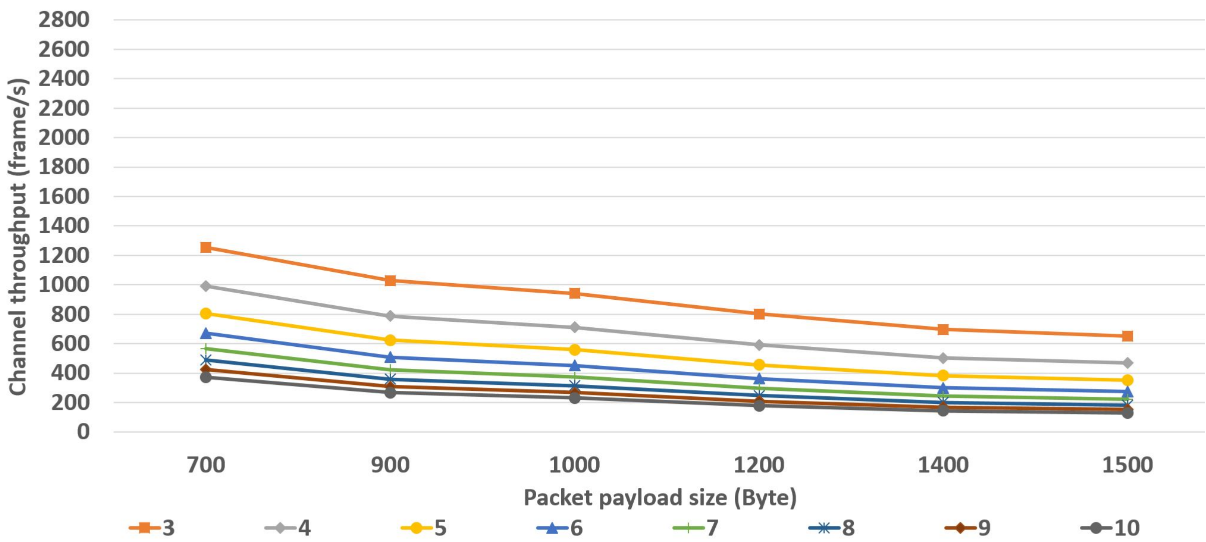


Fig. 6.22 Channel throughput for the inner pair in the three pair scenario, where $p_1 = p_2$.

In the second case study in the three pairs scenario, we have studied consistency of frame bursting length of the inner pair over the outer pairs, where $p_1 \neq p_2$. In this case study, the inner pair has different average frame burst length n to be sent as it increases from 3 to 10, while the outer pairs have only one frame bursting length, where n = 3. In this case, the channel utilisation rate in the outer pairs increases as the packet payload size increases, see Figure 6.23. However, the channel utilisation rate in the outer pairs will decrease when the inner pair is transmitting a large frame bursting. Therefore, the channel utilisation rate in the inner pair will be much higher as it increases if this pair will send larger frame bursting, see Figure 6.24. Hence, the inner pair can occupy the medium longer by sending larger frame bursting compared to the previous first case study. Here, we can understand that the channel utilisation will be higher if the inner pair is having more frame bursting and larger frame bursting length in transmission.

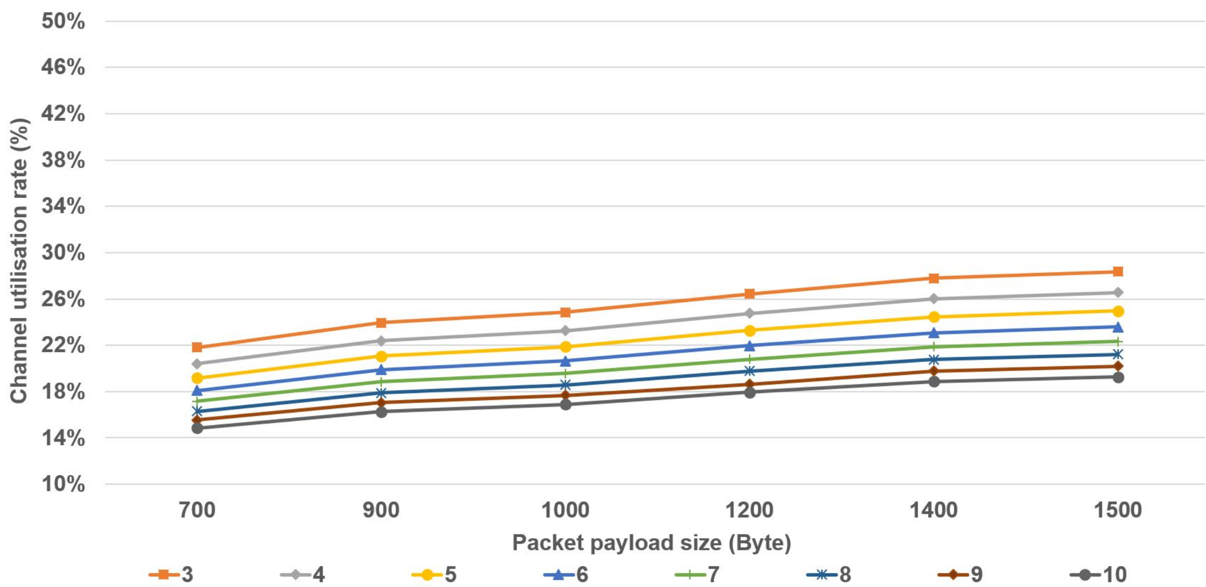


Fig. 6.23 Channel utilisation for the outer pairs in the three pair scenario, where $p_1 \neq p_2$.

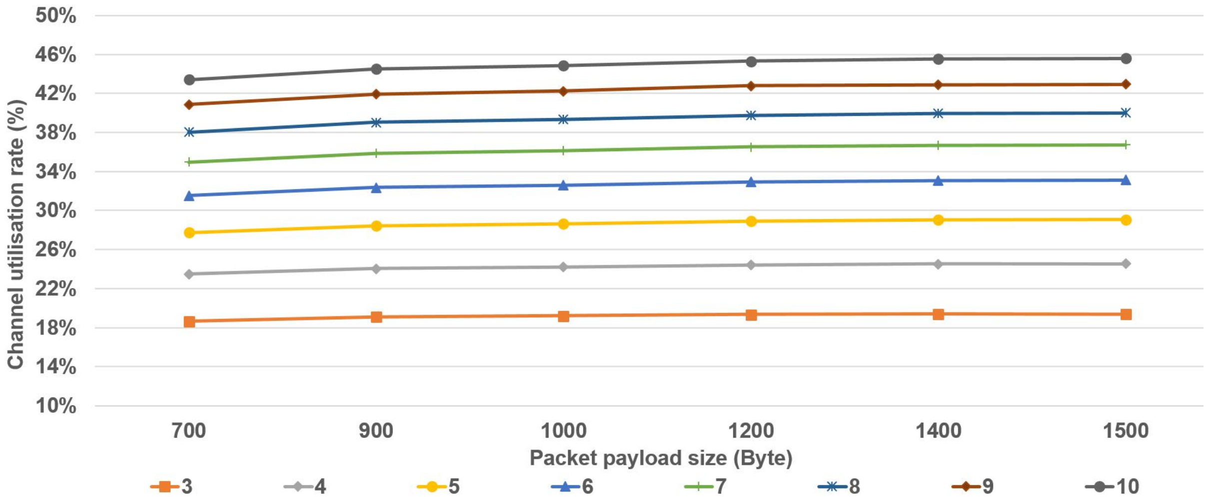


Fig. 6.24 Channel utilisation for the inner pair in the three pair scenario, where $p_1 \neq p_2$.

Moreover, in this case study the channel throughput will decrease in both inner pairs and outer pair, when we will increase the packet payload size. The channel throughput in both outer pairs and inner pair are presented in Figures 6.25 and 6.26 respectively. Also, in this case study, we have observed that the channel throughput in the inner pair is much higher than the channel throughput in same pair, if we will compare it to the previous case study. Hence, we can understand that the inner pair in our second case study has different frame bursting in transmission, which it will stay longer in a medium for transmitting its frame. Additionally, the second case study addressed very low unfairness in terms of channel throughput and performance fairness, if we will compare it to the previous case study. Finally, from these case studies we can understand that we will profitably gain less unfairness if the inner pair will send longer frame bursting in transmission.

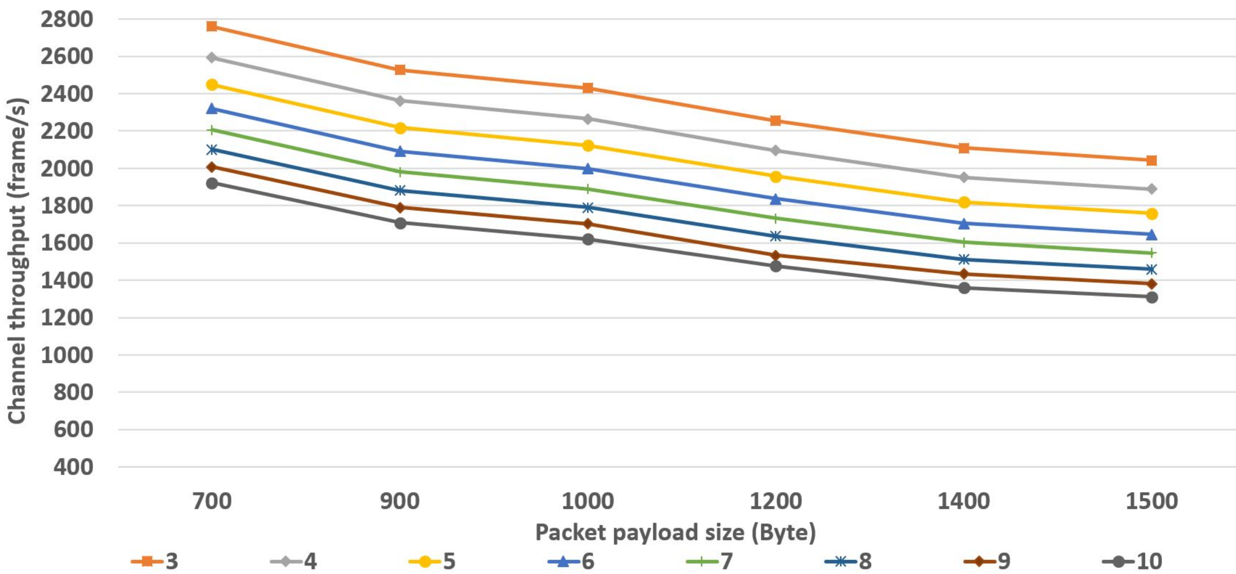


Fig. 6.25 Channel throughput for the outer pairs in the three pair scenario, where $p_1 \neq p_2$.

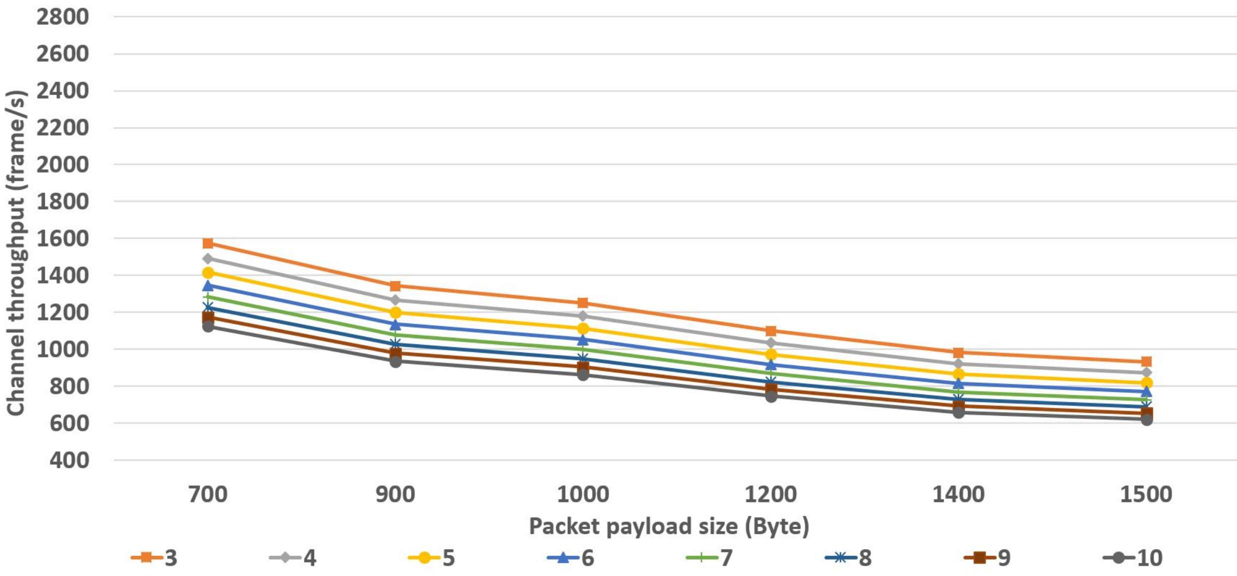


Fig. 6.26 Channel throughput for the inner pair in the three pair scenario, where $p_1 \neq p_2$.

6.6 Sensitivity to geometric assumption, when the pair has exact frames.

In our previous case study, all models were considered of the average number of frames to be transmitted. But, in this section we examined a model for two pairs scenario, when each pair has an exact number of frames to be sent. In this case, we wanted to study how much the performance will change from the average frames to exact frames, which are sent by the pairs. Thus, we created a model to study the number of exact frames to be transmitted. In our new model, we examined 2,4,6,8 or 10 as an exact frames to be sent, which it denoted by n. Then, we have compared the obtained results of our exact model (called the deterministic model) to our previous results (called the geometric model).

The following specification shows `Pair_A` in our new model (deterministic model). Here, we can see that this pair has two exact frames to be sent. Generally, the behavior of the pair and the medium in this model are similar to our previous model in the two pairs case (scenario 6.2). But, in our new model when state Pair_A1 has a choice to Pair_A2, then Pair_A2 starts to transmit its first message at the rate of μ_{data1} to Pair_A2b, or stays in a queue at Pair_A5.

Pair_A2b will send its second frame with the same μ_{data1} rate to Pair_A3, or stays in a queue in Pair_A5. The action of sending frame will be repeated depends on the number of exact frames that we want to be sent it. In this scenario, the same process will be applied to the second pair (`Pair_B`) for transmitting an exact frames.

Note:- Pair_A2b has added, which is used to transmit the second exact frame. If we need to transmit three exact frames, then we need to add another new state similar to Pair_A2b to transmit the third exact frame (which a new state can be called Pair_A2c). Thus, with each increase in frame frequency, we need to increase the state frequency, to transmit exact frame content. For example, if we have exactly 10 frames to be sent then we need to have 10 states of Pair_A2 for these 10 separate frames. The specification of component `Pair_A` is as follows:

$$
\begin{aligned}
Pair\_A &\stackrel{def}{=} (draw\_backoff, r).Pair\_A0 \\
Pair\_A0 &\stackrel{def}{=} (count\_difsA, \mu difs).Pair\_A1 + (queueA, \top).Pair\_A5 \\
Pair\_A1 &\stackrel{def}{=} (count\_backoffA, p\mu_{bck}).Pair\_A1 + (end\_backoffA, q\mu_{bck}).Pair\_A2 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A2 &\stackrel{def}{=} (transmitA, \mu_{data}).Pair\_A2b + (queueA, \top).Pair\_A5 \\
Pair\_A2b &\stackrel{def}{=} (transmitA, \mu_{data}).Pair\_A3 + (queueA, \top).Pair\_A5 \\
Pair\_A3 &\stackrel{def}{=} (count\_sifs, \mu_{sifs}).Pair\_A6 \\
Pair\_A4 &\stackrel{def}{=} (count\_difsA, \mu_{difs}).Pair\_A1 + (count\_eifsA, \mu_{eifs}).Pair\_A1 \\
&+ (queueA, \top).Pair\_A5 \\
Pair\_A5 &\stackrel{def}{=} (wait, \mu_{data}).Pair\_A4 \\
Pair\_A6 &\stackrel{def}{=} (BA\_A, \mu_{ack}).Pair\_A
\end{aligned}
$$

We investigated the fairness metric of channel utilisation in 2 pairs scenario, using the above model. Figures 6.27 and 6.28 will illustrate the relative accuracy of geometric approximation of utilisation and throughput for 150 Mbps speed respectively. The following equations were used to find the relative accuracy of geometric approximation of channel utilisation and throughput:

$$
\text{Relative accuracy of utilisation} = \left| \frac{\text{Utilisation of geometric-Utilisation of deterministic}}{\text{Utilisation of geometric}} \right|
$$

$$
\text{Relative accuracy of throughput} = \left| \frac{\text{Throughput of geometric-Throughput of deterministic}}{\text{Throughput of geometric}} \right|
$$

The relative accuracy of geometric approximation of channel utilisation and throughput will increase, when we increase the packet payload size and n=2. But, by increasing the frame burst length "n" from 2 to 10, then the relative accuracy of geometric approximation of channel utilisation and throughput will decrease, by increasing the packet payload size.

From Figures 6.27 and 6.28, we can understand that the geometric model is more significant approximation as a model. The geometric model would be easy for modelling, as we can have one model for any burst size (we only need to change one parameter in a model, rather than the entire model). However, in a deterministic model if we have 10 phases, then we need to expand and add many extra states, to illustrate the effects of a large burst size.

The more phases we have in a burst, the more accurate in geometric model we can obtain, compared to deterministic model. In this experimental study, we can understand if the model have few phases (n=2) then the results will present small changes, which is less than 2%. But, large phases in a model will show an extremely small changes, as these figures shows if n=10, then the utilisation and throughput will be less than 0.025%, when packet payload size is 700.

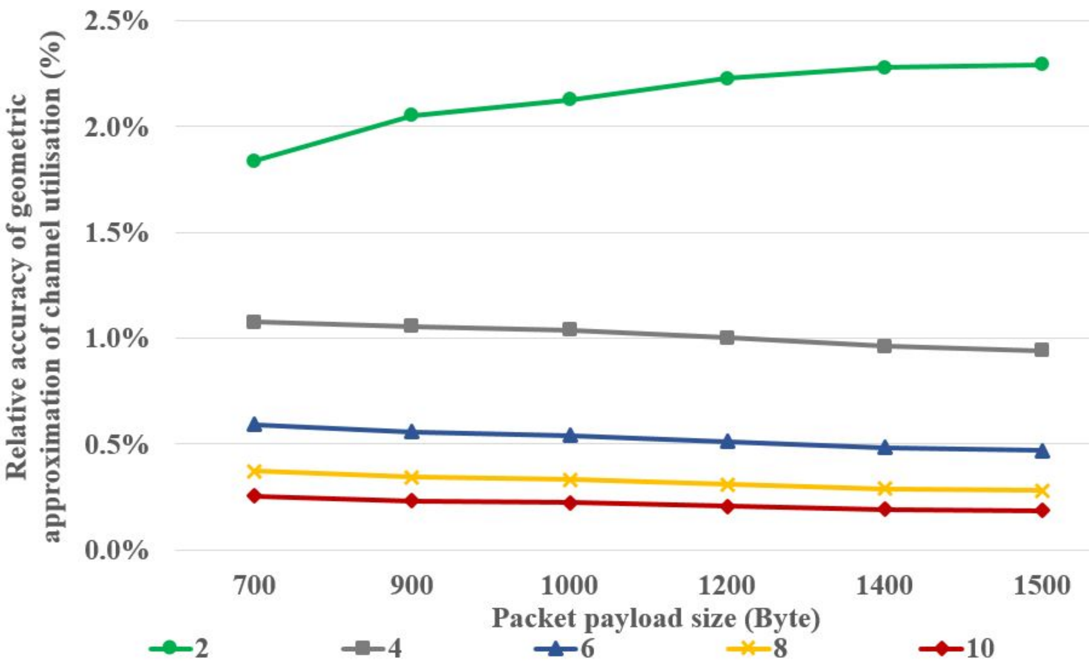


Fig. 6.27 Relative accuracy of geometric approximation of utilisation the exact frames.

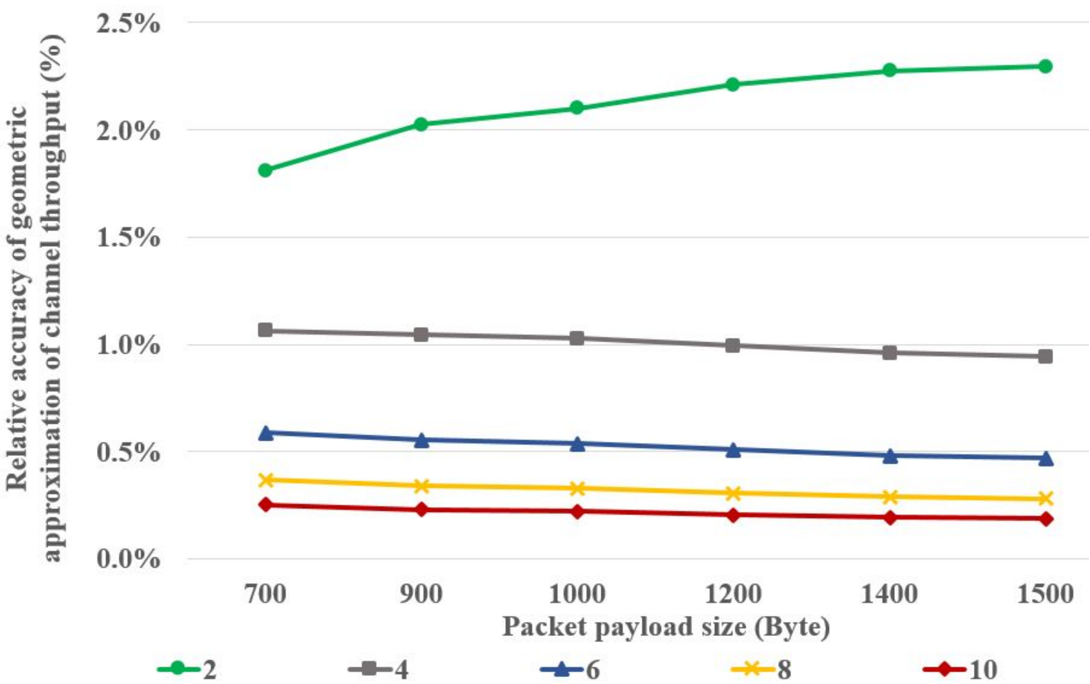


Fig. 6.28 Relative accuracy of geometric approximation of throughput for exact frames.

6.7 Chapter summary.

This chapter presented an analytical model based on IEEE 802.11n MAC layer enhancements using PEPA for the one pair, two pairs and three pairs scenarios. We modelled five models for the one pair scenario based on MAC enhancements in IEEE 802.11n protocol. In model 1, we presented that only a single frame can be sent and a single Acknowledgement (*ACK*) can be received. However, models 2 to 5 presented the evolution of frame bursting based on this enhancements. As we observed higher throughput obtained in model 5, then a pair sends multiple frames without repeated waiting and uses a single *BA*, to acknowledge the entire frames.

The two pairs scenario explored the effect of frame bursting length in two case studies. The first case study presented that both pairs have the same number of frame bursting during transmission (if any pair sends the largest number of frame bursting, then it occupies the medium for longer). But, the second case presented the model that a particular pair has several frame bursting, while the second pair only has a fixed number of frame bursting to be sent. In this case, Pair A sends more frames than Pair B, and Pair B waits for longer in the queue than Pair A, also pair A gained the benefit as it transmitted more frames than Pair B. The efficient usage of the medium affected by Pair B, and this pair raised more drawback in terms of channel access.

In the three pairs scenario, the inner pair penalised by outer pairs as it monitors the medium for longer, and has less chance to occupy the medium compared to the outers. Hence, we observed unfairness between the nodes. This scenario shown that the longer frame bursts increased the more unfairness. Our results presented that if all pairs have the same average frame burst length n simultaneously, then the inner pair transmits less, while the outer pairs will occupy the channel for longer. This eventually limits the inner pair to transmit that increases the unfairness. However, the outer pairs can be restricted to send short frame bursts, that gives the inner pair more freedom to transmit longer frame bursts and this will increase the overall fairness of the system. Hence, we can utilise the length of frame bursts to promote fairness in a network. Finally, we investigated the sensitivity to geometric assumption in the two pairs scenario, when both pairs have exact frames to be transmitted. From this study, we illustrated that the geometric model does not make a significant difference in results compared to deterministic model. The geometric model would still be accurate in terms of results.

The next chapter will present the thesis conclusion and future work. It will summarise the main implications of previous chapters in brief and provide recommendation for future research.

Chapter 7

Conclusion and Future work

This chapter will show, the conclusion of our research work that presented in this thesis. It concludes the investigating on performance modelling of fairness in IEEE 802.11b, 802.11g and 802.11n protocols, used the stochastic process algebra PEPA. This chapter will discuss the strengths of the approaches in the relation to the research aims, hypothesis improvement and the obtained results in all chapters. It presents the outline of the thesis contributions and several interesting topics in the future with motivating a number of ongoing research efforts. The main results are summarised to address the fairness of IEEE 802.11, which improved our understand of the effect on these protocols.

7.1 Summary of the research.

WLANs have remarkably increased with the dramatic necessity of communication capabilities. IEEE 802.11 family as an ubiquitous deployment based WLANs have been widely used in many hotspots, it makes WLAN an attractive method to support broadband wireless services. The legacy protocol has evolved to produce a new standard. The newer standard provides higher speed, with different ranges that can be compatible with the older standard. Many users can obtain network resources via the wide growing of WLAN in the globe without intrusive wiring. IEEE organisation [1] have been developing WLAN standards for many years. The 802.11 on MAC is specified to two main mechanisms which are, DCF and PCF. This research employed DCF based on CSMA/CA, as we examined the 802.11 on the efficiency and performance of different models in PEPA. Particularly, we adopted a number of approaches and contributions to analyse fairness issue on IEEE 802.11b/g/n. We investigated the performance between different communicating pairs of nodes used 802.11 within a restricted network topology.

Chapter 2 presented an overview of previous studies with the relevant literature review about this research. An introduction and related work are provided in this chapter, with a cross discipline review of the diverse problem area to the IEEE 802.11 protocols and PEPA modelling language.

The hidden node problem on IEEE 802.11b/g explored in Chapter 3, as another topological effects of performance in WLAN systems. Here, no signal detected before transmission and if the other node is already transmitting, collision occurs. If collision is detected, the node enters its backoff process. Each transmitting node could not sense the other, therefore collisions are inevitable and consequently bandwidth is wasted and the performance is impacted. We described that faster transmission provides better maximum throughput in less time with fewer collisions. The slower the speed of transmission relative to the IFS duration, lead to greater probability of collision in transmission. The comparison of the results presented between IEEE 802.11b and 11g, which showed some interesting similarities in performance profiles. In this chapter, we presented the sensitivity of backoff rate for 802.11g protocol.

Chapter 4 investigated the performance modelling of fairness properties on IEEE 802.11b used PEPA. It considered single hop transmission in terms of channel access with performance metrics of interest including the channel utilisation and throughput on two, three and four pairs scenarios. The two pairs case is fair to access the medium, however the three pairs case is unfair, as the central pair has less chance to access the medium compared to the external pairs. The central has unfairly disadvantaged, as it waits most of time to use the medium, whilst, the externals have more chance to access the medium. Interestingly, the external pairs in the four pairs case accessed the medium simultaneously with less congestions, and they occupied the channel longer than the central pairs. Thus, by increasing nodes the probability of fairness increased, which gives more chance to the central pair(s) to access the medium; as each external pair(s) used the channel more fairly rather than the central pair(s). In spite of the central pair(s) penalised, this is less of an issue than has been reported compared to the central pair, on the three pairs case. Additionally, we illustrated the fairness metric of channel utilisation for three and four pairs scenario with sensitivity of backoff rate. Finally, we investigated the sensitivity to geometric assumption, where CW augmented.

Chapter 5 analysed the performance modelling on IEEE 802.11g developed by PEPA models. The first part in this chapter evaluated the channel access and fairness in three scenarios, due to topographic effects in the layout of communicating nodes focused on CSMA/CA. The inherent symmetry of the two pairs case have equal access to the medium. This deployment gives rise to unfairness in the three pairs case and the performance obtained by the affected nodes, is significantly below which is expected when there is competition for accessing the channel. This causes significant issues for individuals or service delivery. The four pairs scenario is fairer than three pairs case, as all nodes competed to gain access and all have the opportunity to access except when their nearest neighbours are transmitting. In addition, the second part considered the variations in performance among different communicating pairs, under heavy load in a limited network topology. The potential unfairness highlighted in network access, leads to one or more pair of communicating nodes being adversely penalised, that in high bandwidth applications could not be supported. The effect of variable frame lengths on fairness was explored. We examined the reduction of relative frame length variance at affected nodes, as one way to alleviate some of the effect of unfairness in network access. A hyper-exponential transmission of frames introduced in order to study the effect of increased variance in frame length distribution. If there is no competition to access the medium, the increased variance has no impact on the utilisation and throughput. But, if there is a competition, nodes with a higher variance experience a weaker performance, as disproportionately long frames are more likely to be delayed. In addition, we explored the fairness metric of channel utilisation when the backoff rate in a node is 200000.

Similarly, we studied the sensitivity of fairness metric with backoff rate at r=20. Finally, we investigated the range of variable frame lengths (α) from 0.99 to 0.64.

Chapter 6 investigated the IEEE 802.11n network by presenting an analytical modelling in PEPA. The performance enhancements demonstrated on IEEE 802.11n MAC layer attributes frame aggregation and block acknowledgement. Chapter 6 proposed a novel modelling performance of frame burst in 802.11n. The Inter-Frame Spacing reduced in our models and the performance fairness increased through overhead reduction and increased number of frame bursting in data transmission. The fairness issue examined with the topological scenarios in this protocol developed models and scenarios, deliberating the frame bursting length in data transmission. Finally, the sensitivity to geometric assumption in the two pairs scenario was investigated, when both pairs have exact frames to be transmitted.

7.2 Summary of contributions.

The IEEE 802.11 have dominated all forms of WLAN in the globe. Thus, the performance of WLAN needs to be improved. In this thesis, we created powerful models with effects of using the performance modelling in IEEE 802.11 protocols. We considered the PEPA models to investigate the fairness matters concentrated with WLANs 802.11 MAC layer in terms of channel access based CSMA/CA in various scenarios by different nodes (when nodes competed to access the medium by using framing techniques, and data can be flowed and receive onto the media, used media access control). The main aim in this thesis was achieved by obtaining higher performance and capacity in the WLANs system. PEPA is the main modelling technique used in this research, with a CTMC considered in our experiment. The main contribution of this thesis was the use of a stochastic process algebra and WLAN modelling which provided a better performance by each pairs of communicating nodes. Moreover, we investigated the performance fairness in WLANs standards under specified model scenarios. Such contribution in this research provided useful guidance for the recent protocols to achieve higher performance in communication while more than one node(s) attempts to access the medium.

Related numerical analysis and basic access mechanism were used to study quantitative properties of models of WLANs systems, we used the formal methods Performance Evaluation Process Algebra (PEPA) and Continuous-Time Markov Chain (CTMC)) in our study to analyse the IEEE 802.11 protocols in terms of channel utilisation, throughput and probability of transmission. They were adopted to better understand the protocols, and explored the effect of fairness in each models. The novel points in this research used the formal modelling techniques (mainly PEPA) in IEEE 802.11b/g/n models. We examined, the hidden node problem in IEEE 802.11b/g, the fairness issue in IEEE 802,11b, fairness and the effects of variable frame lengths in IEEE 802.11g. Finally, we investigated the significant novel models presented in IEEE 802.11n based on MAC layer enhancements and the increment in the high throughput studied by concentrated on the frame bursting in this protocol.

7.3 Limitations of the research.

In this thesis, we mainly concentrated on IEEE 802.11b/g/n protocols as they are widely in use and were published for more than a decade. We highlighted the main issues of these protocols and presented solutions to increase the overall performance fairness of these protocols. We studied several scenarios, and the maximum communications pair that examined, is the four pairs scenario, which is considered to be a complicated and complex scenario compared to other studies in the literature. However, other complicated scenarios (more than four pairs) could have been examined and due to time limitation it is left for future work. More traffics and congestions in communication might occur in multi hop scenario, which causes more route traffic between neighbour(s) in multi pairs scenario. Moreover, IEEE 802.11ac is very interesting protocol, that nowadays is available for customers to use. Time limitation also prevented us to investigate and replicate the previous scenario to see how its higher speed affects the performance fairness of the protocol. We focused on the performance modelling in PEPA tool, as it is a very user friendly tool with powerful features. The CTMC techniques concentrated in our research as we did not have a large number of repeated components, thus the ODEs did not considered in this study (ODE process of modelling is useful for large groups of the environment), but this research only focused on the small populations. Moreover, a large amount of CPU was not required to solve the model in this study, due to the small size of state spaces in our models. The smallest model in this research only had 6 state spaces (in one pair scenario), and the four pairs scenario (when pairs have exact number of frames to be sent) only had 3440 state spaces. Thus, as the state spaces are small in this study, this meant that generating the models were less time consuming. Finally, the most used assumptions in our models was based on Kloul and Valois [46] model, which they validated it in the context of 802.11b. We adopted these assumptions to investigate 802.11g and 802.11n protocols. We also tested our models assumptions, in the context of backoff duration and geometric assumptions for the frame bursting.

7.4 Suggestions for future work.

Recommendations for research and interesting work in the future will be described in this section. Future work will explore the existing protocol to design new models for more recent protocols, such as IEEE 802.11ac or IEEE 802.11ax (these protocols are still under improvements, but they will significantly increase the efficiency of WLAN networks with the wider channels, more spatial streams and higher-order modulation). Furthermore, through this research we will be able to expand our current experiments as they have applied in the IEEE 802.11b/g/n protocols to investigate another scenario(s), so more complex scenario can be proposed. Similarly, the proposed models in this current research can be valid in more areas by comparing the presented results in this thesis with any simulations tool, such as NS-3 simulation. A furtherer simulations work or implications validations left for future work.

In addition, we propose to investigate wireless sensor network in future research, for example the IEEE 802.15.4 protocol. Although, the IEEE 802.15.4 is intended, we would need to take into consideration the energy concerns of network devices, which is called sensor nodes in wireless sensor networks. It is clear that repeated attempting and failing to transmit has an impact not only on performance, but also energy use within wireless nodes. It would therefore be interesting to derive metrics for energy consumption from models such as the ones presented in our model(s) in this research in order to predict the impact of unfairness on energy usage and the longevity of battery powered nodes. Such issues can become particularly significant for protocols such as IEEE 802.15.4 operating in a low-rate wireless (low radio power in transmission). If we have more congestion or collision between nodes, then more waiting time between nodes will be required, in these circumstances more energy is needed to resend data. As a consequence, by having the contention or competition between wireless nodes, then more power will be used by each node. Finally, it is noteworthy to consider that better understanding of the relationship between throughput, fairness and energy usage in wireless networks is an area of significant theoretical challenge and practical interest. It will be useful to model and analyse the wireless sensor network in such protocol by using PEPA or any other tools.

Despite these suggestions for future works and the mentioned limitations in this research, we obtained very significant results in our studies (as presented and discussed in this thesis). Throughout this thesis, the fairness issues investigated in terms of channel utilisation and throughput, and the performance modelling on WLAN IEEE 802.11 protocols illustrated, as finally we highly improved the performance fairness on these protocols in different scenarios used PEPA.

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