Performance Evaluation of Collision Avoidance Schemes in Ad-hoc Networks

by

Suryakant Bhandare

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Approved by

Dr. Saad Biaz, Co-Chair, Professor of Computer Science and Software Engineering
Dr. Prathima Agrawal, Co-Chair, Professor of Electrical and Computer Engineering
Dr. Shiwen Mao, Professor of Electrical and Computer Engineering

Abstract

IEEE 802.11 DCF (Distributed Coordination Function) is a popular protocol used for the physical and MAC layers in most ad hoc networks. DCF employs carrier sense multiple access with collision avoidance (CSMA/CA) and a binary slotted exponential backoff. It has been observed that the hidden and exposed terminal problems among stations are responsible for DCF's performance-degradation. The issue of fairness is also a major contributor to its low-grade performance. Hence, the effectiveness of 802.11 DCF mechanism in ad hoc networks has attracted many research studies.

There has been many proposals of Collision Avoidance schemes to compete against the IEEE 802.11 DCF. This is because the performance of the MAC layer directly impacts the performance of higher-layer protocols and hence the entire network. An evaluation of these schemes will be helpful in understanding the limitations of wireless ad hoc networks. In this thesis, we survey various collision avoidance schemes, classify them based on their mechanism, and then provide a comparative study of the selected schemes based on their performance. They are evaluated in a Chain topology, a Pair topology and a Random topology with static environment to provide extensive results on their Throughput, Fairness, Collision and Delay performance. Based on the evaluation, we conclude that GDCF (Gentle DCF) is the best scheme that has lesser collisions with improved throughput and fairness. A comparison with the legacy CSMA/CA suggests that these proposed schemes do tend to be promising and would inspire future researchers who are interested to find solutions to the age-old collision and fairness issues in ad-hoc networks.

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Chapter 1

Introduction

1.1 Motivation

A wireless ad hoc network is a congregation of wireless stations that can configure themselves to form a network without the assistance of any infrastructure. It is required that in a wireless network, the stations sharing the same communication channel should be given a fair chance to access the medium. Fairness is one of the major issues that all MAC protocols must address. Unfairness occurs when some stations grab most of the channel's bandwidth while others starve.

Wireless channels are characterized by bursty and location-dependent errors [Lu et al. [28]]. These issues are addressed by a fair packet scheduling algorithm. We can find some packet scheduling algorithms for wireless networks in [Lu et al. [28], Ramanathan and Agrawal [33]].

Collision of packets in networks where a single channel is shared among the nodes is another common unavoidable phenomenon. Single-channel wireless ad hoc networks suffer from the hidden sender, hidden receiver, exposed sender, and exposed receiver problems and hence require effective mechanisms for collision avoidance and fair contention resolution [Bharghavan [7]].

An example is shown in Figure 1.1 to illustrate the *hidden terminal problem*. Station A and H are the senders. Station H is in the range of the Station B but cannot hear Station A. When both, Station A and station H want to send packets to their common neighbour - Station B, collisions occur at B and it hears only garbled frames. In addition, it is generally seen that even the provision of ”sensing the common channel before an attempt to access the channel” does not eliminate collisions. Thus, there is a degradation in the performance of

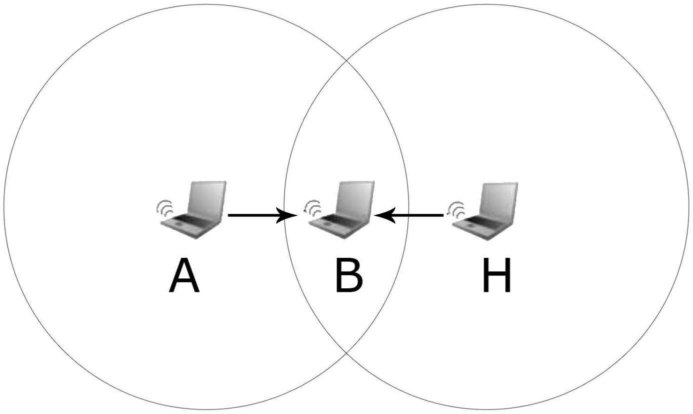

Figure 1.1: Hidden Terminal Problem

the network due to a reduction in the network capacity for transmission of useful data. This scenario is referred to as the *hidden terminal problem*. We call Station H a hidden terminal from Station A. The hidden node problem causes unfairness in wireless networks [Wang and Kar [43]].

To understand the *exposed terminal problem*, consider Station E which is in the range of the transmitter Station A, but not that of receiver Station B. This is shown in Figure 1.2. With the regular carrier sensing mechanism, Station E will defer from accessing the shared channel when A attempts to transmit to B. Thus Station E is prevented from transmitting. Station E is the exposed terminal whose transmission to C is deferred.

Collision is an important design challenge for wireless local area networks (LANs). At the time of collision, considerable amount of radio resources are wasted. This is because the source node still continues to transmit the packet completely. The performance degradation due to these collisions tend to become more severe as the frame size increases, since the bandwidth wasted by collisions becomes relatively large. Hence, the amount of resources wasted in an ad-hoc network depends upon the size of the packet. Moreover, collisions cause retransmissions. This consumes a significant amount of energy, thus reducing the lifetime of battery-powered wireless devices. The problem of collision is worse in a multi-hop

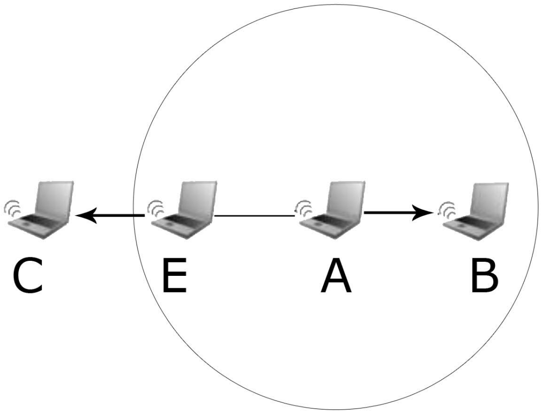

Figure 1.2: Exposed Terminal Problem

environment than in a single-hop environment [Haas and Deng [19]]. Collision Avoidance is implemented in the medium access control (MAC) layers. There is a trade-off between collision avoidance and throughput as collisions reduce overall throughput on the network. A MAC protocol for wireless LANs should provide an effective mechanism to share the available limited spectrum resources along with high throughput and fairness to all the stations [Kwon et al. [27]].

In the past few years, multiple MAC protocols were developed considering the tradeoff factors such as throughput, fairness, delay and collisions. A MAC protocol can be either contention-based MAC or reservation-based. Contention-based MAC protocols are used for applications requiring bursty data flow under a light network load and low delay. A reservation-based MAC protocol is generally used for applications with real-time traffic providing high QoS (Quality of Service) under heavy network load [Acharya et al. [3], Bianchi and Tinnirello [9]]. They are typically used in centralized network architectures. A classic unfairness issue arises in a wireless mesh network when a node nearer to the access point keeps sending its own traffic to the access point gateway while starving the nodes farther from the access point [Kongara et al. [26]].

Research on contention-based MAC protocol started with ALOHA in the 1970s. Later, MACA [Karn [22]], MACAW [Bharghavan et al. [8]], FAMA [Fullmer and Garcia-Luna-Aceves [18]] and DFWMAC [Diepstraten et al. [17]] were proposed by incorporating the carrier sense multiple access (CSMA) technique as well as the RTS and CTS handshaking mechanism for collision avoidance (CA). The evolution of these famous MAC protocols will be covered in the following chapter.

This work provides a survey and an evaluation of few popular approaches that address the problem of collisions in wireless LANs. The objective of this work is to categorize those approaches based on the method they use to achieve collision avoidance. This thesis also addresses the common issues that must be considered to design a collision avoidance scheme.

1.2 Thesis Organization

The remainder of this thesis is organized as follows: Chapter 2, reviews collision avoidance schemes that are popular among researchers. This is followed by a classification of the CA schemes in Chapter 3. We then discuss the schemes we have selected for performance evaluation in Chapter 4. We present the simulation settings and discuss the performance of this work in Chapter 5 and then conclude our work in Chapter 6.

Chapter 2

Survey

IEEE 802.11g has been the most common standard for wireless local area networks. This standard is an enhancement of previously defined standards IEEE 802.11 and IEEE 802.11b.

IEEE 802.11g uses OFDM(Orthogonal Frequency-Division Multiplexing) in addition to CCK (Complementary Code Keying) as its modulation method to support data rates of up to 54 MBit/s. It is compatible and interoperable with 802.11b as it shares the medium access, link layer control, and the frequency range of 2.4 - 2.485 GHz with its predecessors.

This chapter provides a brief overview of the collision avoidance technique of IEEE 802.11g and other proposed schemes.

2.1 Evolution of Collision Avoidance Methods

ALOHA is the earliest MAC protocol proposed for wireless networks [Abramson [2], Kleinrock and Tobagi [23]]. In pure ALOHA, the stations transmit whenever they have data to send, regardless of the current state of the medium. An acknowledgement is required by the sender to determine if the transmission was successful. If no acknowledgement is received, a collision is assumed to have occurred and the sender must retransmit after a random delay. Since ALOHA does not use carrier sensing, a data packet is vulnerable to collision, if another node is transmitting at the same time. A subsequent variation called slotted ALOHA was introduced to improve channel efficiency.

The fundamental cause of ALOHA's low channel utilization is that senders don't listen to other users' transmissions [Kleinrock and Tobagi [23]]. This led to the development of

CSMA or Carrier Sense Multiple Access, in which a station attempts to avoid collisions by listening to the carrier of other user's transmission prior to its transmit.

In [Kleinrock and Tobagi [24]], the authors showed that the existence of hidden terminals significantly degrades the performance of CSMA. When two senders who cannot hear each other attempt to communicate with a common neighbor, we have a hidden terminal problem. To resolve this issue, they proposed the Busy Tone Multiple Access (BTMA) [Kleinrock and Tobagi [24]] protocol as an extension of CSMA. In BTMA, the available bandwidth is split into two separate channels: a data channel and a control channel. A busy-tone is placed on the control channel by the receiver as long as the receiver station sense messages on its data channel. The other stations sense this busy-tone channel and determine the state of the data channel at receivers and if busy, the senders defer their transmissions. This resolves the hidden terminal problem. BTMA can also solve the exposed terminal problem. A sending station could just ignore the carrier sense signal when there is no busy-tone. The BTMA, with its split channels, is actually a complex system from a hardware perspective. The other problem associated with BTMA is that it increases the spectrum requirement of each user station [Karn [22]].

To avoid the need for a continuous busy-tone signal, the Split-channel Reservation Multiple Access(SRMA)[Kleinrock and Tobagi [25]] was proposed. This is the first protocol to propose handshakes between the sending and receiving stations. This protocol requires a separate channel for transmitting the handshake signals. This requirement was not necessary as the data transfer does not start until the handshaking is completed. Hence, the same channel could be used for the handshake signals too.

The BTMA and SRMA extensions to CSMA are not efficient and hence MACA (Multiple Access Collision Avoidance) was proposed by Karn [22]. MACA avoids the use of physical carrier sensing. MACA uses the RTS (Request-to-send) and CTS (Clear-to-send) handshake before data exchange. In MACA, any station over-hearing the RTS would defer so that the transmitting station can receive the expected CTS and any station over-hearing the CTS would defer to avoid colliding with the imminent data transmission. Thus MACA overcomes the hidden and exposed terminal problem. If the sender does not receive a CTS packet in response to its RTS packet, the sender uses a randomized exponential backoff algorithm to backoff for a random time before retrying. Each station waits a randomly chosen interval and tries again and will double the average interval on each successive attempt.

MACA suffers from unfairness and hence an improved version of MACA, called MACAW was proposed by Bharghavan et al. [8]. MACAW is an acronym for Multiple Access with Collision Avoidance for Wireless. MACAW improves MACA with a new message sequence employing additional control packets and a Multiplicative Increase and Linear Decrease backoff algorithm to improve both throughput and fairness. MACAW uses a different backoff algorithm than MACA. Unlike MACA's backoff algorithm, in MACAW the value of the backoff counter is increased by a factor of 1.5 instead of 2 for each collision, and decreased by 1 for each success to provide a gentle reduction of the backoff. MACAW uses a RTS-CTS-DS-DATA-ACK message exchange sequence. A short data-send (DS) packet precedes DATA packet, which is to inform neighbors that a data packet is about to be transmitted. This reduces the probablity of the packet to collide. The following ACK packet improves the reliabity of the system. An additional control packet RRTS (Request for RTS) was used to let the receiver contend for the sender to improve fairness in cases when there are two receivers in the vicinity of each other and only one can win. MACAW does not generally solve the exposed terminal problem.

Distributed Foundation Wireless Medium Access Control (DFWMAC) [Diepstraten et al. [17]] protocol supports basic access method(CSMA/CA) and allows an option to use the RTS/CTS based access method. The binary exponential backoff (BEB) algorithm used in DFWMAC protocol helps to ease contention when the network load increases. The contention window size is doubled after every unsuccessful transmission till it reaches a fixed maximum value. The contention window size returns to the minimum value if a data packet is successfully transmitted.

The IEEE 802.11 is a widely used WLAN technology that is partially based upon DFWMAC. It supports high speed communications up to 54 Mbps in the unlicensed bands at 2.4 GHz and 5 GHz [Choi et al. [15]]. The IEEE 802.11 standard specifies two MAC schemes: a mandatory Distributed Coordination Function (DCF) and an optional Point Coordination Function (PCF). Out of these, DCF is most widely implemented in WLAN technologies (based on DFWMAC) because it is simple and offers an efficient best-effort service. DCF uses carrier sense multiple access with collision avoidance (CSMA/CA). With CSMA/CA, a station transmits its frame only if the medium is sensed idle. If the medium is determined to be busy, the station defers until the end of the current transmission. After the defer period is over, or prior to attempting to transmit again immediately after a successful transmission, the station will select a random backoff interval and will decrement the backoff interval counter while the medium is sensed idle [1]. A transmission is considered successful when an ACK frame is received by the sender. The collision avoidance technique uses a random backoff prior to the transmission of each frame. The random backoff procedure reduces the probability of collision, but cannot completely eliminate the collisions since it is quite possible that two or more stations finish their backoff procedures simultaneously. As the number of contending stations increases, the number of collisions will likely increase.

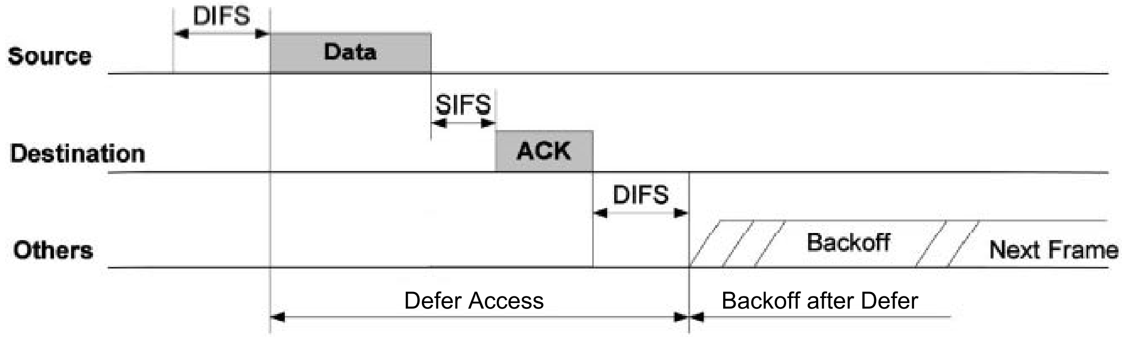

Figure 2.1: Basic Access Mechanism of *IEEE 802.11 DCF*

Figure 2.1 [Choi et al. [15]] illustrates the basic access method of IEEE 802.11 in DCF mode. If a station wants to transmit a frame when there is no ongoing backoff procedure, it determines whether the medium is idle or not. If the medium is sensed idle, the station immediately proceeds with its transmission after an idle interval equal to the DCF Inter Frame Space (DIFS). For a busy medium, the station defers its access until the medium is determined to be idle for a DIFS interval, and then it starts a backoff procedure.

For the backoff procedure, the station sets its backoff timer to a randomly selected backoff time based on the current contention window size CW

$$\textit{Backoff Time (BT)} = \textit{Random()} * \textit{aSlotTime} \tag{2.1}$$

Random() is an integer randomly selected from an uniformly distributed interval [0,CW].

The station performs a backoff procedure after a DIFS idle time. The carrier sensing technique is adopted to check if there is any activity during each backoff slot. If the medium is idle during a particular backoff slot, then the backoff time is decremented by a slot time (BTnew = BTold - aSlotT ime). During a busy slot, the decrementing is suspended. After the medium is determined to be idle for DIFS period, the decrementing resumes. The transmission resumes when the backoff counter reaches zero. If the destination receives the packet successfully without errors, an acknowledgement (ACK) packet is sent after a short inter-frame space (SIFS) idle period, by the destination. The contention window (CW) of the source station resets to the initial (minimum) value CWmin with the acknowledgement. For every unsuccesful transmission, the contention window (CW) size is increased, beginning with the initial value CWmin, up to the maximum value CWmax (in the IEEE 802.11 specification). If the previously received frame contains error then a station defers for EIFS (Extended Interframe space) duration instead of DIFS before transmitting a frame. This process is called binary exponential backoff (BEB), which resolves collisions in the contention cycle.

To improve channel efficiency for long packet transmissions or in heavy-contending WLAN environments, the IEEE 802.11 protocol can use a short Request To Send (RTS) control frame and a short Clear To Send (CTS) frame to reserve access to the channel before a data frame transmission. The mechanism is shown in Figure 2.2. The RTS/CTS access method is used to alleviate the hidden terminal problem. RTS and CTS packets include a field called Network Allocation Vector (NAV). The stations who overhear the RTS and/or the CTS packets are informed how long they should defer access to the channel by the NAV.

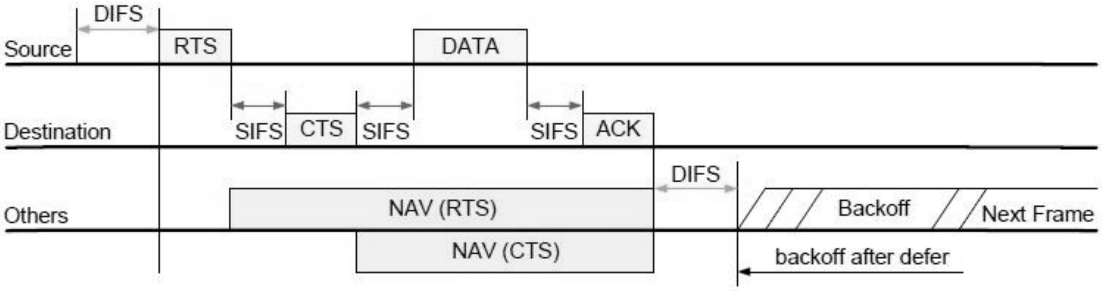

Figure 2.2: *RTS-CTS* exchange mechanism of *IEEE 802.11*

According to the IEEE 802.11 standard, the transmitter makes the decision to use the RTS frame. The RTS frame is used when the size of the pending data frame is equal to or larger than the RTS threshold value (2347 bytes). However, most 802.11 devices operating in infrastructure-based WLANs with access points (APs), do not use the RTS/CTS exchange by setting the RTS threshold to the largest value. RTS and CTS frames are rarely observed on real world networks.

The *hidden/exposed-terminal* problem persists in IEEE 802.11. We would look at two scenarios of *hidden/exposed terminals*. This is shown in Figure 2.3. Sender A and receiver B exchange RTS and CTS control messages to notify neighbouring competitors about the data packet transmission to follow the exchange. As a result, exposed sender G will defer its transmission when it receives A's RTS message and/or when it senses A to B transmission. Hidden sender M will also defer its transmission on reception of receiver B's CTS message. Therefore, the hidden/exposed-sender problem is solved by 802.11's RTS/CTS handshake.

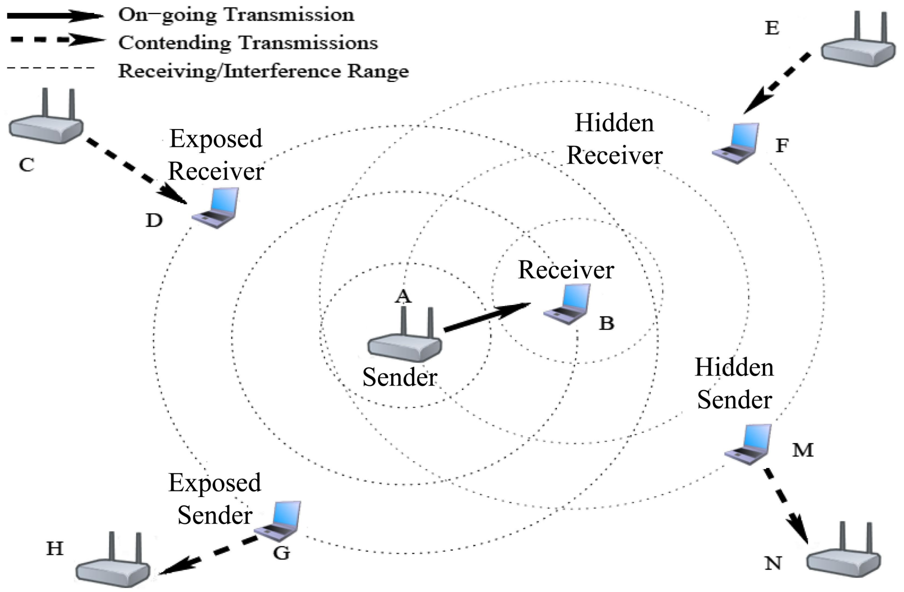

Figure 2.3: Hidden/exposed-terminal problem in 802.11 networks. Sender G and receiver D are *exposed* in As ongoing transmission, whereas sender M and receiver F are *hidden* from As transmission.

However, it is obaerved that, there are no schemes to handle the hidden/exposed-receiver problem within the 802.11's framework of single-channel operation [Chen et al. [12]].

In Figure 2.3 [Chen et al. [12]], receiver D is exposed, whereas receiver F is hidden to sender A. They have to remain idle until receiver B receives the data packet and sender A receives the acknowledgment (ACK). However, neither sender C nor E is aware of the ongoing transmission from A to B. Hence, C or E may initiate RTS requests to their intended receiver, D or F, in the middle of an A to B transmission. Sender C's RTS message will collide with sender A's signal at exposed receiver D. Hidden receiver F cannot respond to E's RTS, because F has received a CTS from receiver B and must remain idle until the A to B transmission finishes - a mechanism named ”virtual carrier sense” in IEEE 802.11. After the timer for CTS expires, sender C (or E) doubles its contention window size and engages in another round of random backoff before it tries to send a RTS again. Unsuccessful RTS attempts increase the senders 802.11 contention window quickly according to the binary exponential backoff algorithm and cause unfair channel access. Also, repeated RTS attempts prevent the sender's neighbors from transmitting, lowering the shared channel utilization.

The situation becomes worse when RTS/CTS is disabled and a two-way DATA/ACK handshake is employed, which is the IEEE 802.11 basic access method. The consequences of the hidden/exposed-receiver problem are severe. Most of the research done lately has focused on the general hidden/exposed-terminal problem that too devoted to the hidden/exposed-sender problem only. There has been attempts to alleviate the effects of a hidden/exposed receiver, but the problem itself remains open. The fundamental challenge lies in the lack of effective and efficient mechanisms to exchange channel availability information between senders and receivers, at packet-level time granularity, before a channel access attempt is made [12].

In scenarios wherein there is unevenly distributed traffic load, a station that senses less competing nodes has more chances of succeeding in sending packets and thus of resetting its contention window to the minimum value. A station which is successful has a shorter backoff timer than other stations that were not successful. When the traffic load is high, these other stations may suffer excessively long access delays, severe throughput degradation and ultimately, starvation as the traffic load increases.

2.2 Conclusions

In this chapter, we discussed the evolution of collision-avoidance schemes - from ALOHA to IEEE 802.11 DCF. We looked at the problems associated with these schemes that led to the development of other better schemes. We also reviewed some popular schemes used that address the problem of collisions in wireless networks. Now we have an idea of problems associated with wireless networks and the schemes that were proposed to address these problems. In the next chapter, we would classify the schemes we surveyed based on their characteristics.

Chapter 3

Classification of Collision Avoidance Schemes

3.1 Classification

IEEE 802.11 is a widely deployed standard for WLAN systems and still has multiple issues to deal with. The *hidden and exposed terminal problem* are some of the critical issues that have to be addressed. These problems directly affect the Throughput, Fairness and Collision performances of the network. Researchers have since proposed several schemes/protocols to address these issues. In this work, we have classified the various collision avoidance schemes for an ease of evaluation. This classifcation is based on the mechanism employed by these schemes to tackle collisions. A scheme can fall into more than one category as its mechanism can be a function of more than one variable. We broadly classify these schemes into five categories as follows:

1. **Backoff Tuning**: These schemes primarily function by modifying the backoff timers of the active nodes. Basically, they modify the backoff algorithm and/or adjust the size of the contention window. Some of the schemes that come under this category are ECA (Enhanced Collision Avoidance) by Barcelo et al. [5], FCR (Fast Collision Resolution) by Kwon et al. [27], GDCF (Gentle DCF) by Wang et al. [41], PDCF (Probability based DCF) by Wang et al. [40], NBA (Neighbourhood Backoff Algorithm) by Taifour et al. [37], Real-time MAC by Baldwin et al. [4], LMILD (Linear/Multiplicative Increase and Linear Decrease) MAC by Deng et al. [16], Dynamically tuned 802.11 by Cali et al. [10], Neighbour Aware CA-MAC by Romaszko and Blondia [34], Logarithmic based MAC by Manaseer and Ould-khaoua [29]. Our evaluation is focused on the schemes

that fall under this category. We have selected ECA, FCR and GDCF for evaluation, and deal them in detail in Chapter 4.

2. **Reservation Based/ Virtual Carrier Sensing**: These schemes propose some handshaking methods to tackle the collision and hidden/exposed terminal problem. They adopt additional handshake messages to address the issues associated with WLANs. These schemes use handshake messages to emulate physical carrier sensing, and hence have been termed as Virtual Carrier Sensing schemes. Some of the schemes that come under this category are MACA by Karn [22], MACAW by Bharghavan et al. [8], MACA-BI (MACA by Invitation) by Talucci et al. [38], MACA-P (with Enhanced Parallelism) by Acharya et al. [3], Bianchi and Tinnirello [9], DBRS (Distributed Backoff Reservation and Scheduling) by Choi and Lee [13], STRC (Sender's Transmission Range Cover), RTRC (Receiver's Transmission Range Cover), SCRC (Sender's Carrier-sensing Range Cover) and RCRC (Receiver's Carrier-sensing Range Cover) by [36], SEEDEX by Rozovsky and Kumar [35], DCF+ by Wu et al. [44].

3. **Power based**: The schemes that fall under this category vary the transmission power depending upon the packet type. Some of these schemes advertise interference margins. Few protocols that belong to this category are PCMA (Power Controlled Multiple Access) by Monks et al. [30], PCDC (Power Controlled Dual Channel) by Muqattash and Krunz [31], POWMAC (Power controlled MAC) by Muqattash and Krunz [32], Improved busy-tone scheme using DBTMA by Wang and Zhuang [42], STRC, RTRC, SCRC and RCRC by [36].

4. **Out-of-Band Signalling**: These schemes use a separate channel for signalling. Usually this channel is a control channel used to indicate other users whether the medium is busy or not. Some schemes under this category are Busy-tone Solution by Kleinrock and Tobagi [24], DBTMA by Haas and Deng [19], Improved busy-tone scheme by Wang and Zhuang [42].

Table 3.1: Classification of CA Schemes

Backoff Tuning	**Reservation/Virtual carrier Mechanism**	**Power Based**	**Out-of-band Signalling**	**Original Ideas**
ECA, FCR, GDCF, PDCF, NBA, DCF+, EIED, EILD, HBAB, MACAW, DFWMAC, Real-time MAC, LMILD, Dynamically tuned 802.11, Neighbor Aware CA-MAC, Logarithmic based MAC	MACA, MACAW, MACA-BI, MACA-P, DFWMAC, DBRS, STRC, RTRC, SCRC, RCRC, SEEDEX	PCMA, PCDC, POWMAC, Improved busy-tone scheme using DBTMA, STRC, RTRC, SCRC, RCRC	Busy-tone Solution, DBTMA, Improved busy-tone	SRMA, Busy-tone solution, Grand-to-send, MACA, SELECT

5. **Original Ideas**: The schemes under this category are those which are novel ideas or which were the first schemes to use a particular approach rather than its derivation. Schemes that can be considered novel are statistics based MAC by Hu and Raymond [20], Busy-tone solution by Kleinrock and Tobagi [24], Grand-to-send by Choi and Levis [14], MACA by Karn [22], SRMA by Kleinrock and Tobagi [25].

Table 3.1 shows a list of collision avoidance algorithms (references are as above). Though not all the proposed protocols can guarantee an ‘A’ grade performance, it is seen that they tend to address and improve one or more issues specifically. Based on the issues and metrics they address, we can further classify these schemes as shown in Table 3.2. Remember, this is a general classification. Not all schemes address all the issues. But the classification tries to generalize the performance issues that are specifically addressed by these schemes. We observe that backoff tuning improves the throughput and delivers a better fairness. The *hidden and exposed terminal* problem is addressed by schemes that have a reservation mechanism that would notify neighbors that they need to stay quiet for a transmission that is about to commence. Power based MACs usually focus on throughput and spectrum efficiency. The schemes that use an extra channel for sending control signals address the *hidden terminal* issue.

Table 3.2: Specific issues addressed by the CA scheme categories

		Type of CA schemes			
		Backoff Tuning	Reservation/Virtual carrier Mechanism	Power Based	Out-of-band Signalling
Issues addressed	Throughput	X		X	
	Fairness	X	X		
	Collisions	X	X		X
	Mean Delay	X			
	Hidden-Terminal problem		X		X
	Exposed-Terminal problem		X		
	Spectrum Efficiency		X	X	
	Power Efficiency		X	X	

3.2 Conclusions

In this section, we discussed popular schemes which were proposed by researchers in the past few years. We looked at the functionality of these schemes and provided a classifcation based on the steps they adopt to avoid/mitigate collisions. We also looked at the specific issues that a particular type of scheme addresses. For this thesis, we would focus on the schemes that fall under the backoff-tuning category. We have selected three schemes (ECA, FCR and GDCF) from this category for evaluation purpose. We go through each of these schemes in the next chapter.

Chapter 4

Selected Schemes

This section provides a brief overview of the collision avoidance schemes we will evaluate. We looked at the issues these schemes address and chose three schemes from the backoff-tuning category of our classification. The chosen schemes are ECA, GDCF and FCR. These schemes have been very popular in the recent years and many recent works have cited them. This is the reason why they got selected for the evaluation. In addition, we make sure that these schemes address similar type of issues. These schemes will be evaluated and compared with the performance of IEEE 802.11 DCF with and without the RTS-CTS mechanism.

4.1 Enhanced Collision Avoidance

CSMA/ECA's main feature is that it attempts to reduce collisions by using a deterministic backoff after successful transmissions [Barcelo et al. [5]]. CSMA/ECA introduces a new parameter: a deterministic backoff value (V) after successful transmissions. V is defined as:

$$V = \lceil (CWmin - 1)/2 \rceil \tag{4.1}$$

For our evaluation, we choose V= 15 as CWmin = 31. The proposers of this work - Jaume Barcelo, Boris Bellalta, Cristina Cano, Anna Sfairopoulou, Miquel Oliver show that CSMA/CA and CSMA/ECA deliver the same throughput when the network can handle all the offered traffic. When the offered load exceeds the network capacity, CSMA/ECA performs better than CSMA/CA.

They show that, by choosing a deterministic backoff after a successful transmission and a random backoff otherwise, the system converges to a collision-free operation when the number of active stations is not greater than the value of the deterministic backoff. The scheme relies on the deterministic behaviour to stabilize the system, in case of a successful transmission, and the randomness of the backoff to avoid collisions. They provide a theoretical analysis to show that when a deterministic backoff is used, two stations that successfully transmitted in their last transmission attempt cannot collide among them. This gradually reduces the number of collisions. After all stations have had successful consecutive transmissions, the operation of the system is collision-free and deterministic.

4.2 Gentle DCF

GDCF is a modification of IEEE 802.11 DCF. In 802.11 DCF, the contention window is reset to the initial value after each successful transmission, which essentially assumes that each successful transmission is an indication that the system is under less load. GDCF takes a more conservative measure by halving the contention window size after a fixed number of consecutive successful transmissions [Wang et al. [41]]. They show that this 'gentle' reduction decreases the probability of collision when the load is high.

According to the collision resolution process of GDCF, if there are 'c' consecutive successful transmissions, GDCF will halve the CW and select a backoff timer value uniformly from [0, CW]. Then, the counter for recording the number of continuous successful transmissions is reset to zero. Otherwise, GDCF increases the counter for the number of consecutive successful transmissions and maintains the same contention window. On a collision, GDCF will double the contention window and select a random backoff value similar to DCF's but GDCF also resets the counter for recording the number of consecutive successful transmissions. The Idle state behavior of GDCF is same as DCF's. In [41], Chonggang Wang, Bo Li and Lemin Li showed that the optimal value of counter 'c' is in the range of 4 and 8 and is nearly independent of the number of nodes when there are more than 10 nodes. When the counter is in the optimal range of 4 and 8, GDCF improves throughput by about 15% to 20% for large networks but just a small improvement for small networks. They also show that better fairness could be obtained by using a higher value of 'c'. For our simualtions, we set c to 8.

4.3 Fast Collision Resolution

FCR (Fast Collision Resolution) is a novel MAC protocol proposed by Younggoo Kwon, Yuguang Fang and Haniph Latchmanand. It is an efficient contention-based MAC protocol for WLANs. The logic behind this algorithm is to speed up the collision resolution by actively redistributing the backoff timers for all the nodes that are active. The algorithm also reduces the average number of idle slots by using smaller contention window sizes for nodes with successful packet transmissions. The backoff timer is decremented exponentially when a fixed number of consecutive idle slots are detected [Kwon et al. [27]]. The key features of FCR are:

1. A smaller initial (minimum) contention window size CWmin than IEEE 802.11's;
2. A larger maximum contention window size CWmax than IEEE 802.11 MAC;
3. An increase in the contention window size of a station when it is in either collision state or deferring state;
4. A backoff timer that reduces exponentially faster when a prefixed number of consecutive idle slots are detected.

The FCR algorithm works as follows. When a station following FCR's backoff procedure senses an idle slot, it decrements its backoff time (BT) by a slot time. The station will transmit a packet when its backoff timer reaches zero. If [(CWmin + 1) * 2 - 1] consecutive idle slots are detected, the backoff timer is decremented exponentially. After that, if idle slots are detected, the backoff timer will be decreased by one half until either it reaches zero or it senses a busy slot, whichever comes first. On collision, the contention window size of the station is increased and a random backoff time is chosen. For a successful transmission, the contention window is reduced to the initial (minimum) contention window size CWmin and a random backoff time (BT) value is accordingly chosen. When a station detects the start of a new busy period, either due to a collison or because of the occupation of the medium, the station will increase its contention window size and pick a new random backoff time.

In the FCR algorithm, the station which successfully transmitted has the smallest CW size and a smaller backoff timer, hence it has a higher probability of grabbing the medium, while others have relatively larger CW size and larger backoff timers. After a number of successful packet transmissions for one station, another station may win the contention and this new station will then have higher chance of getting access to the medium. Table 5.1 shows the parameter values specific to FCR.

Now that we know the schemes that are being evaluated, we present the hightlights of the selected algorithms in Table 4.1. Since we are specifically looking into the backoff-redistribution category, we only consider how these alogrithms process the contention window and backoff timer.

4.4 Conclusions

In this section, we presented the schemes that would be considered for evaluation - IEEE 802.11 CSMA, IEEE 802.11 RTS-CTS, ECA, GDCF and FCR. We also gave a brief overview of the functionality of these schemes to give a fair idea of the schemes to our readers. The following chapter would analyse the performances of these schemes under various scenarios.

Table 4.1: Highlights of the Selected Backoff Redistribution Schemes

		Backoff Redistribution Schemes			
		IEEE 802.11 CSMA/CA	ECA	GDCF	FCR
Event	Transmission Success	Reset CW to initial value, select a random backoff timer value uniformly from [0, CW]	Reset backoff counter to 15 (deterministic backoff)	Count the number of consecutive successful transmission till the threshold (8), don't alter CW	Reset CW to initial value, select a random backoff timer value uniformly from [0, CW]
	Collision	Double CW and select a random backoff timer value uniformly [0, CW]	Double CW and select a random backoff timer value uniformly [0, CW]	Double CW, select a random backoff timer value uniformly [0, CW], reset counter 'c'	Double CW and select a random backoff timer value uniformly [0, CW]
	Channel Idle	Decrease backoff timer by one slot	Decrease backoff timer by one slot	Decrease backoff timer by one slot	Decrease backoff timer by one slot till 7 consecutive idle slots
	Channel Busy	Suspend backoff	Suspend backoff	Suspend backoff	Suspend backoff
	Consecutive Idle slots	same as any idle slot detection	same as any idle slot detection	same as any idle slot detection	Halve backoff timer when 7 consecutive idle slots are sensed
	Consecutive Success	same as any successful transmission	same as any successful transmission	Halve the CW and select a backoff timer value from [0,CW] if 'c' consecutive successful transmissions have happened	same as any successful transmission

Chapter 5

Performance Evaluation

In this section, we describe the experiments to evaluate the performance of the selected schemes. As wireless systems are complex, it is not always possible to capture all relevant features with just one topology while performing the analysis. So for a thorough evaluation, we consider three scenarios as follows:

1. Chain Topology
2. Pair Topology
3. Random Topology with varying node density

The topologies mentioned above are shown in Figure 5.1. We evaluated these schemes on OMNeT++ [Varga [39]] with INETMANET Framework, since the current version provides significant support for comprehensive simulation setups for studying 802.11 systems. We use the 802.11g model availabe in this framework. The MAC layer is operating at a bitrate of 54Mbps for data frames and a basic bitrate of 2Mbps for RTS/CTS and ACK frames. Each node has a transmitter power of 2mW and a receiver sensitivy of -85dBm that results in a transmission range of 250m. Table 5.1 shows the parameter settings for this analysis. The

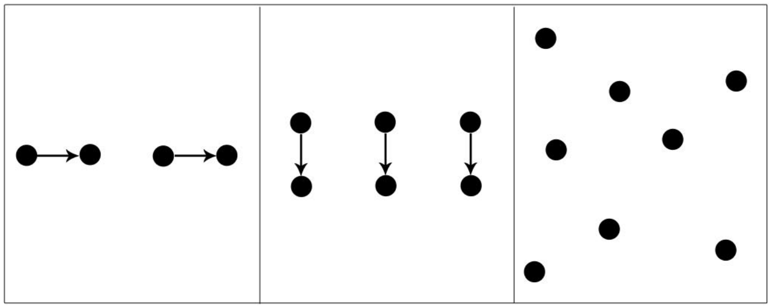

Figure 5.1: Topologies: a) Chain b) Pair c) Random

nodes are allowed to start sending at the same time so they get a fair chance to contend from the beginning of the simulations. To isolate the performance of MAC layer from that of higher layers, we use constant bitrate UDP traffic. It is usually seen that TCP adds its own congestion avoidance/rate control in the performance analysis of 802.11. We compare the performances in terms of throughput, fairness index, number of collisions and mean packet delay. These metrics are defined as follows:

1. **Throughput**: Throughput is measured as the number of bits received over the total simulation time. When we mention aggregate throughput, we mean the average of throughputs measured for all packet sizes. The speed of 802.11 networks is distance dependent. The more the distance between two stations, the lower the speed. We also observe that the actual data throughput is generally less than half of the rated speed i.e. a system working at a rate of 54 Mbps would yield only about 27 Mbps in real throughput. This is because 802.11 uses a collision avoidance technique rather than the collision detection method. Wired systems can detect a collision, but wireless cannot, thus, with CSMA/CA, the sender waits for an acknowledgment from the receiver to determine if the packet was transmitted successfully. The highest throughput measured in our simulation was 23 Mbps when there was just a single sender-receiver pair.

2. **Fairness**: Fairness among stations is an important problem in wireless networks. The Fairness index can show if resources are fairly allocated to each station. Here we are using Jain's fairness index formula [Jain et al. [21]]. Jain's fairness index is calculated as

   $$I_J = \frac{(\sum_{i=1}^{n} r_i)^2}{n \sum_{i=1}^{n} r_i^2} \tag{5.1}$$

   where r is the throughput achieved on connection i among n competing hosts.

   Jain's fairness index always lies between 0 and 1. A fairness index of 1 indicates that it is the most fair algorithm.

Table 5.1: Parameters used for Evaluation

Parameters	**Values**
Slot time	20μs
SIFS	10μs
DIFS	50μs
Bit Rate	54Mbps
CWmin	3 for FCR 31 for others
CWmax	2047 for FCR 1023 for others
Retry Counter	n = 0 to 9 for FCR n= 0 to 7 for others
RTS	160 bits
CTS	112 bits
ACK	112 bits
PHY Header Length	192 bits

3. **Collision Rate**: The collision performance is evaluated using collision rate. Collision rate measures the percentage of packets that are involved in collisions. This is measured at the receiver. For calculations, we consider the packets that were sent originally and neglect the retransmitted packets.

4. **Mean Packet Delay**: Mean packet delay is the average of the end-to-end delay of all received packets.

5.1 Chain Topology

The topology used to evaluate the schemes is as shown in Figure 5.2. It is a four-node chain topology. This topology presents the long-term fairness issues [Bensaou et al. [6]]. Long-term fairness is the fairness measured over a long period of time. The unfairness issue arises because the two emitters cannot hear eachother and one receiver is pressed with more collisions than the other receiver [Chaudet et al. [11]].

As shown in Figure 5.2, Nodes A and C can communicate with node B but both (A and C) cannot hear eachother. A always senses the medium free, whereas any transmission from C to D always succeeds if it manages to start, as collisions cannot happen at D. The sender who starts first determines the overall performance of this network.

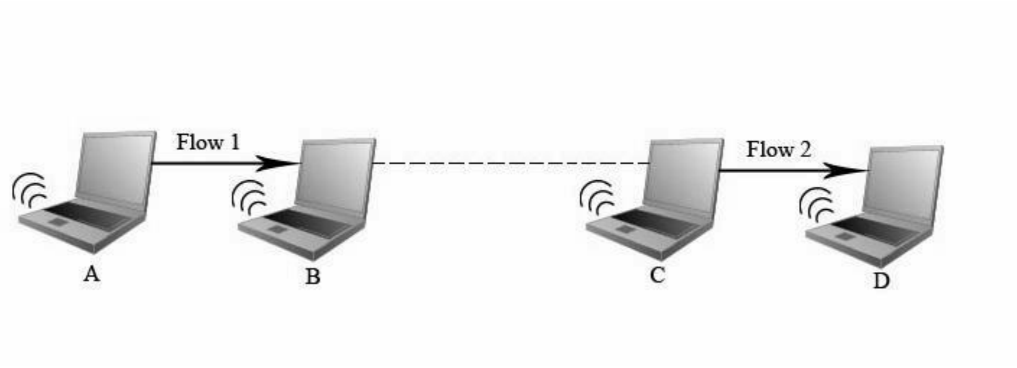

Figure 5.2: Four node Chain Topology

We measure the throughput, fairness, delay and collision rate on Flow F1 (A to B) and Flow F2 (C to D) for the collision avoidance schemes selected for evaluation. The nodes are 230m apart. Each sender sends 100k packets to its destination over a simulation period of 50 seconds. We simulated this for 20 runs. The metrics are recorded at the destination. The parameters for evaluation are given in Table 5.2.

Table 5.2: Settings used for Chain Topology

Parameters	**Values**
Data Type	Constant Bitrate UDP
Messages generated per second	2000
Message Length	100-1400 bytes
Simulation Time	50 seconds

5.1.1 Throughput

The throughputs for all the selected schemes is shown in Figure 5.3. FCR achieves the best throughput, delivering an aggregate throughput of 5.17 Mbps, followed by GDCF with 4.98 Mbps. The worst scheme is IEEE 802.11 with RTS-CTS, with an aggregate throughtput of only 2.13Mbps. When compared with the legacy IEEE 802.11 CSMA/CA, FCR achieved an improvement of 43% whereas RTS-CTS scheme showed a 41% degradation .

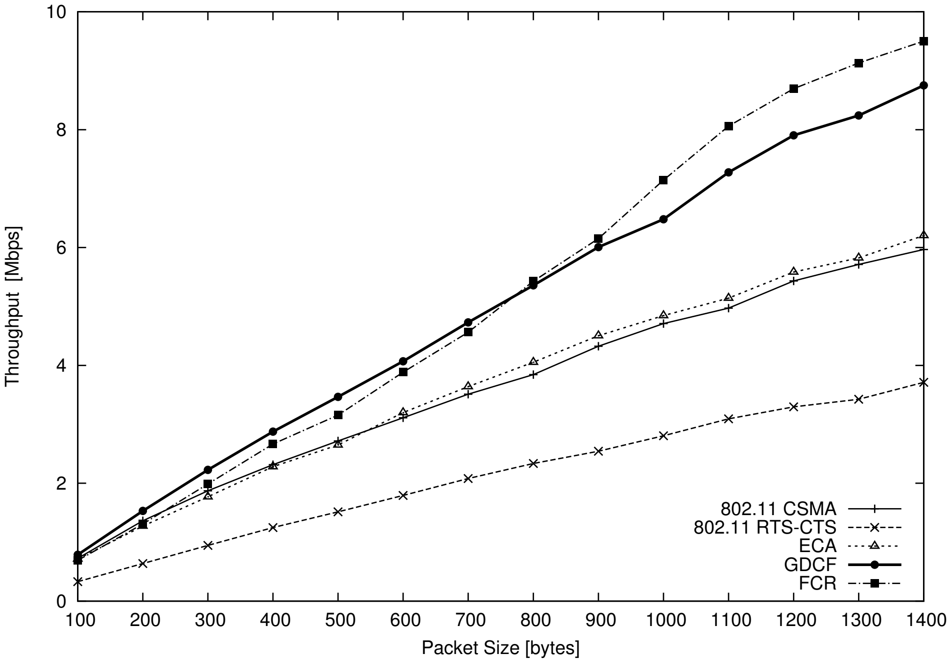

Figure 5.3: Relationship between throughput and the packet sizes

Figure 5.4 plots the cumulative distribution of throughputs achieved for each scheme. The RTS-CTS scheme performs worst. With RTS-CTS, 80% of all flows achieve less than 2.8 Mbps. Furthermore, FCR and GDCF both shows a similar distribution, with 80% of all flows receive less than 7 Mbps.

5.1.2 Fairness

In Figure 5.5, ECA shows better fairness than all the other schemes. It follows almost the same trend as the legacy scheme as shown in the plot. ECA shows 91.66% fairness for the chain, close to 802.11 CSMA/CA's 88.66%. We observe that FCR delivers higher throughputs, but at the cost of fairness (58.47%). The unfairness of FCR can be clearly seen in Figure 5.6, wherein D receives almost 8 Mbps while B receives 2 Mbps. GDCF is shown to have a balanced performance in terms of throughput and fairness amongst the nodes.

The cumulative distribution in Figure 5.7 shows that 80% of all flows have a fairness index less than 0.65 in case of FCR. FCR is obsviously badly performing. On the other

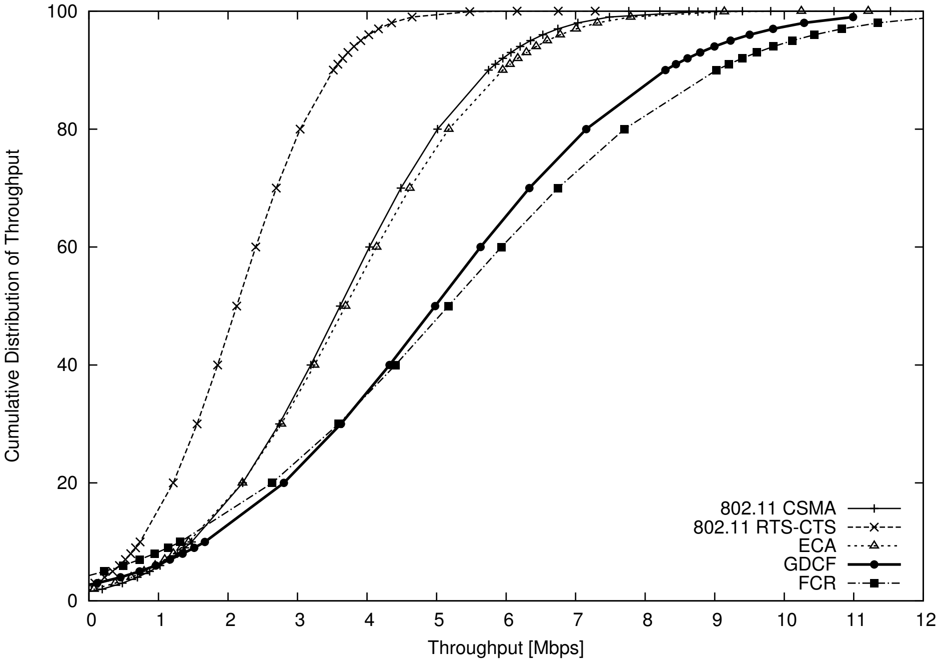

Figure 5.4: CDF of throughput received by flows

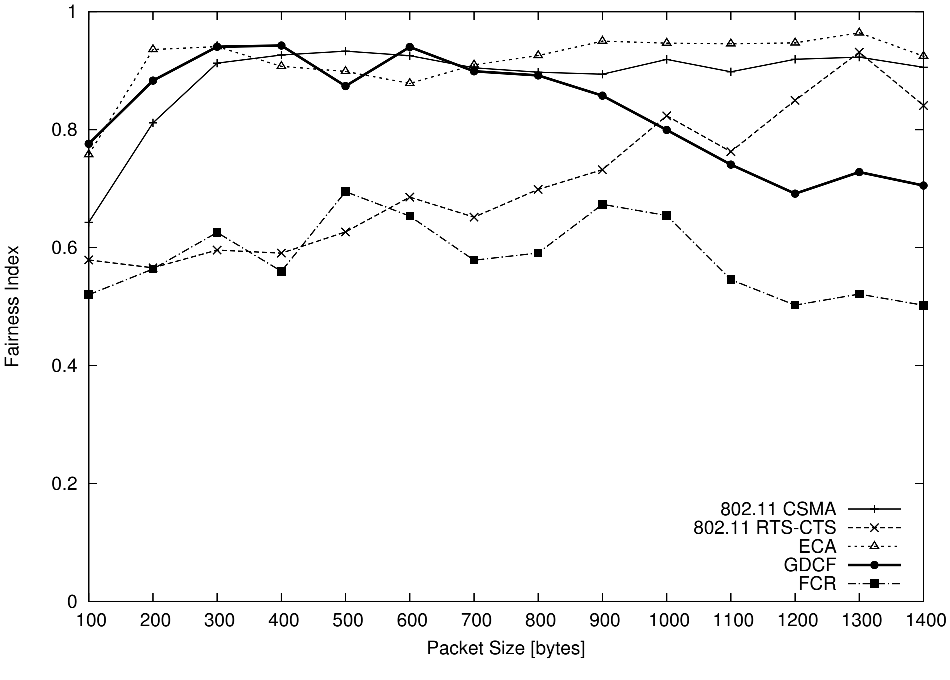

Figure 5.5: Fairness-Index as a function of Packet-size

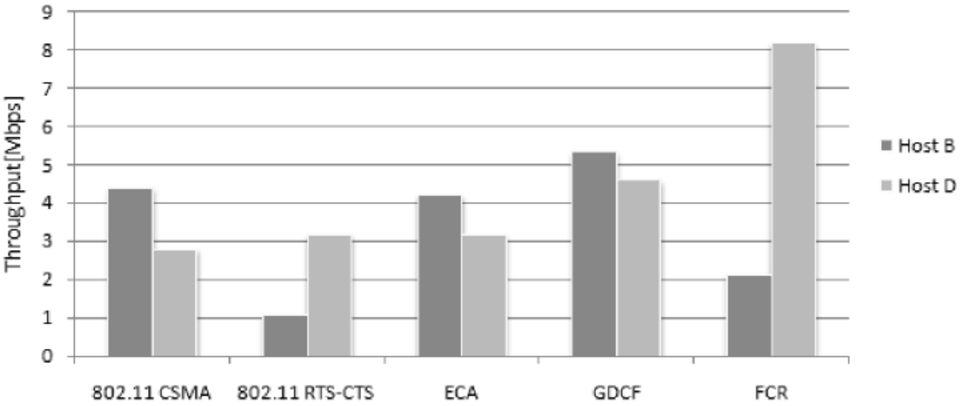

Figure 5.6: Throughput achieved at each node for each scheme

hand, ECA flows achieve a very good fairness: 80% of flows in ECA have a fairness less than 0.93, which is nearly same as IEEE 802.11 basic access scheme.

5.1.3 Collisions

Figure 5.8 plots how the collision rate varies with packet size. FCR experiences a very drastic drop in performance because of collisions. Although the plot shows that FCR has lesser collisions for higher packet sizes, it does not show a very consistent performance for all packet sizes, like GDCF. GDCF maintains an aggregate collision rate of 5.08% which is a massive reduction of -48% when comapred with the legacy IEEE 802.11 CSMA/CA. Here the aggreagte collision is calculated by averaging the collision rate for each size of packet.

5.1.4 Packet Delay

The packet-delay performance of these schemes as a function of packet-size is shown Figure 5.9. As expected, the reservation mechanism of RTS-CTS introduces additional delay in packet transmission, delivering a mean delay of 278 msec. This is an increase of approximately 191% compared to IEEE 802.11 CSMA/CA. We also observe that GDCF offers the lowest delay by reducing the mean delay by -53%.

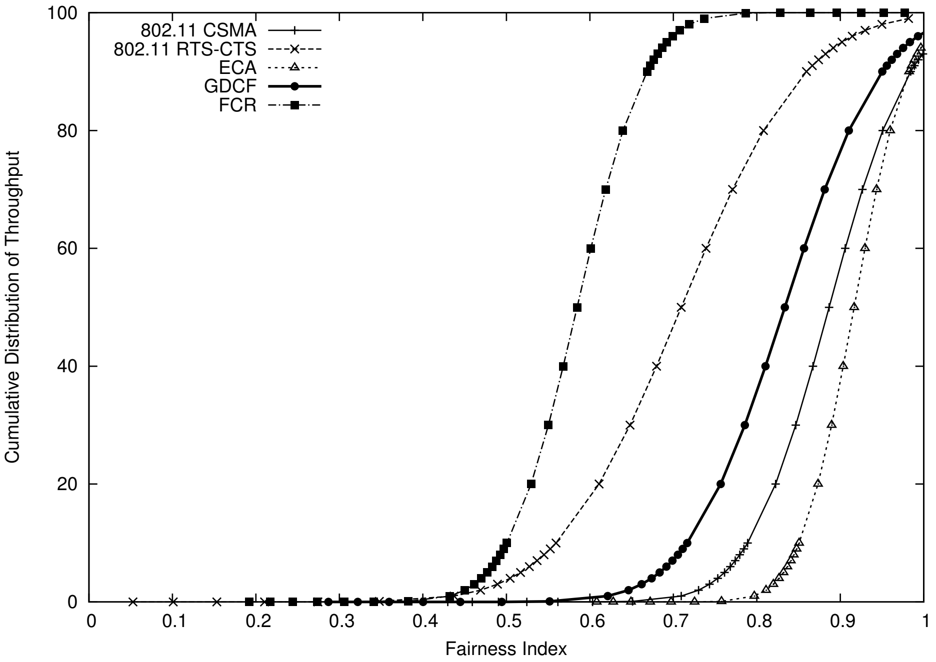

Figure 5.7: CDF of Jain's Fairness-Index

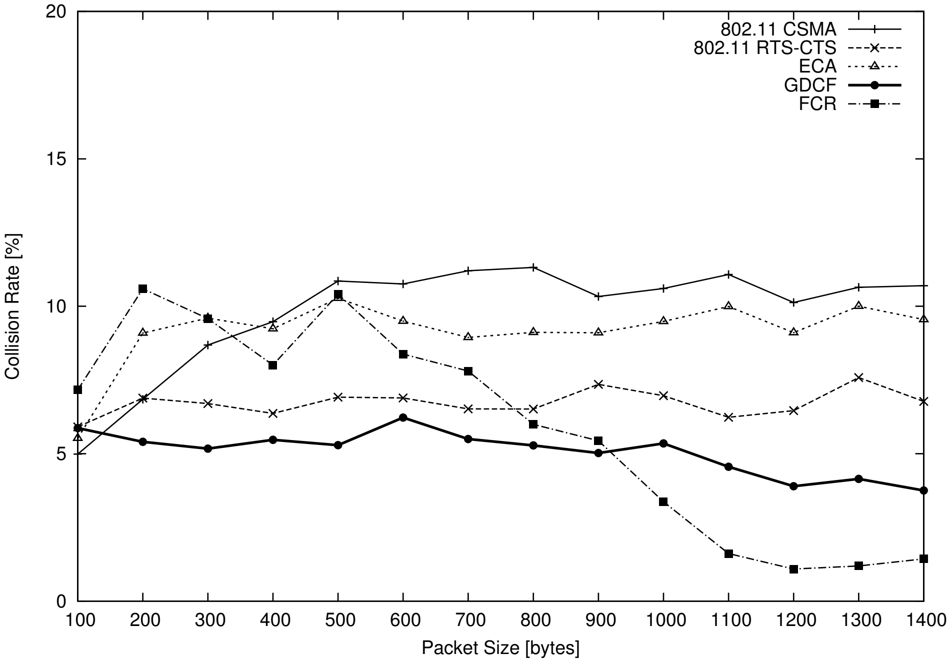

Figure 5.8: Collision Rate v/s Packet Size

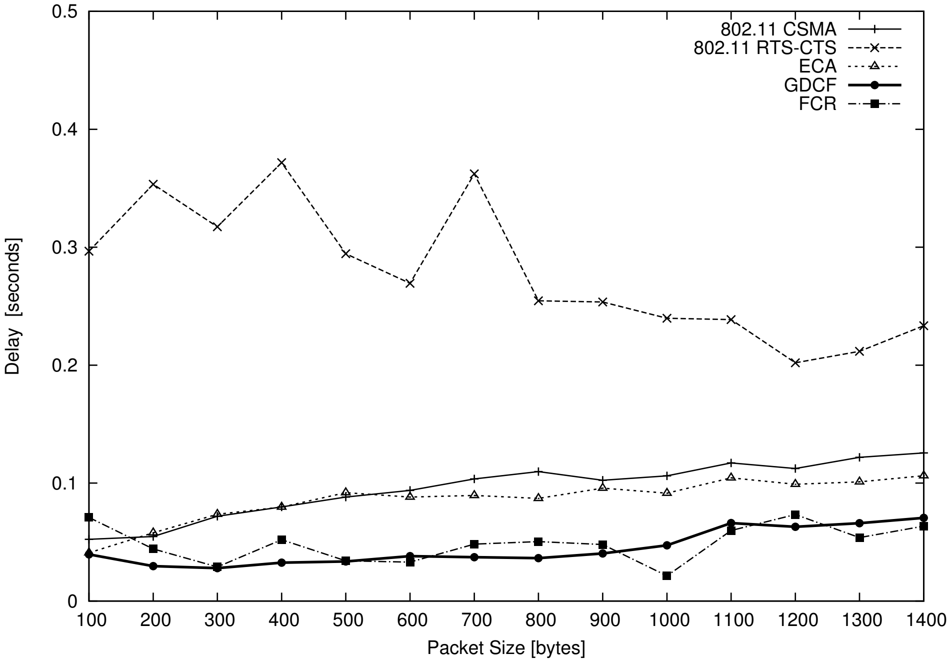

Figure 5.9: Mean Packet Delay vs Packet Size

5.1.5 Summary

Here we summarize the performance of all the schemes on a chain topology. A brief summary is shown in Table 5.3. The bold numerals are the minimum or maximum achieved values for the measured metrics. It was observed that ECA has the best fairness and FCR achieves best throughput. But overall, GDCF achieves the best performance with lowest delays, lowest collision rate, and a relatively good throughput and fairness performance.

Table 5.3: Summary of Performance for Chain Topology

Scheme	**Mean Delay**[ms]	**Collision Rate** [%]	**Throughput** [**Mbps**]	**Fairness**[%]
802.11 CSMA/CA	95.67	**9.83**	3.61	88.66
802.11 RT-CTS	**278.48**	6.72	**2.13**	70.95
ECA	86.21	9.18	3.69	**91.66**
GDCF	**44.86**	**5.08**	4.98	83.35
FCR	48.68	5.867	**5.17**	**58.47**

5.2 Pair Topology

This is a critical scenario where strong unfairness appears. It is based on the asymmetry between the pairs, and on the use of the EIFS delay. In this scenario, three pairs of communicating nodes are considered as shown in Figure 5.10. We consider that the adjacent senders are within transmission range. Here, A and E cannot hear each other. But as C is able to sort an understanding with both A and E, its flow should achieve a higher throughput than the other senders.

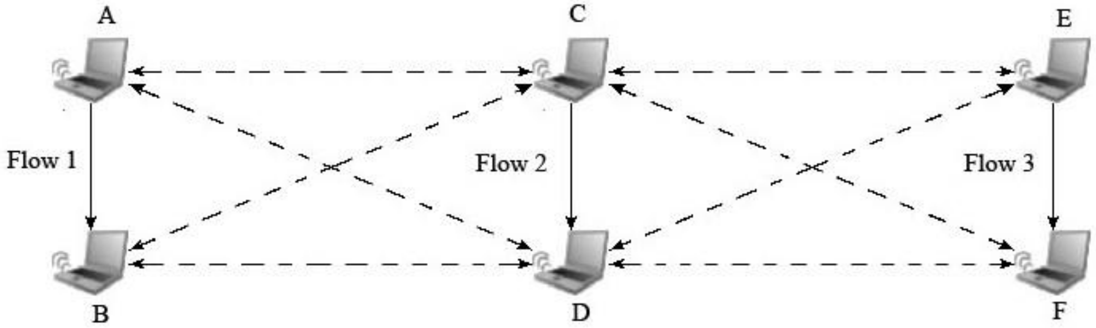

Figure 5.10: Three Pair Topology

The parameters for evaluation are given in Table 5.4. We used the same simulation settings used for the chain topology.

Table 5.4: Settings used for Pair Topology

Parameters	**Values**
Data Type	Constant Bitrate UDP
Messages generated per second	2000
Message Length	100-1400 bytes
Simulation Time	50 seconds

5.2.1 Throughput

The throughput performance for a three - pair topology is shown in Figure 5.11. GDCF shows the best throughput performace over the other schemes. It delivers an aggregate throughput of 3.83 Mbps, which is significantly better than the other schemes. The worst performer amongst the schemes is IEEE 802.11 with RTS-CTS, that delivers an aggregate throughtput of only 1.58 Mbps. A reservation mechanism is bound to deliver a lower throughput because of the delay it introduces. The delay performance of RTS-CTS confirms this.

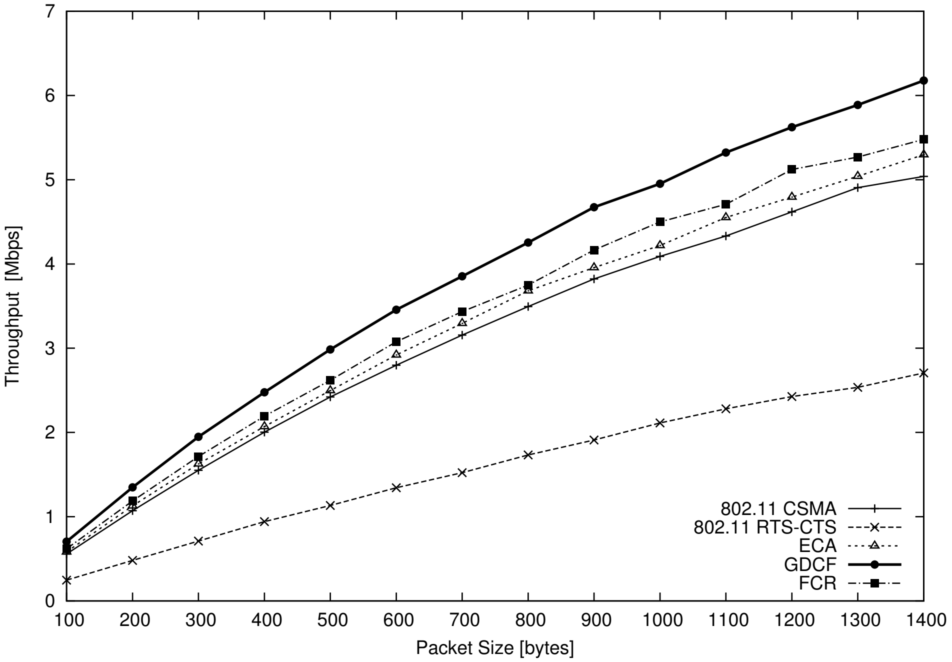

Figure 5.11: Relationship between throughput and the packet sizes

Figure 5.12 plots the throughput achieved by each flow for each scheme. ECA, with its deterministic backoff process, tries to stabilise the network and thus introduces fairness.

Figure 5.13 plots the cumulative distribution of aggregate throughputs for each scheme. It is clear from the distribution that the use of RTS-CTS mechanism degrades the performance of the system. About 80% of all flows receive less than 2 Mbps throughput for 802.11 with RTS-CTS. About 80% of all flows in GDCF receive more than 2 Mbps.

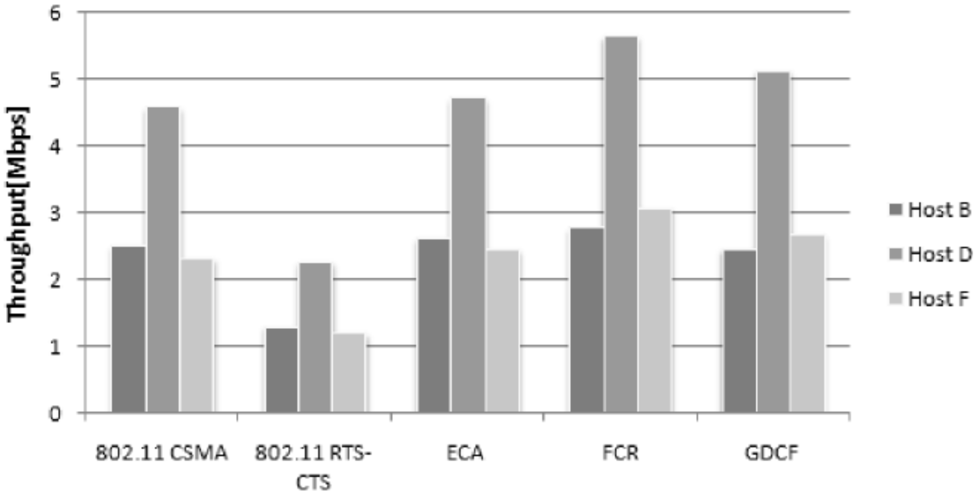

Figure 5.12: Throughput achieved at each node for each scheme

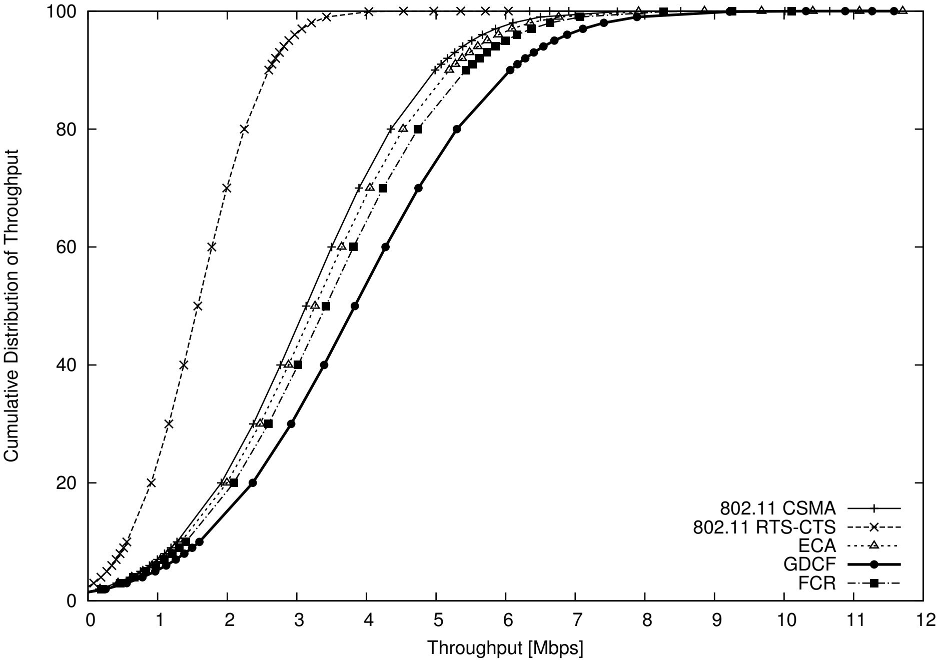

Figure 5.13: Relationship between throughput and the packet sizes

5.2.2 Fairness

For the three pair topology, the fairness provided by 802.11 CSMA/CA and 802.11 CSMA/ECA deliver similar fairness of about 88% fairness. Figure 5.14 shows that ECA delivers a better fairness comparable to CSMA/CA. GDCF and FCR trade off fairness for the throughput, but this trade-off is less when we consider the fairness of other schemes. They are only 5% lesser fair the other schemes.

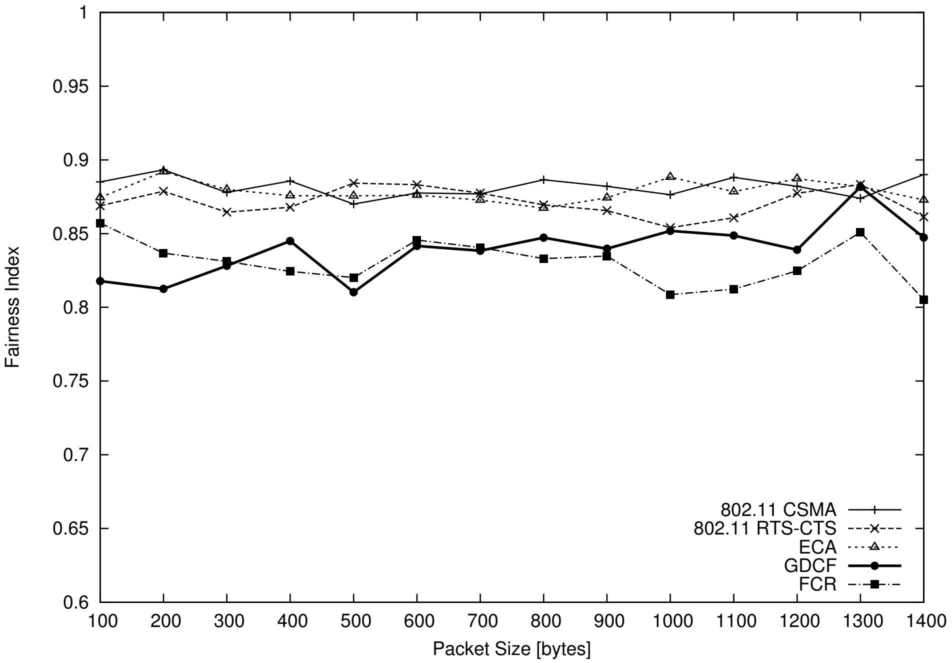

Figure 5.14: Fairness-Index as a function of Packet-size

Figure 5.15 plots the cumulative distribution of fairness index over various packet sizes. FCR introduces heavy unfairness. About 80% of the flows experience fairness less than 0.84 with FCR. The maximum fairness achieved by all these schemes is 0.9.

5.2.3 Collisions

Figure 5.16 illustrates the effect of the size of the packets on collisions rate. FCR is the worst performer when it comes to collisions in a pair topology. FCR's collision rate is almost double than the collision rate of 802.11 CSMA/CA. GDCF shows a very steady collision

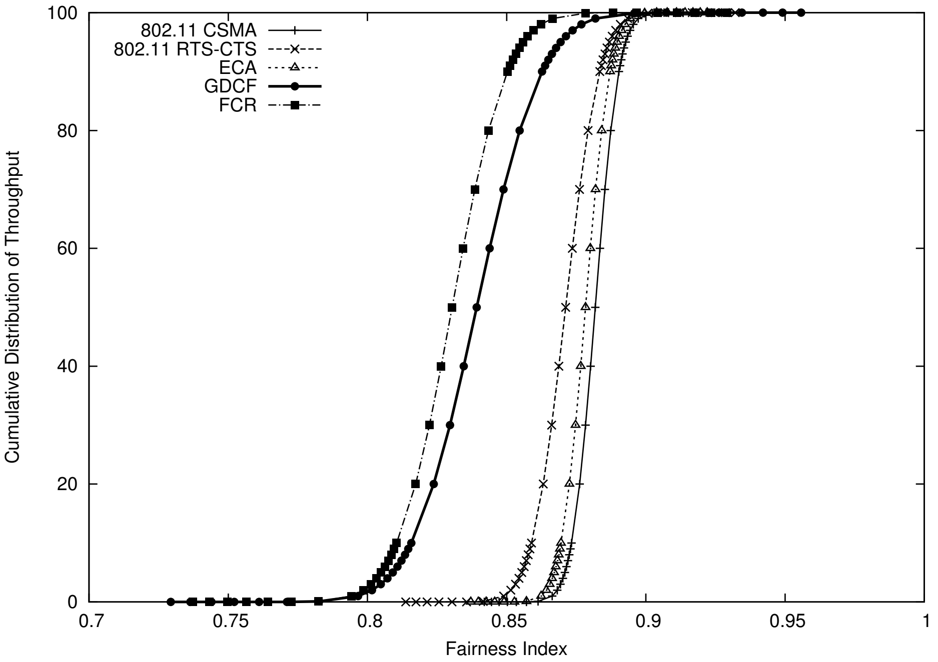

Figure 5.15: CDF of Jain's Fairness-Index

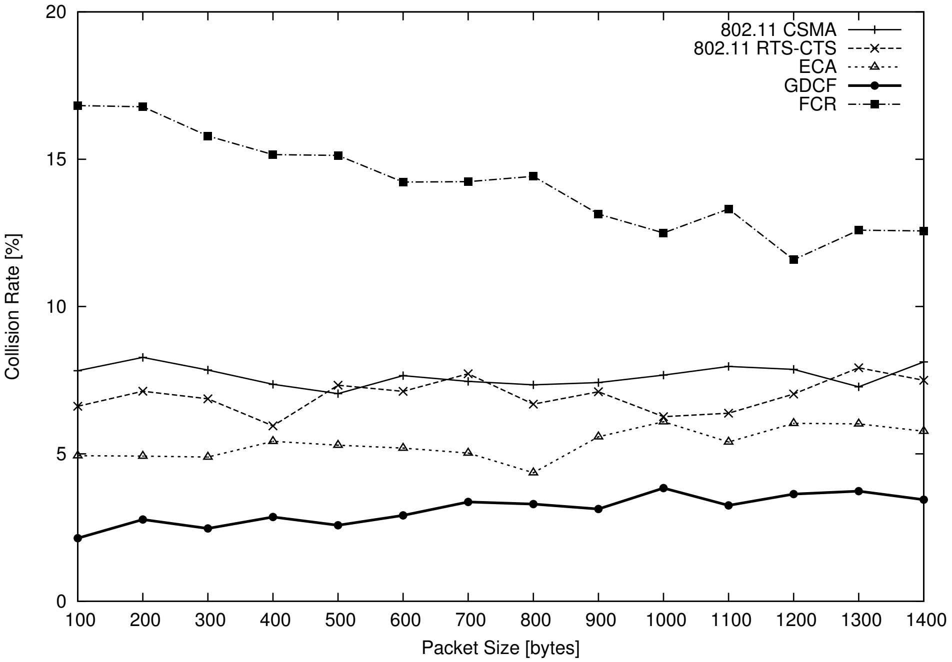

Figure 5.16: Collisions Rate v/s Packet Size

performance throughout the packet-size variation. In fact, it shows a better performance than CSMA/CA by nearly halving the overall number of collisions.

5.2.4 Packet Delay

The packet delay of these schemes as a function of packet-size is plotted on Figure 5.17. As expected, the RTS-CTS handshake degrades the delay performance. The average delay is 260 msec which has a bad impact on the overall throughput performance. But GDCF is seen to be much faster, as was expected. It shows a mean delay of 95 msec, nearly comparable to FCR's 97 msec. Both GDCF and FCR perform better than the legacy, reducing the overall delay by about 22

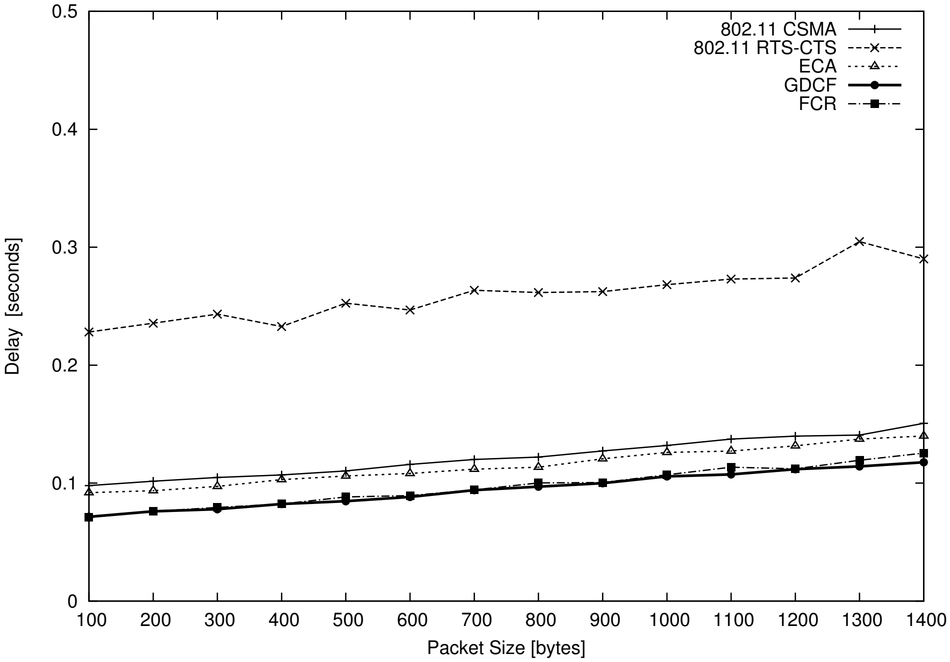

Figure 5.17: Mean Packet Delay v/s Packet Size

5.2.5 Summary

To summarize the behaviour of the schemes in a pair topology, we say that GDCF has shown promising performance with respect to delay, collisions, throughput and fairness. A brief summary is shown in Table 5.5. The bold numerals are the minimum and maximum achieved values for each metric.

Table 5.5: Summary of Performance for Pair Topology

Scheme	**Mean Delay**[ms]	**Collision Rate** [%]	**Throughput** [**Mbps**]	**Fairness**[%]
802.11 CSMA/CA	122	7.65	3.13	**88.18**
802.11 RT-CTS	**260**	6.97	**1.58**	87.12
ECA	115	5.35	3.26	87.83
GDCF	**95**	**3.10**	**3.83**	83.92
FCR	97	**14.16**	3.42	**83.04**

5.3 Random Topology

This is an arbitrary topology where stations are uniformly distributed. Each station can either be a sender or a receiver. The random placement algorithm places a station randomly such that one station has at least one station in its range. This ensures that the resource-wasting scenario is avoided and that the network is fully connected. We consideer 3 sub-scenarios for a random topology:

1. Low Density Random topology of 10 stations
2. Medium Density Random topology of 30 stations
3. High Density Random topology of 100 stations

The parameters set for evaluation purpose are provided in Table 5.6. We know that half of the stations are senders and the remainder are receivers.

Table 5.6: Settings used for Random Topology

Parameters	**Values**
Data Type	Constant Bitrate UDP
Messages generated per second	2000
Message Length	100-1400 bytes
Number of hosts	10,30 and100
Simulation Time	10 seconds
Playground Area	600m x 600m

5.3.1 Throughput

The throughput performance for the random topology based on density is shown in Figures 5.18, 5.19, and 5.20. GDCF delivers the best throughput, with an aggregate throughput of 1.56 Mbps, 0.26 Mbps and 0.1 Mbps for low, medium and high density topology respectively. GDCF performs 42% better than the basic access method for low density and 13% better for medium density. Also observed is that IEEE 802.11 with RTS-CTS performs terribly, with a degradation of around 40% in all the three cases.

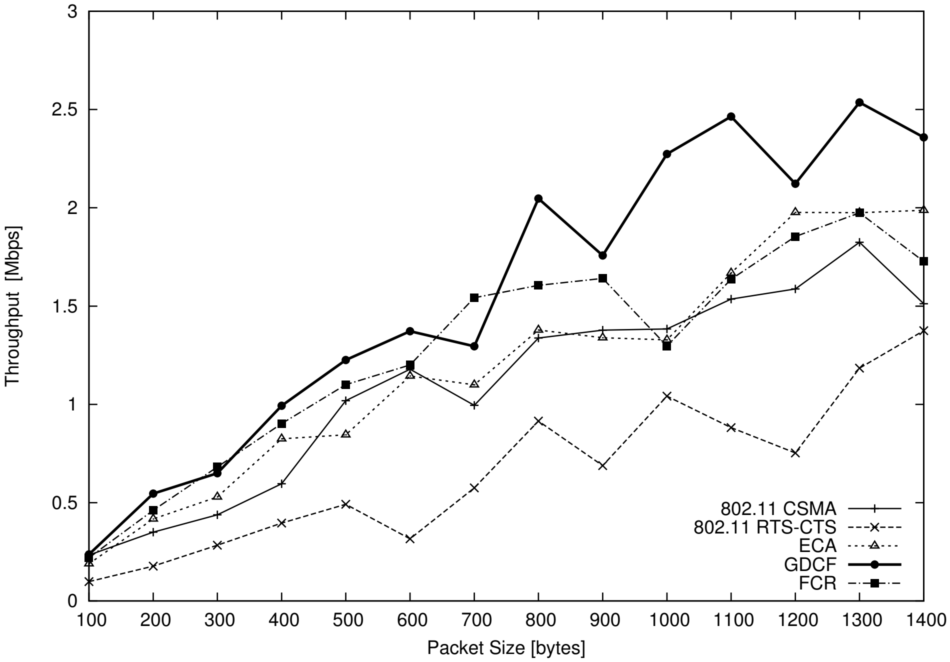

Figure 5.18: Throughput vs packet sizes (Low Density)

Figures 5.21, 5.22, and 5.23 plot the cumulative distribution of aggregate throughputs in low, medium and high desity topology respectively. The distribution indicates that GDCF performs best and the RTS-CTS mechanism performs worst.

5.3.2 Fairness

The fairness for the three densities are plotted in Figures 5.24, 5.25, and 5.26. As the number of nodes increases, the fairness of the 802.11 basic access method is better than

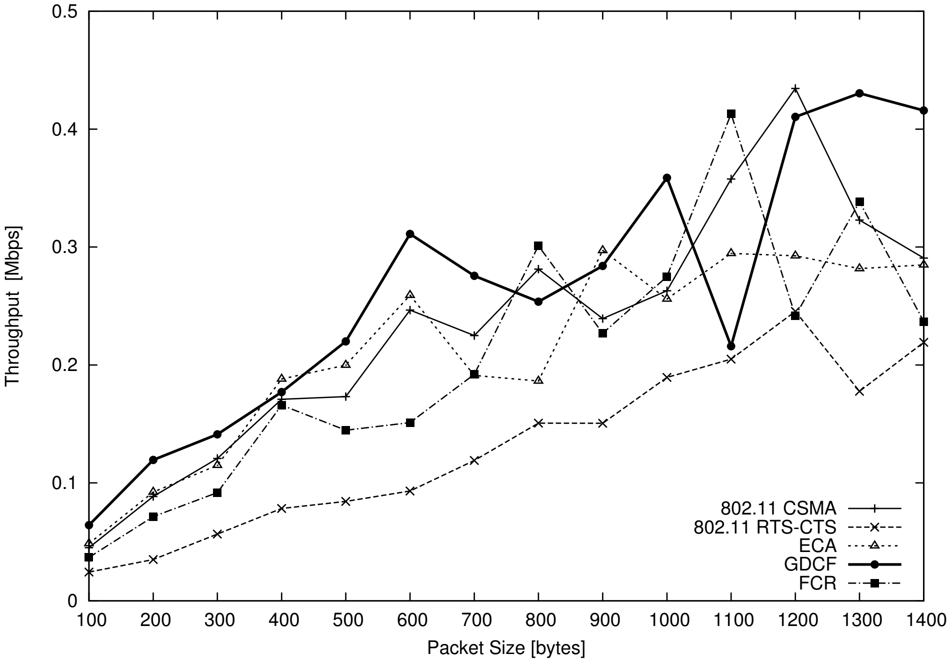

Figure 5.19: Throughput vs packet sizes (Medium Density)

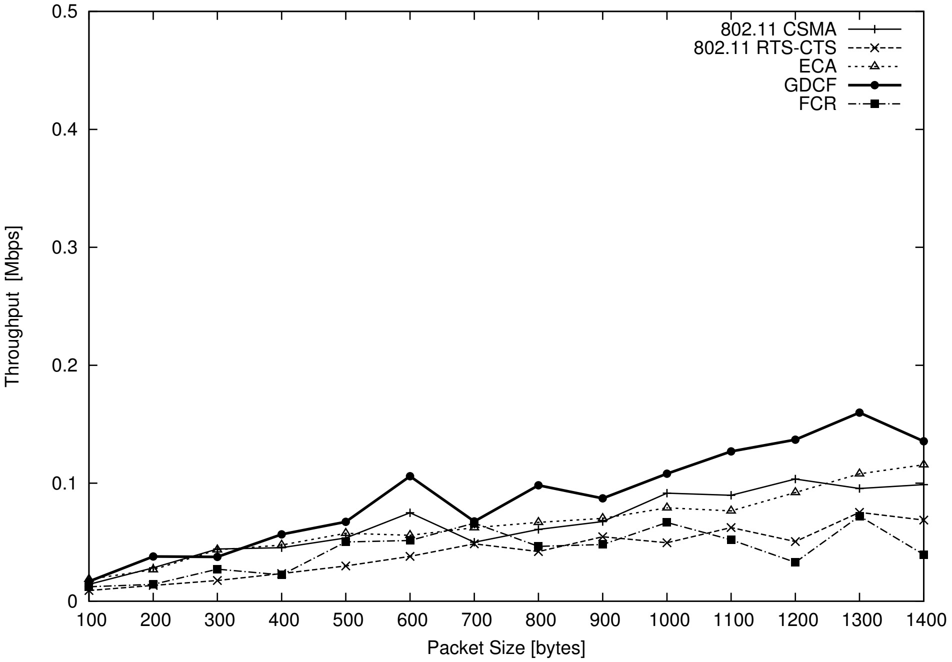

Figure 5.20: Throughput vs packet sizes (High Density)

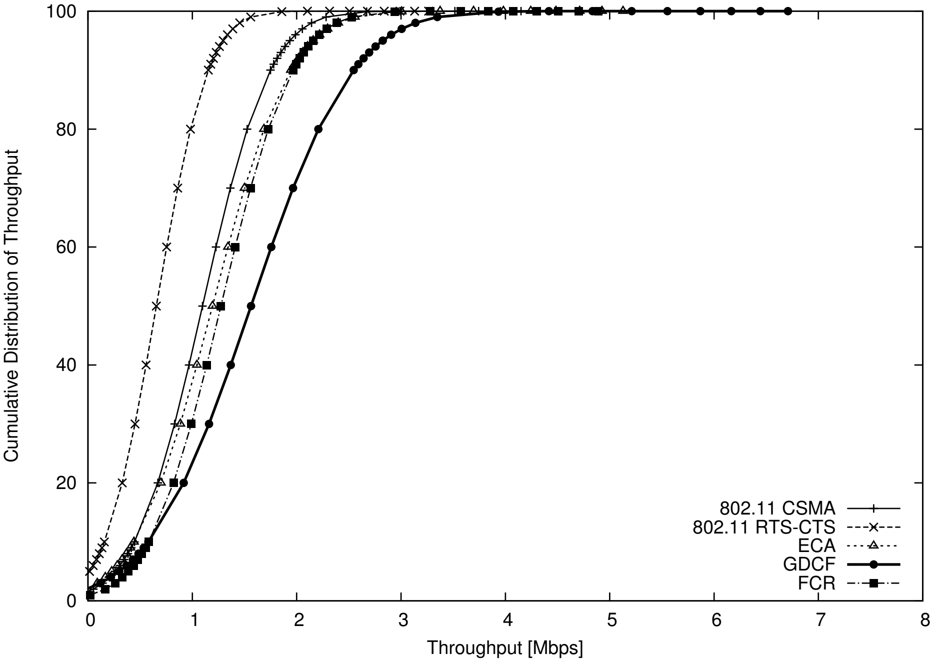

Figure 5.21: Throughput CDF (Low Density)

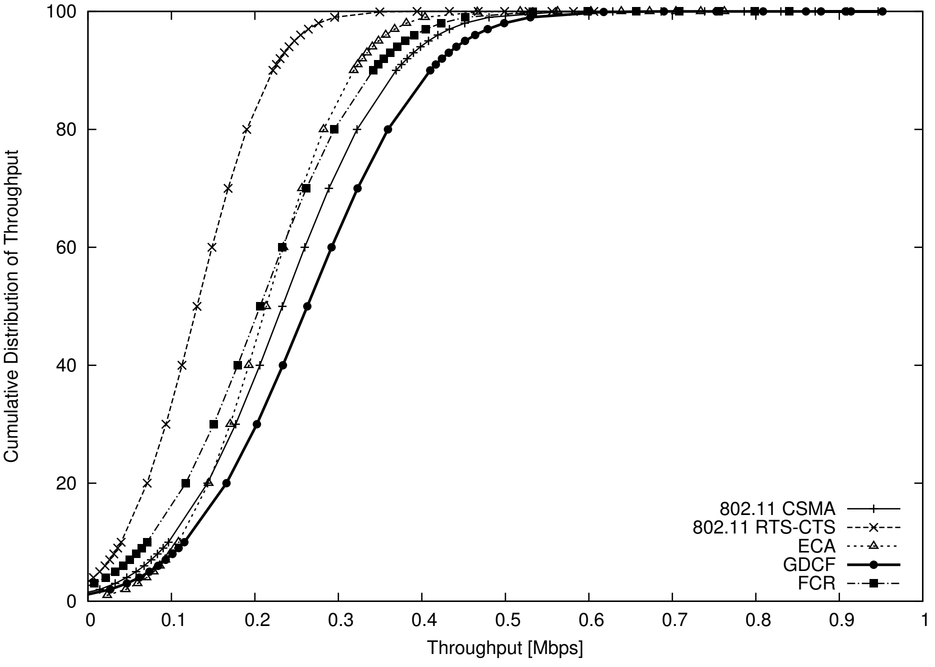

Figure 5.22: Throughput CDF (Medium Density)

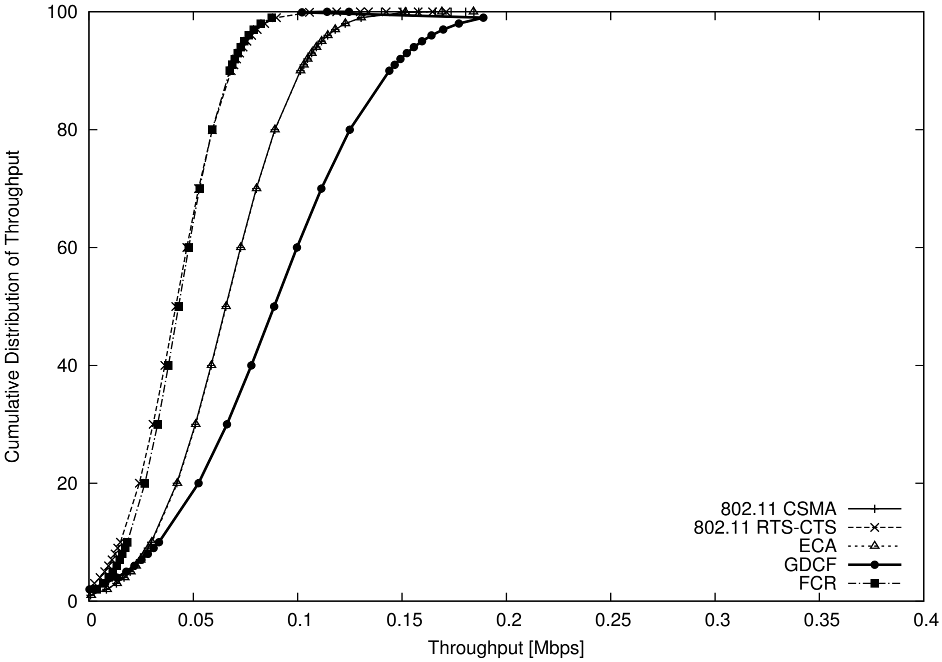

Figure 5.23: Throughput CDF (High Density)

the rest, but at the same time we can see that the performance of ECA and GDCF is close. GDCF gives a 51% fairness for low density, 28.81% fairness for medium density and 28.81% fairness for high density.

Figures 5.27, 5.27, and 5.27 show the cumulative distribution of fairness indexes. As mentioned earlier, the IEEE 802.11 basic access method has more fairness in all the three random scenarios, similar to GDCF's.

5.3.3 Collisions

When it comes to collisions, FCR is the worst performer in all the three random scenarios. FCR has almost twice the number of collision as the best performer in those scenarios. Figure 5.30, 5.31, and 5.32 shows the collision performance of the schemes in our random topologies.

FCR's bad performance is clearly shown in the cumulative plots in Figure 5.33, 5.34, and 5.35.

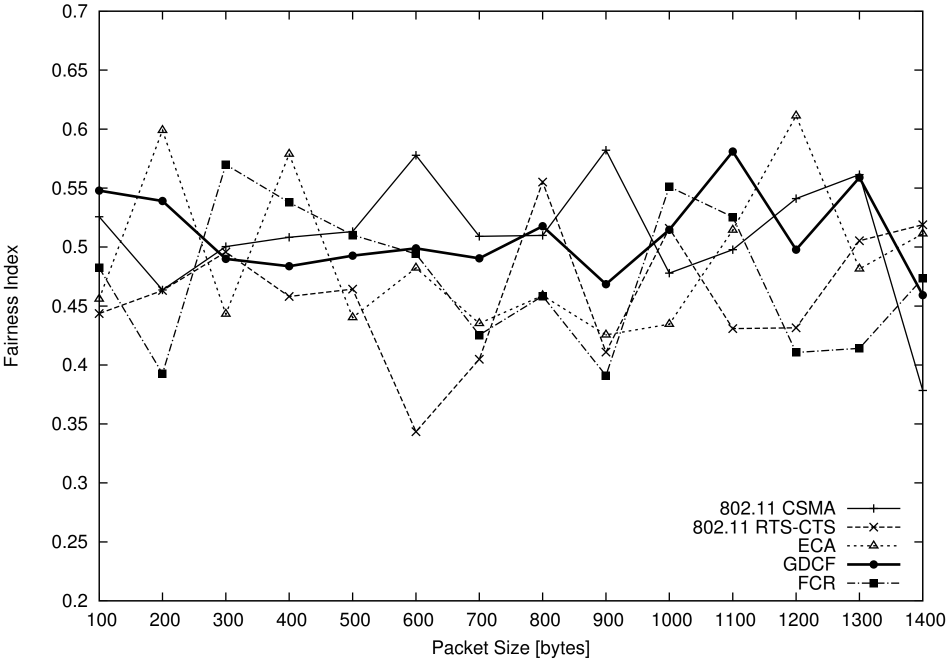

Figure 5.24: Fairness-Index as a function of Packet-size (Low Density)

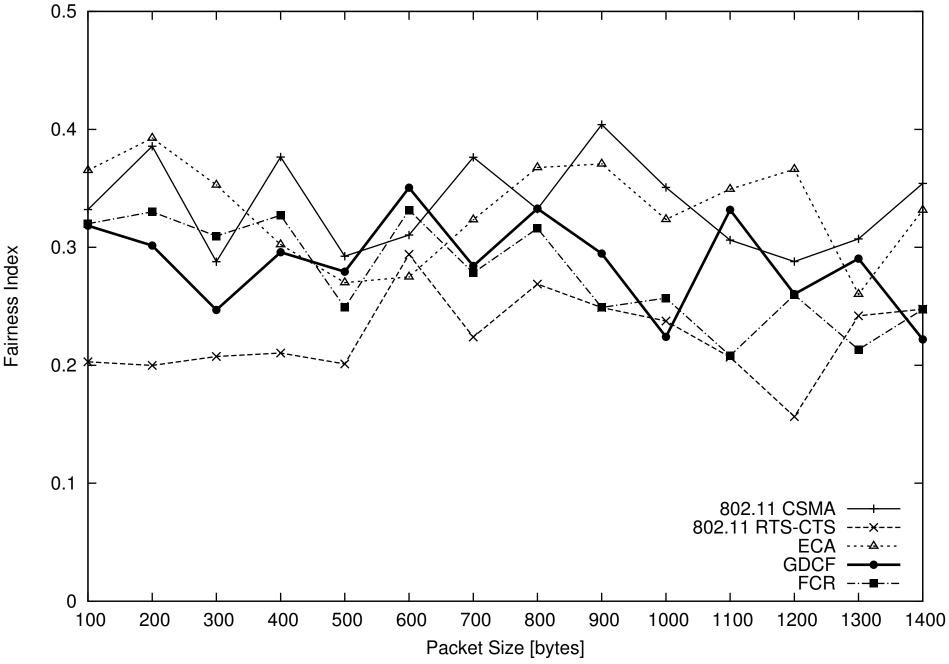

Figure 5.25: Fairness-Index as a function of Packet-size (Medium Density)

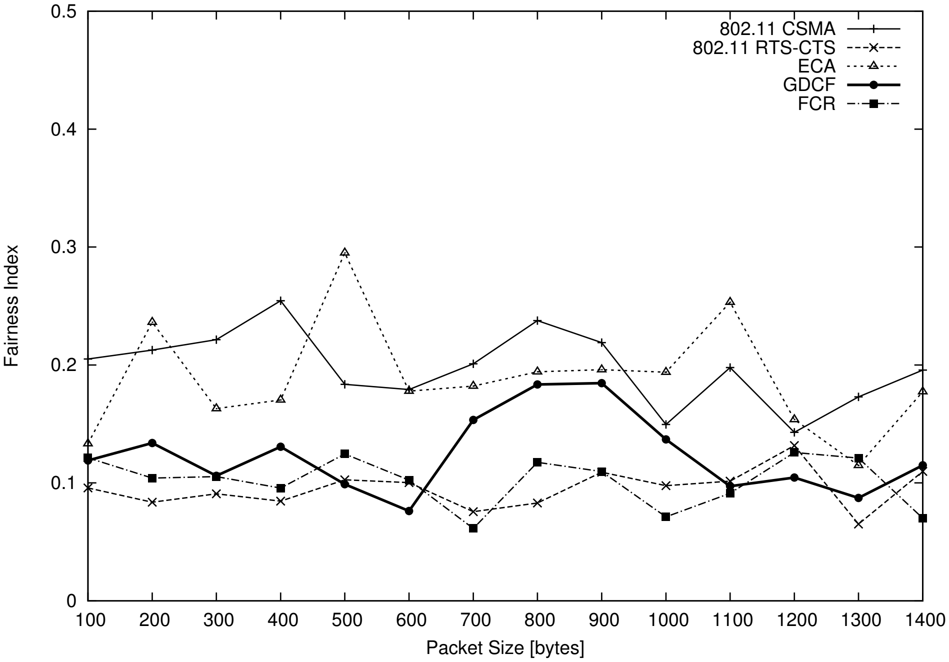

Figure 5.26: Fairness-Index as a function of Packet-size (High Density)

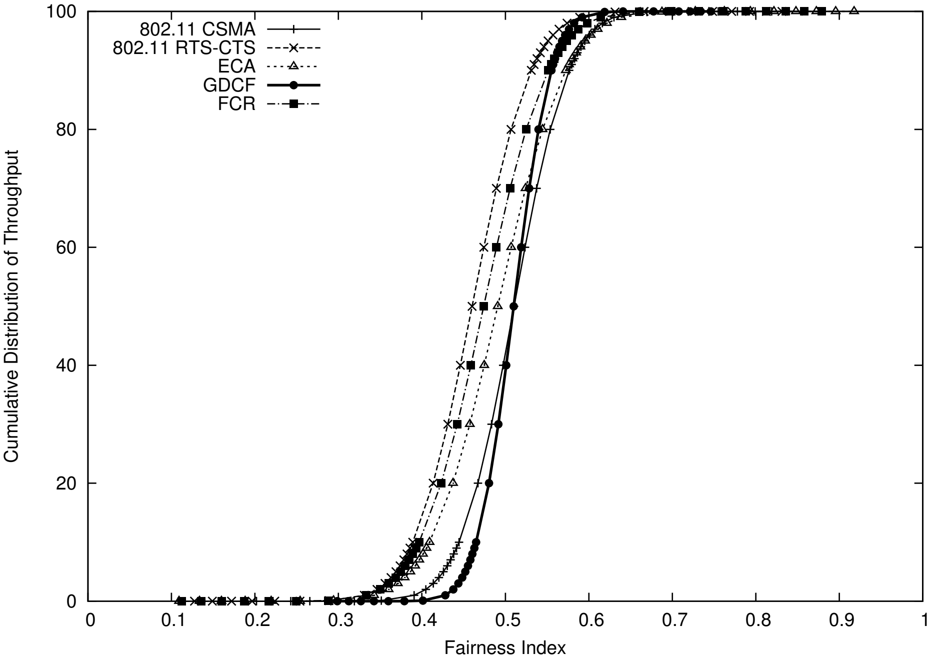

Figure 5.27: CDF of Fairness Index (Low Density)

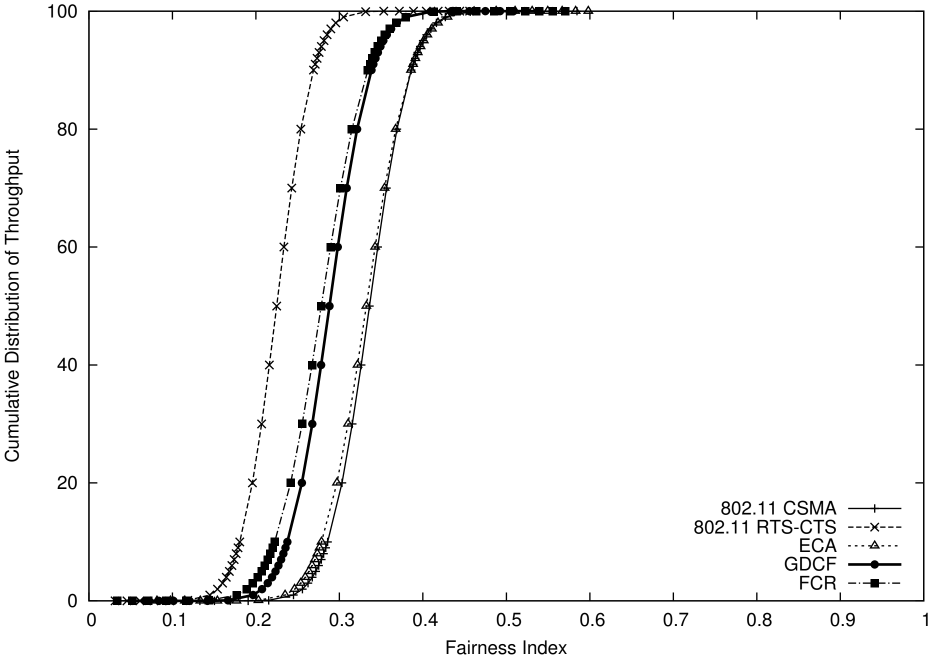

Figure 5.28: CDF of Fairness Index (Medium Density)

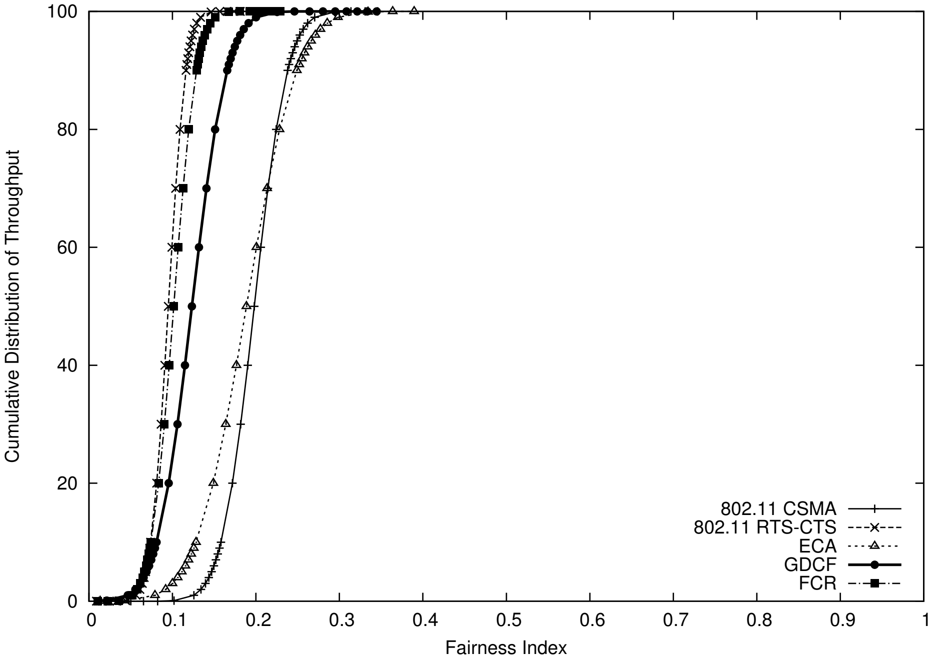

Figure 5.29: CDF of Fairness Index (High Density)

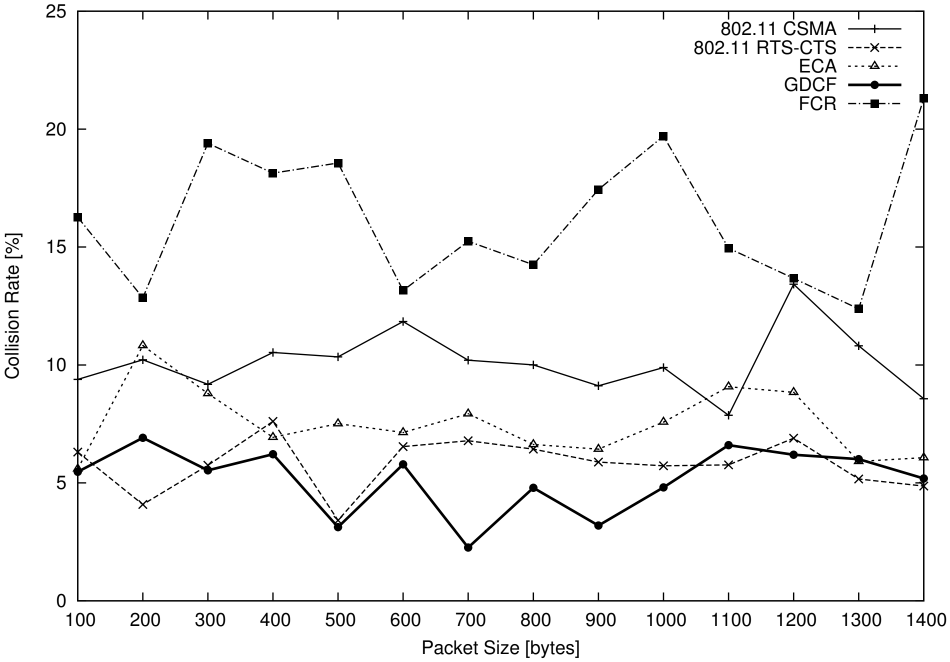

Figure 5.30: Collision Rate v/s Packet Size (Low Density)

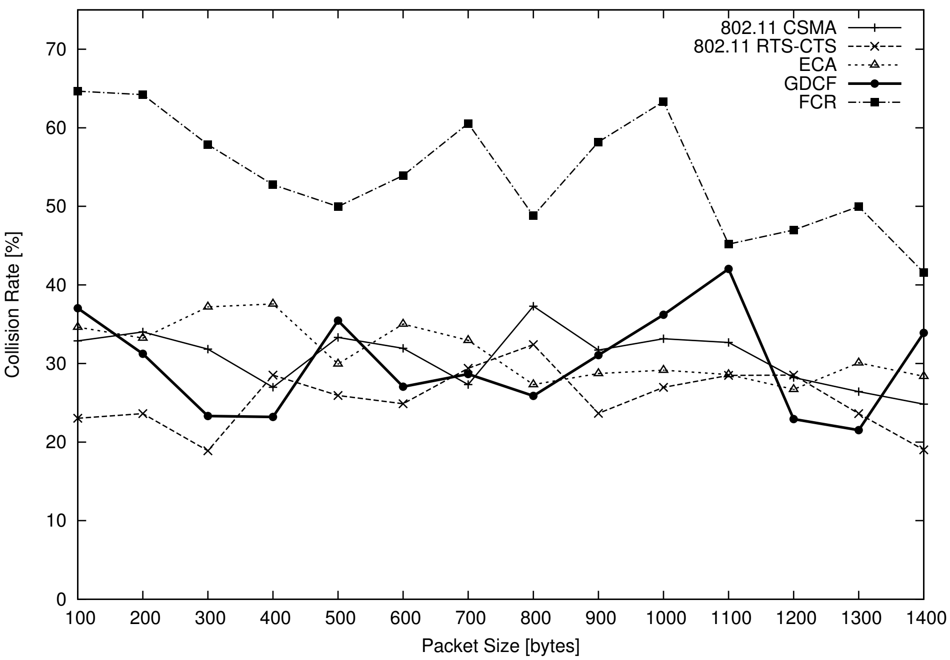

Figure 5.31: Collision Rate v/s Packet Size (Medium Density)

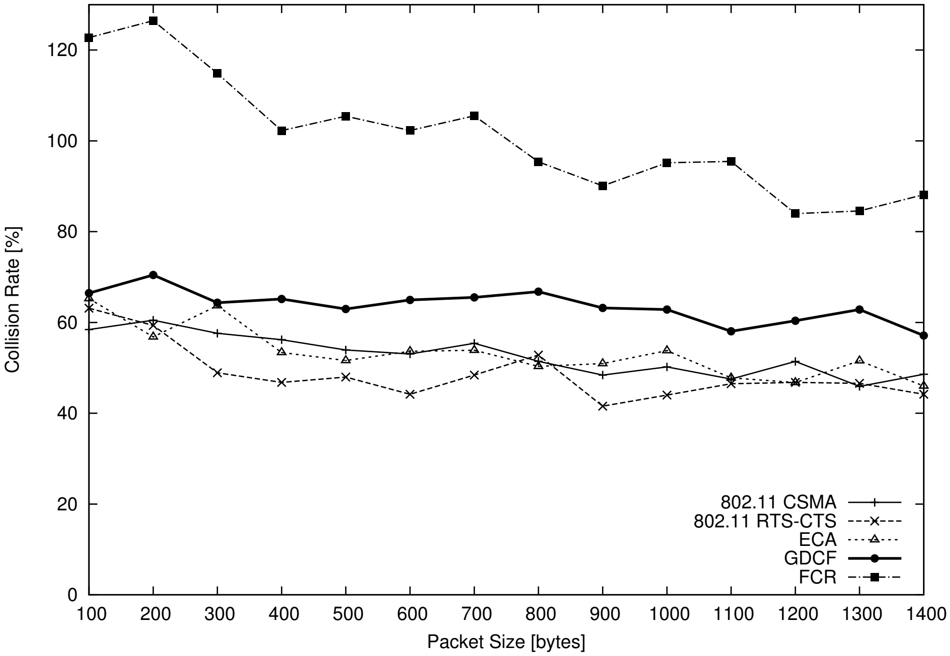

Figure 5.32: Collision Rate v/s Packet Size (High Density)

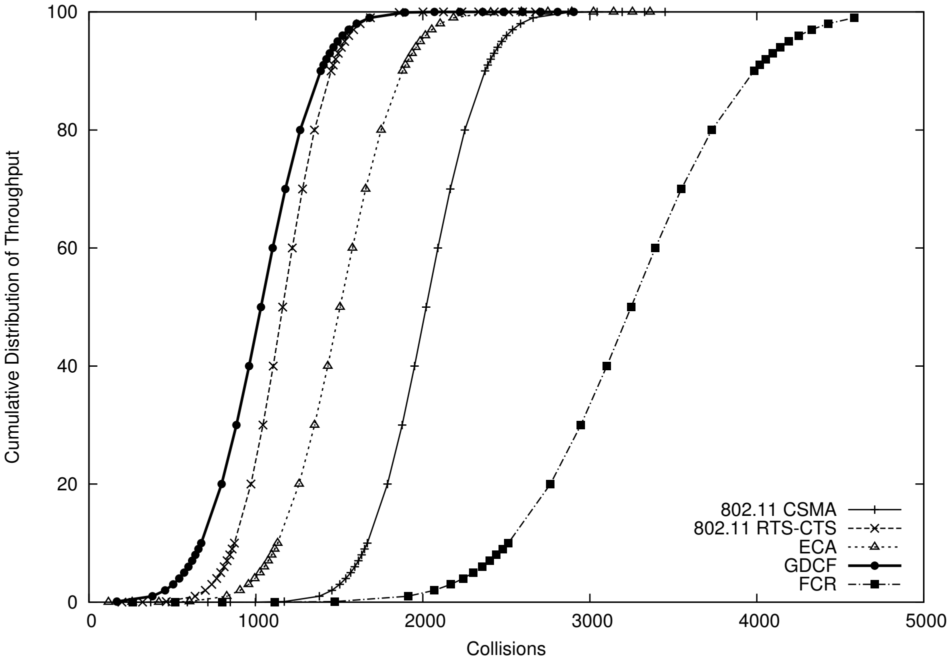

Figure 5.33: CDF of Average Collisions (Low Density)

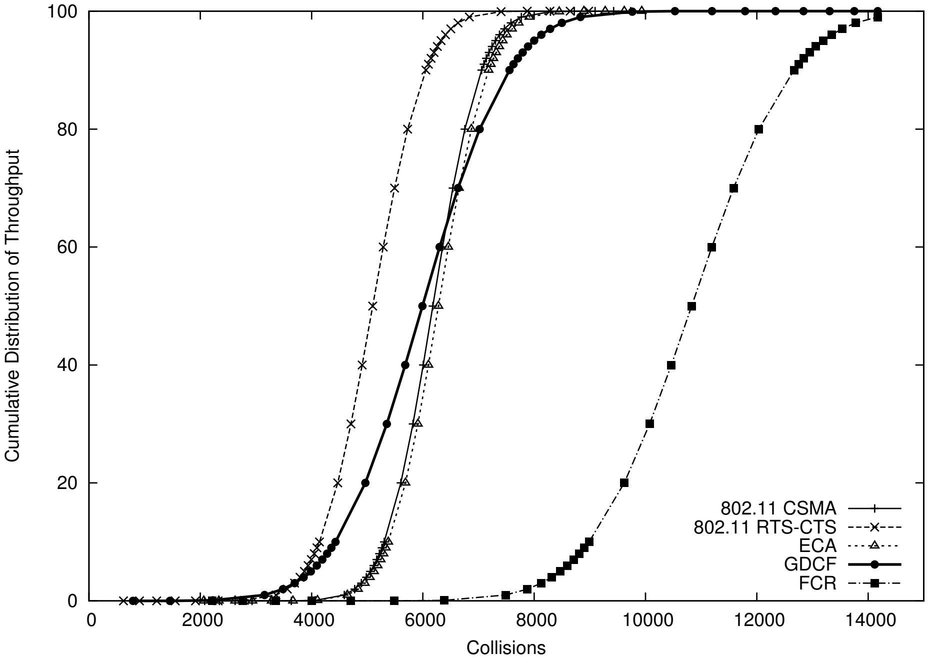

Figure 5.34: CDF of Average Collisions (Medium Density)

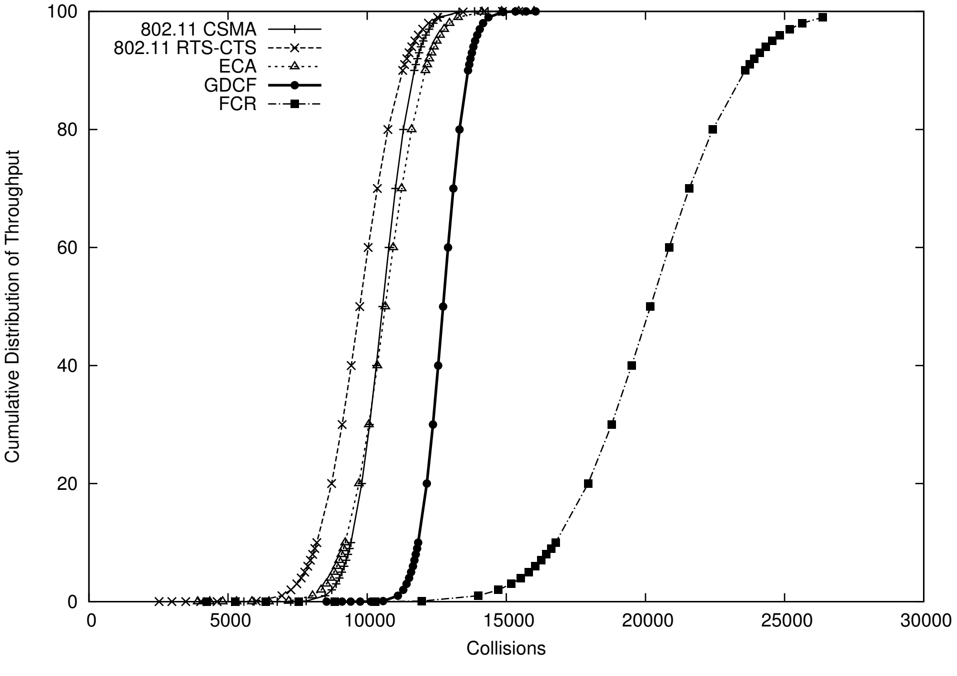

Figure 5.35: CDF of Average Collisions (High Density)

5.3.4 Packet Delay

The packet delay of these schemes as a function of packet-size is shown Figures 5.36, 5.37, and 5.38. The RTS-CTS experience higher delays in all the three cases. FCR showed a relatively lower delay as compared to the rest of the schemes.

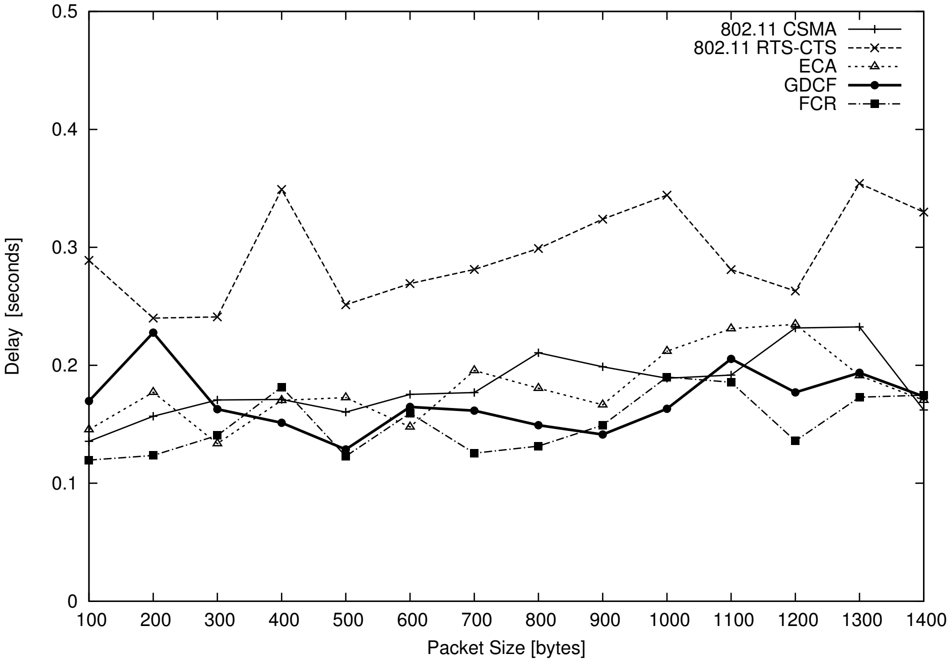

Figure 5.36: Mean Packet Delay v/s Packet Size (Low Density)

Figure 5.39, 5.40, and 5.41 clearly shows how the reservation scheme performs when we consider the mean delay.

5.3.5 Summary

A brief summary for the random topologies is shown in Table 5.7, 5.8, and 5.9. FCR shows high number of collisions but has a good delay performance. On the other hand GDCF achieves comparatively higher throughput, lower collisions and a better fairness. The bold numerals are the minimum and maximum achieved values for each metric.

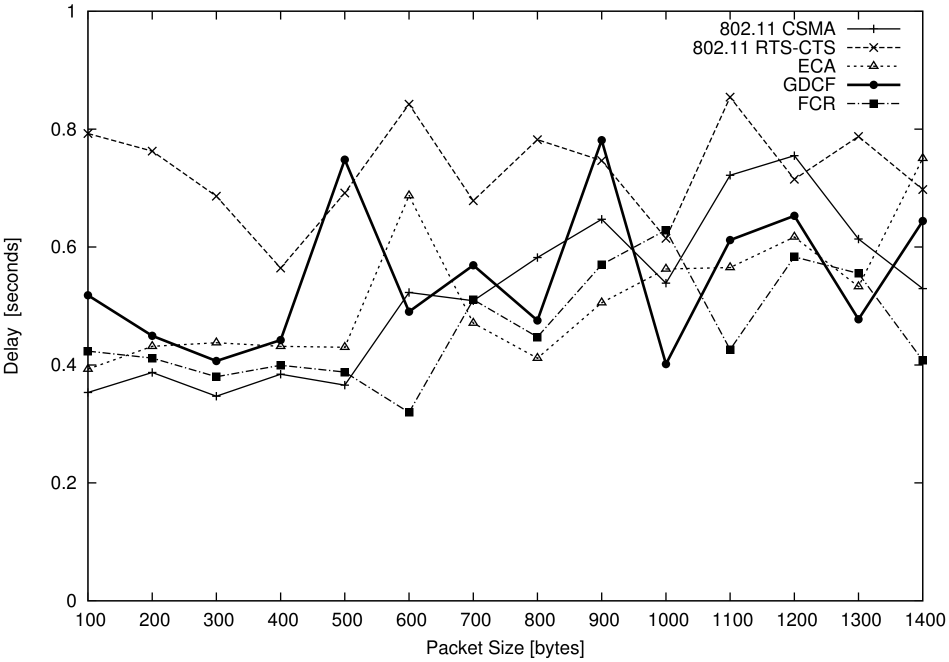

Figure 5.37: Mean Packet Delay v/s Packet Size (Medium Density)

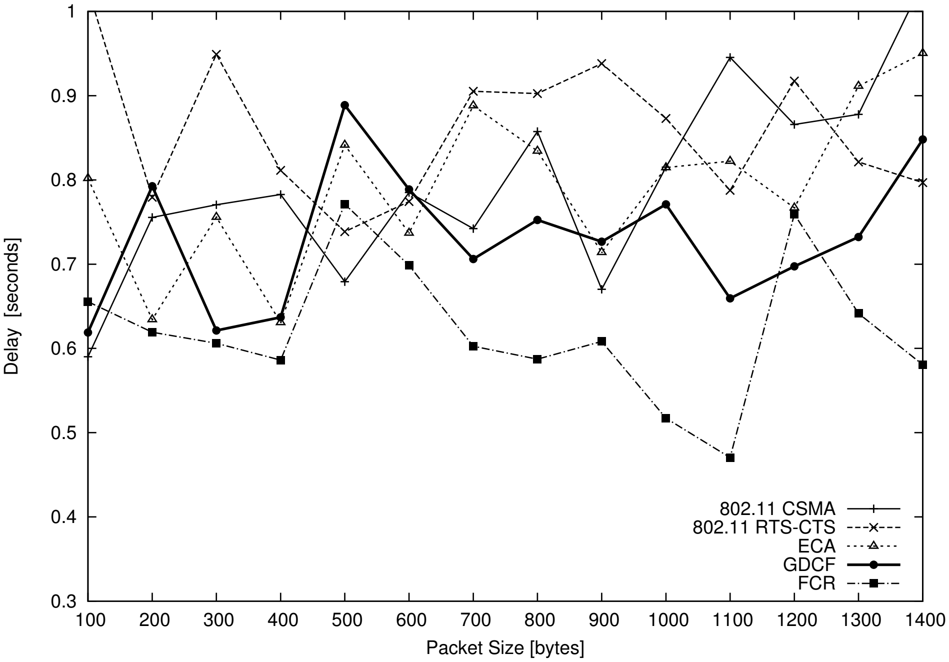

Figure 5.38: Mean Packet Delay v/s Packet Size (High Density)

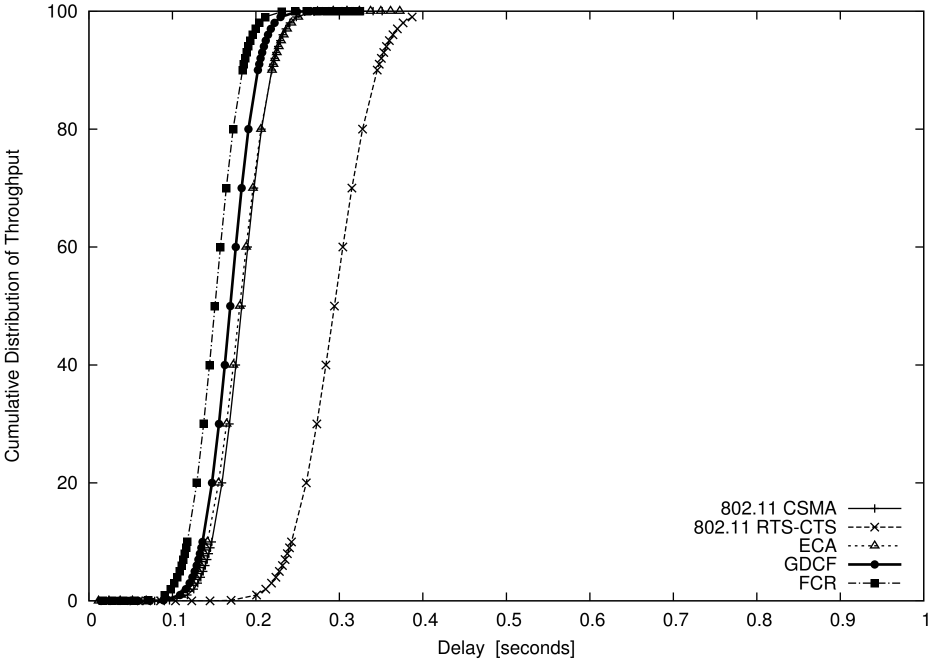

Figure 5.39: CDF of Mean Delay (Low Density)

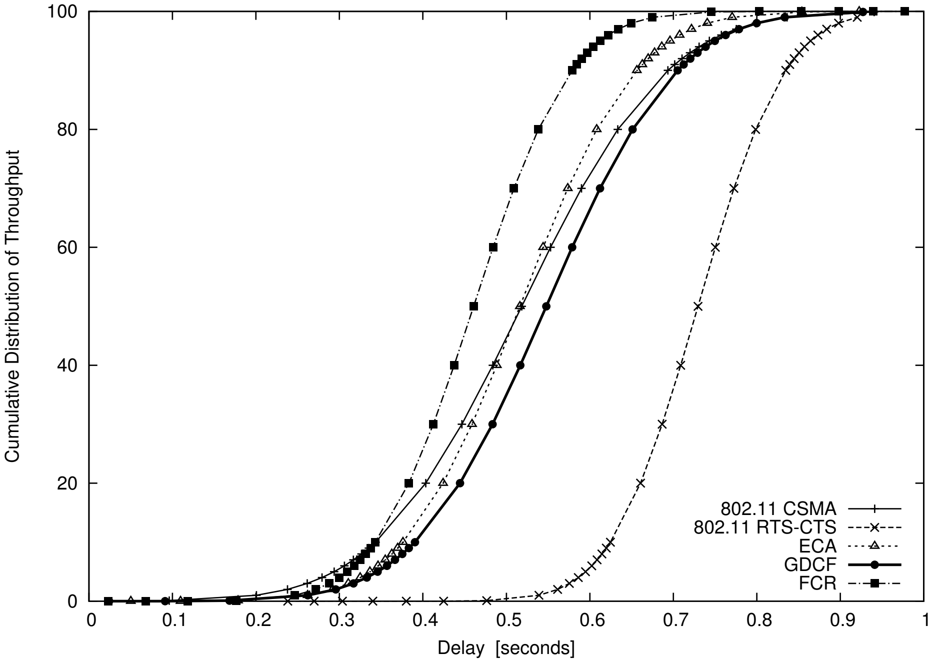

Figure 5.40: CDF of Mean Delay (Medium Density)

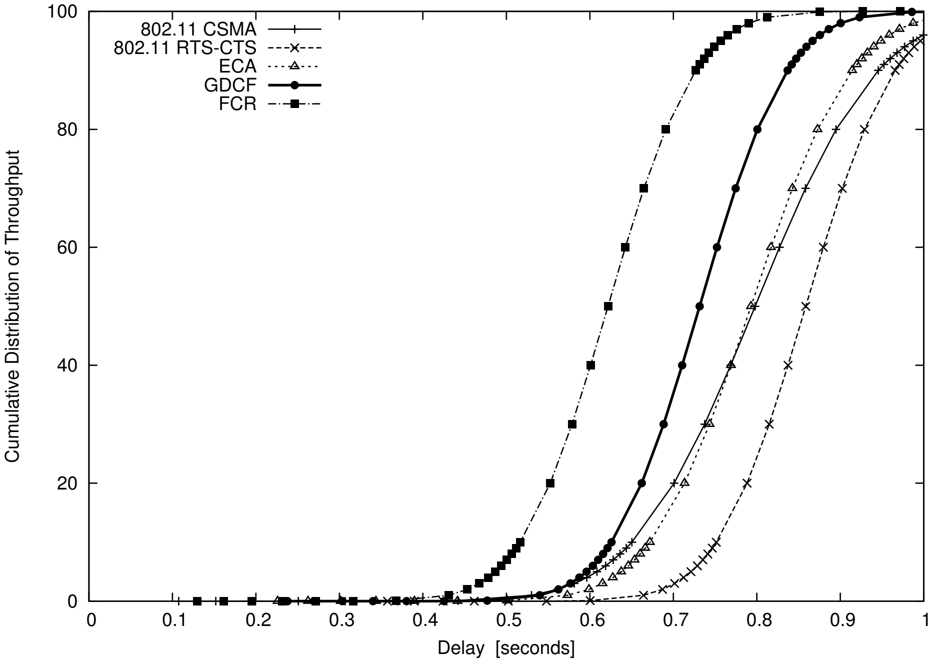

Figure 5.41: CDF of Mean Delay (High Density)

Table 5.7: Summary of Performance for Low Density Random Topology

Scheme	**Mean Delay**[ms]	**Collision Rate** [%]	**Throughput** [Mbps]	**Fairness**[%]
802.11 CSMA/CA	183.06	10.10	1.01	**51.05**
802.11 RT-CTS	**294.01**	5.80	**0.66**	**46.01**
ECA	180.63	7.52	1.19	49.08
GDCF	169.26	**5.15**	**1.56**	51.00
FCR	**150.92**	**16.27**	1.27	47.41

Table 5.8: Summary of Performance for Medium Density Random Topology

Scheme	**Mean Delay**[ms]	**Collision Rate** [%]	**Throughput** [Mbps]	**Fairness**[%]
802.11 CSMA/CA	518.40	30.90	0.23	**33.6**
802.11 RT-CTS	**729.66**	**25.50**	**0.13**	**22.48**
ECA	516.24	31.40	0.21	33.22
GDCF	547.78	29.97	**0.26**	28.81
FCR	**460.81**	**54.14**	0.21	27.83

Table 5.9: Summary of Performance for High Density Random Topology

Scheme	**Mean Delay**[ms]	**Collision Rate** [%]	**Throughput** [Mbps]	**Fairness**[%]
802.11 CSMA/CA	797.96	52.76	0.0656	**19.81**
802.11 RTS-CTS	**858.62**	**48.66**	**0.0416**	**9.51**
ECA	793.07	53.25	0.0657	18.87
GDCF	731.48	63.64	**0.09**	12.34
FCR	**621.71**	**100.88**	0.0429	10.15

Chapter 6

Concluding remarks

In this thesis, we first descirbed some of the problems associated with a wireless network. We described the *hidden/exposed terminal* problem that leads to collisions. We also looked at the fairness issue and the limitations of the throughput achieved by a 802.11 MAC layer. Then, we surveyed the schemes that address these problems and studied the evolution of these schemes and their limitations.

We also proposed a classification of collision avoidance schemes to enable our readers understand the variables that lead to these problems and the ways in which they can be resolved. We also study and evaluate three schemes (ECA, FCR and GDCF), selected from one of the five categories in our classification. To provide a rigorous evaluation, we simulate them in a chain, pair, and random topology. The metrics that we measured are throughput, fairness, collision rate and mean packet delay. We compare the performance of these schemes against the legacy 802.11 DCF.

In our evaluation, we observed that GDCF performs better than the other protocols. GDCF delivers an improved throughput, an optimal fairness and a low collision rate. The wild oscillations of the Binary Exponetial Backoff (BEB) has been reduced in GDCF. BEB is a very aggressive approach. It reduces the backoff counter to its minimum value immediately upon a successful transmission. This large variations in the backoff counter after every successful transmission increases the probability of contention. GDCF applies a minor adjustment to the backoff computation by halving the backoff counter after a fixed number of consecutive successful transmissions. This improves the efficiency of MAC layer and hence the entire network.

Readers are encouraged to study the other schemes too. We have demonstrated that each scheme has its own speciality and can outperform the rest in particular scenarios, and hence these schemes can be adopted based on the application requirements.

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