Performance Analysis of Relay based Cooperative MAC Protocols

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To my parents, wife and two daughters

Abstract

The incessant demand for access to information at 'anytime' and 'anywhere' has motivated researchers to look into Next Generation Networks (NGNs) which will be a of platform for co-existence of different technologies. Ad Hoc Networks (AHNs) being a vital component of the NGNs still need to address challenges such as throughput, energy consumption, latency and time varying channel conditions. Considering the drive to 'go green' and vendors' commitments to reduce their energy emissions, NGNs must be environmentally friendly, and this underpins the importance of energy conservation. Cooperative communications has emerged as a promising solution which exploits the broadcast nature of wireless networks to yield higher throughput, achieve lower energy consumption, increase network lifetime and provide network resilience.

This thesis aims at contributing to the field of cooperative AHNs. The focus of this research is on the relay based MAC layer: design of cooperative MAC protocols, performance modelling, and protocol enhancements. The first contribution of this thesis is dedicated to the modelling of energy consumption which aids MAC protocol developers in the design phase to devise efficient protocols and energy saving solutions. This model can predict energy consumption in an ideal and non-ideal environment. It is shown that using a relay results in not only better throughput but also higher energy efficiency. In the next contribution, we propose an Enhanced relay-enabled Distributed Coordination Function (ErDCF), which uses high data rate nodes to work as relays for the low data rate nodes. ErDCF in saturation achieves higher throughput, lower delay and lower energy consumption as compared to conventional 802.11 Distributed Coordination Function (DCF) in ideal conditions. The performance of ErDCF under

non-ideal condition is evaluated and it proves that the gain of ErDCF can still be maintained under reasonable link quality and distance. Finally a multiple relay MAC protocol is proposed and its performance is evaluated. The results confirm the throughput advantage of multiple relays, but they also show that beyond two relays the throughput gain becomes increasingly marginal due to the cost of higher overhead.

Declaration

"I, Rizwan Ahmad, declare that the PhD thesis entitled "Performance Analysis of relay based cooperative MAC protocols" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature   Date

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Abbreviations

2PSP	2-Hop Path Selection Protocol
3G	Third Generation
4G	Fourth Generation
ACK	Acknowledgement
AF	Amplify and Forward
AHN	Ad Hoc Network
AP	Access Point
AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSS	Basic Service Set
CDMA	Code Division Multiple Access
CD-MAC	Cooperative Diversity MAC
CF	Compress and Forward
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-To-Send
CW	Contention Window
DARPA	Defense Advanced Projects Agency
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame
DF	Decode and Forward
DSSS	Direct Sequence Spread Spectrum
DSTBC	Distributed Space Time Block Coding
EIFS	Extended Inter Frame
EMR	Efficient Multi-rate Relying
ErDCF	Enhanced relay-enabled Distributed Coordination Function
FDMA	Frequency Division Multiple Access

FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
IBSS	Independent Basic Service Set
IR	Infra Red
ISM	Industrial, Scientific and Medical
LLC	Logical Link Control
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MANET	Mobile Ad hoc Network
MrMAC	Multiple relay Medium Access Control
NAV	Network Allocation Vector
NGN	Next Generation Network
OFDM	Orthogonal Frequency Division Multiplexing
ORAS	Opportunistic-Relay-Agrees-to-Send
ORP	Opportunistic Relay Protocol
OSI	Open System Interconnection
PCF	Point Coordination Function
PCS	Physical Carrier Sensing
PDA	Personal Digital Assistant
PDP	Packet Drop Probability
PDT	Packet Drop Time
PLCP	Physical layer convergence procedure
PMD	Physical Medium Dependant
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAMA	Relay-Aided Medium Access
RAS	Relay-Agrees-to-Send
RBAR	Receiving-based Auto Rate
RCTS	Relay-Clear-To-Send
rDCF	relay-enabled Distributed Coordination Function
RRTS1	Relay-Ready-To Send1
RRTS2	Relay-Ready-To Send2
RSSI	Receiver Signal Strength Indication

RTR	Ready-To-Relay
RTS	Ready-To-Send
SBI	Short Backoff Internal
SIFS	Short Inter Frame
SINR	Signal-to-Interference plus Noise ratio
SF	Store and Forward
STC	Space Time Coding
TDMA	Time Division Multiple Access
UTD-MAC	University of Texas at Dallas-MAC
VCS	Virtual Carrier Sensing
WLAN	Wireless Local Area Network
WWRF	World Wireless Research Forum

List of Notations/ Symbols

$s(t)$	Stochastic process representing the backoff stage of the station at time t
$b(t)$	Stochastic process to represent the backoff time counter for a given station at time t
m	Maximum number of backoff stages
m'	Number of Contention window sizes
$CW(i)$	Contention window size of the i^{th} backoff stage
$CW_{\max}$	Maximum CW size
$CW_{\min}$	Minimum CW size
E[P]	Average payload
$P(i)\|(j)$	The transition probability from state (j) to state (i) in a 1-dimensional Markov chain model
$P(i, j)\|(r, k)$	The transition probability from state (r, k) to state (i, j) in a 2-dimensional Markov chain model
p	The probability of an unsuccessful transmission, either due to collision or error or both
P_s	The probability that a successful transmission
P_{tr}	The probability that a station transmits
R_1	Data rate source to relay
R_2	Data rate relay to destination
T_{event}	The duration for an event
T_c	The time required for a collision

σ	The length of one IEEE 802.11 time slot
T_s	The time required for a successful transmission
ρ_σ	Idle power
ρ_{tr}	Receive power
ρ_{rx}	Transmit power
τ	The transmission probability of a given station
S	Throughput
γ	Throughput gain
β	Frame generation probability
T_e^{packet}	Time for a packet in error
P_e^{packet}	Probability of packet in error
L_{packet}	Length of a packet
T_{packet}	Time to transmit a packet
J_s^{tx}	Energy consumed in successful transmission
J_s^{rx}	Energy consumed in successful reception
J_c^{tx}	Energy consumed in transmission of collided packet
J_c^{rx}	Energy consumed in reception of collided packet
J_e^{tx}	Energy consumed in transmission of packet in error
J_e^{rx}	Energy consumed in reception of packet in error
$T^*_{control}$	Time for collision of a control packet
P_b	Bit error probability
P_e	Probability of packet error

Chapter 1

Introduction

1.0 Motivation

Success in wireless networks in the last decade has made our life so convenient and hassle free that even imagining a life without this technology seems to be a nightmare. Users are so much addicted to modern wireless devices such as mobile phones, laptops, Personal Digital Assistants (PDAs), navigators, cordless phones, gaming consoles etc. that their demand for higher bandwidth is increasing exponentially. This trend is supported by the World Wireless Research Forum (WWRF) forecast which shows that by 2017, we will have seven trillion wireless devices serving seven billion people [1].

These wireless devices have shown a marked shift in user behaviour from plain data and voice applications to multimedia applications. This progress is moving the world towards the vision of fourth generation (4G) or the Next Generation networks (NGNs) [2], which enable the users to connect to 'anything', 'anytime' and 'anywhere' by providing seamless interaction. The NGNs will consist of an amalgam of devices and standards. Another important requirement for NGNs is its backward compatibility with current networks during the intermediate phase, where both networks will co-exist. This backward compatibility will limit the performance for NGNs, as it will heavily rely on efficiency of the current networks. Therefore, much research currently is focused on improving the efficiency of current networks to make this integration viable for NGNs. This can be achieved in numerous ways such as efficient algorithms, protocol modification, development of new protocols etc.

Currently, Ad Hoc Networks (AHNs) and Wireless Local Area Networks (WLANs) are densely deployed all around the world and are the main source of information access. They will form a vital component of NGNs. Their user base ranges from household users to commercial users in university/office environments. However, in order to meet the vision of NGNs, current networks still need to address challenges such as energy consumption and throughput.

One critical issue worth consideration is the impact of the energy consumed by these devices and data processing on the environment, which may cause global warming. The impact of energy on the environment is reflected by the carbon footprint. A study conducted by Gartner [3] shows that the carbon footprint of the entire ICT industry is estimated to be 2% of the total human carbon footprint, which is equal to the carbon emission by airplanes. In addition, devices in AHNs are powered by batteries which have limited life span and require proper energy management to elongate the network lifetime.

Among other issues AHNs and WLANs suffers from scarcity of bandwidth which limits the network throughput and requires efficient utilization of this valuable resource. One such example of these issues is from the existing AHNs and WLANs, where the performance of the whole system degrades greatly once low data rate nodes become dominant.

The above mentioned issues i.e., energy consumption and throughput, motivate the research community to devise energy conscious solutions and at the same time improve the throughput of AHNs for integration into NGNs. One solution arises from the advent of cooperative communications which makes use of dual-hop relay based protocols to resolve the issues of throughput and energy consumption. This is achieved by using a high data rate dual-hop path instead of a low data rate direct path between the source and destination. This results in intermediate data rates which provide higher throughput, lower energy consumption, lower latency and capability to fight against the time varying channel conditions.

1.1 Social Impact of Convergence to NGNs

The advances in wireless networking are driven by the user demands to have an affordable ubiquitous access to all their information, communication and entertainment requirements. These advances in technology are expected to result in a better quality of life and environment. NGNs (which contain current AHNs and WLANs) will greatly influence the user behaviours and lifestyles, by defining how people will access information and services in future. Access to information will play an important role in bridging the digital divide and will help in environment conservation. This will enable similar business opportunities to people from rural areas and flexible working (working from home) for all. It will also allow users a cheaper and reliable alternate to unnecessary travel, i.e. communication via video conferencing, thus further playing an important role in reducing the carbon emissions.

The expectations from NGNs are very high, however, it is important to consider that the transition to this lifestyle is gradual. In today's world due to the reasons such as cost and lack of infrastructure, it may not be possible for all to adapt the NGNs at once and make the current networks obsolete. For developed and developing countries who have invested a lot of money on existing networks, it may take longer to completely migrate to NGNs due to high user density. However, for the underdeveloped countries that still lack infrastructure, the adaptation may be easy, but there are cost constraints for them as well.

The important phase that deserves a lot of attention before this complete convergence to NGNs is the co-existence of the current networks (such as AHNs and WLANs) and NGNs. During this phase, the performance of the NGNs will heavily rely on the performance of the current networks. Therefore, it is important to direct the research efforts into making this interaction as smooth as possible.

1.2 Summary of Main Contributions and Publications

The primary aim of this research is to investigate and propose possible solutions that will improve the performance of existing networks such as AHNs and WLANs, thus allowing smooth integration of the current networks and NGNs. One solution arises from the advent of dual-hop relay based Medium Access Control (MAC) protocols, which use cooperative communication at the MAC layer, to resolve the issues in throughput, energy consumption and delay. Their performance in all the above areas makes them a strong contender for the integration with the NGNs. This research highlights the design consideration and issues of dual-hop MAC protocols and introduces several improvements to existing protocols.

In an effort to achieve the above mentioned goals, a novel method is presented for modeling the energy consumption of dual-hop relay based MAC protocols. This thesis consists of three main parts: the literature review is in Chapter 2 and two technical parts are included in Chapters 3 – 5.

The literature review part of the thesis comprises:

1. An introduction to Ad Hoc networks. This is followed by their shortcomings and the main design issues faced at the MAC layer.
2. How these shortcomings and the MAC layer issues are resolved by the advent of cooperation in Ad Hoc networks.
3. A classification of cooperative MAC protocols, and the working of existing proactive cooperative MAC protocols.

The first technical part is Chapter 3. This includes development of a new analytical model for energy efficiency and consumption. This model helps in predicting the energy consumption and is useful in devising solutions to minimize the energy critical operations. This model considers varying channel conditions, relay based transmission and saturated traffic load. The main contributions in this part are as follows:

1. An analytical model based on an improved Markov chain to predict the energy consumption in the saturation case of dual-hop relay based MAC protocols.
2. Extension of the above analytical model to incorporate transmission errors.
3. Decomposition of the energy consumption to quantify the energy consumed in various operations.

The second technical part of the thesis comprises Chapters 4 and 5. Chapter 4 details design and verification of a new Enhanced relay enabled Distribution Coordination Function (ErDCF). ErDCF has the advantage of improving the system performance in terms of throughput, delay, and energy efficiency. Chapter 5 includes design and verification of a novel Multiple relay MAC (MrMAC) protocol. MrMAC can achieve cooperative multiplexing gains and significantly improve the system throughput. The main contributions of this part are summarized as follows:

1. A dual-hop relay based MAC protocol based on the relay-enabled Distributed Coordination Function (rDCF) [4]. This protocol results in better performance in throughput, delay and energy as compared with rDCF. A detailed performance evaluation for ideal channels and with transmission errors is shown.
2. An improved Markov model to cater for the non-saturated traffic.
3. A multi-relay MAC protocol is introduced. Issues in coordination of multiple relays and performance of a multi relay MAC are examined.

These contributions have led to the following publications:

1. R. Ahmad, F.-C. Zheng and M. Drieberg, "Modeling Energy Consumption of dual-hop Relay based MAC Protocols in Ad Hoc Networks," *EURASIP Journal on Wireless Communications and Networking,* vol. 2009, Article ID 968323, 11 pages, 2009. doi:10.1155/2009/968323.
2. R. Ahmad, F.-C. Zheng and M. Drieberg, "An analytical framework for performance analysis of dual-hop Enhanced relay-enabled Distributed Coordination Function in Ad Hoc Networks," submitted to *IEEE Transactions on Vehicular Technology*.
3. R. Ahmad, F.-C. Zheng and M. Drieberg, "Delay Analysis of Enhanced Relay-Enabled Distributed Coordination Function," in *Proc. of IEEE Vehicular Technology Conference* (VTC) 2010-S, Taipei, Taiwan, 16 -19 May 2010.

4. R. Ahmad, F.-C. Zheng, M. Drieberg, S. Olafsson and M. Fitch, "Analysis of Enhanced Relay-Enabled Distributed Coordination Function under Transmission Errors," in *Proc. of IEEE Vehicular Technology Conference* (VTC) 2009-F, Anchorage, USA, 20 - 23 Sept 2009.

5. R. Ahmad, F.-C. Zheng and M. Drieberg, "Impact of transmission errors on Enhanced Relay-Enabled Distributed Coordination Function," in *Proc. of 4th ACORN Multihop Wireless Networking Workshop*, Sydney, Australia, 6 - 8 July 2009.

6. R. Ahmad, F.-C. Zheng, M. Drieberg, S. Olafsson and M. Fitch, "Modelling Energy Consumption of Relay-Enabled MAC Protocols in Ad Hoc Networks," in *Proc. of International Symposium of Wireless Pervasive Computing* (ISWPC) 2009, Melbourne, Australia, 11 - 13 Feb. 2009.

7. R. Ahmad, F.-C. Zheng and M. Drieberg, "Enhanced Relay-Enabled Distributed Coordination Function: Performance Evaluation," in *Proc. of 3rd ACORN Multihop Wireless Networking Workshop*, Melbourne, Australia, 14 - 16 July 2008.

8. R. Ahmad, F.-C. Zheng, M. Drieberg, and S. Olafsson, "Performance Evaluation of Enhanced Relay-Enabled Distribution Coordination Function," in *Proc. of 14th European Wireless Conference*, Prague, Czech Republic, 22 - 25 June 2008.

9. R. Ahmad, F.-C. Zheng, M. Drieberg, and S. Olafsson, "An enhanced relay-enabled medium access control protocol for wireless ad hoc networks," in *Proc. of IEEE Vehicular Technology Conference* (VTC) 2008-S, Singapore, 11-14 May 2008.

1.3 Thesis Outline

The thesis is organized as follows:

Chapter 2 presents the background of Ad Hoc networks and how Cooperative networks are able to deal with the shortcomings of Ad Hoc networks. It further discusses various cooperative MAC protocols. **Chapter 3** presents an analytical method to show the energy consumption. Further it shows the energy decomposition which helps MAC protocol developers to identify and classify energy behaviors. **Chapter 4** describes the evolution of enhanced relay-enabled distributed coordination function which is an improvement on the relay-enabled distributed coordination function. **Chapter 5** presents a multiple relay MAC with its performance analysis. Some concluding remarks and future issues are presented in **Chapter 6**.

Chapter 2

Ad Hoc and Cooperative Networks

2.0 Introduction

The purpose of this chapter is to provide an overview of the recent developments, issues and future trends in ad hoc and cooperative wireless networks. Section 2.1 introduces AHNs and emphasizes on their role and integration into the NGNs. The details of the MAC protocols in AHNs and the issues faced are given. The IEEE 802.11 standard for WLANs is discussed in detail followed by modeling of 802.11 DCF. Section 2.2 introduces cooperative networks and discusses their role and importance in addressing the issue of the IEEE 802.11 DCF. This is followed by the details on the Physical (PHY) and MAC layers of cooperative networks.

2.1 Ad Hoc Networks

Wireless networking has provided much convenience in people's daily life. One of networking structures which is currently emerging and gaining momentum is AHN. In AHN, a group of nodes can form a network autonomously without relying on any central control (hence infrastructure less) by allowing peer-to-peer communications. Most of the earlier research in AHNs was supported by Defense Advanced Projects Agency (DARPA), the same organization that developed the Internet. AHN potentially provides many unprecedented advantages such as rapid deployment, robustness, fast

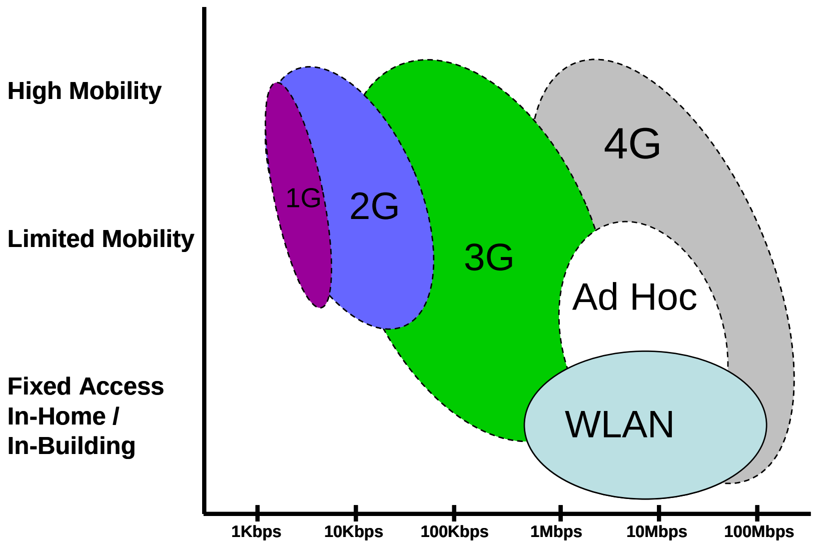


Figure 2.1: Evolution of Wireless Networks.

reconfiguration, autonomous execution and far less management overhead. In an AHN, the network tasks are distributed in nature, and the topology is dynamic and routing is adaptive. In fact, AHN is now widely viewed as the next frontier of wireless technology. Fig 2.1 shows the position of AHNs in the evolution of wireless networks and its important role in the transition from third generation (3G) to 4G networks. AHN follows the Open System Interconnection Model (OSI), which is an abstract description for layered communications and computer network protocol design. It was developed as part of the OSI initiative [5]. It divides network architecture into seven layers. AHN finds applications in areas such as military applications (battlefields), emergency operations (search, relief & rescue), monitoring (warning) and collaborative computing.

There is currently an enormous interest in AHN research in the research community. However, there are still many challenging issues in AHN at different layers that remain to be solved such as scalability, deployment, quality of service (QoS) provisioning, security, mobility, routing, medium access scheme and energy management [6 - 9]. These issues are related to design, deployment, operation and maintenance of AHNs.

However, in recent years the most actively researched area is the MAC layer of AHNs. Indeed MAC layer is responsible for efficient coordination of access to the shared wireless medium. This vital position makes the MAC layer deal with significant challenges either arising within or trickled from other layers.

2.1.1 Medium Access Control Protocols in Ad Hoc Networks

MAC layer is responsible for regulating the shared wireless medium access among the nodes. This being the primary task in AHN greatly influences the performance of the network. MAC layer is expected to judiciously utilize the scarce wireless medium to improve throughput and reduce delay while keeping the collisions to a minimum. Collisions can occur due to two nodes transmitting simultaneously or due to hidden terminals.

MAC protocols in AHN are broadly classified as synchronous and asynchronous protocols [7]. Synchronous protocols allocate their users with specific time slot (Time Division Multiple Access (TDMA) based) or specific data channels (based on Frequency Division Multiple Access (FDMA) or Code Division Multiple Access (CDMA)). The synchronous protocols based on TDMA allocate timeslots to the users which makes it suitable for heavy and medium traffic conditions only, where all or most slots are utilized. The asynchronous protocols are well suited to low traffic conditions.

These protocols are based on the Carrier Sense Multiple Access (CSMA) and its variants. In CSMA based protocols, the node senses the medium and if it observes the medium free for a defined interval it transmits or else it defers its transmission. These protocols are effective and easy to implement as these allow transmission with minimum delay. One of the most widely tested and deployed asynchronous protocol is the IEEE 802.11.

2.1.2 Design Issues for MAC Protocols in Ad Hoc networks

With the increasing bandwidth demand in AHN, it is important to devise MAC protocols for efficient utilization of. bandwidth. The distributed nature of MAC protocols in AHN makes it difficult and gives rise to enormous challenges. Some of the important design considerations [6 - 9] for the MAC protocol developers are listed below:

- **Distributed Operation:** AHN are required to operate in special circumstances and are self configurable. It is expected that these should be autonomous and distributed in nature with minimum overheads.
- **Synchronization:** Synchronization is important for the TDMA based MAC protocols as it is used to improve the utilization of bandwidth and battery.
- **Hidden Terminals:** Hidden terminals are nodes that are not in the range of the source but are in the range of destination. These nodes can cause collision at destination. This may result in a retransmission which will reduce the overall throughput.
- **Exposed Terminals:** Exposed terminals are the nodes in the source's transmission range, which are blocked from transmitting due to an ongoing transmission. In order to improve the bandwidth utilization it is important to allow parallel transmission in a controlled manner.

- **Throughput:** Throughput is an average rate of data received successfully. To enhance throughput it is important to reduce collisions, maximize the channel utilization and keep the control overhead to a minimum.

- **Access Delay:** Access delay is an average delay that a packet experiences before it is transmitted. The MAC protocol should minimize this delay to improve the channel utilization.

- **Fairness:** Fairness is an equal distribution of bandwidth to all nodes. Some MAC protocols tend to support nodes with previous successful transmission, which results in some nodes being deprived of access to medium and causes successful nodes to drain its resources much faster.

- **Power Control:** Energy consumption is linked to transmission power control and can be minimized by judicious power control mechanisms (which also reduces the interference to other nodes). Power control in the MAC layer affects the contention region.

- **Rate Adaptation:** Varying channel conditions can reduce the overall system throughput. It is important for the MAC protocol to adapt the transmission rate to varying channel conditions i.e. lower the data rate for bad channel and increase the data rate for good channel conditions.

- **Mobility:** The mobility in AHN is an important characteristic but at the same time it makes things difficult for the MAC protocols. For the best performance MAC protocols should be able to provide support for the mobility.

2.2 IEEE 802.11

The IEEE 802.xx standards [10 - 12] defines two separate sub layers, the Logical Link Control (LLC) and media access control, for the Data Link layer of the OSI model. The relationship of OSI to IEEE 802 standard is shown in the Fig. 2.2.

The IEEE 802.11x family of standards comprises mainly the standards IEEE 802.11 [13], IEEE 802.11b [14], IEEE 802.11a [15], IEEE 802.11g [16] and IEEE 802.11n [17]. All the others are standards dealing with specific issues such as quality of service (IEEE 802.11e), transmit power management (IEEE 802.11h), security (IEEE 802.11i), etc.

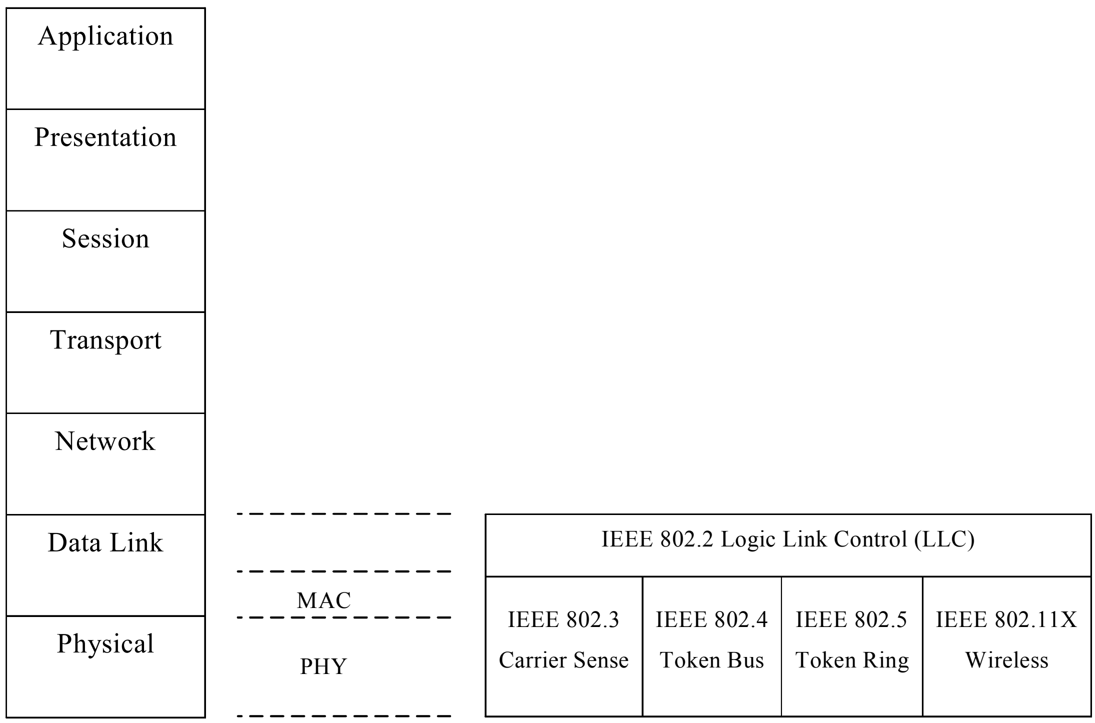
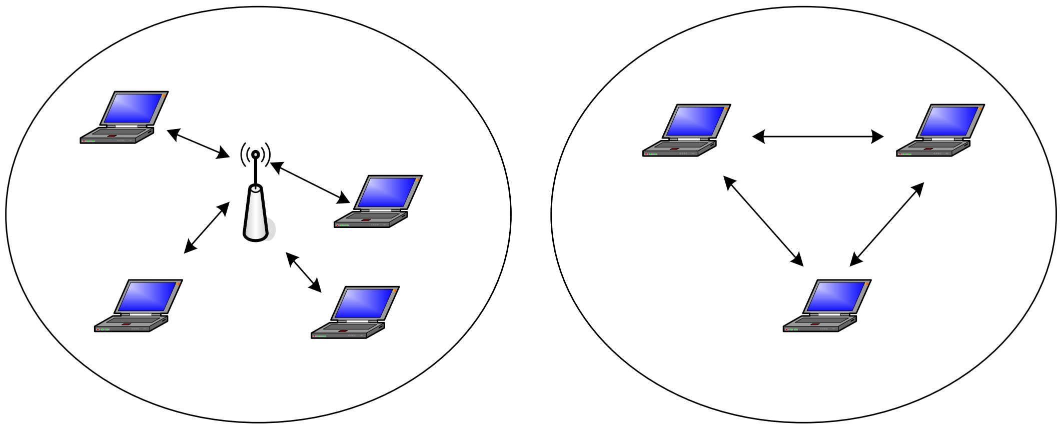


Figure 2.2: Relationship of IEEE 802.xx standards to OSI layers.

The 802.11 standard specifies a common MAC Layer, which manages and maintains communication between 802.11 stations by coordinating access to shared wireless channel. The MAC layer uses 802.11 physical layers, such as 802.11a or 802.11b, to perform the tasks of carrier sensing, transmission, and receiving of 802.11 frames. In this section, we present a brief introduction of IEEE 802.11 protocol. This protocol allows two network architectures:

1. Infrastructure networks: In the infrastructure networks, nodes communicate with each other via a central node called Access Point (AP). A source node first sends the message to the AP which in turn forwards the message to the destination node.
2. Ad hoc networks: In ad hoc the mode, nodes communicate directly with each other, without any AP.

The IEEE 802.11 architecture is built around a basic service set (BSS) which is a set of nodes that try to communicate with each other. If all nodes in the BSS are mobile and there is no connection to wired network, the BSS is called an independent BSS (IBSS).



a) b)

Figure 2.3: IEEE 802.11: a) BSS, and b) IBSS.

In the above Fig 2.3.a basic service set is shown. This represents the infrastructure network where we have a central AP and nodes communicate via the AP. Fig 2.3.b shows an IBSS which is an ad hoc network where nodes communicate directly to each other.

2.2.1 IEEE 802.11 Physical Layer

The physical layer is responsible to transmit and receive data packets over shared wireless medium. It provides an interface between MAC layer and wireless medium. The main tasks of the physical layer are: 1) interaction and packet exchange with MAC layer, 2) uses signal carrier and spread spectrum to transmit data packets, and 3) carrier sense indication for MAC layer. The physical layer is composed of two sub-layers i.e. Physical Layer Convergence Procedure (PLCP) and Physical Medium Dependant (PMD) [12]. PLCP is responsible to control the frame exchange between Physical and MAC layer and PMD controls the transmission of the data frames on the medium. The IEEE 802.11 standard includes the following physical layers:

a) **IEEE 802.11:** This was the legacy standard [13] based on the direct-sequence Spread Spectrum (DSSS) released in 1997. It supported two data rates (i.e. 1 and 2 Mbps) in the 2.4 GHz band. This standard is obsolete now.

b) **IEEE 802.11b:** This was the standard [14] which took over the legacy IEEE 802.11. It was released in 1999. It is currently the most prevalent physical layer and is based on the DSSS and able to support maximum data rate of 11 Mbps in the 2.4 GHz band. The main issue faced by 802.11b is the interference from the other devices in the free Industrial, Scientific and Medical band (ISM).

c) **IEEE 802.11a:** The 802.11a standard [15] was released in 1999. It uses the Orthogonal Frequency Division Multiplexing (OFDM) based physical layer. It operates in the 5 GHz band and is able to support the maximum data rate of 54 Mbps. The main issue with 802.11a is its short range.

d) **IEEE 802.11g:** The 802.11g standard [16] was released in 2003. It is backward compatible with 802.11b and uses both DSSS and OFDM based physical layers. It operates in 2.4 GHz band and is able to support maximum data rate of 54 Mbps. It suffers from the interference in ISM band.

e) **IEEE 802.11n**: This standard [17] was released in last quarter of 2009. It adds the multiple input multiple output (MIMO) support to the physical layer. It operates in both 2.4 and 5 GHz band. It is able to support data rates of more than 100 Mbps.

Many parameters used at MAC layer are physical layer dependent. Main characteristics of above mentioned physical layer standards are specified in detail in the Table 2.1.

2.2.2 IEEE 802.11 Medium Access Control Layer

The IEEE 802.11 MAC is responsible to provide reliable delivery mechanism for user data over noisy and unreliable wireless channels. The IEEE 802.11 MAC specifies two access mechanisms i.e. the polling-based Point Coordination Function (PCF) and the contention-based Distributed Coordination Function (DCF). PCF is not widely deployed because of its complexity, inefficient polling schemes and limited QoS provisioning. In this dissertation, we only look into the IEEE 802.11 DCF which is the most prevalent MAC protocol. The IEEE 802.11 protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

Table 2.1: IEEE 802.11 Standards [13 - 17].

Standard	Frequency (GHz)	Physical Technique	Modulation	Data rates (Mbps)	Bandwidth (MHz)
802.11	2.4	DSSS	BPSK	1,2	20
802.11b	2.4	DSSS	BPSK, QPSK, CCK	1, 2, 5,5, 11	20
802.11a	5	OFDM	BPSK, QPSK, 16QAM, 64QAM	6, 9, 12, 18, 24, 36, 48, 54	20
802.11g	2.4	DSSS, OFDM	BPSK, QPSK, 16QAM, 64QAM	1, 2, 6, 9, 12, 18, 24, 36, 48, 54	20
802.11n	2.4/ 5	OFDM	BPSK, QPSK, 16QAM, 64QAM	7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2	20
				15, 30, 45, 60, 90, 120, 135, 150	40

The default scheme used for data transmission in DCF is the two-way handshaking technique called basic access mechanism. This includes the CSMA/CA with binary exponential backoff (BEB). The BEB mechanism chooses a random number which represents the amount of time that must elapse after DIFS where there is no transmission taking place.

Another scheme is an optional Request-To-Send (RTS)/Clear-To-Send (CTS) four-way handshaking mechanism used to combat the effects of collisions and to facilitate transmission of large data packets. Though the RTS/CTS exchange reduces the likelihood of collision, it causes several drawbacks, such as low channel utilization due to no parallel transmissions, wasting node's energy and creating interference to other nodes.

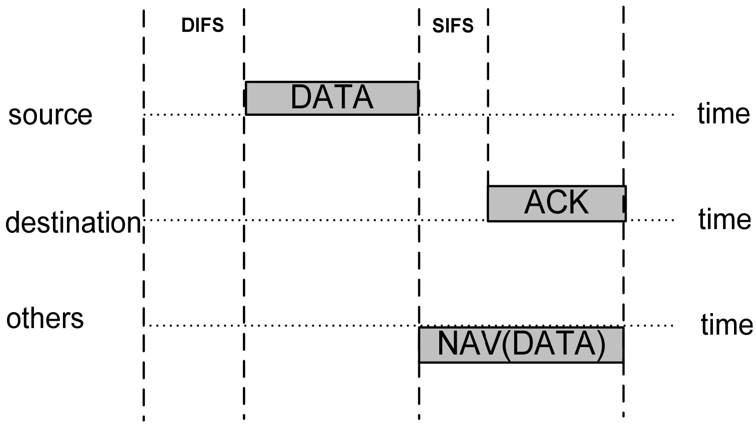
The IEEE 802.11 defines three main Inter Frame Space (IFS) periods of time: 1) Short IFS (SIFS), 2) DCF IFS (DIFS) and 3) Extended IFS (EIFS). These are used to determine the priority levels to access the channel. The SIFS being the shortest is used between two subsequent frames involved in the transmission such as between RTS and CTS. The SIFS interval is linked to particular physical layers. The DIFS duration is used by the nodes to sense the medium idle before starting a new transmission. A node is able to transmit when it observes the medium free for DIFS duration and the relevant backoff time. DIFS is equal to SIFS plus two slot times. EIFS is a much larger duration than the others and is meant to prevent the collision with an ongoing transmission. When a node intending to transmit is able to sense some activity on the channel and is unable to decode due to collision/ error or distance, it defers its transmission for EIFS duration.

In DCF when a source node is ready to transmit a packet, it first senses the activity on the transmission channel until an idle period equal to DIFS is detected. This is physical carrier sensing (PCS). In this instance, the source waits for another random backoff interval before transmission to avoid collision with other nodes. The duration of this random backoff is a random value within the interval [0, *CW*], where *CW* is the contention window. The random backoff time counter is decremented in terms of time slots as long as the channel is sensed free. The counter is suspended once a transmission is detected on the channel. It resumes with the old remaining backoff interval when the channel is sensed idle again for a DIFS period. The source transmits its packet when the backoff time becomes zero.

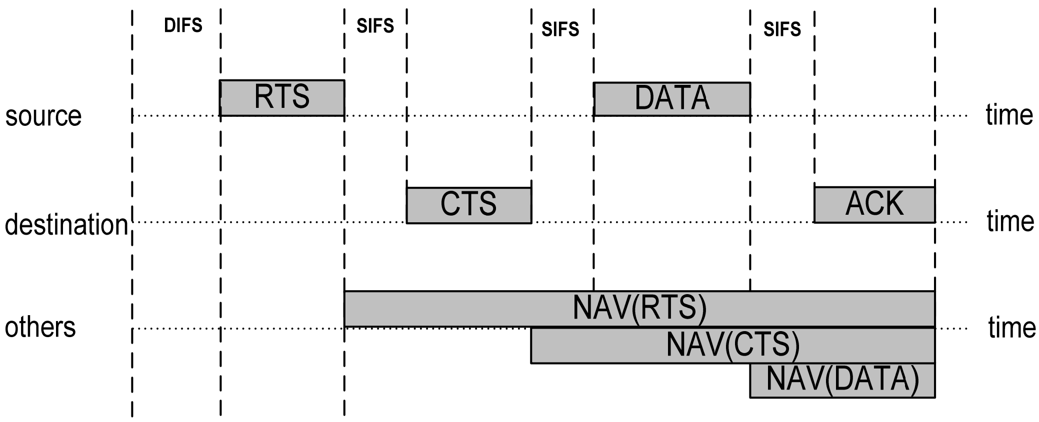
In the case of basic access (Fig 2.4a) the source starts by sending the data packet. If the data packet is received correctly, the destination responds by sending an acknowledgement (ACK) packet after SIFS interval. The *CW* is reset to initial value upon successful transmission. If the ACK is not received at the source, a collision is assumed to have occurred. The value of *CW* is doubled upon each failure until it reaches the maximum value. The *CW* is reset if a failure occurs at the maximum retry limit. In the case of failure at the maximum contention window, the packet is dropped. The source attempts to send the data packet again when the channel is free for a DIFS period followed by the random backoff interval.

In the RTS/CTS access, control packets are used to reserve the channel for transmission of data packets. The RTC/CTS control overhead is suitable to transmit large data packets as a collision would lead to waste of less bandwidth. On the other hand, it makes no sense to transmit short data packets with the control overhead as this would lead to consumption of extra bandwidth.

In the RTS/ CTS case (Fig 2.4b), the source starts the process by sending an RTS control packet. If the control packet is received correctly, the destination sends a CTS control packet after a SIFS interval. Once the CTS frame is received, the source transmits its data packet after a SIFS interval. If the source does not receive the CTS, a collision is assumed to have occurred.



a)



b)

Figure 2.4: IEEE 802.11: a) Basic access, and b) Optional RTS/CTS access

In this case, the source attempts to send the RTS packet again when the channel is free for a DIFS period followed by the new backoff. In addition to the physical carrier sensing, DCF also makes use of virtual carrier sensing (VCS). VCS is implemented by means of the network allocation vector (NAV). The NAV is maintained by all nodes that are not currently involved in any transmission or reception of packets. A non zero NAV means that the node needs to block its own transmission to yield another ongoing transmission. It tracks the remaining time of any ongoing data transmission. When a node receives RTS, CTS or DATA packet which is not destined for it, it sets its NAV according to the information received in the Duration/ ID field of that particular packet. The Duration field contains the reservation duration of this whole packet exchange sequence. The RTS/CTS with the NAV settings is able to resolve the hidden terminal problem to some extent. A node blocks its own transmissions if either PCS or VCS shows a busy channel.

In order to highlight the issues in 802.11 DCF and look for appropriate solutions, accurate modeling of the 802.11 DCF is very important. As such, the next section presents some information on the modeling of 802.11 DCF.

2.2.3 Modeling of 802.11

In recent years, a rapid evolution in AHN and WLANs has lead to wide use of IEEE 802.11 DCF protocol triggering huge interest in its performance modeling. Many works on the analytical modeling of IEEE 802.11 DCF have been reported [18 - 24]. Bianchi [18] in his groundbreaking work was the first to derive a model that incorporates the exponential backoff process and evaluates the saturation throughput of IEEE 802.11 as a 2-dimensional Markov chain. Since then the 2-dimensional Markov chain model has become the most common method and perhaps the de facto standard for studying the performance of the IEEE 802.11 MAC protocol and its enhancements.

Bianchi's model, though short on some finer details (such as backoff suspension and finite retries), was able to model the behavior of 802.11 DCF accurately. Backoff suspension is the freezing of the backoff counter when a busy channel is observed and it is resumed again once the channel is observed free for DIFS interval.

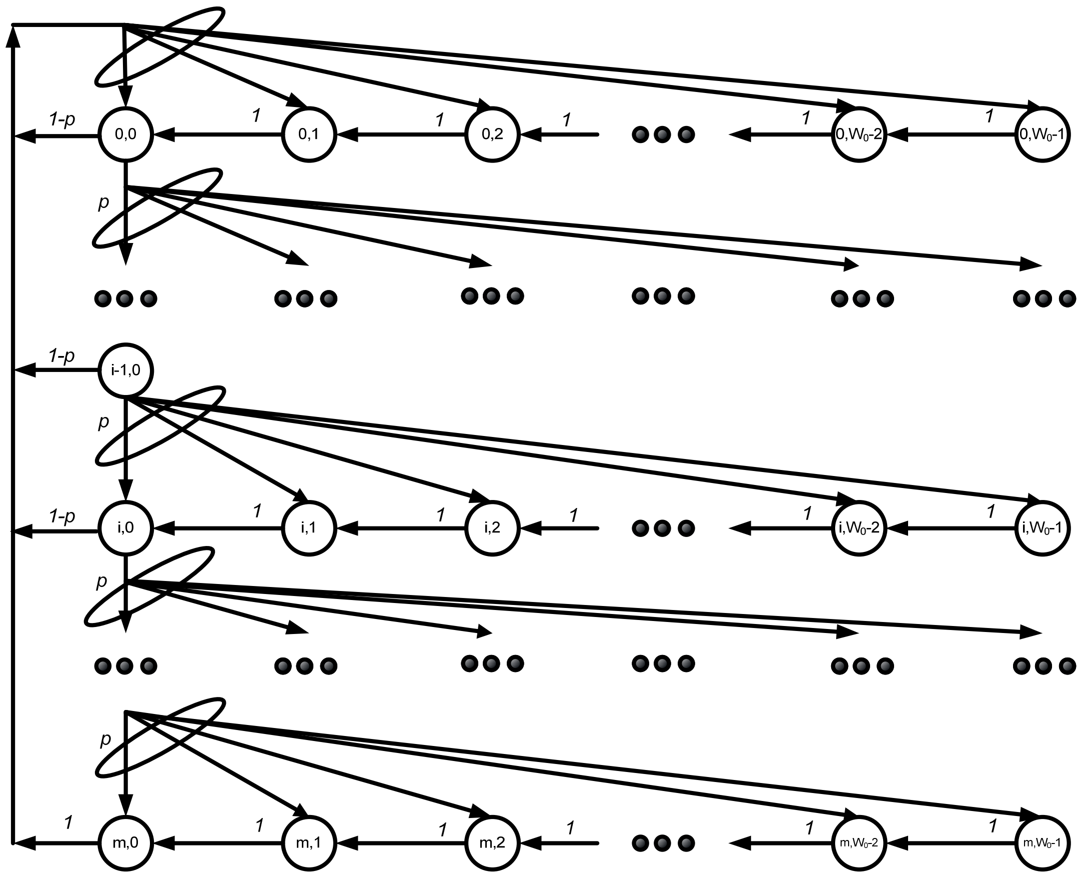


Figure 2.5 Markov chain model.

The number of retransmissions available for a packet in collision is defined in the standard and it is a finite value. Bianchi's model allows for infinite retries and assumes an ideal channel and saturation environment. It was later improved by Wu to include the finite retry limit and is shown in Fig 2.5. Here a fixed number of contending stations n in ideal channel conditions and saturation mode (i.e. each node always have a packet to transmit). In the above Markov model [19], $b(t)$ is the stochastic process to represent the backoff time counter for a given station and $s(t)$ is the stochastic process representing the backoff stage (0, …,m) of the station at time t. The backoff counter value depends on the stations history, therefore $b(t)$ is non – Markovian. The contention window size W at the backoff stage i is defined as: $W_i = 2^i W$, for $i \leq m'$ and as: $W_i =$

$2^{m'}W$, for $i > m'$. Let $W = CW_{\min} + 1$, and $2^{m'}W = CW_{\max} + 1$. In the above Markov chain, the one-step transition probabilities are as follows:

$$
\begin{aligned}
& P\{i,k|i,k+1\} = 1 \quad k \in (1, W_i - 2), i \in (0,m) \\
& P\{0,k|i,0\} = \frac{1-p}{W_0} \quad k \in (0, W_0 - 1), i \in (0, m-1) \\
& P\{i,k|i-1,0\} = \frac{p}{W_i} \quad k \in (0, W_i - 1), i \in (1,m) \\
& P\{0,k|m,0\} = \frac{1}{W_0} \quad k \in (0, W_0 - 1)
\end{aligned}
\tag{2.1}
$$

In (2.1), $P\{i,k|i,k+1\}$ is the probability when a station senses that the channel is idle it decreases its backoff timer, $P\{0,k|i,0\}$ is the probability after a successful transmission, the new packet starts at backoff stage 0, and the backoff stage is uniformly chosen in the range $(0, W_0 - 1)$, $P\{i,k|i-1,0\}$ is the probability after every unsuccessful transmission, the backoff window doubles until it reaches the maximum backoff window size and $P\{0,k|m,0\}$ is the probability that once the backoff stage reaches the value *m*, it is not increased in subsequent packet transmission. In (2.1), W_0 is the minimum contention window and *m* is the maximum number of backoff stages.

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}, i \in (0,m), k \in (0, W_i - 1)$ be stationary distribution of the above chain. A closed form solution for this Markov chain is as follows:

$$
\begin{aligned}
& b_{i-1,0} \cdot p = b_{i,0} \\
& b_{i,0} = p^i b_{0,0} \\
& b_{m-1,0} \cdot p = (1-p) b_{m,0} \\
& b_{m,0} = \frac{p^m}{1-p} b_{0,0}
\end{aligned}
\tag{2.2}
$$

Due to chain regularities,

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p)\sum_{j=0}^{m} b_{j,0} + b_{m,0} & i = 0 \\ p b_{i-1,0} & 0 < i < m \end{cases} \tag{2.3}$$

Based on (2.2) and the fact that $\sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p}$, (2.3) is written as:

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad i \in (0,m), k \in (0, W_i - 1) \tag{2.4}$$

By imposing normalization condition and equation (2.2), it is possible to obtain $b_{0,0}$ as a function of p

$$1 = \sum_{i=1}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=1}^{m} b_{i,0} \sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{i=1}^{m} b_{i,0} \frac{W_i + 1}{2} \tag{2.5}$$

Thus $b_{0,0}$ can be simplified to:

$$b_{0,0} = \begin{cases} \dfrac{2(1-2p)(1-p)}{W\left(1-(2p)^{m+1}\right)(1-p) + (1-2p)(1-p^{m+1})} & m \le m' \\ \dfrac{2(1-2p)(1-p)}{\left(\begin{array}{l} W\left(1-(2p)^{m'+1}\right)(1-p) + (1-2p)(1-p^{m+1}) + \\ W 2^{m'} p^{m'+1} (1-2p)(1-p^{m'-m}) \end{array} \right)} & m > m' \end{cases} \tag{2.6}$$

We define probability τ that a station transmits in a randomly chosen slot time as:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-p^{m+1}}{1-p} b_{0,0}$$

$$= \begin{cases} \dfrac{2(1-2p)(1-p^{m+1})}{W\left(1-(2p)^{m+1}\right)(1-p) + (1-2p)(1-p^{m+1})} & m \le m' \\ \dfrac{2(1-2p)(1-p^{m+1})}{\left(\begin{array}{l} W\left(1-(2p)^{m'+1}\right)(1-p) + (1-2p)(1-p^{m+1}) + \\ W 2^{m'} p^{m'+1} (1-2p)(1-p^{m'-m}) \end{array} \right)} & m > m' \end{cases} \tag{2.7}$$

Now τ depends on the conditional collision probability p such that a packet collides if one of the (n-1) stations transmits. This is given below:

$$p = 1 - (1 - \tau)^{n-1} \tag{2.8}$$

Up to this point, (2.7) and (2.8) represent a nonlinear equation system which can be solved numerically to find p and τ. To calculate the saturation throughput we define P_{tr} in (2.9) as the probability which represent that there is at least one transmission in the considered slot time:

$$P_{tr} = 1 - \left(1 - \tau\right)^{n} \tag{2.9}$$

P_s in (2.10) below represents the probability that a transmission on the channel is successful given that only one station transmits.

$$P_s = \frac{n\tau\left(1 - \tau\right)^{n-1}}{P_{tr}} \tag{2.10}$$

Let S be the normalized system throughput which is defined as the fraction of time the channel is used to transmit data. Therefore we define throughput as:

$$S = \frac{E[\text{Payload transmitted in a slot time}]}{E[\text{Length of a slot time}]} \tag{2.11}$$

Considering the slot time it is possible to see that it comprises the time spend in staying idle, successful transmission and collision. Therefore the expression for average length of a slot time for successful transmission is:

$E[\text{Length of a slot time}] = \left(1 - P_{tr}\right)\sigma + P_{tr}P_sT_s + P_{tr}\left(1 - P_s\right)T_c$. This leads to the following equation:

$$S = \frac{P_sP_{tr}E\left[P\right]}{\left(1 - P_{tr}\right)\sigma + P_{tr}P_sT_s + P_{tr}\left(1 - P_s\right)T_c}. \tag{2.12}$$

where $E[P]$ is the expected payload, σ is the slot time, T_c and T_s are the average times channel is sensed busy during collision and successful transmission. The term $P_sP_{tr}E[P]$ represents the data transmitted successfully. (1- P_{tr}) is the probability of staying idle, P_sP_{tr} is the probability of successful transmission and $P_{tr}(1-P_s)$ is the probability of collision. To calculate the throughput we have to define the access mode of IEEE 802.11 and include the propagation delay δ. For basic access, we have the following equations:

$$\begin{aligned} T_s &= T_{DATA} + T_{ACK} + 2\delta + T_{SIFS} + T_{DIFS} \\ T_c &= T_{DATA} + \delta + T_{DIFS} \end{aligned} \quad (2.13)$$

In a similar way, for RTS/ CTS access the equations are as follows:

$$\begin{aligned} T_s &= T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + 4\delta + 3T_{SIFS} + T_{DIFS} \\ T_c &= T_{RTS} + \delta + T_{DIFS} \end{aligned} \quad (2.14)$$

Fig 2.6 represents the saturation throughput results for both basic and RTS/CTS access.

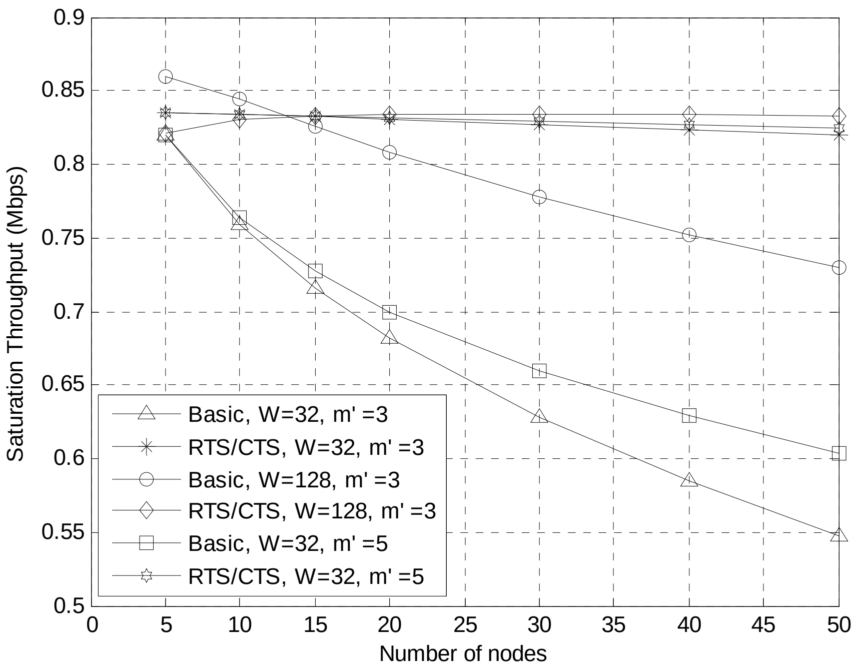


Figure 2.6: Saturation Throughput Analysis.

Wu et al. [19] improved the model by considering packet retransmission limits to avoid overestimating the throughput of 802.11. Their model assumed ideal channel, saturation environment and defined a limit on the maximum number of retransmissions. However, it did not consider the backoff suspension. In [25] Ziouva et al. considered backoff suspension in their model. However, it was not exactly based on the IEEE 802.11 standard and neglected the backoff stage after successful transmission and finite number of retries. It is assumed that, after successful transmission, a station can access the medium without backoff, which is not compliant with the IEEE 802.11 standard. Ergen and Varaiya [20], extended Bianchi's model by taking into account the freezing of the backoff timer during a busy channel occurrence.

In a similar fashion many people have used the Markov chain models to analyze other performance characteristics such as delay, energy, channel with errors and non-saturation.

Other than the above mentioned works where ideal channel was considered, some researchers have tried to address the issue of realistic channel with transmission errors: Chatzimisios [21] presented an analytical model for saturation throughput of 802.11 DCF under channel errors. Two shortcomings of this model, however, are: (1) it applies bit errors to data packets only, and (2) it assumes that the average time intervals for medium sensed busy due to successful transmission, collision and channel error are the same. This is not in accordance with the standard itself. Qiang in [26] presented an improved model which applies bit errors to both DATA and ACK packets. However, both [21] and [26] are for the basic access (DATA/ACK) mode of 802.11 DCF. Ci [27] presented a model for the saturation throughput of 802.11 MAC under fading channels. This model works for RTS/CTS mode of 802.11 DCF as well.

In [28], Carvalho presented an analytical model based on the average service time and jitter in ideal conditions. This model provides detailed delay performance analysis. Chatzimisios in [29] presented an analytical model for delay of 802.11 DCF based on the throughput model of [18]. This model assumes saturated condition, ideal channel and does not consider packet retry limit. Chatzimisios [30] later improved the analytical model for delay of 802.11 DCF by incorporating packet retry limit and bit errors respectively.

In another stream, Carvalho et al. [31] model node's energy consumption in a single-hop IEEE 802.11 Ad hoc network. Carvalho et al. calculated the average service time of a packet transmitted in a saturated Ad hoc network. Results show that passive modes (idle, overhear, receive) dominate the energy consumption and transmission of large payloads is more advantageous. However, this model treats receiving and idle state in the same way. Wang et al. [32] proposed a model for energy efficiency in IEEE 802.11 DCF and tried to maximize energy efficiency based on packet size and contention window. They have considered channel errors on the data packet only, which is not reflective of the real situation. Ergen and Varaiya presented a model in [33] for decomposition of energy consumption in IEEE 802.11. They derived the formula for the amount of energy consumed by a node in order to transmit 1 MB of data in a network with n nodes. This model can differentiate receiving and idle states. K. Szczypiorski and J. Lubacz [34, 35] improved Wu's model by considering at the same time the effect of backoff suspension, finite number of retransmissions, maximum size of the contention window and the impact of transmission errors.

Despite of all the above efforts there is still room for a detailed analytical model. These models allow the MAC protocol designers to evaluate the performance of their schemes while still in the design phase. It further helps them to analyze the problems faced by 802.11 DCF and propose appropriate solutions. The main design issues faced by the 802.11 DCF are:

- **Hidden Terminal:** As mentioned earlier, hidden terminal is a node which is not in the carrier sensing range of the source but is in the carrier sensing range of the destination. This node is unaware of the source's transmission and may cause collision at the receiver.

- **Exposed Terminal:** Exposed terminal is a node in the carrier sensing range of the source and not the destination. This node senses the medium busy and does not transmit its own data thus leading to low throughput.

- **Blocking problem:** A blocked destination node is one which is unable to respond to an RTS destined to it because of an ongoing transmission in its carrier sensing range.

- **Fairness:** This is related to the scenarios where some nodes are able to monopolize the channel access, thus leading to severe throughput degradation

- **Varying channel conditions:** Due to the ubiquitous nature of wireless links, it is prone to varying channel conditions.

- **Capture Effect**: The capture effect is the phenomenon where the receiver picks the strong signal and completely suppresses the weak signal.

- **Dominance of low data rate nodes:** One problem faced in IEEE 802.11 DCF is the dominance of low data rate nodes. These nodes when communicating with each other at low data rates such as 1 or 2 Mbps degrade the throughput of the whole network [36, 37]. At the same time they create unfairness as other nodes are blocked for a longer duration.

Many researchers have tried to resolve some of the above mentioned problems by taking approaches such as power control, rate adaptation, etc. However none of the approaches was able to completely resolve most of the issues until the advent of Cooperative communication. This unique solution provides a response to majority of the above concerns in an efficient way.

2.3 Cooperative Networks

In wireless communication, nodes share a common broadcast medium which leads to limited spectrum and interference. This has led to the advent of cooperative communications which is a promising technique to enhance system capacity, reduce power consumption, reduce packet loss rate and achieve higher network resilience. Among the research community, the most common analogy for cooperative communication [38 - 40] is as follows:

> *Consider a room full of people enjoying a party. A husband and wife are at extreme corners of the room. Now the wife wants to communicate to the husband that its time to go home. She shouts from her end but due to noise in the room the husband cannot hear what she said. However, one person in the middle of the room was able to hear her saying home and decides to help the couple. This person repeats the word home and the husband on hearing this realizes that his wife wants to go home.*

Now in this analogy the room is our shared wireless medium Wife, husband and person in the middle are source, destination and relay respectively.

Cooperative communications finds its inception in the famous work of Cover and Elgamal [41] on the use of fixed relays. The notion of the current Cooperative communication was first introduced by Sendonaris et al. in [42]. In last few years, research community has seen a new trend with ample of research activities focused on cooperative communications. The flag bearers of this research are mainly from the information theory and signal processing domain. Some noted contributions in the information theory area are from [38, 42 - 44]. Due to this information theory dominance, the main focus of this research was limited to physical layer. Though the physical layer has been widely explored but these people are fast in realizing that they have reached the point of diminishing returns. To maximize the gains from the physical layer they need support of higher layer such as MAC and Network layer.

The current concept of cooperative communications is different from that of earlier relay based systems. Cooperative nodes are not only the relays but also transmit their own information. Cooperative communications takes advantage of the broadcast nature of wireless medium which was earlier considered a drawback. Broadcast and spatial diversity are utilized to fight against unreliable wireless links. Cooperative communication has applications in cellular, ad hoc, wireless mesh and sensor networks.

Cooperation in communications is achieved in various ways such as cooperation by relay to forward source's data, cooperation among nodes in a cluster and cooperation between source and relay to transmit together to achieve diversity. There are numerous cooperative / relay based algorithms for physical layer cooperation but to get the most out of the system it requires the support of MAC layer. MAC layer guarantees fairness between users and efficient utilization of bandwidth. Cooperation can be incorporated at MAC layer. This is achieved by cooperative MAC protocols, relay based MAC protocols or multihop MAC protocols. Cooperation at MAC layer is all about replacing the slow single hop transmission by fast two hop transmissions. Now the question arises: how is this two hop transmission at MAC better compared with multihop transmission at network layer?

Most of the current literature is based on contention based MAC protocols for cooperative communications. These MAC protocols work with WLANs and AHN based on the legacy IEEE 802.11 a/b/g. Some important MAC protocols for cooperative communication are CoopMAC [45, 46], rDCF [4, 47], CODE [48] and 2PSP [49] which are explained in detail in later sections.

This section helps the reader to appreciate the importance of cooperation at MAC layer. Further it elaborates the main issues in MAC protocols for cooperative communications such as relay node selection, hidden & exposed terminal problems, throughput, energy efficiency, mobility of nodes, impact of power control, malicious behaviour of nodes and compatibility with existing standards. These issues are analyzed for different design goals and tradeoffs. It also highlights the problems in the existing MAC protocols and suggests a few future directions for improvement such as the use of directional antennas, adaptive of power control etc.

2.3.1 Cooperative Communications at Physical Layer

Cooperative communications at physical layer is mainly classified into the following main schemes:

a. Amplify and Forward (AF)

This scheme was originally proposed in [50]. In this scheme the relay amplifies the source's data and retransmits to the destination. The drawback of this scheme is that with amplification the noise received at the relay is amplified as well. The main advantage of this scheme is its simplicity.

b. Decode and Forward (DF)

This scheme was originally proposed in [51]. In this scheme the relay tries to decode the source's data and retransmits after encoding to the destination. The advantage of this scheme is that the relay upon reception and successfully decoding transmits a noise free copy of the message.

c. Compress and Forward (CF)

This scheme was originally proposed in Theorem 6 and 7 of [41]. In this scheme the relay compresses the source's data and retransmits to the destination. The compressed version of the data is combined with the data received directly from source. The disadvantage of this scheme is its complexity.

d. Store and Forward (SF)

In this scheme [42, 43] the relay stores the source's data without decoding and retransmits to the destination. This is similar to the case of classic multihop and is simple to implement. It is similar to AF except there is no amplification at the relay.

A few more complex schemes such as coded cooperation [52] and space time coded cooperation [44] were also presented to achieve more gain. Cooperative diversity has been widely explored for physical layer cooperation. However, to maximize its benefits, the support of MAC layer is needed too [38, 53 - 56]. Cooperation can be incorporated at MAC layer by replacing single-hop slow transmission by dual-hop fast transmissions. Cooperative communications successfully exploits the broadcast nature of wireless communication to enhance throughput. As an outcome spatial diversity is also achieved by using high data rate nodes as cooperative nodes and is utilized to combat unreliable wireless links. Due to its ability to enhance system capacity, reduce energy consumption and provide higher network resilience, cooperative communications has attracted much attention in recent years, especially in terms of physical layer cooperation. However, to maximize the benefits, the support of MAC layer or a cross layer approach is equally important.

2.3.2 Cooperative Communication at Medium Access Control Layer

At MAC layer we can classify cooperative protocols as proactive and reactive. In the proactive protocols, the cooperation is based on some pre-arranged optimal or random format [57]. These protocols are time critical and incur higher overheads. They require frequent information exchange for timely delivery of data. Proactive protocols are suitable for delay intolerant environments. Whereas, in reactive protocols [58 - 60], the cooperation is initiated with a negative ACK due to collision or error. Reactive protocols are appropriate for applications that are delay tolerant and incur lower overhead.

In this dissertation we concentrate on the proactive protocols only. The proactive protocols can be further classified as 1) Space Time Coding (STC) based protocols, and 2) broadcasting based protocols. The space time coding approach [61] utilizes diversity but tends to be more complicated and may require hardware modifications. Broadcast based methods represent relatively simple strategy by utilizing the broadcasting nature of the wireless medium. The broadcast based protocols can be further sub classified as 1) Single relay protocols, and 2) Multiple relay protocols. As it is evident from the name single relay protocols use only one relay in a transmission whereas multiple relay protocols use more than one relay.

Fig 2.7 illustrates the classification of cooperative MAC protocols. It is apparent that most of the existing literature focuses on the single broadcast based protocols due to their easy implementation and backward compatibility. Multiple relay broadcast protocols though not very well researched requires better coordination among the multiple relays, thus increasing the complexity. In the next section, we provide details of some existing protocols.

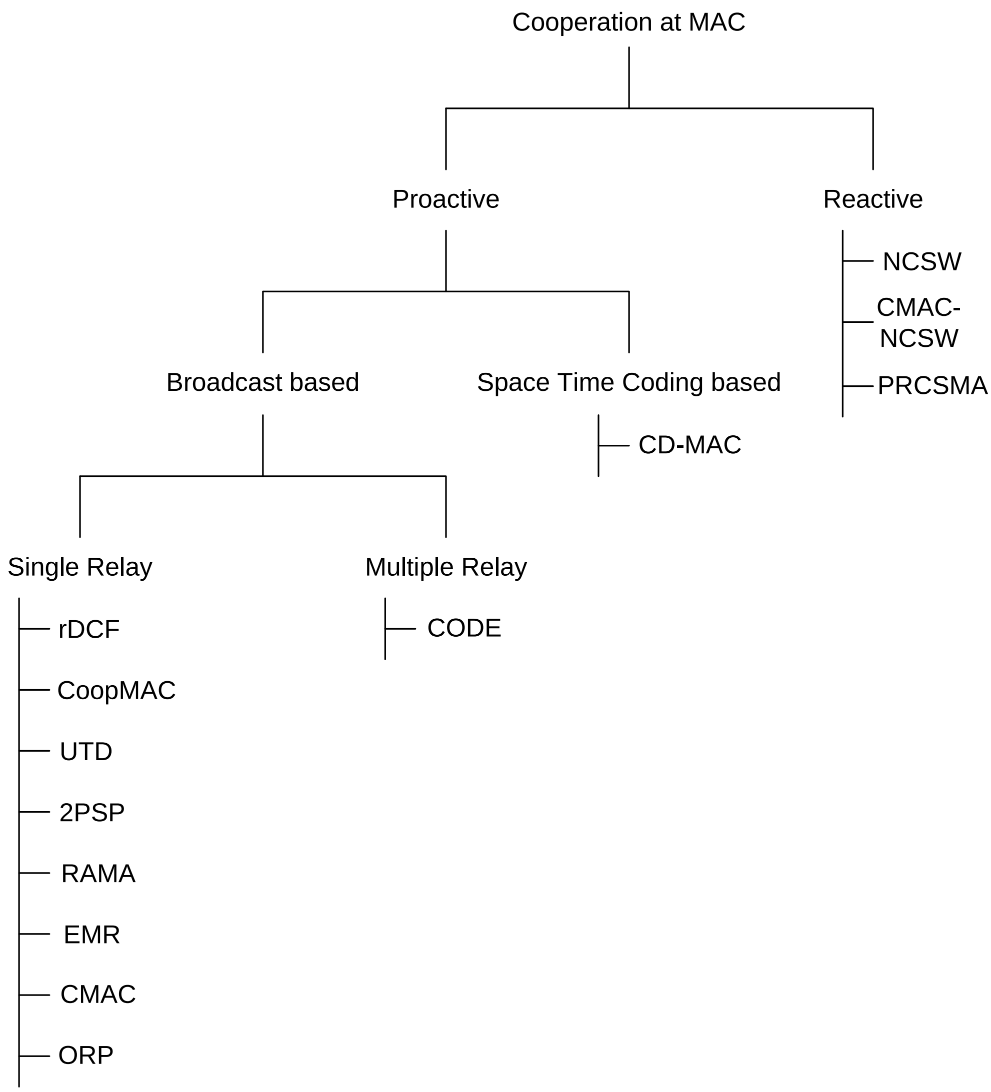


Figure 2.7: Classification of Cooperative MAC protocols.

2.4 Existing Protocols

In this section, we introduce the working of existing proactive cooperative MAC protocols and finally compare the broadcast based MAC protocols.

2.4.1 Relay-enabled Distributed Coordination Function (rDCF)

A relay-enabled distributed coordination function (rDCF) for 802.11 DCF based Ad Hoc networks was proposed in [4, 47], where a high data rate dual-hop path is used instead of a low data rate direct path between the source and destination. The rDCF utilizes the broadcasting nature of the wireless medium and is relatively simple, requiring only firmware upgrade. According to the results in [4], however, it is only suitable to use relay enabled dual-hop transmission if the packet length is approximately larger than 400 bytes. For shorter packet lengths, rDCF gives worse performance when compared to DCF because of its relatively higher overhead. Further details of rDCF are provided in Chapter 3 where it is used as a case study for the modeling of energy consumption. Following the success of rDCF, lot of research was devoted to improving its performance [48, 49, 62 - 64].

2.4.2 Cooperative MAC (CoopMAC)

Authors of [45, 46] proposed CoopMAC for WLANs, which uses received signal strength to determine the rates available for data transmission. Using CoopMAC, a source node selects the relay that offers the best data rate using information which it specifies in the MAC header. However, maintaining Receiver Signal Strength Information (RSSI) for each potential relay incurs high overheads and the accuracy of this information is also doubtful. Recently CoopMAC has been extended to cater for the

Ad Hoc networks [65]. It was put to trials and this motivated several researches to come up with extension to CoopMAC [61, 66].

2.4.3 University of Texas at Dallas (UTD) MAC

Agarwal et al. [67] proposed UTD MAC for AHNs and compared it against CoopMAC. It shows similar performance to CoopMAC, however, it results in higher throughput and lower delay when the relay is either placed too close to the source or the destination. This is due to the fact that in UTD MAC relay is always used as opposed to CoopMAC which uses relay only when a gain is available.

2.4.4 2-Hop Path Selection Protocol (2PSP)

The 2-Hop Path Selection Protocol (2PSP) [49] allows nodes to make use of the physical layer multi-rate capability of relaying data for other nodes. 2PSP is based on the RTS/ CTS access of IEEE 802.11 MAC and IEEE 802.11a Physical layer. This protocol is designed to work in Ad hoc network scenario. 2PSP uses modified control packets to coordinate relay and transmit data to achieve higher data rates.

The main objective of this protocol is to build an opportunistic rate adaptation in order to assist a source, relay and destination to achieve a higher data rate through MAC layer relaying. In this work a relay selection mechanism is proposed to further improve the performance of 2PSP protocol. The relays in this mechanism use a new contention window, called a Short Backoff Internal (SBI). A node that qualifies as a potential relay sends a Ready-To-Relay (RTR) message to inform other nodes. There is a rare possibility of collision when there is more than one potential relay nodes. This is resolved by the collision resolution algorithms proposed in this work. Simulation results show that the proposed 2PSP protocol results in reduction of delay and power consumption and an improvement in the throughput compared to both Receiving-based Auto Rate (RBAR) and IEEE 802.11 DCF. In 2PSP, the control packets are transmitted at base rate to enable other nodes to hear them. Transmission in this protocol is initiated by the source which transmits a relay RTS (RRTS) and the destination responds with a relay CTS (RCTS). The potential relay nodes overhear RRTS and RCTS and determine the available rates on the basis of Signal-to-Interference Noise ratio (SINR).

2.4.5 Relay-Aided Medium Access (RAMA)

A Relay-Aided Medium Access (RAMA) protocol was proposed by Zou et. al in [68]. RAMA can be designed on top of any rate adaptive protocol. Authors have proposed the relay based transmission to improve the performance and reduce the transmission time. RAMA consists of two parts: first is the invitation part which is used to configure the relay and second is the transmission part. RAMA allows only one relay in a transmission and in case of collision of the invitation, the relay node does not need to transmit and wait for the next transmission.

2.4.6 Efficient Multi-rate Relaying (EMR)

Efficient Multi-rate Relaying (EMR) [69] employs the multi-rate capability of IEEE 802.11 DCF based Ad Hoc networks to enable fast forwarding of packets. It modifies the RTS/CTS access and exchanges the control packet at the base rate. Potential relay nodes work out their distance from the source and destination based on the RSSI of the control packets. In EMR, scheme the effective throughput is worked out for various combinations of the source, destination and relay. This combination is based on a particular packet length. This effective throughput is mapped to a priority (a 4 bit value), where higher number means high priority. In EMR, the current priority value is integrated into the control packets. On reception of the control packets potential relays will calculate their own priority and compare it against current priority in control packets. In case of a higher priority the multiple relays may send out their relay request broadcast packet, which contains the relay address and priority path. The source then selects the best relay and responds with relay response packet which contains relays address and agreed priority value.

2.4.7 Cooperative Communication MAC (CMAC)

Cooperative Communication MAC (CMAC) [70] introduces spatial diversity via user cooperation. In this protocol, each node is equipped with two queues, one for its own data and other for its partner's data. The source transmits a data packet which is stored by the relay in its partner queue. If after a certain interval no ACK is heard the relay transmits the data again from its partner queue. This protocol shows further improvements by using Forward Error Correction (FEC) for each packet. This protocol exploits the spatial diversity to achieve gain at the cost of additional overheads due to partner queue and FEC for each packet.

2.4.8 Opportunistic Relay Protocol (ORP)

Opportunistic Relay Protocol (ORP) [71, 72] is a protocol for WLANs where nodes are able to increase their effective transmission rate by using dual-hop high data rate path instead of a single hop low data rate path. The advantage of the ORP is that it does not rely on the RSSI for relay and corresponding rate selection. It optimistically makes a packet available for forwarding and all nodes able to decode and forward it within the time constraint are potential relays. To avoid collision between multiple relays a short backoff is associated to all relays.

2.4.9 CODE: Cooperative Medium Access for Multirate AHNs

This scheme [48] uses two relays to form the virtual antenna array and additionally makes use of the physical layer network coding technique to achieve the gain. For bidirectional traffic between the source and destination, network coding is applied at the relay node to increase system throughput. CODE is 802.11 backward compliant and is capable of using cooperative communication and network coding.

2.4.10 Cooperative Diversity Medium Access Control (CD-MAC)

Moh et al. proposed a Cooperative Diversity MAC (CD-MAC) for Ad hoc networks in [61]. CD-MAC is based on the IEEE 802.11 DCF, assuming single channel and single user. This protocol makes use of the Distributed Space Time Block Coding (DSTBC) at physical layer, which requires necessary hardware support. In this protocol, both source and destination have pre selected relays. These relays are used when a source receives no reply for its RTS packet. As a second attempt the source sends a C-RTS along with a pre selected relay using the D-STBC code. Destination and its relay reply using C-CTS packet. In this case channel reservation, data transmission and acknowledgment are all done in cooperative manner. CD-MAC outperforms the legacy IEEE 802.11 DCF in terms of packet delivery ratio. However, this is achieved at the cost of high complexity and high transmission overheads as both sender and relay repeat the whole control and the data packets in different codes.

2.5 Conclusion

Table 2.2 (inspired by [79]) shows some relative comparison of existing MAC protocols in terms of architecture, relay selection, complexity, scalability etc. The essence of the above discussion is that all the protocols use the same basic mechanism of replacing slow single hop with fast dual-hop transmission. However they may differ in their number of relay, relay selection, architecture, implementation, initiation and mode of operation. Apart from the above mentioned protocols there has been much work on the performance improvement of existing MAC protocols.

This chapter has briefly presented the developments in AHN and cooperative networks. A discussion was given on Ad Hoc networks and issues faced by them. A major emphasis was on the IEEE 802.11 protocol and the analytical modeling of 802.11 DCF. A detailed discussion was also presented for cooperative communication at physical and MAC layer and in particular different cooperative MAC protocols.

Table 2.2: Comparison of Broadcast based Cooperative MAC protocols.

Feature	rDCF	CoopMAC	UTD	2PSP	RAMA	EMR	CMAC	ORP	CODE
Relay	Single	Single	Single	Single	Single	Single	Single	Single	Multiple
Relay Selection	Maximum transmission rate	Maximum Transmission Rate	Preselected based on routing protocols	Maximum transmission rate	Maximum transmission rate	Priority based on effective throughput	Random	Opportunistic Random	Maximum Transmission Rate
Architecture	Ad Hoc mode	Ad Hoc/ Infrastructure mode	Ad Hoc mode	Ad Hoc mode	Ad Hoc mode	Ad Hoc mode	Ad Hoc/ Infrastructure mode	Infrastructure mode	Ad Hoc mode
Control	Distributed	Distributed	Distributed	Distributed	Distributed	Distributed	Central / Distributed	Distributed	Distributed
Initiation	Receiver	Source	Source	Relay	Relay	Source or relay	Source or Relay	Source	Receiver
Complexity	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low	Low	High
Scalability	Moderate	Low	Moderate			Moderate	Low	Low	Moderate
Operation mode	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access	RTS/CTS based access
Implemen-tation	Minor modification to data format	Hardware modification, backward compatible	Minor modification	Minor modification to data format	Minor modification to data format	Minor modification to data format	Additional queue and FEC	Minor modifcation	Firmware upgrade, backward compatible
Mobility	High	Low	Low	High			Low	Low	High

Chapter 3

Energy Consumption Analysis

3.0 Introduction

NGNs or 4G as they are better known, are expected to provide voice, data and multimedia access to users on an 'anytime' and 'anywhere' basis. The NGNs consist of an amalgam of devices and standards ranging from mobile phones, laptops, PDAs and other handheld devices. This vision of 4G forms the requirement to achieve high throughput, high energy efficiency and low latency to provide QoS and efficient utilization of the scarce bandwidth. Therefore, NGNs are expected to result in a better quality of life and environment.

Another important requirement for NGNs (which forms a blend of standards) is backward compatibility with existing networks. In today's world, due to reasons such as cost and lack of infrastructure, it may not be possible for all to adapt new networks at once and make the existing ones obsolete. This may happen eventually with time; however, we expect to have a hybrid of the new and existing networks for quite some time. It is of high importance to have smooth interaction between existing networks and NGNs. This intermediate period where both networks will co-exist is an important step towards complete transition to next generation networks which ensures a better quality of life and environment. Due to high number of users, the developed and developing countries which have made much investment on existing networks may take longer to completely migrate to NGNs. However underdeveloped countries, which still lack infrastructure, may adapt easily but cost constraints will be an issue for these as well.

Existing networks have many issues which, when integrated into the new networks, will greatly influence the overall performance. Therefore, much research currently is focused on improving the performance of existing networks. This can be achieved in numerous ways such as efficient algorithms, protocol modification, new protocols etc. One such example of issues is from the existing 802.11 (as presented earlier in Chapter 2, Section 2.2.3) networks where the performance of the whole system degrades greatly once low data rate nodes become dominant.

A solution to address this issue comes from the advent of cooperative communication [53, 54] in the form of relay based MAC protocols. This results in intermediate data rates to provide higher throughput and capability to fight against the varying channel conditions. At MAC layer, cooperation can be incorporated by replacing slow single-hop transmission by fast dual-hop transmissions. This means that the source, after acquiring the medium, transmits to a relay, first at a higher rate, and the relay will then transmit to the destination as shown in Fig 3.1b. This solution, although appropriate for the throughput, has emerged in an era when the awareness to "go green" is widely discussed. This has triggered a debate on the energy consumption which has now gained importance in the minds of the MAC protocol developers. It is important to reiterate the fact that before the ultimate phase of complete convergence to 4G networks, a hybrid phase will dominate.

Relay based MAC protocols are in their infancy and most of the current literature deals with the throughput improvement gained by using these. To the best of our knowledge,

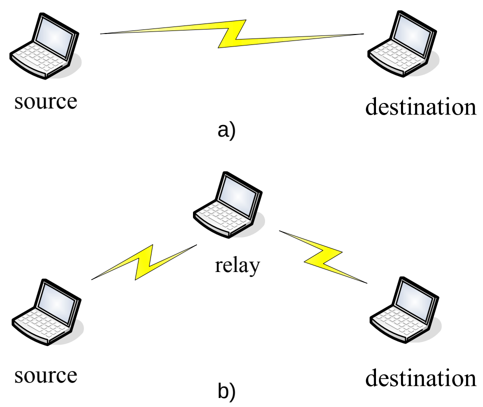


Figure 3.1: a) Slow Single hop direct transmission, b) Fast Dual-hop transmission via relay.

the literature on the relay based MAC protocols still lacks studies on energy issues in MAC protocols and energy consumption models.

Therefore it is a matter of high importance for MAC protocol developers to have an idea of the energy consumption while still in the design phase. Most ad hoc network nodes are powered by batteries, thus have limited access to energy resources. Therefore efficient utilization of this scarce resource is a main concern in ad hoc networks. In addition to this, another concern of importance is the impact of relay nodes on the energy efficiency as relay nodes will utilize their own energy reserves to help other nodes.

Most of the existing closely related research literature is about the single hop IEEE 802.11 DCF. Carvalho et al. [31] model a node's energy consumption in a single-hop IEEE 802.11 ad hoc network as shown in Fig 3.1a. Carvalho et al. calculated the average service time of a packet transmitted in a saturated ad hoc network. Their results show that passive modes (idle, overhear, receive) dominate the energy consumption and they conclude that transmission of large payloads is more advantageous. However, this model treats receiving and idle states in the same way and gives no consideration to channel condition.

Ergen and Varaiya presented a model in [33] for decomposition of energy consumption in IEEE 802.11. They derived the formula for the amount of energy consumed by a node in order to transmit 1 MB of data in a network with n nodes in ideal channel conditions. This model can differentiate receiving and idle states. Kuo in [73] modeled the energy consumption of 802.11a by jointly considering the PHY and MAC layers. This model treats receiving, overhearing and idle states in the same way and concludes that 802.11 MAC wastes lot of energy due to binary exponential backoff process. This model neglects the finite retry limit and impact of the channel.

Zanella and De Pellegrini [74] proposed an analytical framework to investigate the cost of communicating in a cluster of IEEE 802.11 DCF in terms of the average life of terminals. This model provides a complete statistical description of the energy spent per packet and helps in evaluating the average life of a terminal, which may be of interest to sensor networks. Wang [32] proposed a model for energy efficiency in IEEE 802.11 DCF and tried to maximize energy efficiency based on packet size and contention window. Wang considered channel errors on the data packet only, which is not reflective of the real situation. However, none of the above models are suitable for the relay based MAC protocols and they require significant modifications for the later situation.

In this chapter, we propose a generalized model for energy consumption and address the energy concerns of using dual-hop relay based MAC protocols, as it is important to examine the impact of using a relay on energy consumptions compared to IEEE 802.11 DCF. Use of relay requires justification both from throughput and from energy perspectives. It is important to see the impact of using a relay on the energy efficiency, as relay nodes will utilize their own energy reserves to help other nodes.

The main contribution of this chapter is the generalized analytical energy model for dual-hop relay based MAC protocols in saturated condition. This model is able to predict performance in an ideal channel, in a channel with transmission errors, on impact of packet length on energy consumption and the decomposition of energy.

In this chapter we have used an existing protocol called rDCF [4] as a case study to show the efficacy of the proposed energy model. Therefore, it is a matter of high importance for MAC protocol developers to have an idea of the energy consumption while still in design phase. The results of energy consumption with a different number of nodes and rate combinations for relay links are shown. Furthermore, the impact of variable packet length (expected payload) on energy consumption is discussed. Decomposition of energy for various operations is also shown and will help in the design of energy efficient MAC protocols. This is particularly useful for devising energy saving mechanisms and policies for existing and new protocols. The energy model will benefit the application of dual-hop relay based MAC protocols (e.g. rDCF) in energy critical areas such as sensor networks and integration with next generation networks.

This chapter presents an energy model based on Wu's [19] saturation throughput model, which is able to cater for dual-hop relay based transmissions. Wu's model is a more accurate model for saturation throughput which incorporates the finite retry limit. In [75, 76] we have used the Markov chain model of [19] to show the energy consumption of relay based ad hoc networks. The proposed energy model considers the transmission errors. In addition, the following challenges have been addressed in the chapter: 1) treatment of relay node; 2) how relay nodes differ from other nodes in energy consumption behaviour; and 3) impact on energy in the presence of transmission errors.

3.1 System Model

Consider a wireless network of n nodes based on IEEE 802.11 MAC that can support multiple transmission rates and relay based transmissions. The wireless medium is shared among multiple contending nodes, i.e. a single physical channel is available for wireless transmission. The control packets are used to solve the hidden terminal problem and to improve the system performance. Another assumption in this model is that the collision can only take place at the first control packet. For the modeling of energy, a saturated network is assumed; where nodes always have packets to transmit. In addition to this it is assumed that there is always a relay available to help. All nodes are capable of relaying data for other nodes. The relay nodes simply forward the packets and reduce the overall transmission time via dual-hop transmission at higher data rates. Relays are not required to contest for the access as once a source node acquires the medium; the transmission is carried out via the relay.

The rationale for using the Markov chain to model the behaviour of a single node comes from Bianchi's seminal work reported in [18], where he obtained the stationary probability that the station transmits a packet in a randomly chosen slot time. This was the first contribution which was able to accurately capture the effects of the contention window and binary exponential back-off procedure used by DCF in 802.11. This probability is independent of the access mechanism (i.e., Basic or RTS/CTS) employed. He further studied the events that can occur within a generic slot time. Since then it is quite a standard to use the Markov chain to represent the complex operation of 802.11 DCF and the backoff algorithms within. The discrete time Markov chain in Fig. 3.2 is a refinement of Wu's work [19] and is inspired by [27]. It adds on to include the transmission errors.

It represents a 2-dimensional process {*s(t), b(t)*}, where *s(t)* is the stochastic process representing the backoff stage and *b(t)* is the stochastic process representing the backoff window size for a given station at slot time *t*. Note that the slot time is referred to as a constant value σ which is defined according to 802.11 physical layer. In the Markov chain below, the transition probabilities are modified (compared to Wu's model) as follows:

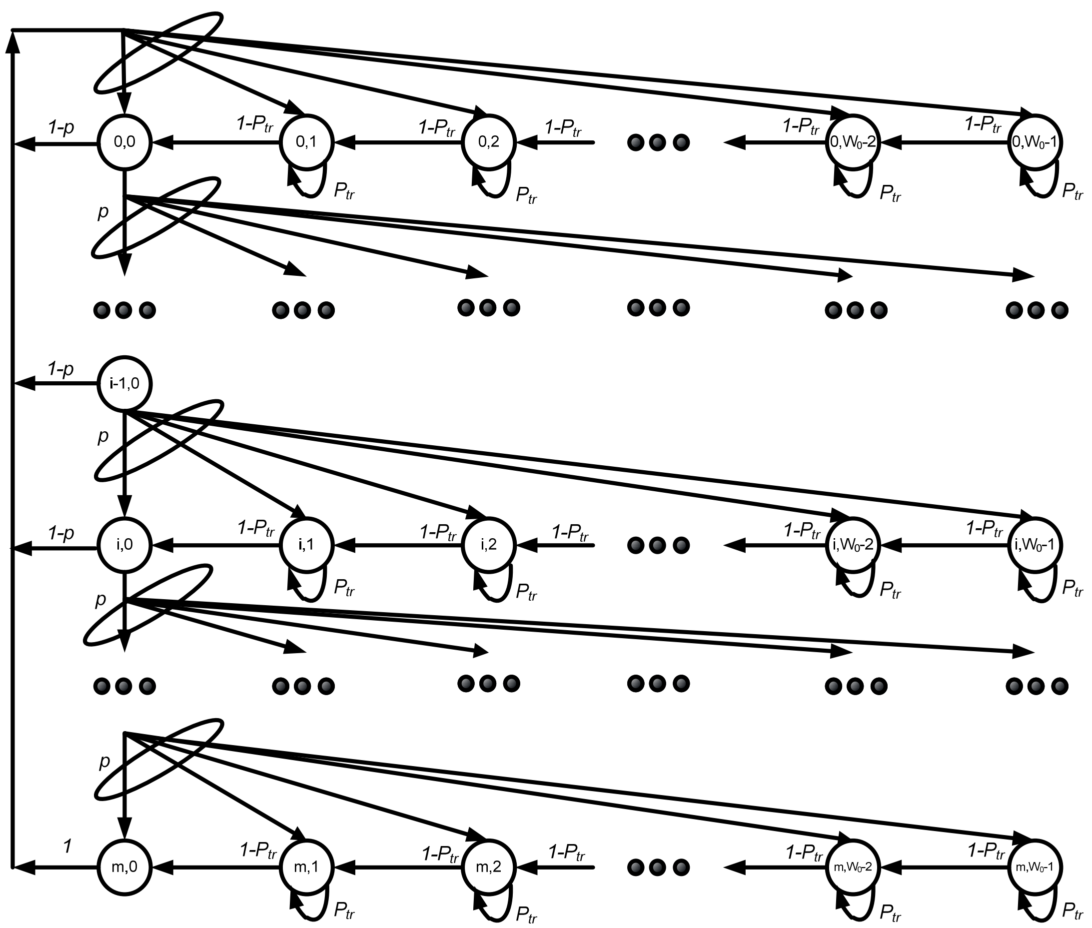


Figure 3.2: Discrete time Markov chain model.

$$P\{i,k|i,k+1\} = 1 - P_{tr}, \quad k \in (1, W_i - 2), i \in (0, m)$$

$$P\{i,k|i,k\} = P_{tr}, \quad k \in (1, W_i - 2), i \in (0, m)$$

$$P\{0,k|i,0\} = \frac{1-p}{W_0}, \quad k \in (0, W_0 - 1), i \in (0, m-1) \tag{3.1}$$

$$P\{i,k|i-1,0\} = \frac{p}{W_i}, \quad k \in (0, W_i - 1), i \in (1, m)$$

$$P\{0,k|m,0\} = \frac{1}{W_0}. \quad k \in (0, W_0 - 1)$$

In the above equation (3.1), $P\{i,k|i,k+1\}$ is the probability when a station senses that the channel is idle it decreases its backoff timer; $P\{i,k|i,k\}$ is the probability when a station senses that the channel is busy, it suspends its backoff timer; $P\{0,k|i,0\}$ is the probability after a successful transmission, the new packet starts at backoff stage 0; $P\{i,k|i-1,0\}$ is the probability after every unsuccessful transmission, the backoff window doubles until it reaches the maximum backoff window size; and $P\{0,k|m,0\}$ is the probability when the maximum backoff stage of the contention window is reached, it will eventually reset to the initial value if there is a unsuccessful or successful transmission. Due to chain regularities, we have:

$$b_{i,0} = (1 - P_{tr}) b_{i,1} + \frac{1}{W_i} \begin{cases} (1-p)\sum_{j=0}^{m-1} b_{j,0} + b_{m,k} & i = 0 \\ p b_{i-1,0} & i \in (1, m) \end{cases}$$

$$b_{i,k} = (1 - P_{tr}) b_{i,k+1} + P_{tr} b_{i,k} + \frac{1}{W_i} \begin{cases} (1-p)\sum_{j=0}^{m-1} b_{j,0} + b_{m,k} & i = 0 \\ p b_{i-1,0} & i \in (1, m) \end{cases} \tag{3.2}$$

$$b_{i,w_i-1} = P_{tr} b_{i,w_i-1} + \frac{1}{W_i} \begin{cases} (1-p)\sum_{j=0}^{m-1} b_{j,0} + b_{m,k} & i = 0 \\ p b_{i-1,0} & i \in (1, m) \end{cases}$$

Here, equation (3.3) shows the probability τ, that a node transmits in a randomly chosen slot, depends on the conditional probability of packet failure p.

$$\tau = \begin{cases} \dfrac{2(1-2p)(1-p^{m+1})}{W\left(1-(2p)^{m+1}\right)(1-p)+(1-2p)(1-p^{m+1})} & m \le m' \\ \dfrac{2(1-2p)(1-p^{m+1})}{\left(\begin{array}{l} W\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-p^{m+1})+ \\ W2^{m'}p^{m'+1}(1-2p)(1-p^{m'-m}) \end{array}\right)} & m > m' \end{cases} \quad (3.3)$$

$$p = 1-\left(1-\tau\right)^{n-1}(1-P_e) \quad (3.4)$$

Equation (3.4) gives the packet failure probability in terms of collision (i.e. $(1-\tau)^{n-1}$) and packet errors (P_e), where n is the total number of nodes. This equation differs from its counterpart in [19] shown in (2.8) where the probability of failure is only due to collisions. From (3.4), it is possible to see that the packet failure is due to collision, transmission errors or both. Here the probability of having failure occurring due to both is almost negligible. Equations (3.3) and (3.4) are a nonlinear system which can be solved numerically to find p and τ.

From the above results, we can calculate P_{tr} and P_s. Equation (2.9) gives P_{tr} which is the probability that there is at least one transmission in the considered slot time. In expression (2.10), P_s is the probability of a successful transmission.

3.2 Energy Model

Nodes in the network are classified as active (source, relay and destination) and non active (all other nodes listening) nodes. Energy consumed in each kind of slot is the product of slot duration and power consumption in that slot. In this analysis three physical states are considered: *transmit*, *receive* and *listen* (idle/ overhearing) as shown in Fig. 3.3. Active nodes transmit, receive and listen during a transmission whereas non active nodes only listen to transmission. The above system model is used to derive the energy analysis in an ideal channel and in a channel with transmission errors. The above shown Markov chain is employed to model the energy consumption behavior of a dual-hop relay based MAC protocol. The total energy in joules consumed by node l to successfully transmit and receive 1 MB of data can then be defined as:

$$J(n) = \frac{E\left[\text{Energy consumed in one slot}\right]}{E[\text{Data transmitted and received in one slot}]} \tag{3.5}$$

In (3.5) $J(n)$ is the energy consumed in J/MB. This is the ratio of expected energy (in joules) consumed by node l in one slot to the expected data (in MB) successfully transmitted and received by node l in one slot. In (3.5) slot refers to a transmission slot and successful transmission includes transmission by source, forwarding by relay and reception by destination. Equation (3.6) gives the expression for expected data (in MB) transmitted and received by a node l in one slot, where $E[P']$ is the packet size in MB.

$$E[\text{MB transmitted by } l \text{ in one slot}] = \frac{P_s P_{tr}}{n} E[P'] \tag{3.6}$$

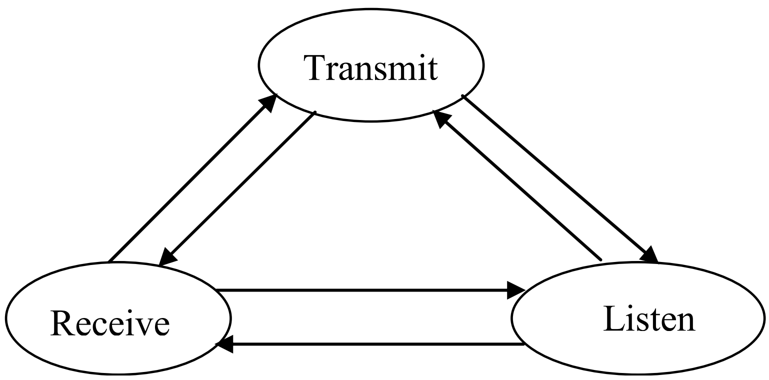


Figure 3.3: Physical States.

In the following sections, operations for active and non active nodes involved are defined based on the physical states.

3.2.1 Energy Analysis for Ideal Channels

For energy consumption in an ideal channel, it is known that the packet failure is only due to collision and there are no transmission errors, i.e. P_e is zero. Based on the above classification of active and non active nodes, there are three available states: transmit, receive and listen. Further operations within the three states are: (a) successful transmission; (b) successful reception; (c) overhearing (reception of packets intended for other stations); (d) idle listening (when the channel is idle); (e) unsuccessful (collided) transmissions; and (f) reception of collisions. The probabilities of different operations in an ideal channel are represented as follows:

$J_s^{rx}(l)$: The probability of successful reception of packet destined for node l, and is equal to $\tau(1-\tau)^{(n-1)}(1-P_e)$;

$J_s^{rx}(\sim l)$: The probability of successful reception of packet not destined for node l, and is equal to $(n-3)\,\tau(1-\tau)^{(n-1)}(1-P_e)$;

$J_s^{rx}(r)$: The probability of successful reception of packet destined for relay r, and is equal to $\tau(1-\tau)^{(n-1)}(1-P_e)$;

J_s^{tx}: The probability of successful transmission of a packet by node l, and is equal to $\tau(1-p)$;

J_c^{rx}: The probability of reception of a collided packet, and is equal to $(1-\tau)$. $[1-(1-\tau)^{(n-1)}(1-P_e)-(n-1)\,\tau(1-\tau)(n-2)]$;

J_c^{tx}: The probability of collision on transmission of a packet by node l, and is equal to $\tau p(1-P_e)$;

J_σ: The probability of idle slots, and is equal to (1- P_{tr});

$J_s^{rx}(l)$ reflects successful reception of packets destined for node l provided that there is a transmission free from collision and error. Similarly, $J_s^{rx}(r)$ represents the successful reception by relay with the same conditions. It is true as the relay is not involved in the contention process. $J_s^{rx}(\sim l)$ indicates the successful reception by all non active overhearing nodes. The term (n-3) ensures that only non active nodes are considered. J_s^{tx} reflects the successful transmission of a packet provided there is a transmission without any failure. J_c^{tx} represents the transmission where there is no error and failure is due to collision only. J_c^{rx} is the reception of collided packet, and J_σ the probability that there is no transmission. As such, we have

$$\begin{aligned} J_s^{rx} &= \rho_{rx}\left[\sum_{i=0}^{r} T_{control} + \sum_{j=0}^{s} T_{data}\right] + \rho_{tx}\left[\sum_{k=0}^{t} T_{control} + \sum_{l=0}^{u} T_{data}\right] \\ &+ \rho_\sigma\left[(u+v+x+y-1)(T_{SIFS}+\delta) + (T_{DIFS}+\delta)\right] \end{aligned} \tag{3.7}$$

$$\begin{aligned} J_s^{tx} &= \rho_{rx}\left[\sum_{i=0}^{r} T_{control} + \sum_{j=0}^{s} T_{data}\right] + \rho_{tx}\left[\sum_{k=0}^{t} T_{control} + \sum_{l=0}^{u} T_{data}\right] \\ &+ \rho_\sigma\left[(u+v+x+y-1)(T_{SIFS}+\delta) + (T_{DIFS}+\delta)\right] \end{aligned} \tag{3.8}$$

$$J_c^{tx} = \rho_{tx} T_{control}^{*} + \rho_\sigma(\delta + T_{EIFS}) \tag{3.9}$$

$$J_c^{rx} = \rho_{rx} T_{control}^{*} + \rho_\sigma(\delta + T_{EIFS}) \tag{3.10}$$

$$J_\sigma = \rho_\sigma \sigma \tag{3.11}$$

$$J_e^{tx} = \rho_{tx} T_e + \rho_\sigma(\delta + T_{EIFS}) \tag{3.12}$$

$$J_e^{rx} = \rho_{rx} T_e + \rho_\sigma(\delta + T_{EIFS}) \tag{3.13}$$

$$E[\textit{energy consumed by } l \textit{ in one slot}] = (1-P_{tr})J_{\sigma} + \tau p J_c^{tx} + \tau(1-\tau)^{(n-1)}(1-P_e) \times [J_s^{rx}(l) + J_s^{rx}(r)] + (n-3)\tau(1-\tau)^{(n-1)}(1-P_e)J_s^{rx}(\sim l) + (1-\tau)[1-(1-\tau)^{(n-1)} \times (1-P_e) - (n-1)\tau(1-\tau)^{(n-2)}]J_c^{rx} + \tau(1-p)J_s^{tx} + \tau P_e J_e^{tx} + \tau(1-\tau)^{(n-1)} P_e [J_e^{rx}(l) + J_e^{rx}(r)] + (n-3)\tau(1-\tau)^{(n-1)} P_e J_e^{rx}(\sim l) \tag{3.14}$$

The numerator in (3.5) is defined in expression (3.14). As it is evident from the nature of relay based MAC protocols, the control packets are used to coordinate relays which are followed by the data and ACK packets. As from the operations described earlier in this section, there are active nodes and non active nodes. In order to model this behavior of transmitting and receiving (active nodes) or receiving only (non active nodes) control and data packets, a set of generic equations (3.7) - (3.11) is formulated to show the working of the MAC protocol. To calculate the energy consumed by nodes (active and non active), equations (3.7) - (3.11) shown above are used in (3.14).

For an ideal scenario where there are no transmission errors, it is possible to simplify (3.14) by substituting $P_e = 0$. These equations are independent of the protocol. Also, ρ_{tx}, ρ_{rx} and ρ_{σ} are the power consumed (in Watts) to transmit, receive and listen (idle/ overhearing) respectively. T_{SIFS}, T_{DIFS} and T_{EIFS} are the SIFS, DIFS and EIFS times. δ is the propagation delay and σ is the slot time. In (3.7) and (3.8), reception and transmission of multiple packets is shown. Equation (3.7) gives a generalized equation for determining $J_s^{rx}(r)$ and $J_s^{rx}(l)$, which are probabilities of successful reception of packets by relay and destination (which are active nodes). Equation (3.8) consists of the sum of energy consumed in receiving, transmitting and listening. Energy consumed in each of these states is the product of slot duration and respective power. Here the slot duration in transmitting and receiving of the control and data packets is the sum of their time durations. u and v are the total number of control and data packets received.

Similarly, *x* and *y* are the total number of control and data packets transmitted. The sum of *u*, *v*, *x* and *y* is the total number of control and data packets in a protocol.

The same expression is used to determine J_s^{rx} (~*l*), where no transmission of packets is involved. In (3.8) successful transmission of a packet by an active node (source) is given. In (3.9) and (3.10), T^*_{control} is the time for collision of control packet (initiated from source to relay or destination) and J_c^{tx} are J_c^{rx} the probabilities of transmission and reception of collided packets. Equation (3.11) shows the listening (idle) state as a product of idle slot and idle power. Equations (3.7) – (3.11) are for the ideal case where there are no errors and are the same as in [76]. This set of equations represents a generic model and is used to show performance of relay based MAC protocols and can easily be adapted to cater for 802.11 a/b/g [14 - 16] physical layers, with the parameters changed appropriately.

3.2.2 Energy Analysis for Channels with Transmission Errors

In this section, the impact of transmission errors on the energy consumption is considered. Unlike collision which occurs at the first control packet, transmission errors can occur at any packet. Therefore, it is important to take into consideration that even with successful reception of one or more packets involved in the transmission a failure can still take place due to one of the following packets being in error.

For energy analysis of a channel with transmission errors, more operations are added to those defined earlier in Section 3.2.1. The additional operations due to errors are: (g) unsuccessful (error) transmissions and (h) reception of errors. The probabilities of additional operations are as follows:

J_e^{tx}: The probability of transmission of a packet in error by Node l, and is equal to $\tau(1-\tau)^{(n-1)}P_e$;

$J_e^{rx}(l)$: The probability of reception of a packet in error by destined Node l, and is equal to $\tau(1-\tau)^{(n-1)}P_e$;

$J_e^{rx}(r)$: The probability of reception of a packet in error by destined relay r, and is equal to $\tau(1-\tau)^{(n-1)}P_e$;

$J_e^{rx}(\sim l)$: The probability of reception of a packet in error not destined for Node l, and is equal to $(n-3)\tau(1-\tau)^{(n-1)}P_e$;

These expressions together with those defined earlier will give the energy consumption in the case of transmission errors. J_e^{tx} reflects the transmission of a packet in error provided there is no collision. $J_e^{rx}(l)$, $J_e^{rx}(r)$ and $J_e^{rx}(\sim l)$ are probabilities of reception of a packet destined for Node l, relay r and reception of packet not destined for Node l respectively. Reception of packet in error is conditioned on a transmission free from collision. The term $(n-3)$ in $J_e^{rx}(\sim l)$ ensures that only non active nodes are considered. In (3.12) and (3.13), T_e is the average time for a particular packet in error. In this case it shows the first packet in error. For energy consumption in channel experiencing transmission errors, we define J_e^{tx} and J_e^{rx} as the probabilities of transmission and reception of packets in error. In (3.12) J_e^{tx} is the probability of transmitting a packet in error. Equation (3.13) is for determining $J_e^{rx}(r)$, $J_e^{rx}(l)$ and $J_e^{rx}(\sim l)$, which are probabilities of reception of packet (first packet) in error by relay, destination and overhearing nodes. For simplicity we have only shown the equations (3.12) and (3.13) for the case if the first control packet is in error. The equations become more complex for the following packets being in error and are shown in Appendix A. Finally, the energy (J/MB) is calculated by using (3.6), (3.14) and (3.5). Equation (3.14) is the sum of the products of operations/states and their probabilities.

To this point, we have shown generalized equations for the energy analysis in an ideal channel and channel with transmission errors. In the following section we will apply the above energy analysis to a relay based MAC protocol.

3.3 Relay-enabled Distributed Coordination Function

This section briefly describes the relay-enabled distributed coordination function. The rDCF was originally proposed in [4], where relay is used to improve the system throughput and reduce packet delay. In rDCF, a high data rate dual hop path is used instead of a low data rate direct path between the source and destination as shown in Fig. 3.1b. The rDCF is based on the IEEE 802.11 DCF, but has introduced the following modifications:

- Backward compatibility to 802.11 DCF (non relay mode) and requiring only a firmware upgrade.
- Control packets transmitted at the base rate of 2 Mbps.
- Modified carrier sensing scheme (shown in Fig. 3.4).
- Introduction of Reservation Sub Header (RSH) (transmitted at 2 Mbps and used to broadcast duration information for the rest of packet) in DATA packets transmitted at higher rates from source to relay.
- Frequent broadcasting of willing lists (potential relay entries) between nodes.
- Relay selection based on a credit system.

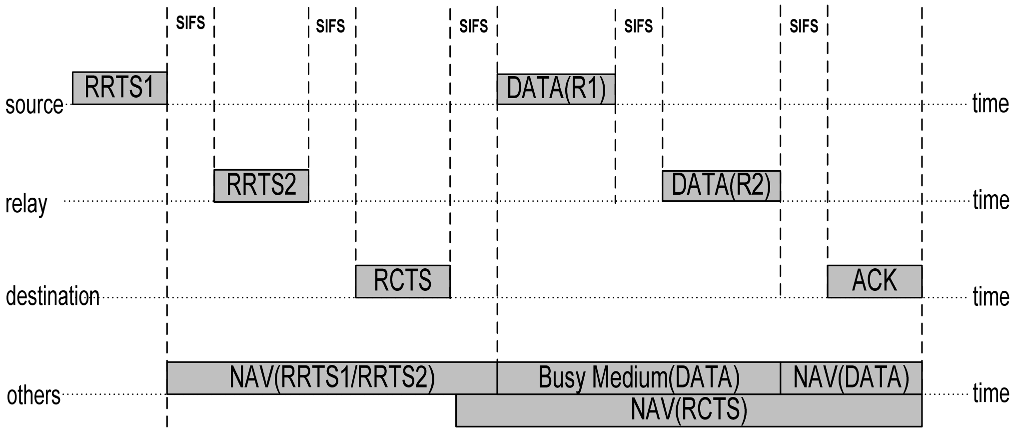


Figure 3.4: Carrier sensing scheme of rDCF.

Considering the fact that rDCF is backward compatible to 802.11 DCF and has the same backoff scheme, we can observe that the process of channel contention and time spent in contention for each node in rDCF is the same as in 802.11 DCF.

The modified carrier sensing scheme used in rDCF achieves better bandwidth utilization [4]. A major advantage of this scheme compared to 802.11 DCF is that the nodes are blocked exactly for the data transmission duration. In 802.11 DCF, if CTS is not received at the source due to collision or channel error, the neighbour nodes of the source are blocked for the whole duration of transmission which reduces the bandwidth utilization.

Unlike the standard DCF, in rDCF if CTS/RCTS is not received, the neighbor nodes are not blocked for the whole duration of transmission. In the 802.11 DCF, the source estimates the possible transmission rate and the duration, whereas in the modified carrier sensing scheme of rDCF, the source first calculates (as all control packets are transmitted at base rate of 2 Mbps) the duration of the RRTS and RCTS/ CTS transmissions only. The destination based on the received RRTS1 and RRTS2, decides in the favour of relay or to revert to the direct transmission. If the destination feels relay based transmission is not suitable it requests for a direct transmission by transmitting a CTS packet. Otherwise if the destination requires relay based transmission it transmits a RCTS packet. The source extracts the agreed transmission rates from RCTS and calculates the duration of data packet and ACK. This information is made available to all overhearing nodes via the RSH attached to the data packet. This prevents the unnecessary blocking of nodes for the entire duration of the transmission.

The rDCF uses the same physical characteristics such as transmission power and RSSI as in IEEE 802.11 DCF. There is no power control and both data and control packets are transmitted at maximum power. Relay transmission is intended to provide higher throughput and reduced blocking time.

All the nodes maintain a willing list based on the channel quality between them and their single hop neighbouring nodes. The length of the willing list is limited to 10 entries to reduce overheads. Nodes keep updating their willing list with better links and frequently broadcast it to their neighbours. The willing list contains an entry for the credit rating of each potential relay node. This rating improves with successful relaying and degrades with inability to relay.

3.3.1 Throughput Analysis of rDCF

To analytically model rDCF, the authors in [4] have used Bianchi's model [18]. For the throughput calculation, saturated condition (i.e. every node always has data to transmit) is assumed. It further assumes that the channel is ideal (i.e. there are no hidden nodes and capture effect), and calculates the saturated throughput for RRTS/ RCTS access. For rDCF, the equations for the average times of channel sensed busy for collision and successful transmission respectively, are:

$$T_c^{rDCF} = T_{RRTS1} + T_{DIFS} + \delta \quad (3.15)$$

$$\begin{aligned} T_s^{rDCF} &= T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_1)} \\ &+ T_{DATA(L,R_2)} + 5T_{SIFS} + 6\delta + T_{DIFS} \end{aligned} \quad (3.16)$$

where T_c and T_s are the average time when the channel is sensed busy during collision and successful transmission. Here, RRTS and RCTS are control packets for coordinating relay-enabled transmission as shown in Fig. 3.4. In the equations (3.15) and (3.16), T_{RRTS1}, T_{RRTS2}, T_{RCTS} and T_{ACK} are the transmission times for RRTS1 (source to relay), RRTS2 (relay to destination), RCTS and ACK respectively. T_{SIFS} and T_{DIFS} are inter-frame times and δ is the propagation delay. $T_{\mathrm{DATA(L,R_1)}}$ and $T_{\mathrm{DATA(L,R_2)}}$ are the times for data packets of length L bytes at rates R_1 and R_2.

3.3.2 Analysis of rDCF with Transmission Errors

Due to the nature of rDCF, we must consider all the links: the link between source and relay (with probability of bit errors P_{b1} and distance d_{sr}), the link between relay and destination (with probability of bit errors P_{b2} and distance d_{rd}), and the link between source and destination (with probability P_b and distance d_{sd}). As a result, the probability of packet errors for the rDCF protocol and overhead caused by packet errors are derived in equations (3.17) and (3.18).

In (3.17), P_e is the probability of packet errors, which is based on transmission of individual packets (control and data) involved in rDCF. Note that for the packets following RRTS1, their probability of error is conditioned on successful reception of the previous packets. For RRTS2 in (3.17), the probability of error is based on the successful reception of RRTS1. If RRTS1 is in error there will be no transmission of RRTS2. In the same way, the total probability of error is based on the successful reception of all control and data packets. Probability of packet error is calculated based on the bit error probability of a particular link and length of that packet.

$$
\begin{aligned}
P_e^{RRTS1} &= 1-(1-P_{b1})^{L_{RRTS1}}, \\
P_e^{RRTS2} &= (1-P_{b1})^{L_{RRTS1}}(1-(1-P_{b2})^{L_{RRTS2}}), \\
P_e^{RCTS} &= (1-P_{b1})^{L_{RRTS1}}(1-P_{b2})^{L_{RRTS2}}(1-(1-P_b)^{L_{RCTS}}), \\
P_e^{DATA1} &= (1-P_{b1})^{L_{RRTS1}}(1-P_{b2})^{L_{RRTS2}}(1-P_b)^{L_{RCTS}}(1-(1-P_{b1})^{L_{DATA1}}), \\
P_e^{DATA2} &= (1-P_{b1})^{L_{RRTS1}}(1-P_{b2})^{L_{RRTS2}}(1-P_b)^{L_{RCTS}}(1-P_{b1})^{L_{DATA1}} \\
&\quad \times(1-(1-P_{b2})^{L_{DATA2}}), \\
P_e^{ACK} &= (1-P_{b1})^{L_{RRTS1}}(1-P_{b2})^{L_{RRTS2}}(1-P_b)^{L_{RCTS}}(1-P_{b1})^{L_{DATA1}} \\
&\quad \times(1-P_{b2})^{L_{DATA2}}(1-(1-P_b)^{L_{ACK}}), \\
P_e &= 1-(1-P_{b1})^{L_{RRTS1}}(1-P_{b2})^{L_{RRTS2}}(1-P_b)^{L_{RCTS}}(1-P_{b1})^{L_{DATA1}} \\
&\quad \times(1-P_{b2})^{L_{DATA2}}(1-P_b)^{L_{ACK}}.
\end{aligned}
\tag{3.17}
$$

$$
\begin{aligned}
T_e^{RRTS1} &= T_{RRTS1} + T_{EIFS} + \delta, \\
T_e^{RRTS2} &= T_{RRTS1} + T_{RRTS2} + T_{SIFS} + 2\delta + T_{EIFS}, \\
T_e^{RCTS} &= T_{RRTS1} + T_{RRTS2} + T_{RCTStimeout} + T_{SIFS} \\
&\quad +3\delta + T_{DIFS}, \\
T_e^{RCTS} &= T_{RRTS1} + T_{RRTS2} + T_{RCTStimeout} + T_{SIFS} \\
&\quad +3\delta + T_{DIFS}, \\
T_e^{DATA1} &= T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{DATA1} \\
&\quad +3T_{SIFS} + 4\delta + T_{EIFS}, \\
T_e^{DATA2} &= T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{DATA1} \\
&\quad +T_{DATA2} + 4T_{SIFS} + 5\delta + T_{EIFS}, \\
T_e^{ACK} &= T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{DATA1} \\
&\quad +T_{DATA2} + T_{ACKtimeout} + 4T_{SIFS} \\
&\quad +6\delta + T_{DIFS}.
\end{aligned}
\tag{3.18}
$$

In (3.18) we work out the average time spent in all the packets in error, where $T_{\text{ACKtimeout}} = T_{\text{ACK}} + T_{\text{SIFS}}$ and $T_{\text{RCTStimeout}} = T_{\text{RCTS}} + T_{\text{SIFS}}$ It is evident that for RRTS1 in error the time spent is shortest and for ACK in error the time spent is the longest.

Energy consumption due to the error taking place depends on the position of errors in transmission. During a transmission we have the following packet flow:

$$RRTS1 \rightarrow RRTS2 \rightarrow RCTS \rightarrow DATA1 \rightarrow DATA2 \rightarrow ACK$$

If an error takes place at RRTS1, the time spent in error and energy consumption is lowest and the contribution to energy consumption due to packet error is the lowest as well. In the same way, if error takes place at DATA1, the time spent in error and the energy consumed is high. So we can say that:

$$T_e^{RRTS1} < T_e^{RRTS2} < T_e^{RCTS} < T_e^{DATA1} < T_e^{DATA2} < T_e^{ACK},$$

and similarly for energy consumption:

$$E_{\text{RRTS1}} < E_{\text{RRTS2}} < E_{\text{RCTS}} < E_{\text{DATA1}} < E_{\text{DATA2}} < E_{\text{ACK}}$$

where T_e^{xxxx} is the time spent in error and E_{xxxx} is the energy consumed for a particular packet (represented by xxxx) being in error.

For rDCF the following expressions can be derived and simplified based on (3.7) to (3.13):

$$\begin{aligned} J_s^{rx}(l) = {} & \rho_{rx}(T_{RRTS1} + T_{RRTS2} + T_{DATA(L,R1)} + T_{DATA(L,R_2)}) + \rho_{tx}(T_{RCTS} + T_{ACK}) \\ & + \rho_{\sigma}(5T_{SIFS} + T_{DIFS} + 6\delta) \end{aligned} \qquad (3.19)$$

$$\begin{aligned} J_s^{rx}(r) = {} & \rho_{rx}(T_{RRTS1} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_1)}) + \rho_{tx}(T_{RRTS2} + T_{DATA(L,R2)}) \\ & + \rho_{\sigma}(5T_{SIFS} + T_{DIFS} + 6\delta) \end{aligned} \qquad (3.20)$$

$$J_s^{rx}(\sim l) = \rho_{rx}(T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_1)} + T_{DATA(L,R_2)}) + \rho_\sigma(5T_{SIFS} + T_{DIFS} + 6\delta) \quad (3.21)$$

$$J_s^{tx} = \rho_{tx}(T_{RRTS1} + T_{DATA(L,R_1)}) + \rho_{rx}(T_{RRTS2} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_2)}) + \rho_\sigma(5T_{SIFS} + T_{DIFS} + 6\delta) \quad (3.22)$$

$$J_c^{rx} = \rho_{rx}T^*_{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.23)$$

$$J_c^{tx} = \rho_{tx}T^*_{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.24)$$

$$J_e^{tx}(l) = \rho_{tx}T_e^{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.25)$$

$$J_e^{rx}(l) = \rho_{rx}T_e^{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.26)$$

$$J_e^{rx}(r) = \rho_{rx}T_e^{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.27)$$

$$J_e^{rx}(\sim l) = \rho_{rx}T_e^{RRTS1} + \rho_\sigma(\delta + T_{EIFS}) \quad (3.28)$$

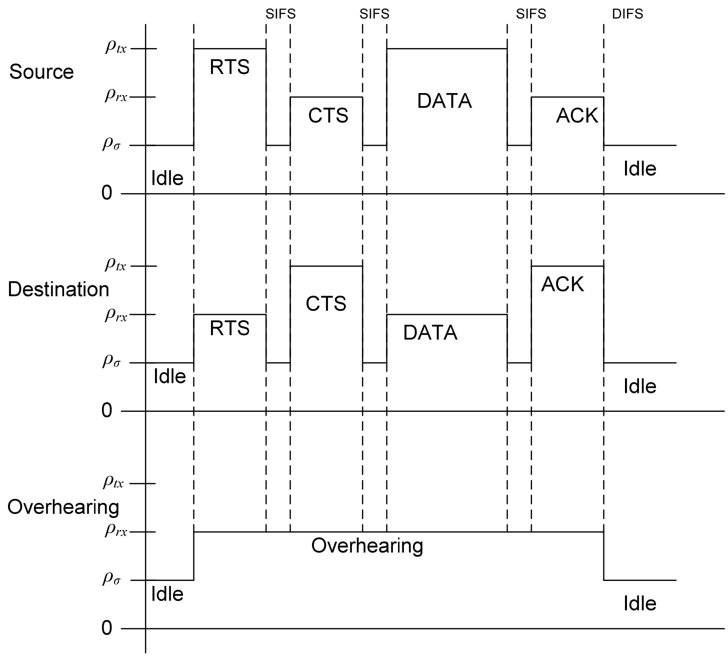
In rDCF, the total number of control and data packets is six, which is the sum of u, v, x and y. This information is substituted in (3.7) and (3.8) to derive equations (3.19) - (3.22). Also, we made use of (3.6) to derive equations (3.19) – (3.21) for rDCF. In (3.19) and (3.20), the probability of successful reception by the relay and destination in rDCF is shown. In (3.21), the probability of successful reception by overhearing nodes is shown. In the same way, (3.8) is used for the derivation of equation (3.22), showing the probability of successful transmission by the source. Now to address collision (which takes place at first control packet only) of control packets (from source to relay or destination) in rDCF, we employ (3.9) and (3.10) to derive (3.23) and (3.24). Expressions (3.23) and (3.24) show the probability of reception and transmission of collided packets by the destination and source nodes respectively. Similarly, equations (3.25) - (3.28) show the probability of transmission (by source) and reception (by relay, destination and overhearing nodes) of packets in error. Further in this case we have shown the calculation for the T_e for RRTS1 only (details for other packets shown in Appendix A). In the following section, we perform rigorous performance analysis to show energy consumption, impact of change in packet length, performance under transmission errors and decomposition of energy.

3.4 Performance Analysis

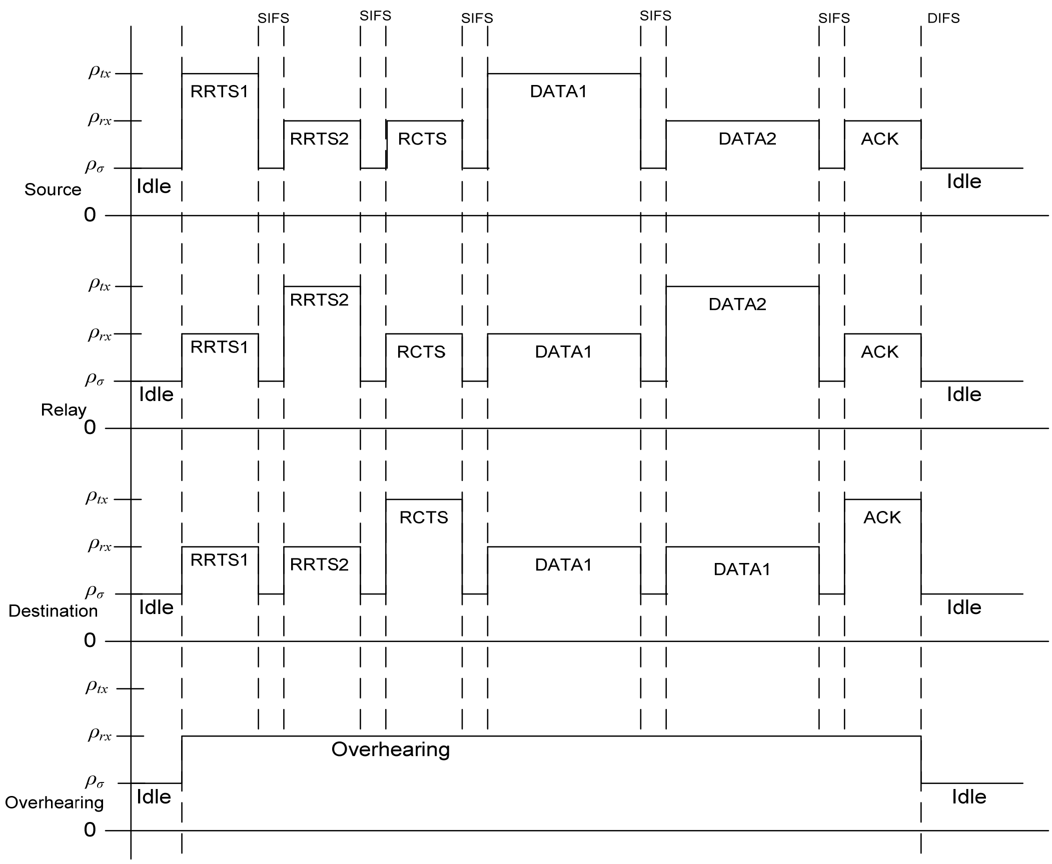
For performance evaluation, we assume that 1) each node always has data to transmit and 2) a relay is available. The results in this section are for rate combinations of 11 and 5.5 Mbps, denoted by rDCF (R_1, R_2), where R_1 is the rate for link between source and relay and R_2 is the rate for link between relay and destination. A typical set of parameters used for the evaluation are given in Table 3.1 shown below.

Table 3.1: IEEE 802.11 DCF and rDCF Specification [4, 14].

Physical Characteristic	IEEE 802.11 b DSSS
CW_{min}	32
m	6
m'	5
DIFS	50 µs
SIFS	10 µs
EIFS	DIFS+SIFS+ACK
Slot	20 µs
MAC header	272 bits
PHY header	96 or 192 µs
RTS	160 bits/control rate + PHY header
CTS	112 bits/control rate + PHY header
ACK	112 bits/control rate + PHY header
RRTS1	256 bits/control rate + PHY header
RRTS2	260 bits/control rate + PHY header
RCTS	120 bits/control rate + PHY header
Control Rate	2 Mbps
Propagation Delay	1 µs
Antenna height	1.5 meters
Transmit Power	15 dBm
Loss	0 dB
Shadowing deviation	10 dB
Data Rates and Modulations	BPSK @ 1 Mbps, QPSK @ 2 Mbps, CCK5.5 @ 5.5 Mbps, CCK11 @ 11 Mbps
Receiver Sensitivity	-94dBm, -91dBm, -87dBm, -82dBm



a)



b)

Figure 3.5: Energy Consumption: a) 802.11 DCF and b) rDCF.

3.4.1 Energy Consumption

In this section, we will analyze the energy consumption of rDCF (Fig. 3.5) to show the effectiveness of the proposed model. We will calculate the energy consumption in (J/MB). Equations (3.7) to (3.13) are modified according to the protocol and are shown for respective operations in (3.19) to (3.28).

Expression (3.11) is used in the existing form. Here, ρ_{tx}, ρ_{rx} and ρ_{σ} are assigned 1.34 watts, 0.90 watts and 0.73 watts respectively [77], these power values were chosen for a fair comparison to the existing work. However, the analytical model can support any power values. Also, for the ideal case $P_e = 0$. Fig 3.5 shows the energy consumption of rDCF and 802.11 DCF with different power levels.

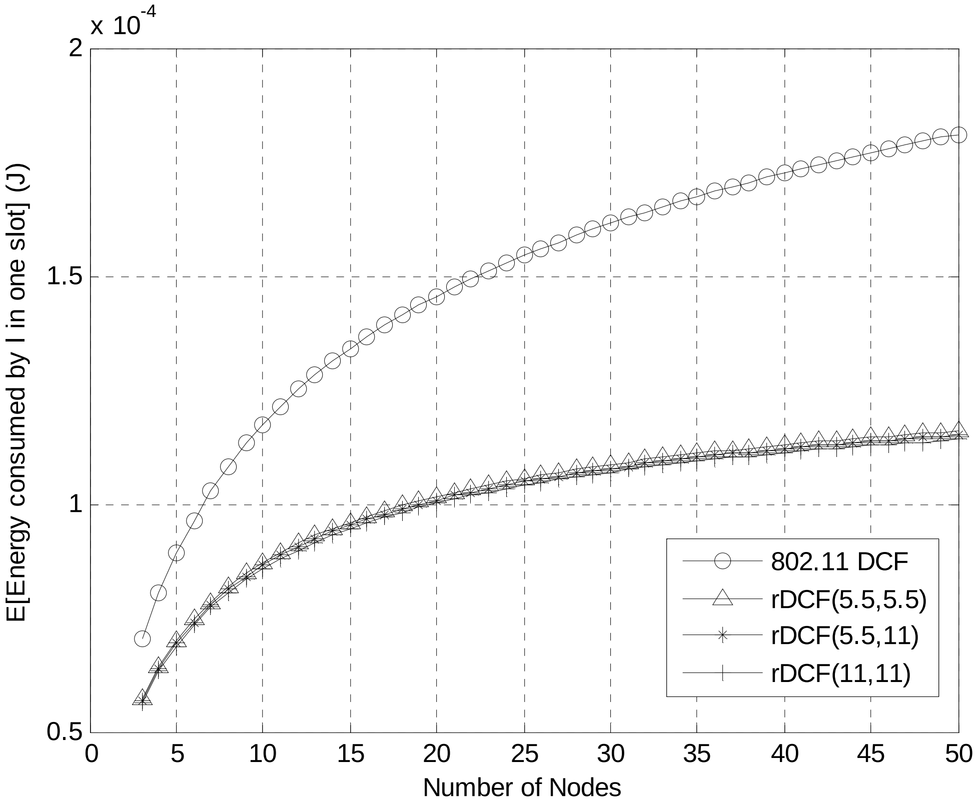


Figure 3.6: Average energy (J) consumed in one slot.

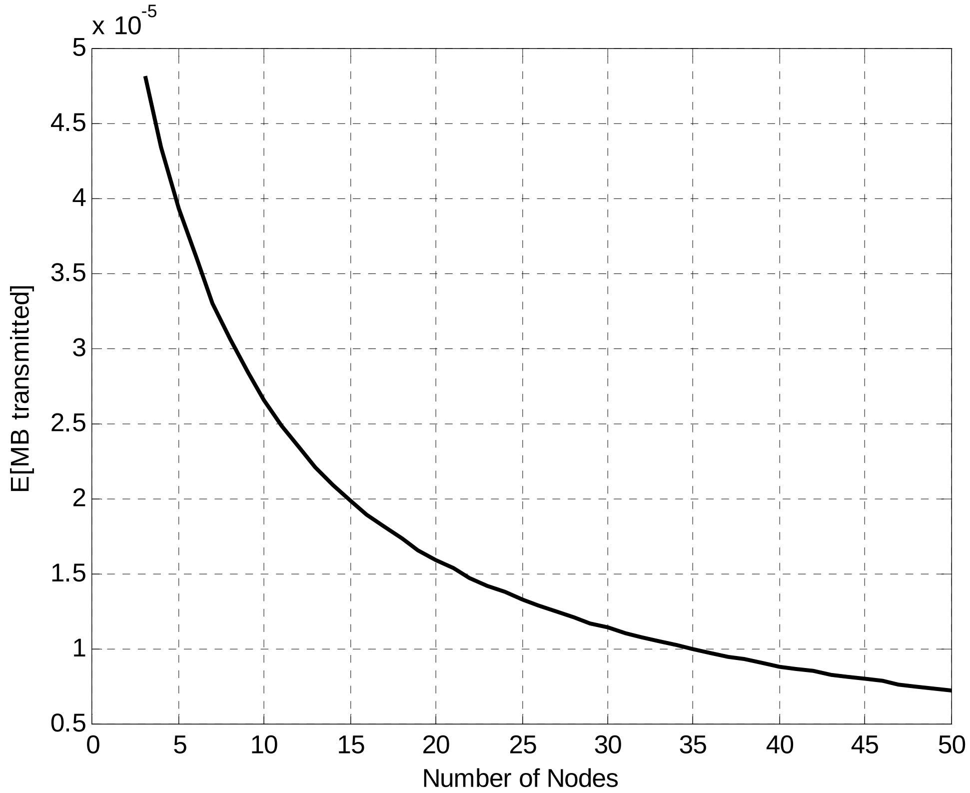


Figure 3.7: Average payload (MB) transmitted and received in one slot.

Fig. 3.6 plots expression (3.14) and shows average energy consumed by each node in one slot of IEEE 802.11 and rDCF for different rate combinations. Data rates used for IEEE 802.11 is 2 Mbps and for rDCF combinations of 5.5 and 11 Mbps. Packet length of 1000 bytes, $CW_{\min} = 32$, $m' = 5$ and $m = 6$ are used. Energy consumption per slot of 802.11 and rDCF increases with the number of nodes.

Fig. 3.7 plots (3.6) and shows average payload per node transmitted and received in one slot and it is the same for 802.11 DCF and rDCF rate combinations. Fig.3.8 plots (3.14) and shows the average energy consumed in transmitting and receiving 1 MB of data at packet length of 1000 bytes in ideal channel. Energy grows linearly with the increasing number of nodes. As seen, all rate combinations of rDCF perform in a similar fashion but rDCF (11, 11) achieves slightly higher savings. As observed in this section, energy consumption grows linearly with the node density. Therefore, it is important to analyze the performance of relay based schemes to see the impact on energy with change in packet length and effectiveness of the proposed method. It is also important to observe the decomposition of energy to make efficient utilization of energy. Decomposition of energy gives information on how much energy is consumed in each operation.

The rDCF (11, 11) achieves maximum savings of 24.9% and 36.99% at 5 and 50 nodes respectively due to faster two hops of 11 Mbps in ideal channel conditions. This is evident from the above results that this model helps in predicting the energy consumption and it is encouraging to observe that using a relay not only results in higher throughput but is energy efficient as well. As a consequence of these results we conclude: 1) relay based transmissions are energy efficient and 2) relaying for others saves energy for the whole network.

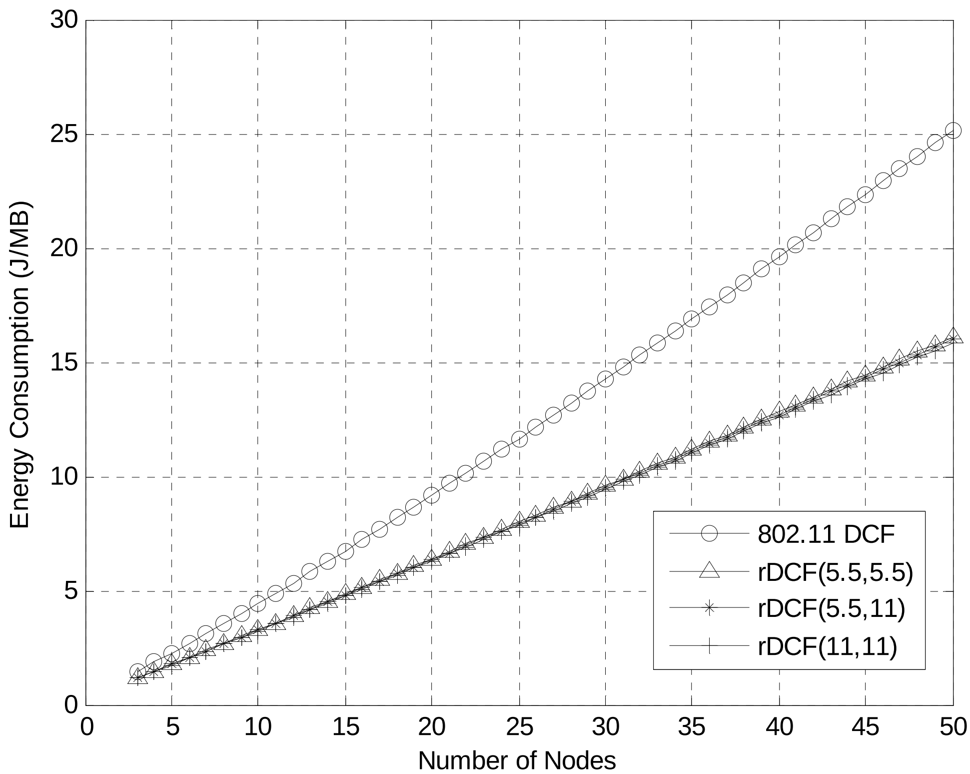


Figure 3.8: Energy consumed (J/MB) for 802.11DCF and rDCF in an ideal channel.

3.4.2 Impact of Change in Packet Length

Since rDCF (11, 11) is the most energy efficient under ideal channel conditions, we use it for the performance analysis. We analyze the performance of rDCF (11, 11) with varying packet sizes of 100, 500 and 1000 bytes in ideal channel conditions. Fig. 3.9 plots the average energy (J/MB) consumed in transmitting and receiving 1 MB of data. The energy consumption grows linearly with the number of nodes while the slope depends on the packet size.

It is interesting to see that the results are in agreement with the findings of single hop 802.11 DCF; i.e. it is still advantageous to transmit large payloads. This is true even with the doubled overhead used due to relay based transmission.

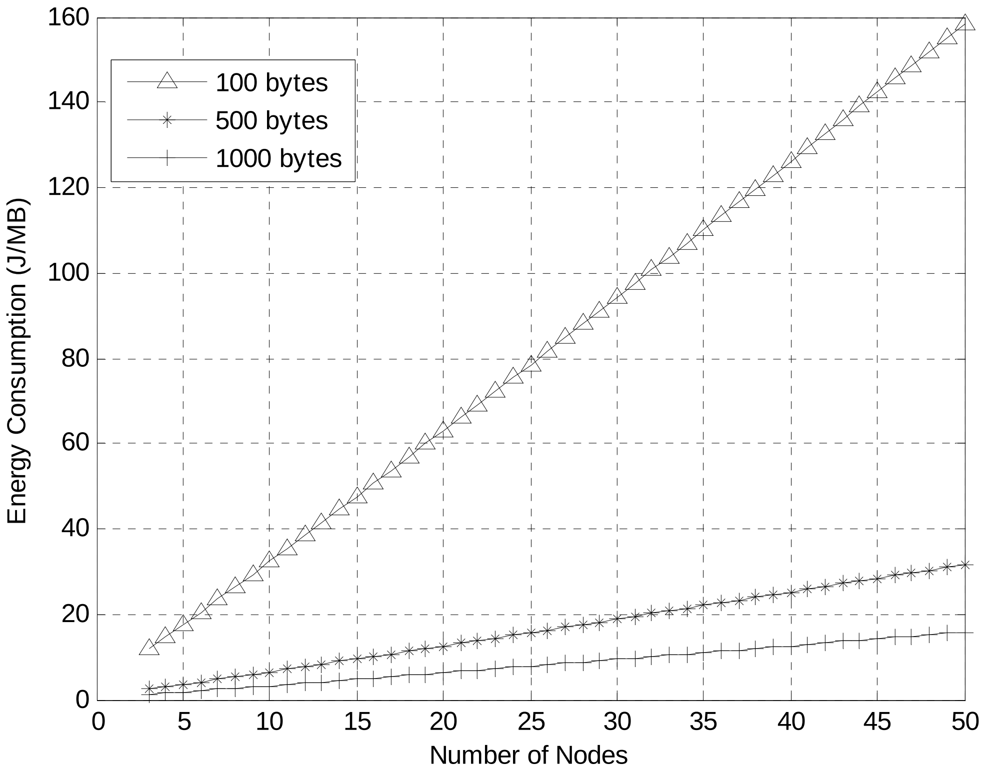


Figure 3.9: Energy consumed (J/MB) for rDCF (11, 11) in an ideal channel at different packet sizes.

3.4.3 Performance under Transmission Errors

For the performance of rDCF (R_1, R_2) under transmission errors we consider bit error probabilities of different modulation schemes used in IEEE 802.11b under Additive White Gaussian Noise (AWGN). The bit error probabilities for Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), Complimentary Code keying (CCK) 5.5 and CCK 11 can be easily obtained from [78] to calculate the corresponding packet error rate. In this chapter we use the two-ray ground reflection model and card specifications of ORINOCO11b in NS-2 [80]. The two-ray ground model consists of two cases: 1) Free space path loss when distance d is less than the Friss cutoff distance, d_{friss} :

$$d_{friss} = \frac{(4\pi h_t h_r)}{\lambda}.\ PL_{FreeSpace} = \left(\frac{4\pi d}{\lambda}\right)^2 \quad d < d_{friss} \tag{3.29}$$

2) The two-ray propagation loss when d is greater than d_{friss}:

$$PL_{TwoRayGround} = \left(\frac{d^2}{h_t h_r}\right)^2, \quad d > d_{friss} \tag{3.30}$$

where d_{friss} is calculated as follows:

$$d_{friss} = \frac{(4\pi h_t h_r)}{\lambda} \tag{3.31}$$

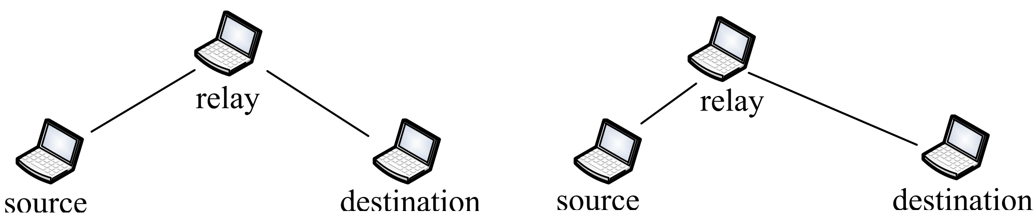


Figure 3.10: a) Symmetric, and b) Asymmetric scenarios.

Here, d is the distance between source and destination, h_t and h_r are transmit and receive antenna heights and λ is the wavelength. The bit error rates were obtained using the two-ray ground model where d_{friss} = 230 meters and $h_t = h_r$ = 1.5 meters.

We consider two scenarios: a) the symmetric (i.e. P_{b1} equal to P_{b2}) and b) the asymmetric link (i.e. P_{b1} not equal to P_{b2}) as shown in Fig.3.10. For the symmetric scenario (Fig. 3.10a), we have placed the relay exactly between source and destination (i.e. d_{sd} = 400 m @ 2 Mbps with $P_b = 10^{-5}$, $d_{sr} = d_{rd}$ = 200 m @ 5.5 Mbps with $P_{b1} = P_{b2} = 3\text{x}10^{-9}$). The probability of errors for the direct link is 10^{-5} (which is equivalent to a packet error rate of 8% at a packet length of 1000 bytes). Error probabilities for relay links are worked out relatively based on [80].

For the asymmetric scenario (Fig. 3.10b), we have placed the relay closer to the source (i.e. d_{sd} = 400 m @ 2 Mbps with $P_b = 10^{-5}$, d_{sr} = 160 m @ 11 Mbps with $P_{b1} = 10^{-7}$ and d_{rd} = 270 m @ 5.5 Mbps with $P_{b2} = 7\text{x}10^{-6}$). We observe higher energy consumption for the rDCF (symmetric and asymmetric) in transmission errors as compared to rDCF (ideal) in Fig. 3.11. The energy consumption increases with the number of nodes and almost doubles for both the symmetric and asymmetric cases at 50 nodes, whereas the symmetric and asymmetric scenarios results in similar energy consumption. The difference between the two scenarios is very small. It is mainly due to the average time spent in errors (shown in Appendix A) with different rate combinations.

3.4.4 Decomposition of Energy Consumed

To show the decomposition of energy, rDCF (11, 11) in the ideal case, a packet length 1000 bytes is used. From the decomposition of energy in Fig. 3.12, we observe the energy consumed in various operations. The operations can be mainly classified as useful and overheads. The useful operations are successful transmission (by source) and successful reception of packets (by relay and destination). The overhead operations which waste energy are: successful reception of packets (overhearing nodes), reception of collided packet, transmission of collided packet and staying idle. It is observed that the energy consumed in successful transmission and reception of data by destination and relay is almost constant. Here it is interesting to see that most of the energy is consumed in listening/overhearing by other nodes. This increases with respect to the number of nodes. In addition to this, the energy consumed in receiving a collided packet and staying idle also increases with the increase in the number of nodes.

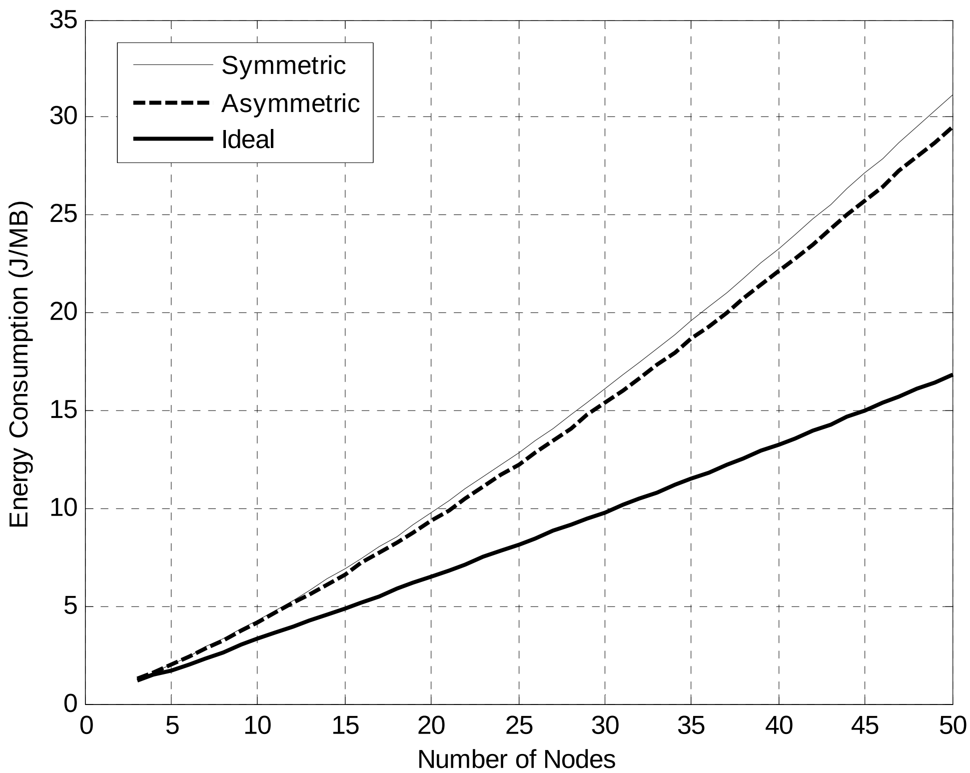


Figure 3.11: Energy consumed (J/MB) for rDCF in channel errors.

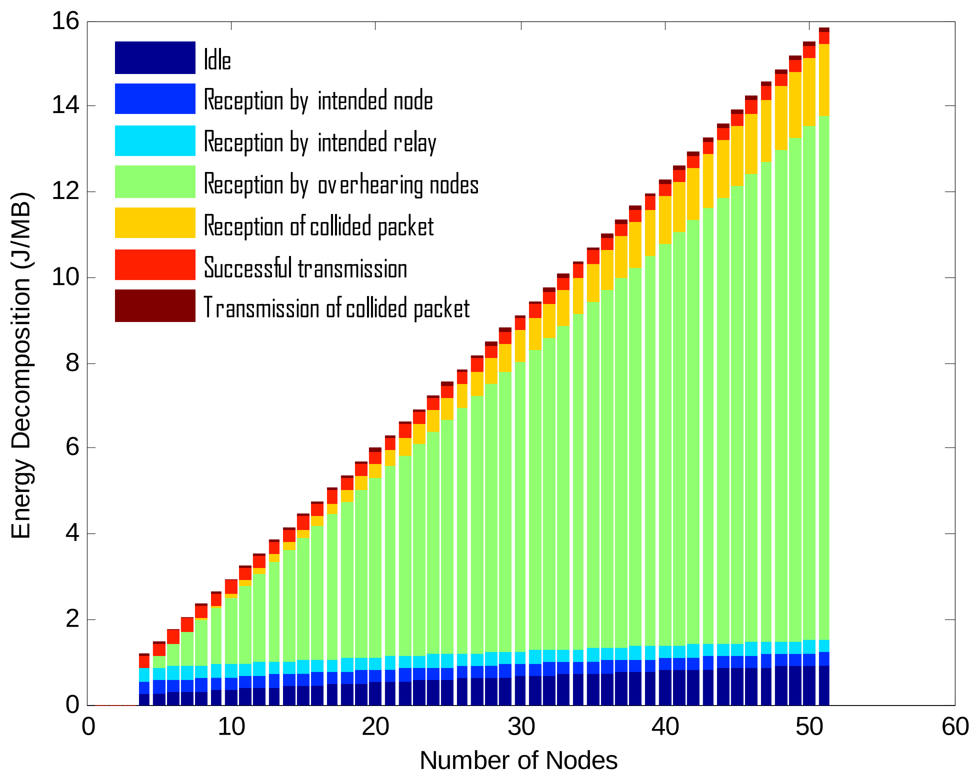


Figure 3.12: Decomposition of energy (J/MB) for rDCF(11, 11) in an ideal channel.

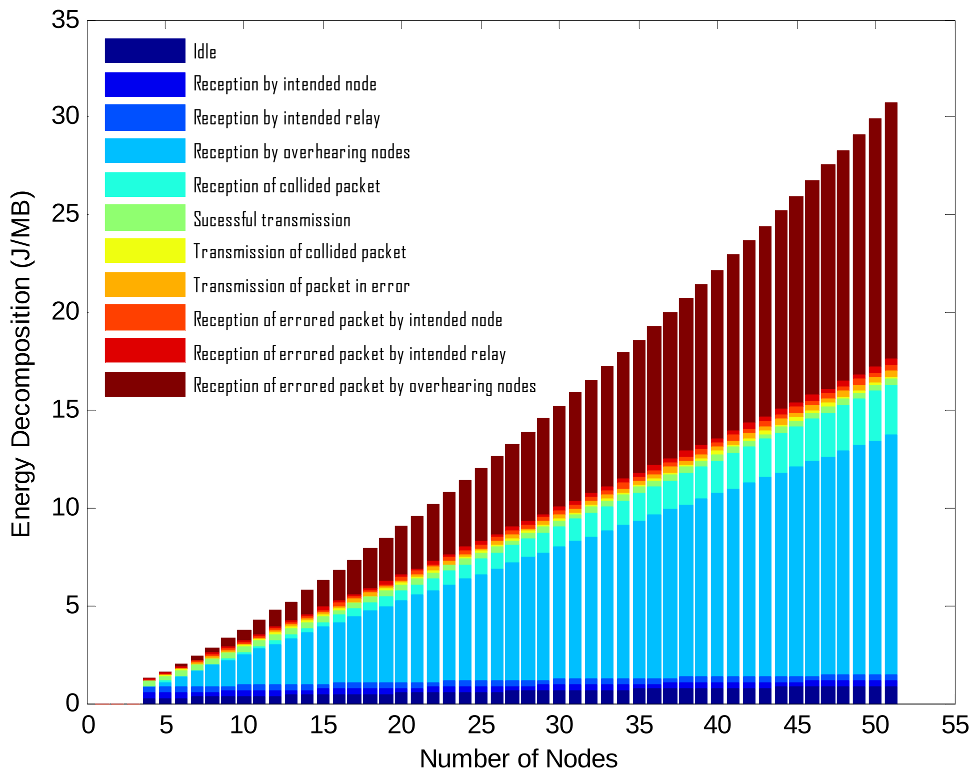


Figure 3.13: Decomposition of energy (J/MB) for rDCF(11, 5.5) in a channel with errors.

Table 3.2: Energy Consumption of rDCF.

Energy Consumption (J/MB)	5 nodes	50 nodes
rDCF(11, 5.5) Ideal	1.75	16.89
rDCF(11, 5.5) Errors	1.98	29.52

Further to this we can see from Fig. 3.13 (asymmetric scenario), that overhearing is related to both successful transmission and transmission in error. It is important to see that the energy consumption for transmission in error also increases with the number of nodes. In this the major contributor is again overhearing. Overhearing of a packet in error is an increasing function of the number of nodes and it also increases with the average time spent in error (i.e. for RRTS1 in error the energy consumed is minimal and for ACK in error energy consumption is high).

Decomposition of energy in rDCF shows that it is possible to improve the performance of this protocol by devising a policy which can reduce the energy consumption by overhearing nodes. Energy consumption of rDCF is illustrated in Table 3.2.

In error, rDCF consumes 11.6 % and 42.7% extra energy at 5 and 50 nodes respectively. This analysis allows us to design energy efficient protocols by predicting the energy consumption. Finally, it can be used for the prediction of energy consumption and will benefit the design of MAC protocols for energy critical environments.

3.5 Conclusions

We have presented a general analytical energy model for relay based MAC protocols. This model assumes a saturated environment and collision of the first control packet only. This model is applicable to both ideal channel and transmission errors. This model can be used to illustrate energy consumption of any relay based MAC protocol with modification in accordance to the protocol flow and to cater for any physical layer with change in parameters. Furthermore, this model will help in devising energy saving mechanisms/ policies based on the energy consumption behavior and decomposition of energy.

We have used rDCF as a case to show the efficacy of our proposed analytical model. This model also shows the decomposition of energy for relay based MAC which is of interest to protocol designers. Extensive performance analysis for the relay based MAC has also been provided. We have analyzed energy consumption under the impact of varying packet sizes and rate combinations. We have shown that transmission errors can greatly escalate the energy consumption as it will give rise to overhearing again. Possible future work includes the extension of the above model to the unsaturated case and to obtain experimental results from real life scenarios.

Finally energy consumption is one important mode of performance analysis. No performance analysis is complete without throughput and delay, therefore, in the next chapter to follow we show the detailed combined analysis of the throughput, delay and energy.

Chapter 4

ErDCF: Enhanced relay-enabled Distribution Coordination Function

4.0 Introduction

In this chapter, an Enhanced relay-enabled Distributed Coordination Function (ErDCF) is presented which has evolved from the rDCF [5]. To overcome the short coming of rDCF, we propose significant enhancements to achieve higher throughput and lower delay as well as lower energy consumption. The main features of ErDCF [62 - 64] include: 1) the use of dynamic preamble for throughput enhancement, 2) throughput gain for all packet lengths and 3) energy saving mechanism for lower energy consumption. These features allow ErDCF to perform better for networks with energy constraints and with variable payloads (e.g. sensor networks and NGNs). In this chapter, we analyze the saturation throughput, delay and energy consumption of ErDCF in an ideal channel and non-ideal channel. Later, we show the performance of non-saturation throughput, delay and energy in an ideal channel.

4.1 Enhanced relay-enabled Distributed Coordination Function

rDCF protocol describes the basic mechanism to integrate relay into DCF. In this section, results of proposed enhancements to rDCF named ErDCF are shown. Based on the rDCF and IEEE 802.11 DCF, ErDCF inherits some characteristics from rDCF [4]:

- Modified carrier sensing scheme.
- Control packets transmitted at the base rate of 2 Mbps.

- Introduction of Reservation Sub Header (RSH) [4] (transmitted at 2 Mbps and used to broadcast duration information for the rest of packet) in DATA packet transmitted at higher rates from source to relay.
- Frequent broadcasting of willing lists (potential relay entries based on measured channel quality) between nodes.
- Relay selection based on a credit system.

More importantly, ErDCF has introduced the following modifications:

- Use of Dynamic preamble (mixing of short and long preamble) for compatibility.
- It attaches RSH (transmitted at 2 Mbps and used to broadcast duration information for the rest of packet) in both DATA packets transmitted at higher rates from source to relay and relay to destination.
- Energy savings by reducing overall blocking time (use of short preamble) and avoiding unnecessary overhearing (due to modified carrier sensing scheme).

The modified carrier sensing scheme used is shown in Fig. 4.1. A major advantage of this scheme is that the nodes are blocked exactly for the transmission duration.

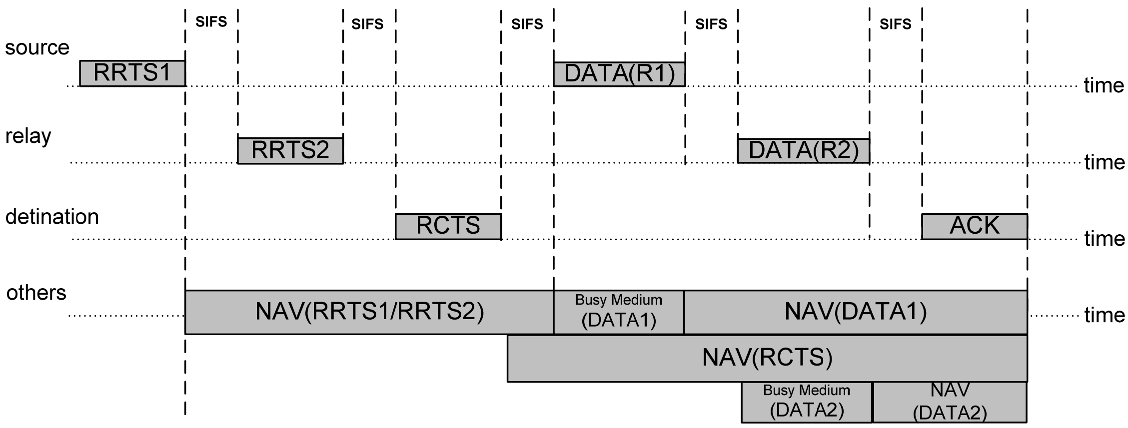


Figure 4.1: ErDCF Carrier Sensing Scheme.

Generally IEEE 802.11 systems use a long preamble, which is intended to provide more time to decode and process the preamble shown in Fig. 4.2a. The IEEE 802.11b is also equipped with an optional short preamble [14] meant to improve efficiency shown in Fig. 4.2b. For efficiency and compatibility, ErDCF makes use of dynamic preamble i.e. mixing of short and long preamble. The difference between the two is the synchronization field. Long preamble uses 128 bits of synchronization and short preamble uses 56 bits of synchronization. Long preamble mainly consists of PLCP preamble and header of 192 μs while short preamble is 96 μs. The short preamble is designed to improve efficiency and maximize network throughput. We propose to use short preamble for relay-enabled transmission and long preamble (for compatibility) or short preamble (no compatibility) for direct transmission in ErDCF. Whenever a source opts for relay-enabled transmission it selects short preamble and for direct transmission long preamble.

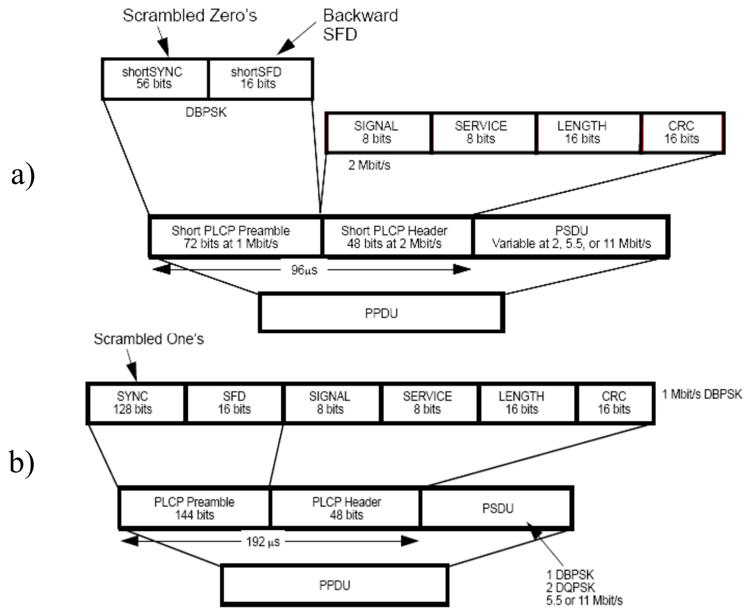


Figure 4.2: a) Short preamble format, and b). Long preamble format [14].

Table 4.1: Comparison of NAV duration of rDCF and ErDCF.

rDCF	ErDCF
RRTS1 [RRTS2+RCTS+3SIFS]	RRTS1 [RRTS2+RCTS+3SIFS]
RRTS2 [DATA(L,R_1)+RCTS +3SIFS]	RRTS2 [DATA(L,R1)+RCTS+3SIFS]
RCTS [DATA(L,R_1)+ DATA(L,R_2) +3SIFS+ACK]	RCTS [DATA(L,R_1)+ DATA(L,R_2) +3SIFS+ACK]
DATA1 [DATA(L,R_1)+ ACK+ 2SIFS]	DATA1 [DATA(L,R_1)+ ACK+2SIFS]
DATA2 [0]	DATA2 [ACK+SIFS]
ACK [0]	ACK [0]

Whenever short preamble is detected by the nodes listening to a transmission, these nodes can predict that relay-enabled transmission is taking place. Use of short preamble for dual-hop relay-enabled transmission is appropriate and justified as relay transmission is intended to provide higher throughput and reduced blocking time. On the other hand, long preamble introduces latency at each hop and suffers from excessive energy consumption for nodes listening to transmission. Short preamble for relay-enabled transmission will not only improve throughput, but also reduce energy consumption and delay and serve as an indicator for overhearing nodes, to distinguish dual-hop relay transmission from single-hop direct transmission.

In case of rDCF, RSH is only attached to the DATA packet from source to relay. The nodes in the transmission range of the relay can start a transmission which may cause collision of ACK. In order to avoid bandwidth degradation (due to collisions), we integrate RSH into DATA packet from relay to destination as well. Neighbour nodes will set their NAV according to the duration specified in the RSH of the DATA packet. Table 4.1 shows the comparison of the NAV duration reserved by each control and data packet in rDCF and ErDCF.

As for the energy consumption of rDCF shown in Chapter 3, most of the energy is spent on listening to the transmission. Modified carrier sensing scheme of ErDCF is meant to reduce the overall blocking time of nodes. Based on this it is possible to conserve energy. In a network, it is proposed that nodes can stop listening once the transmission duration is known. For this purpose, the duration of successful reception of packets not destined for the nodes is split into two parts. The first part is for the nodes in the transmission range of the source and the second part is for nodes in the transmission range of the destination. Nodes in the transmission range of the source and the relay have to wait for RSH which is transmitted as part of the data packet from source to relay and relay to destination to get the duration. While nodes in the transmission range of destination have to wait for RCTS to get the duration of the transmission.

Section 4.2 repeats the framework for saturated Markov chain model as in Chapter 3 to model ErDCF. In the following subsections throughput, delay and energy consumption in saturation are shown. Later in Section 4.3, the Markov chain model is extended to accommodate the non-saturation case. Performance in non-saturation is important to model the behaviour of ErDCF in a more realistic environment. Since in real life, a network may not always be saturated. To begin our analysis we use the same set of base assumptions as in Section 3.1.1. The main challenges in modeling throughput, delay and energy consumption for ErDCF include:

1) how to incorporate relay nodes,

2) treatment of relay nodes in terms of energy consumption, and

3) how relay nodes differ from other nodes in transmission and energy consumption behaviors.

4.2 Saturated Markov Chain Model

Consider a fixed number n of contending nodes. We use the same assumptions as in Section 3.1.1. The 2-dimensional process $\{b(t), s(t)\}$ can be modeled with a discrete-time Markov chain and is shown in Fig. 3.2.

4.2.1 Throughput Analysis of ErDCF

For ErDCF, the equations for the average time the channel is sensed busy for successful transmission and for collision are:

$$\begin{aligned} T_s^{ErDCF} &= T_{RRTS1} + T_{RRTS2} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_1)} \\ &+ T_{DATA(L,R_2)} + 5T_{SIFS} + 6\delta + T_{DIFS} \end{aligned} \tag{4.1}$$

$$T_c^{ErDCF} = T_{RRTS1} + T_{DIFS} + \delta \tag{4.2}$$

T_s and T_c are times of channel sensed busy for successful transmission and for collision. Here, RRTS1, RRTS2 and RCTS are control packets for coordinating relay-enabled transmission in ErDCF. In the above equations, T_{RRTS1}, T_{RRTS2}, T_{RCTS} and T_{ACK} are the transmission times for RRTS1, RRTS2, RCTS and ACK, respectively. T_{SIFS} and T_{DIFS} are inter-frame times and δ is the propagation delay. $T_{\mathrm{DATA(L,R_1)}}$ and $T_{\mathrm{DATA(L,R_2)}}$ are the times for the data packets of length L bytes at rates R_1 and R_2 respectively. ErDCF chooses from 11 and 5.5 Mbps to make different rate combinations for relaying. These combinations result in intermediate data rates. Let S be the throughput of the system which is explained in (2.11) and is defined as the fraction of time the channel is used to successfully transmit payload bits. The throughput is expressed as follows:

$$S = \frac{E[\text{Payload transmitted in a slot time}]}{E[\text{Length of a slot time}]} \tag{4.3}$$

The average amount of data successfully transmitted in a slot time is $P_{tr}P_s(1-P_e)E[P]$, where *E[P]* is the expected payload. The average length of a slot time for a successful transmission comprises empty slot time, successful transmission, collision and transmission with error. Therefore, the expression for average length of a slot time (different from the one defined in Sections 2.2.3) for successful transmission is:

$$E[slot] = \left(1 - P_{tr}\right)\sigma + P_{tr}P_sT_s(1-P_e) + P_{tr}\left(1-P_s\right)T_c + P_{tr}P_sA \qquad (4.4)$$

For ErDCF we have A in (4.4) as follows:

$$A = P_e^{RRTS1}T_e^{RRTS1} + P_e^{RRTS2}T_e^{RRTS2} + P_e^{RCTS}T_e^{RCTS} + P_e^{DATA1}T_e^{DATA1} + P_e^{DATA2}T_e^{DATA2} + P_e^{ACK}T_e^{ACK}.$$

where P_e^{RRTS1}, P_e^{RRTS2}, P_e^{RCTS}, P_e^{DATA1}, P_e^{DATA2} and P_e^{ACK} are the probability of errors for RRTS1, RRTS2, RCTS, DATA1, DATA2 and ACK packets respectively. Similarly T_e^{RRTS1}, T_e^{RRTS2}, T_e^{RCTS}, T_e^{DATA1}, T_e^{DATA2} and T_e^{ACK} are the average duration for packets involved in errors. By substituting (4.8) in (4.7), the expression for the throughput is given below:

$$S = \frac{P_sP_{tr}(1-P_e)E\left[P\right]}{\left(1-P_{tr}\right)\sigma + P_{tr}P_sT_s(1-P_e) + P_{tr}\left(1-P_s\right)T_c + P_{tr}P_sA}. \qquad (4.5)$$

Equation (4.5) is the modified saturated throughput equation along with transmission errors, where the expression for A is adapted in accordance with ErDCF packet flow. *E[P]* is the expected payload and σ is the slot time. In the above equation $1-P_{tr}$ represents the empty slot time, $P_{tr}P_s$ is successful transmission and $P_{tr}(1-P_s)$ is the collision. The above equation shows the saturation throughput in the ideal channel, when the packets errors are equal to zero in (3.4), (4.4) and (4.5) i.e. (3.4) represents a failure due to collision alone.

4.2.1.1 Throughput Gain

We further define the throughput gain γ in (4.6), which is obtained *as a ratio of the throughput of ErDCF to that of 802.11 DCF.*

$$\gamma = \frac{S_{ErDCF}}{S_{802.11DCF}} \tag{4.6}$$

In (4.6), S_{ErDCF} is the throughput of ErDCF and $S_{802.11DCF}$ is the throughput of 802.11 DCF. For the throughput of 802.11 DCF we have A in (4.4) as: $A = P_e^{RTS}T_e^{RTS} + P_e^{CTS}T_e^{CTS} + P_e^{DATA}T_e^{DATA} + P_e^{ACK}T_e^{ACK}$, where P_e^{RTS}, P_e^{CTS}, P_e^{DATA} and P_e^{ACK} are the probability of errors for RTS, CTS, DATA and ACK packets respectively. Similarly, T_e^{RTS}, T_e^{CTS}, T_e^{DATA} and T_e^{ACK} are the average durations for packets involved in errors.

4.2.2 Delay Analysis for ErDCF

To analyze the delay of ErDCF [62], the average packet delay is linked to the packet drop probability and average time to drop the packet. This delay analysis is valid for both ideal channel and channel with errors. In order to derive the average packet delay, it is important to derive the packet drop probability and the average time to drop a packet. The following derivations are inspired by [29, 30].

4.2.2.1 Packet Drop Probability and Average Time to Drop a Packet

In 802.11 DCF, when a packet reaches the retry limit it is dropped and this probability is the packet drop probability p_{drop}. As ErDCF is based on 802.11 DCF it follows the same concept for the retry limit and defines p_{drop} as follows:

$$p_{drop} = p^{m+1} \tag{4.7}$$

This equation reflects the fate of a packet that has reached its retry limit m and is dropped on not receiving an ACK either due to collision or error for $(m+1)^{th}$ retry. Here for the ideal case the failure is only due to collision i.e. $P_e = 0$. Let $E[T_{drop}]$ be the average number of slot times required for a packet to experience $m+1$ failures and it is given below:

$$E[T_{drop}] = \begin{cases} \dfrac{W(2^{m'+1}-1)+(m+1)}{2} & m \le m' \\ \dfrac{W(2^{m'+1}-1)+W2^{m'}(m-m')+(m+1)}{2} & m > m' \end{cases} \tag{4.8}$$

$$E[D_{drop}] = E[T_{drop}].E[slot]. \tag{4.9}$$

From (4.4) we know the average slot time, therefore, we can calculate the average time to drop a packet as shown in (4.9), which is a product of the average number of slot times required and the average length of the slot time.

4.2.2.2 Average Packet Delay

Average delay is based on reception of ACK for a successfully transmitted packet. It is defined as *the time interval when a packet is at the head of its MAC queue ready to be transmitted, until an ACK for this packet is received*. Average delay is related to successful transmission and is exclusive of the delay time for a packet drop due to the expiry of retry limit. The average packet delay *E[D]*, provided an ACK is received for a successfully transmitted packet, is given by:

$$E[D] = E[X].E[slot] \tag{4.10}$$

where *E[X]* is the average number of slot times required for successfully transmitting a packet and is given in (4.11).

$$E[X]=\begin{cases}\dfrac{\left[W\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-p^{m+1})\right]}{2(1-2p)(1-p)}-\dfrac{p^{m+1}}{1-p^{m+1}}.E[T_{drop}]. & m\le m'\\ \dfrac{\left[\begin{array}{l}W\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-p^{m+1})\\ +W2^{m'}p^{m'+1}(1-2p)(1-p^{m'-m})\end{array}\right]}{2(1-2p)(1-p)}-\dfrac{p^{m+1}}{1-p^{m+1}}.E[T_{drop}]. & m>m'\end{cases}$$

(4.11)

From the above equations the results for ideal channel by using the packets error equal to zero in (3.4), (4.4), (4.9) and (4.10) can be derived.

4.2.3 Energy Consumption Analysis of ErDCF

In this section energy consumption of ErDCF is shown. The equations from Section 3.2 are used to derive the formula for the amount of energy consumed by a node in order to transmit 1 MB of data in a network with n nodes. The important equations required for energy consumption analysis of ErDCF from Section 3.2 are shown here for convenience:

$$J(n)=\frac{E\left[\text{energy consumed by } l \text{ in one slot}\right]}{E[\text{MB transmitted by } l \text{ in one slot}]} \quad (4.12)$$

$$E[\text{MB transmitted by } l \text{ in one slot}]=\frac{P_s P_{tr}(1-P_e)}{n}E[P'] \quad (4.13)$$

In expression (4.12), $J(n)$ is the total energy in joules consumed by a node l to transmit 1 MB of data. In (4.13), P_{tr} and P_s are defined in (2.9) and (2.10) respectively, n is the number of nodes, and *E[P']* is the expected packet size in MB. To define the numerator of (4.12) it is important to consider the energy consumed for all operations involved (i.e. transmit, receive and listen). Energy consumed is the product of slot duration and power consumption for each operation. The probabilities of different types of operations are expressed as:

$J_s^{rx}(l)$ is the probability of successful reception of packet destined for node l.

$J_s^{rx}(\sim l)$ is the probability of successful reception of packet not destined for node l.

$J_s^{rx}(r)$ is the probability of successful reception of packet destined for relay r.

J_s^{tx} is the probability of successful transmission of a packet by node l.

J_c^{rx} is the probability of reception of a collided packet.

J_c^{tx} is the probability of collision on transmission of a packet by node l.

J_σ is the probability of idle slots.

J_e^{tx} is the probability of transmission of a packet in error by node l.

$J_e^{rx}(l)$ is the probability of reception of a packet in error by destined node l.

$J_e^{rx}(r)$ is the probability of reception of a packet in error by destined relay r.

$J_e^{rx}(\sim l)$ is the probability of reception of a packet in error not destined for node l. Once the above probabilities are known it is easy to define the numerator in (4.12) as (4.14):

$$\begin{aligned} &E[\textit{energy consumed by } l \textit{ in one slot}] = (1-P_{tr})J_\sigma + \tau p J_c^{tx} + \tau(1-\tau)^{(n-1)}(1-P_e) \\ &\times[J_s^{rx}(l) + J_s^{rx}(r)] + (n-3)\tau(1-\tau)^{(n-1)}(1-P_e)J_s^{rx}(\sim l) + (1-\tau)[1-(1-\tau)^{(n-1)} \\ &\times(1-P_e) - (n-1)\tau(1-\tau)^{(n-2)}]J_c^{rx} + \tau(1-p)J_s^{tx} + \tau P_e J_e^{tx} + \tau(1-\tau)^{(n-1)}P_e[J_e^{rx}(l) \\ &+J_e^{rx}(r)] + (n-3)\tau(1-\tau)^{(n-1)}P_e J_e^{rx}(\sim l) \end{aligned} \tag{4.14}$$

Finally, the energy (J/MB) is calculated by substituting (4.13) and (4.14) in (4.12). The above equations are used to evaluate energy consumption in ideal channel i.e. $P_e = 0$.

4.2.3.1 Energy Savings of ErDCF

As seen from the energy consumption analysis in Chapter 3, most of the energy is spent in listening to the transmission. The modified carrier sensing scheme of ErDCF is meant to reduce the overall blocking time of nodes. Based on this it is possible to conserve energy. In a network, it is proposed that nodes can stop listening once the transmission duration is known. For this purpose the duration of the successful reception of packets not destined for the nodes is split into two parts. The first part is for the nodes in the transmission range of source and the second part is for nodes in the transmission range of the destination. Nodes in the transmission range of source and relay have to wait for the RSH which is transmitted as part of the data packet from source to relay and relay to destination to get the duration, while nodes in the transmission range of destination have to wait for RCTS to get the duration of the transmission. This modification results in savings as most of the energy is spent in listening and overhearing. Modification for energy savings is given below in (4.15):

$$
\begin{aligned}
J_s^{rx}(\sim l) &= J_s^{rx}(\sim l)_{source} + J_s^{rx}(\sim l)_{destination} \\
J_s^{rx}(\sim l)_{source} &= \rho_{rx}T_{RRTS1} + \rho_{\sigma}(T_{SIFS}+\delta) + \rho_{rx}T_{RRTS2} + \rho_{\sigma}(T_{SIFS}+\delta) \\
&\quad + \rho_{rx}T_{RCTS} + \rho_{\sigma}(T_{SIFS}+\delta) + \rho_{rx}T_{DATA(L,R1)} + \rho_{\sigma}(\delta + T_{DIFS}) \\
J_s^{rx}(\sim l)_{destination} &= \rho_{rx}T_{RRTS1} + \rho_{\sigma}(T_{SIFS}+\delta) + \rho_{rx}T_{RRTS2} + \rho_{\sigma}(T_{SIFS}+\delta) \\
&\quad + \rho_{rx}T_{RCTS} + \rho_{\sigma}(\delta + T_{DIFS}).
\end{aligned}
\tag{4.15}
$$

In (4.15), the total energy consumed in overhearing in a network is sum of the energy consumed by nodes in the transmission range of the source and in the transmission range of the destination. In a similar way, it is possible to include nodes in the transmission range of relay in above equation.

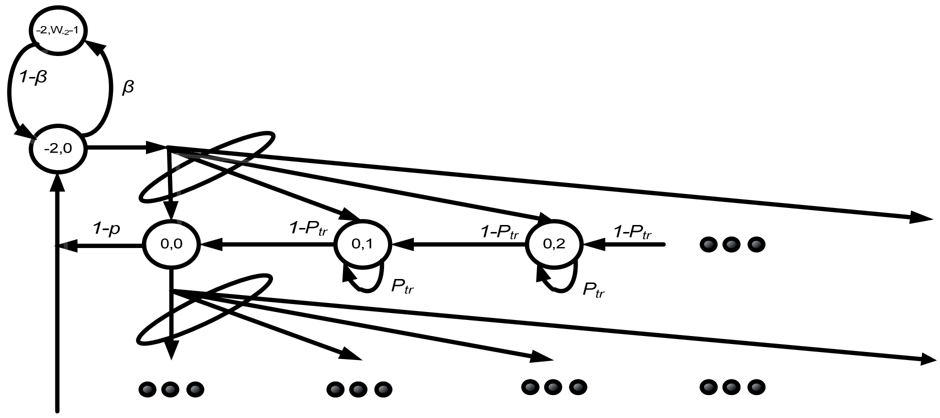


Figure 4.3: The non-saturated situation.

4.3 Non-saturated Markov Chain Model

This section addresses the non-saturated nature of wireless networks and its impact on their performance. The Markov model of saturation case Section 3.1 is extended to cater for the non-saturated case where the nodes in the network do not have data to transmit all the time. In this particular scenario in Fig. 4.3, new states are added to the existing model to include the waiting time for nodes before they have data to transmit. The modified one step transition probabilities inspired by [20] are given in (4.16) as follows:

$$
\begin{aligned}
&P\{-2, W_{-2}-1 | -2, W_{-2}-1\} = 1-\beta \\
&P\{0, j | -2, 0\} = \frac{\beta(1-p)}{W_0} \quad j \in (0, W_0 - 1) \\
&P\{-2, 1 | -2, 0\} = 1-\beta \\
&P\{-2, 0 | -2, 1\} = \beta \\
&P\{-2, 0 | i, 0\} = (1-p) \quad i \in (0, m)
\end{aligned}
\tag{4.16}
$$

In non-saturated condition, a node may wait in the idle state for a packet from upper layers. This corresponds to a delay in the idle state, as shown in Fig 4.3. The delay in the idle state is geometric with parameter β which is the frame generation probability. The transition probabilities are straightforward modifications of those previously obtained for the saturated case. The stationary probabilities add up to 1 and are given as:

$$
\begin{aligned}
1 &= \sum_{i=1}^{m}\sum_{k=0}^{W_i-1} b_{i,k} + \sum_{k=0}^{W_{-2}-1} b_{-2,k} = \text{backoff+idle} \\
&= \sum_{i=1}^{m}\sum_{k=0}^{W_i-1} b_{i,k} + \left(\frac{b_{0,0}}{\beta^2} - 1\right)
\end{aligned} \tag{4.17}
$$

The new τ is given in (4.18) and it reduces to (3.3) for $\beta = 1$, which is the saturation case.

$$
\tau = \begin{cases}
\left[\dfrac{W\left(1-(2p)^{m+1}\right)(1-p)+(1-2p)(1-p^{m+1})}{2(1-2p)(1-p^{m+1})} + \dfrac{1-p}{1-p^{m+1}}\left(\dfrac{1}{\beta^2}-1\right)\right]^{-1} & m \le m' \\
\left[\dfrac{\begin{pmatrix} W\left(1-(2p)^{m'+1}\right)(1-p)+(1-2p)(1-p^{m+1}) + \\ W2^{m'}p^{m'+1}(1-2p)(1-p^{m'-m}) \end{pmatrix}}{2(1-2p)(1-p^{m+1})} + \dfrac{1-p}{1-p^{m+1}}\left(\dfrac{1}{\beta^2}-1\right)\right]^{-1} & m > m'
\end{cases} \tag{4.18}
$$

For the non-saturated analysis, the modified τ and corresponding p, P_{tr}, P_s are used to evaluate non-saturated throughput, delay and energy consumption.

To this point in the chapter we have described the analytical models for the throughput, delay and energy of ErDCF (in saturation and non-saturation), which will be used in the later section to show the performance of ErDCF.

4.4 Performance Analysis and Results

For the performance analysis of ErDCF, we have shown results for both saturation and non-saturation in an ideal channel and non-ideal channel (i.e. transmission errors).

To compare rDCF with ErDCF, we assume saturation condition and an ideal channel as in [4]. It is further assumed that there is always a relay available to help. Throughput gain of rDCF and ErDCF over IEEE 802.11 DCF is shown in Fig. 4.4 in an ideal channel. Throughput gain is the ratio of throughput of rDCF or ErDCF to the throughput of 802.11 DCF. These results are for the scenario [4] R_1 = 5.5 Mbps, R_2 = 11 Mbps, CW_{min} = 32, m' = 5, m = 6 and n = 5 nodes and calculated based on Wu's saturation throughput model [19]. The rDCF yields throughput gain for packet lengths of greater than 400 bytes approximately and gives worse performance for the shorter packet lengths. However, as seen above, ErDCF provides throughput gain at almost all packet lengths. ErDCF achieves a throughput gain of 14% and 8.38% over rDCF at 1000 and 2500 bytes respectively. It is observed that throughput gain of ErDCF over rDCF is a decreasing function of packet length.

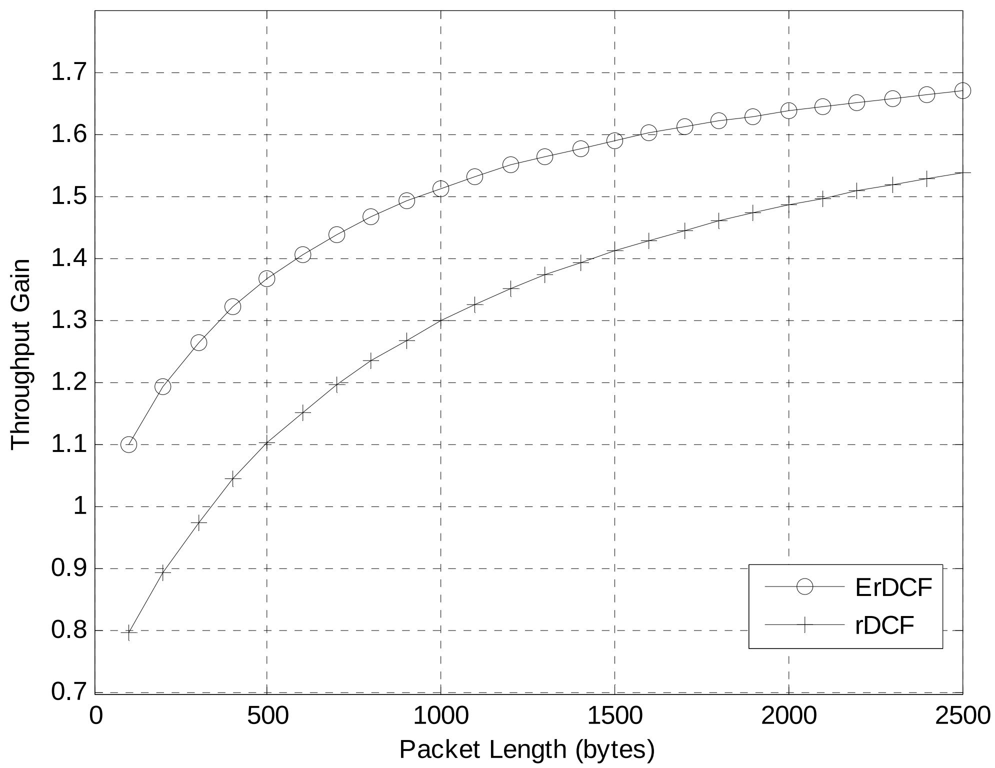


Figure 4.4: Throughput Gain over 802.11 DCF.

Table 4.2: Throughput at 2500 bytes for 5 nodes.

Rate combinations	Throughput (Mb/s)	
(R_1,R_2)	rDCF	ErDCF
11, 11	3.6432	4.0703
11, 5.5	2.7286	2.9614
5.5, 5.5	2.1811	2.3273

Table 4.2 shows that the throughput of ErDCF and rDCF is a function of packet length and rate combination. The throughput increases with the increasing packet length. ErDCF achieves a throughput of about 4 Mbps with rate combination (11, 11). ErDCF shows significant improvement over rDCF for all rate combinations. ErDCF rate pair (11, 11) gives the highest throughput. In Fig. 4.5, the energy consumed in one slot of rDCF compared to that for ErDCF (at R_1, R_2 = 5.5, 11 Mbps) is 1.40 and 1.28 times higher at 5 and 50 nodes respectively.

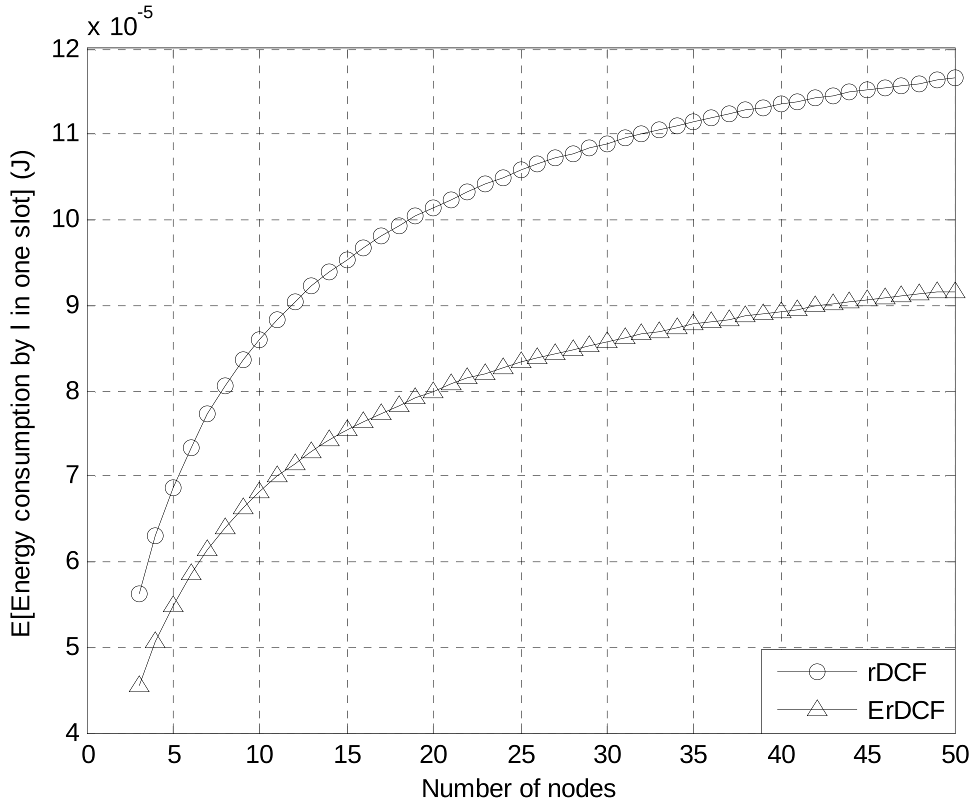


Figure 4.5: Average energy (J) consumed in one slot.

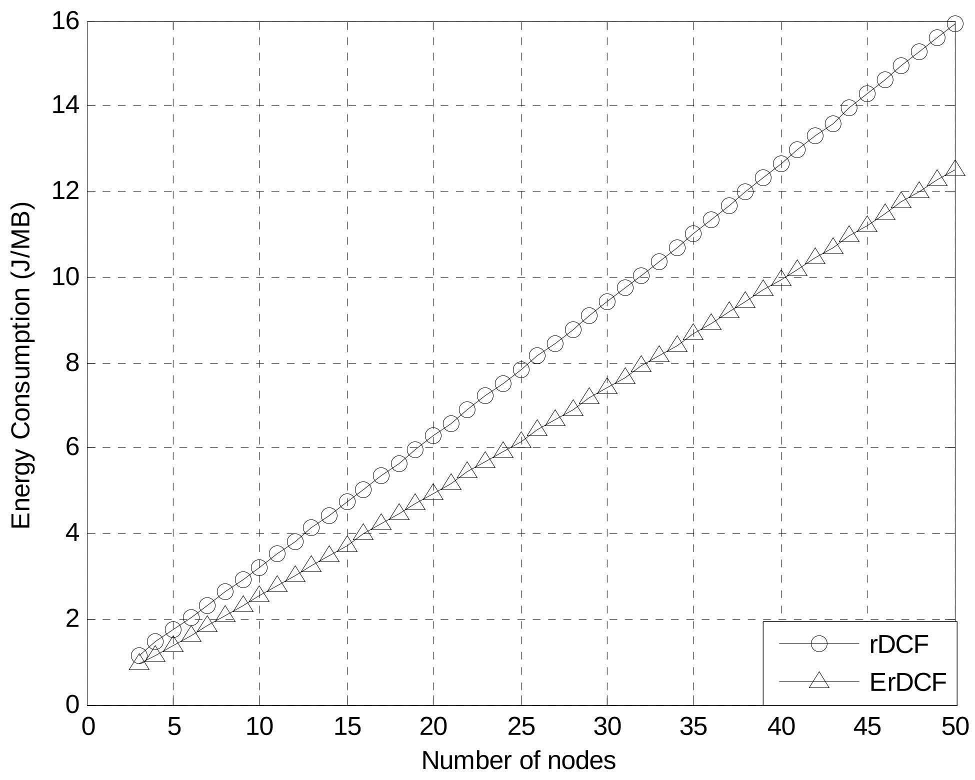


Figure 4.6: Energy consumed (J/MB).

Finally in Fig. 4.6, the energy consumed in transmitting 1 MB of data is shown. It is observed that ErDCF offers savings of 23.5% and 21.87% against rDCF at 5 and 50 nodes respectively. Furthermore, we can see that energy consumption is a function of number of nodes and rate combination. From the above results, we can conclude that ErDCF results in higher throughput gain and lower energy consumption compared to rDCF. As such, ErDCF performs better than rDCF.

4.4.1 Saturated Performance

As revealed earlier, ErDCF performs better compared to rDCF. From this point onwards the saturated performance of ErDCF is shown with reference to IEEE 802.11 DCF. In this subsection saturation performance of ErDCF is shown.

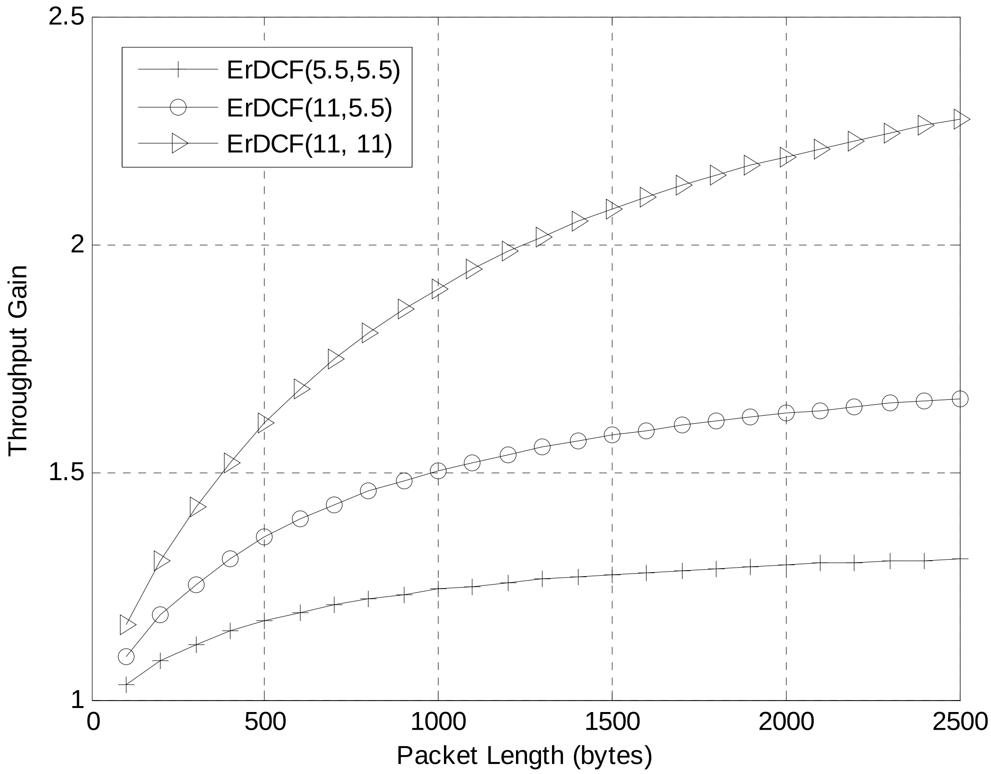


Figure 4.7: Throughput Gain over 802.11 DCF.

4.4.1.1 Saturation Throughput

Throughput gain is the ratio of throughput of ErDCF to that of 802.11 DCF at n = 5 nodes and rest of the parameters are as specified above. ErDCF provides throughput gain for all packet lengths and rate combinations shown in Fig. 4.7. ErDCF(11, 11) (i.e. $R_1 = R_2 = 11$ Mbps) achieves a throughput gain of 92.9 and 129% over 802.11 (i.e. R = 2 Mbps) at 1000 and 2500 bytes, respectively. It is observed that throughput gain of ErDCF for all rate combinations is an increasing function of the packet length. ErDCF(11, 11) results in the highest throughput gain. To this point, we have shown the throughput gain of ErDCF over 802.11 DCF in an ideal channel. Next, we show the saturated throughput of ErDCF in channel with transmission errors.

To demonstrate the impact of transmission errors on the saturated throughput we consider two scenarios as already described in Section 3.1.1: (a) the symmetric link (i.e. P_{b1} equal to P_{b2}), and (b) the asymmetric link (i.e. P_{b1} not equal to P_{b2}), which are shown in Figs. 4.8 and 4.9.

For the symmetric scenario in Fig. 4.8, we have placed relay exactly between source and destination (i.e. d_{sd} = 400 m @ 2 Mbps with P_b= 10^{-5}, d_{sr}= d_{rd}= 200 m @ 5.5 Mbps with P_{b1}= P_{b2} = $3\text{x}10^{-9}$). For the case of the symmetric and the asymmetric links (Figs. 4.8 and 4.9), we have assumed that the probability of errors for the direct link is 10^{-5} (which is equivalent to a packet error rate of 8% at a packet length of 1024 bytes).

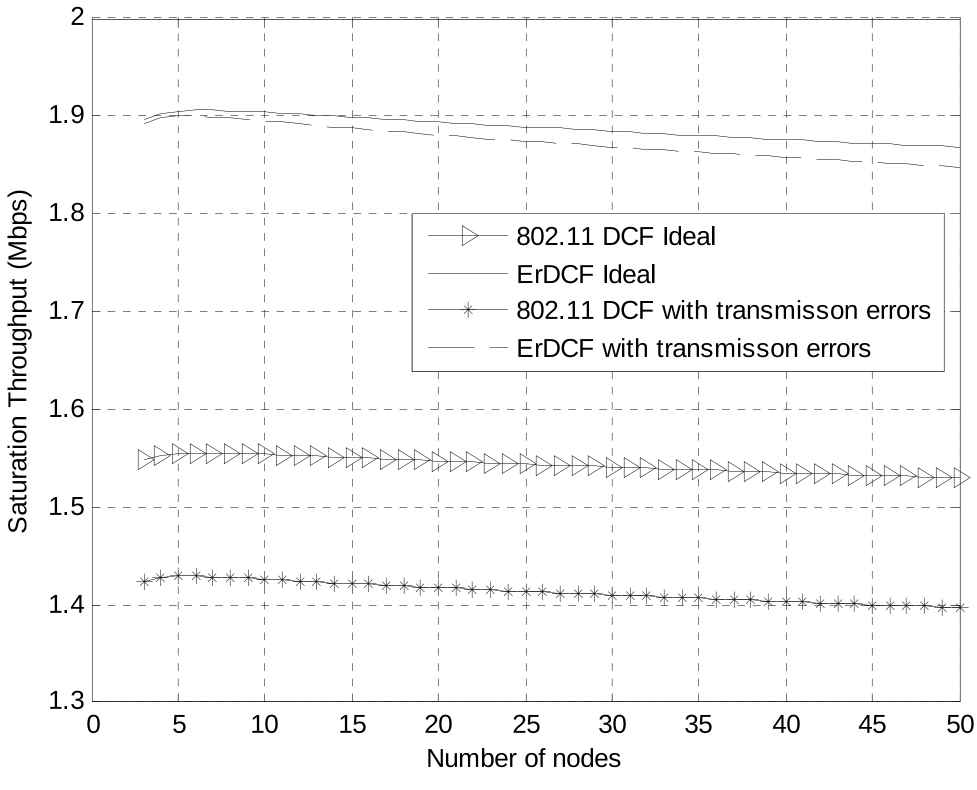


Figure 4.8: Performance of ErDCF (5.5, 5.5) and 802.11 DCF in ideal channel and with transmission errors.

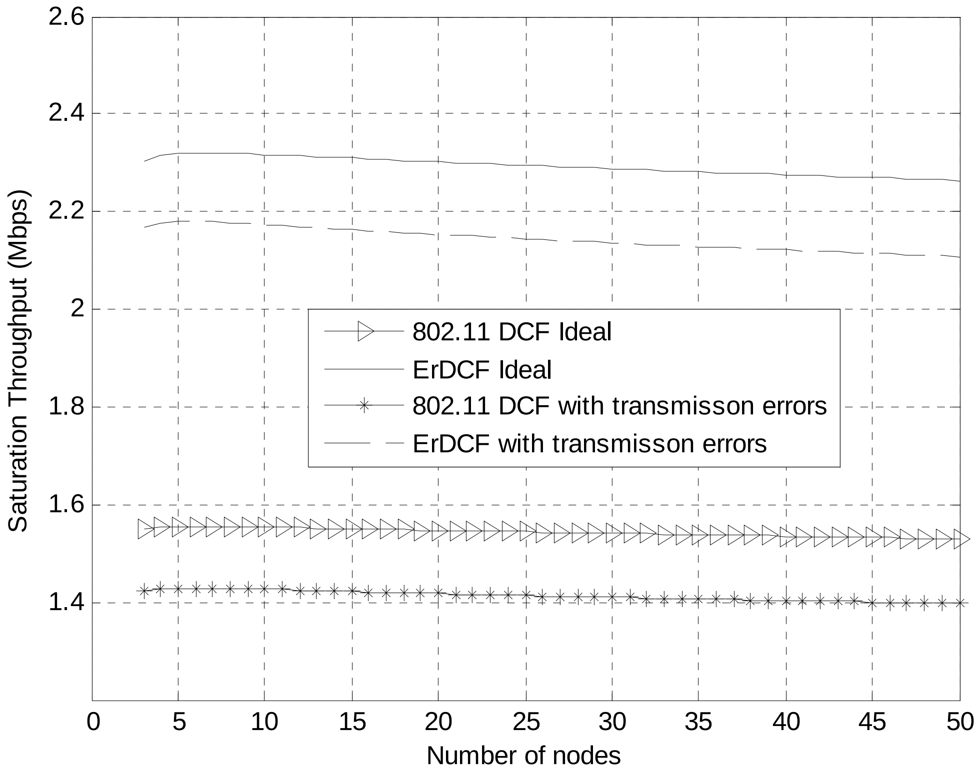


Figure 4.9: Performance of ErDCF (11, 5.5) and 802.11 DCF in ideal channel and with transmission errors.

This is a fair assumption and we have used a low error probability to show the impact of transmission error on the saturation throughput. Error probabilities for the relay links are calculated relatively based on [78]. We observe only a slight reduction in the throughput of ErDCF when the number of nodes is high but a significant degradation in the throughput of 802.11 DCF. This is due to the higher error probability of the direct link compared to the relay links. The resultant packet error probability of the two relay links is lower compared to the packet error probability on direct link.

For the asymmetric scenario in Fig. 4.9, we have placed relay closer to source (i.e. d_{sd} = 400 m @ 2 Mbps with P_b= 10^{-5}, d_{sr}= 160 m @ 11 Mbps with P_{b1}= 10^{-7} and d_{rd} = 270 m @ 5.5 Mbps with P_{b2} = $7\text{x}10^{-6}$). In Fig. 4.9, we see a significant reduction in the throughput of both ErDCF and 802.11 DCF. This is because the asymmetric link between relay and destination has a high probability of errors. The distance between relay and destination is greater than Friss distance, which results in a higher path loss. The resultant packet error probability of the two-relay links is lower compared to the packet error probability on the direct link. Table 4.3 shows the resultant packet error probability for both the symmetric link and the asymmetric link of Figs. 4.8 and 4.9.

As observed from the Table 4.3, packet error probability for the symmetric link scenario i.e. ErDCF(5.5, 5.5) is very low. This is inline with the negligible throughput drop of Fig. 4.8 with both links less than Friss distance. Packet error probability for the asymmetric link scenario i.e. ErDCF(11, 5.5) is high because the distance from relay to the destination is higher than Friss distance thus suffers high path loss.

Table 4.3: Packet error probability.

Protocol	P_e
802.11 DCF	0.0874
ErDCF(5.5, 5.5)	0.0035
ErDCF(11, 5.5)	0.0632

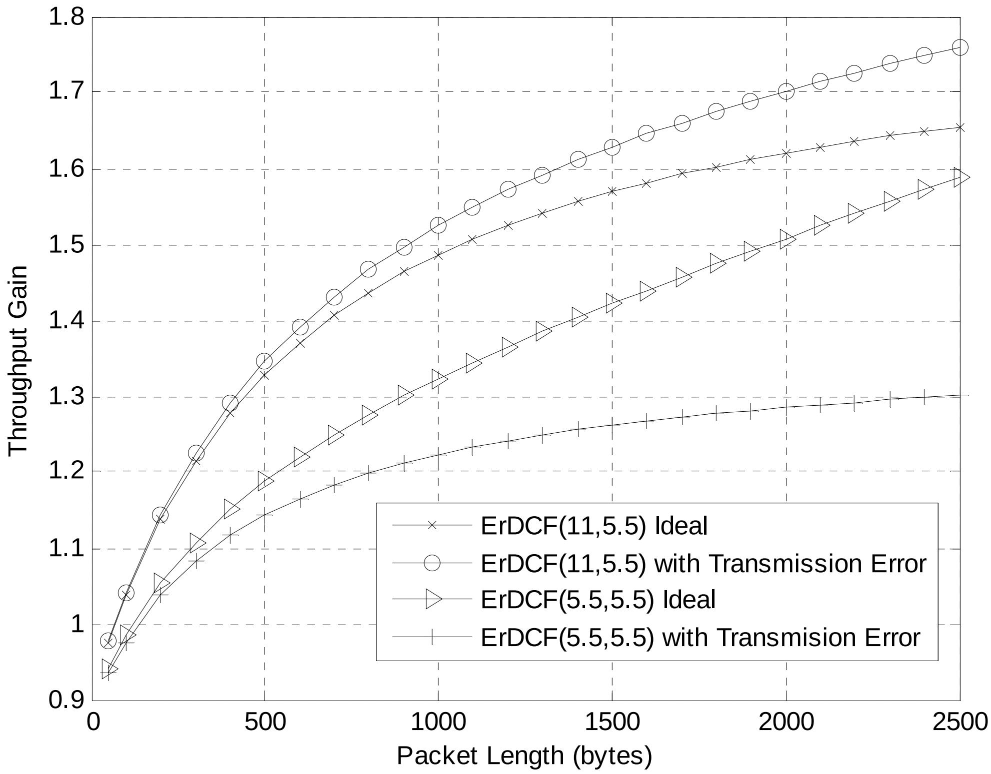


Figure 4.10: Throughput gain of ErDCF (11, 5.5) and (5.5, 5.5) in an ideal channel and with transmission errors.

As mentioned earlier throughput gain is defined as the ratio of the throughput of ErDCF to that of 802.11 DCF. For n = 5 nodes with the rest of the parameters as specified for Figs. 4.8 and 4.9 above, the throughput gain results are shown in Fig. 4.10. Clearly, the ErDCF provides a throughput gain for all packet lengths and rate combinations. ErDCF (11, 5.5) in ideal conditions achieves a throughput gain of 49% and 65% over 802.11 at packet lengths of 1000 bytes and 2500 bytes, respectively. ErDCF (11, 5.5) in error achieves a throughput gain of 52% and 78% over 802.11 at packet lengths of 1000 bytes and 2500 bytes, respectively. ErDCF (5.5, 5.5) in ideal conditions achieves a throughput gain of 22% and 30% over 802.11 at 1000 bytes and 2500 bytes, respectively. ErDCF (5.5, 5.5) in error achieves a throughput gain of 33% and 58% over 802.11 at 1000 bytes and 2500 bytes, respectively. There is no gain for packet lengths below 60 bytes. It is observed that throughput gain of ErDCF for all rate combinations is an increasing function of packet length. Throughput gain of both ErDCF (11, 5.5) and (5.5, 5.5) with transmission errors results in higher gain compared to respective ideal ones. This is due to a more serious throughput degradation of 802.11 DCF which suffers from higher pathloss.

4.4.1.2 Saturation Delay

In Fig. 4.11, we compare the delay (in seconds) of ErDCF(R_1, R_2) against 802.11 DCF. It can be observed that ErDCF(11, 11) has the smallest delay and 802.11 DCF shows highest delay.

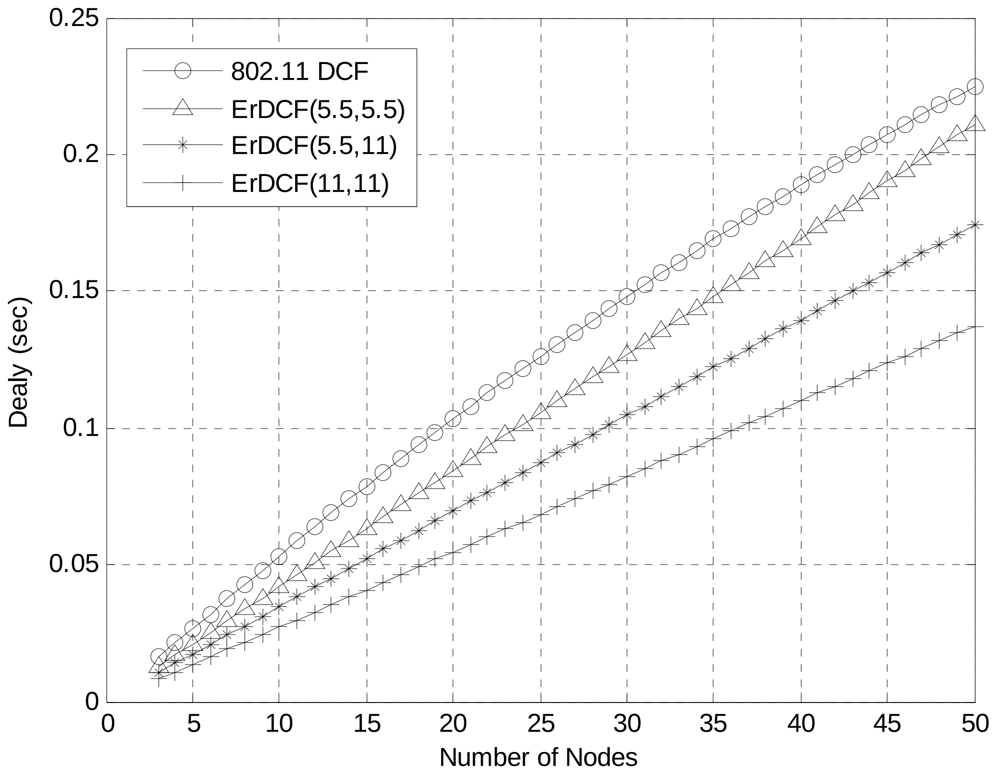


Figure 4.11: Delay of 802.11 DCF and ErDCF (R_1, R_2) in an ideal channel.

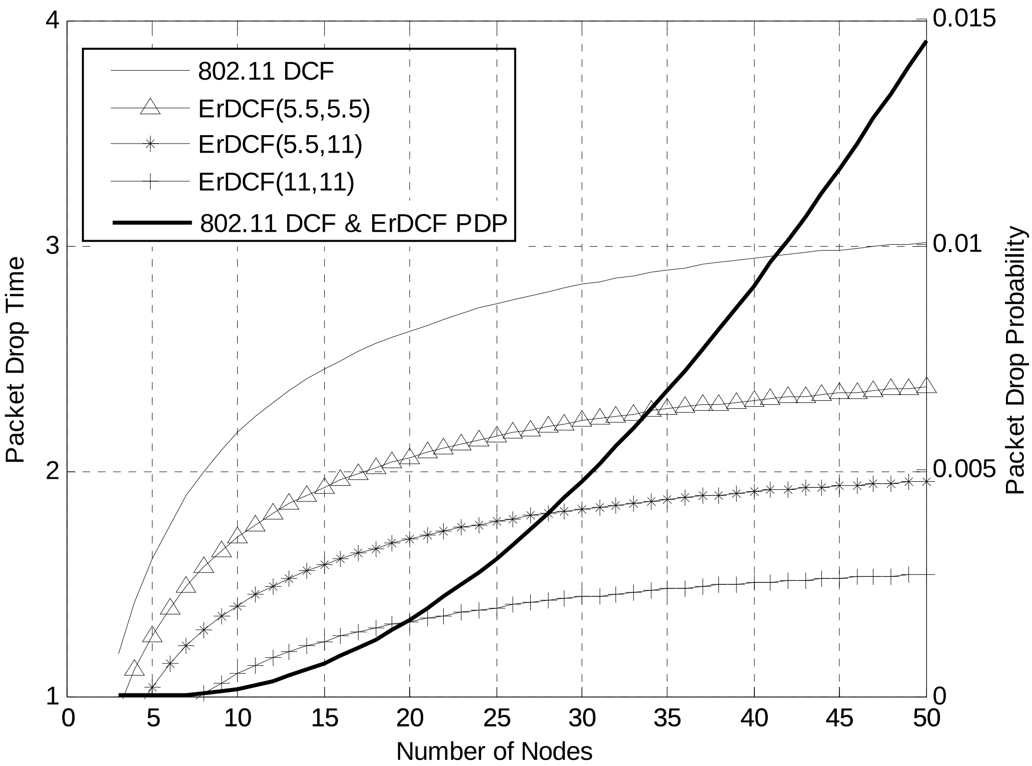


Figure 4.12: Packet Drop Time (PDT) and Packet Drop Probability (PDP) of 802.11 DCF and ErDCF (R_1, R_2) in an ideal channel.

In Fig. 4.12, we compare 802.11 DCF with ErDCF (R_1, R_2) in terms of Packet drop time (in seconds) and packet drop probability. Here, packet drop probability is same for both protocols. However, packet drop time of 802.11 DCF is the highest and that of ErDCF(11, 11) is lowest. This is due to the fact that the direct link of 802.11 DCF supports low data rate (i.e. 2 Mbps), which increases its transmission time. At the same time different rate combinations of ErDCF results in lower transmission time due to the higher transmission rates supported by ErDCF. In both Figs. 4.11 and 4.12, delay, packet drop time and packet drop probability are increasing function of the number of nodes.

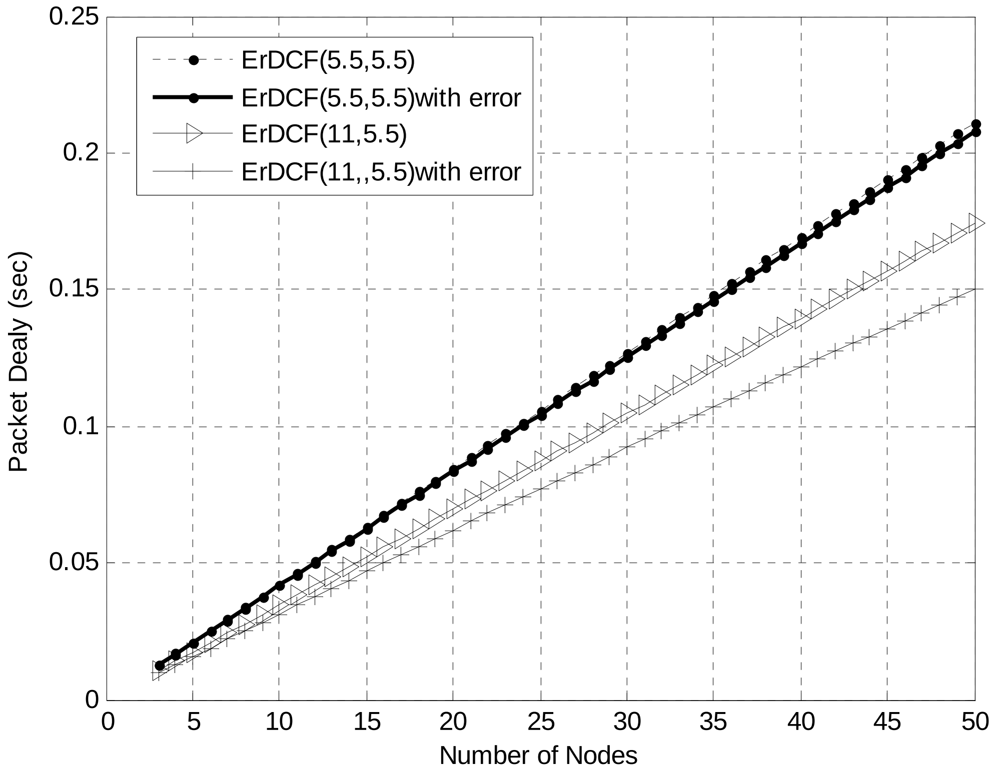


Figure 4.13: Comparing Delay of ErDCF (R_1, R_2) in an ideal channel and with transmission errors.

Next, we show the performance of the symmetric scenario described earlier (i.e. ErDCF (5.5, 5.5) in Fig. 4.13, we compare ErDCF(5.5, 5.5) in an ideal channel and with transmission errors. We have placed relay exactly between source and destination In Fig. 4.13, we observe a negligible reduction in the delay of ErDCF(5.5, 5.5) with transmission errors as compared to an ideal case.

This is due to the fact that the error in control packet reduces the transmission time (due to increase in packet drop time) of a particular node thus reducing the overall delay of ErDCF(5.5, 5.5) with error, Fig. 4.12 illustrates this scenario. This situation is due to the change in probability of failure with the inclusion of errors. For ideal case, failure is only due to collision whereas in transmission errors case the failure is due to errors and collisions, thus further reducing the probability of successful transmissions. When P_e becomes high enough to result in an increased number of dropped packets, the average packet delay decreases for the following two reasons:

(i) the long delays of the dropped packets do not contribute to the average packet delay and

(ii) at high P_e, high backoff stages with large contention window sizes are more often used. Therefore delay for successfully transmitted packets is less. These results are inline with the observations in [30] for basic access of 802.11.

Now for the asymmetric scenario (described earlier) in Fig. 4.13, we see a significant reduction in the delay of ErDCF(11, 5.5) under transmission errors, thus resulting in a significant increase in packet drop time. These results are inline with the trend as the resultant packet error probability for the asymmetric link scenario i.e. ErDCF(11, 5.5) is higher compared to ErDCF(5.5, 5.5). Because length of relay to destination link is longer than Friss distance, thus it suffers higher path loss.

Though from the ideal case we know that ErDCF(11, 5.5) performs better compared to ErDCF(5.5, 5.5), in the channel with errors the performance is highly dependant on the transmission errors. In Fig. 4.14, we observe significant change in packet drop time of ErDCF(11, 5.5) with errors as opposed to that of ErDCF(5.5, 5.5). This results in higher throughput reduction in ErDCF(11, 55). In Fig. 4.15, we compare ErDCF(11, 5.5) and ErDCF(5.5, 5.5) to show the impact of change in packet length in an ideal channel and with transmission errors. Here, delay is a function of increasing packet length for both rate combinations. We observe the same trend as in Fig. 4.13 as delay almost doubles at 2500 bytes.

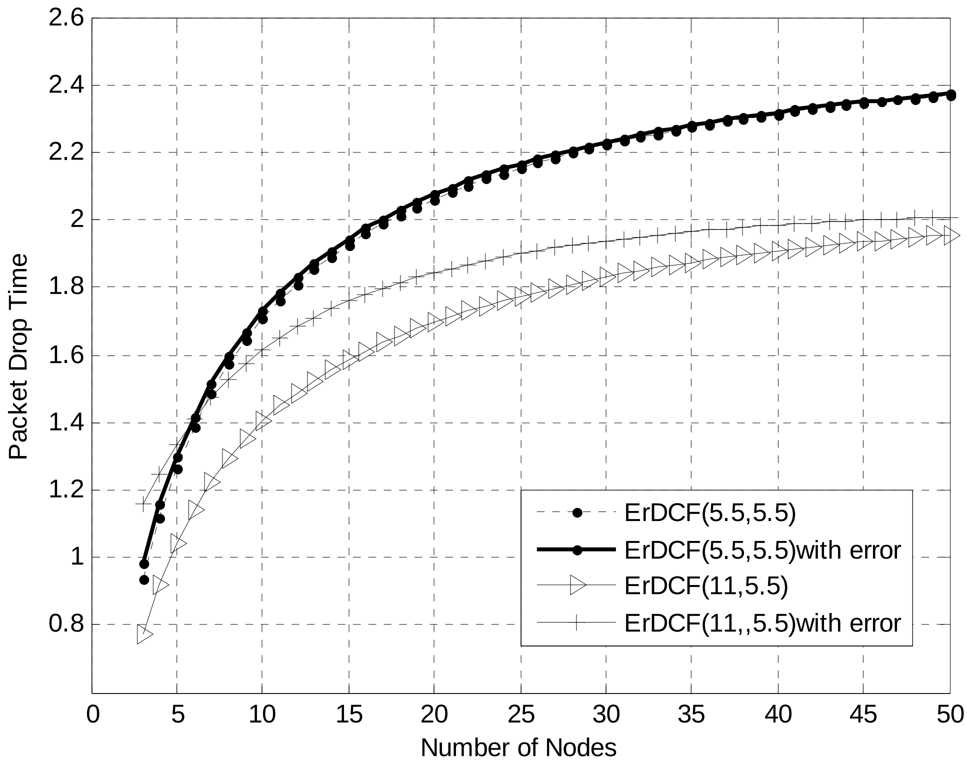


Figure 4.14: Comparing Packet drop time ErDCF (R_1, R_2) in an ideal channel and with transmission errors.

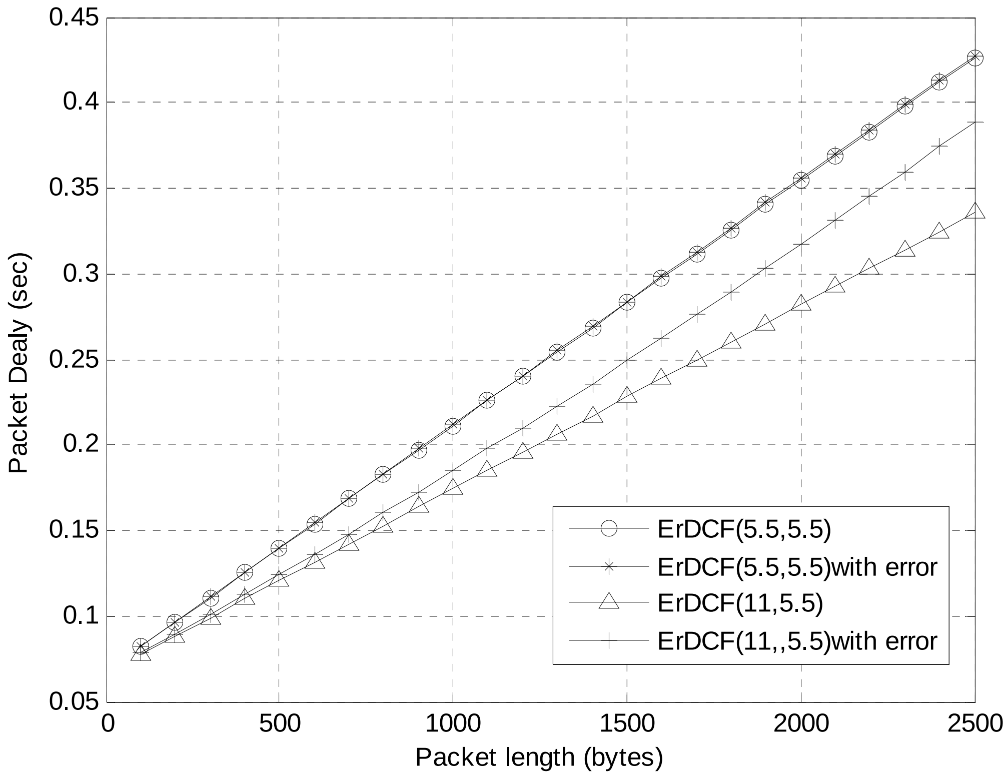


Figure 4.15: Impact of packet length on ErDCF (R_1, R_2) in an ideal channel and with transmission errors.

The resultant packet error probability for the ErDCF(5.5, 5.5) symmetric link scenario is very low (< 1%). This is inline with the negligible delay drop of Fig. 4.13 with both links less than the Friss distance. Packet error probability for the ErDCF(11, 5.5) asymmetric link scenario is high (~ 6%) because length of relay to destination link is higher than Friss distance (thus it suffers high path loss). Thus, we observe that transmission errors play an important role and can greatly reduce the gain of higher rate combination. At high P_e, high backoff stages with large contention window sizes are used. It is possible to improve this situation caused by the errors by using some rate adaptation mechanism in conjunction with the relay based MAC protocol.

4.4.1.3 Saturated Energy Consumption

Fig.4.16 shows the average energy consumed in transmitting 1 MB. Energy grows linearly with the increasing number of nodes. As seen, all rate combinations of ErDCF perform in a similar fashion but ErDCF (11, 11) achieves slightly higher savings. Since ErDCF(11, 11) saves most energy, we use it for further analysis. We can observe higher energy consumption for the rDCF (symmetric and asymmetric) in transmission errors as compared to rDCF (ideal) in Fig. 4.17. The energy consumption almost doubles for both the symmetric and asymmetric cases, whereas the symmetric and asymmetric scenarios results in similar energy consumption. The difference between the two scenarios is very small and is mainly due to the average time calculation for errors with different rate combinations.

The energy decomposition of ErDCF(11, 11) with a packet length of 1000 bytes is examined for the following cases: a) Energy consumption (without energy saving) in an ideal channel, b) Energy consumption (with energy saving) in an ideal channel, and c) Energy consumption in transmission errors.

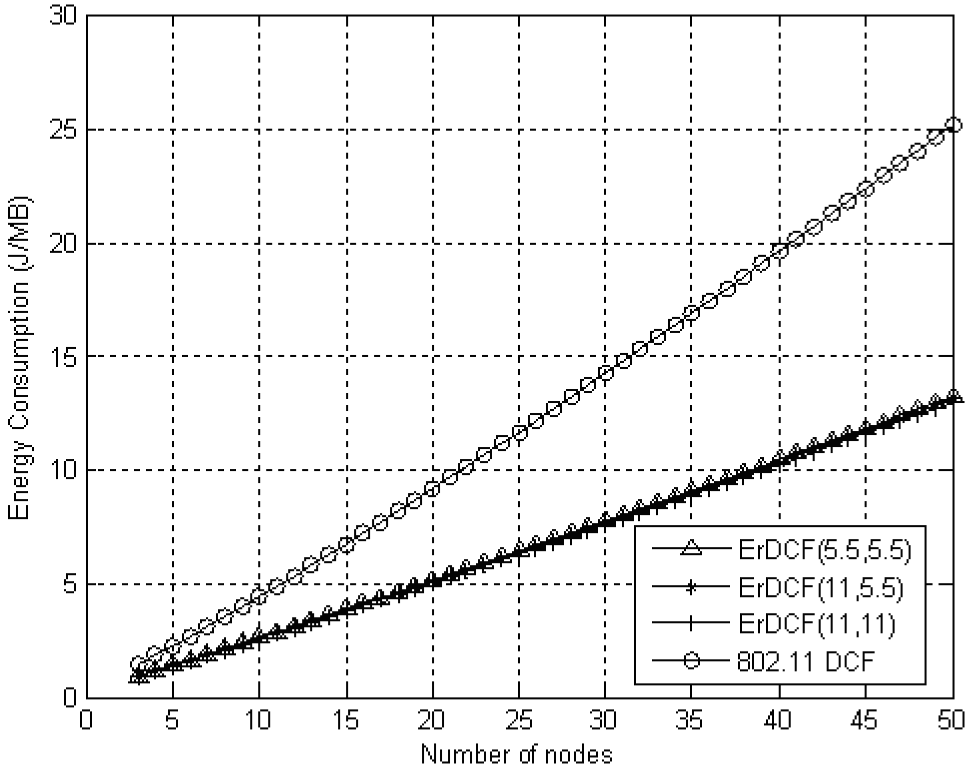


Figure 4.16: Energy consumed (J/MB) for 802.11DCF and ErDCF.

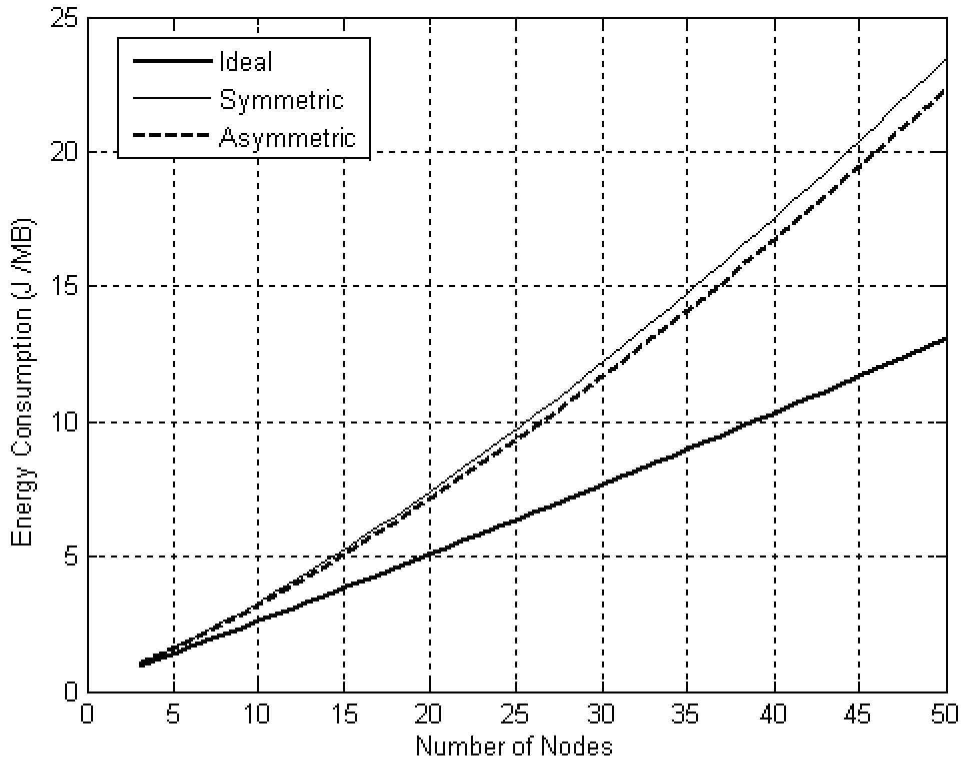


Figure 4.17: Energy consumed (J/MB) for ErDCF in channel errors.

From the decomposition of energy in Fig. 4.18, we observe the energy consumed in various operations. The operations can be mainly classified as useful and overheads. The useful operations are successful transmission (by source) and successful reception of the packets (by relay and destination). The overhead operations which waste energy are: successful reception of the packets (overhearing nodes), reception of the collided packet, transmission of the collided packet and staying idle. It is observed that the energy consumed in successful transmission and reception of data by destination and relay is almost constant. Here, it is interesting to see that most of the energy is consumed in listening/overhearing by other nodes. This increases with respect to the number of nodes. In addition to this, the energy consumed in receiving a collided packet and staying idle also increases with the increase in the number of nodes.

In Fig. 4.19, we show the decomposition of energy in ErDCF with energy savings. This shows significant reduction compared to Fig. 4.18. We can see that it is possible to improve the performance of this protocol compared to rDCF by devising further policies which can reduce the energy consumption by overhearing nodes.

Further to this we can see from Fig. 4.20, decomposition of energy in non-ideal channel (asymmetric scenario), that overhearing is related to both the successful transmission and transmission in error. It is important to see here that the energy consumption for transmission in error also increases with the number of nodes. In this the major contributor is again overhearing. Overhearing of a packet in error is an increasing function of the number of nodes and it also increases with the average time spent in error.

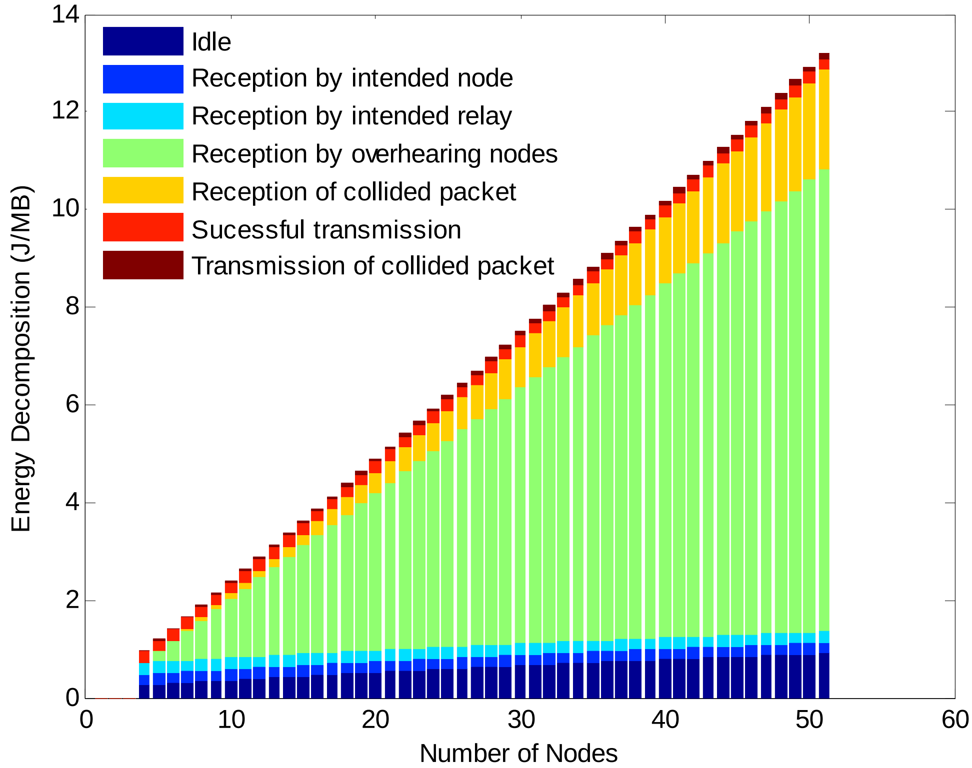


Figure 4.18: Decomposition of energy consumed.

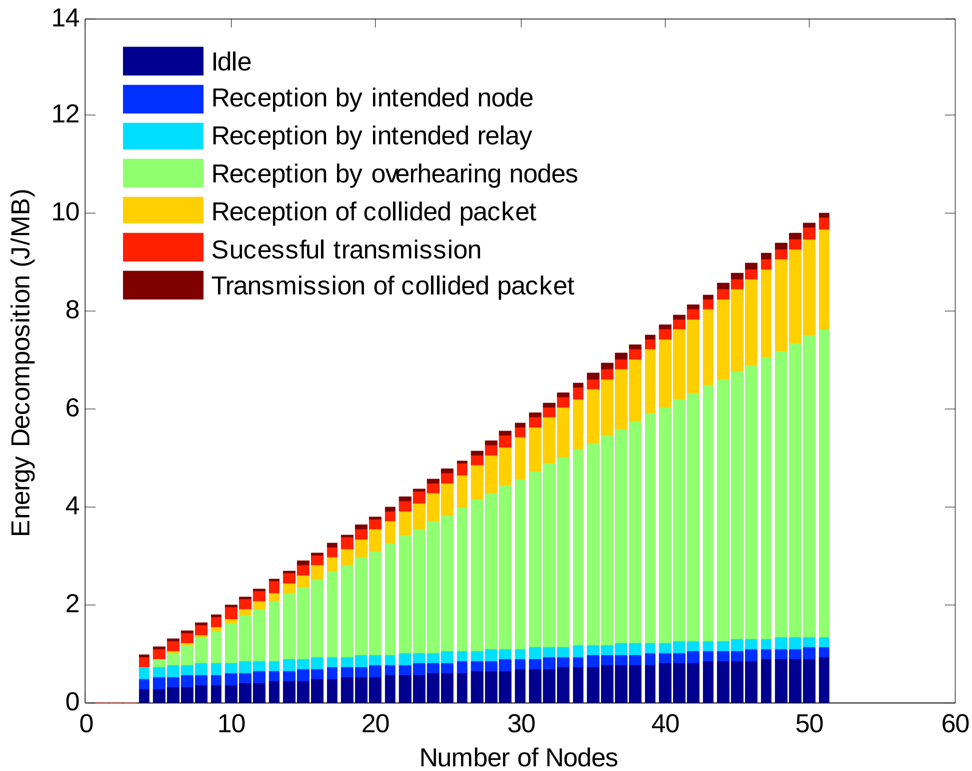


Figure 4.19: Decomposition of energy consumed (with energy savings).

4.4.2 Non-saturated Performance

In real life, a network is mostly in non-saturated mode. A node does not have packets at all time and this behaviour is shown in Fig. 4.3. A node waiting to get a packet to transmit is modeled as a delay with β, where $\beta = 1$ corresponds to the saturation case. For the analytical performance in non-saturated case, we make use of τ in Section 4.3 to evaluate the throughput, delay and energy in ideal channel conditions.

In Fig. 4.21, non-saturated throughput of ErDCF(11, 5.5) in ideal channel condition is shown. The throughput for small number of nodes i.e. 5 and 10 is the highest throughput and when number of nodes reaches 20 or more, the throughput starts to decrease. For large number of nodes, the highest throughput is observed before they reach saturation. The lowest throughput is observed for 50 nodes.

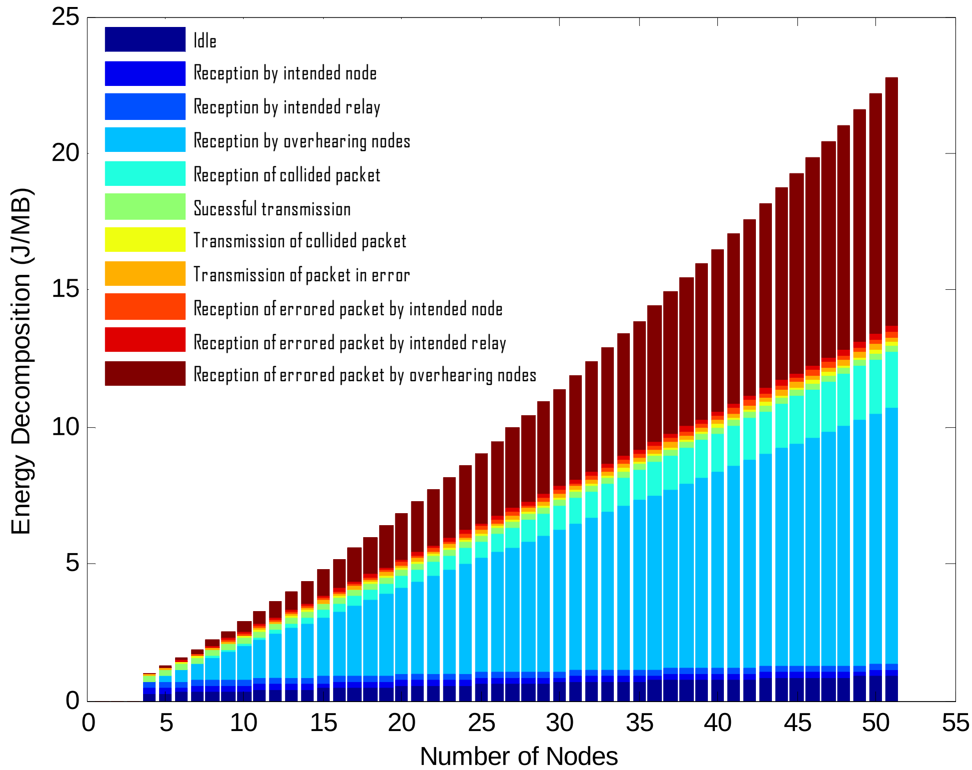


Figure 4.20: Decomposition of energy consumed with transmission errors.

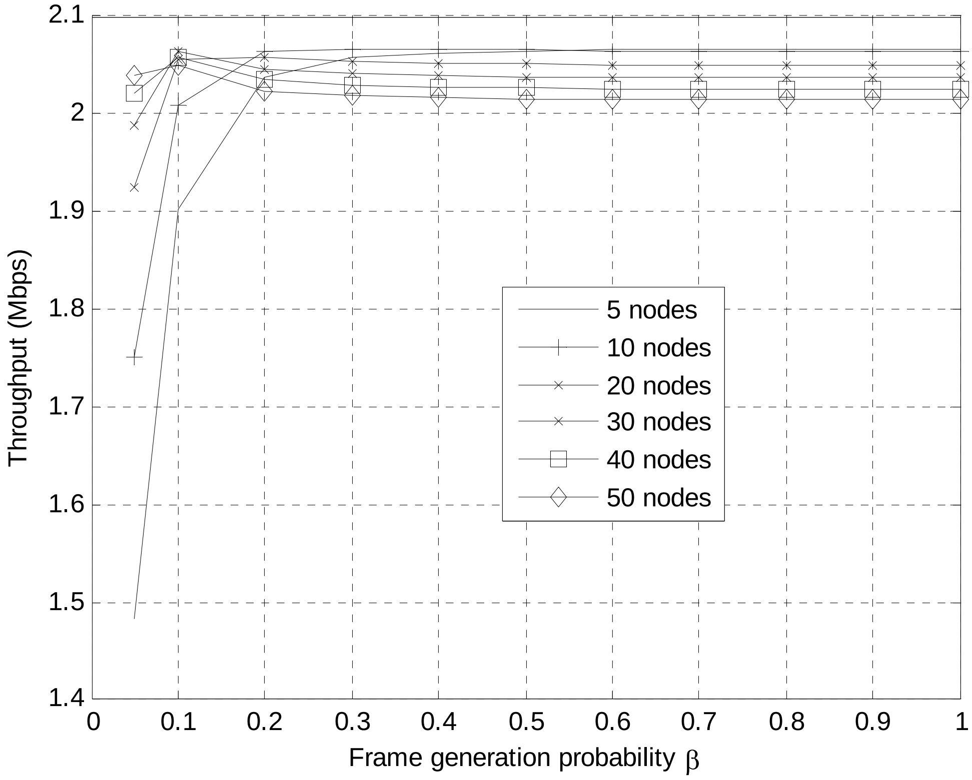


Figure 4.21: Non-saturated throughput of ErDCF(11, 5.5) in an ideal channel.

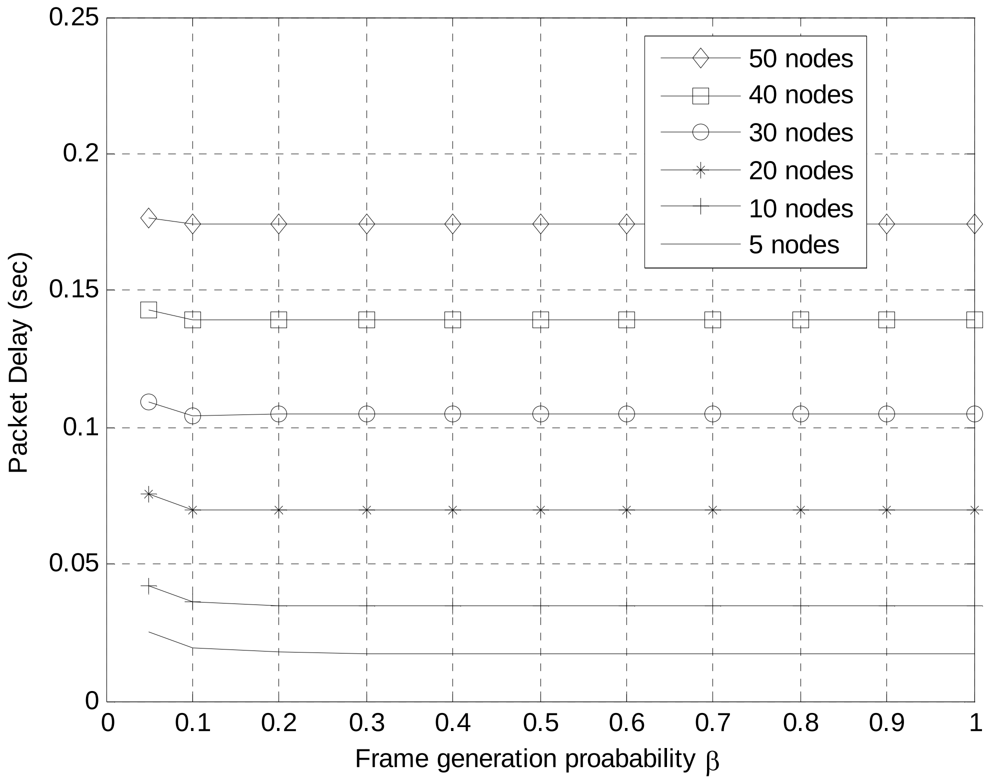


Figure 4.22: Non-saturated Packet Delay of ErDCF(11, 5.5) in an ideal channel.

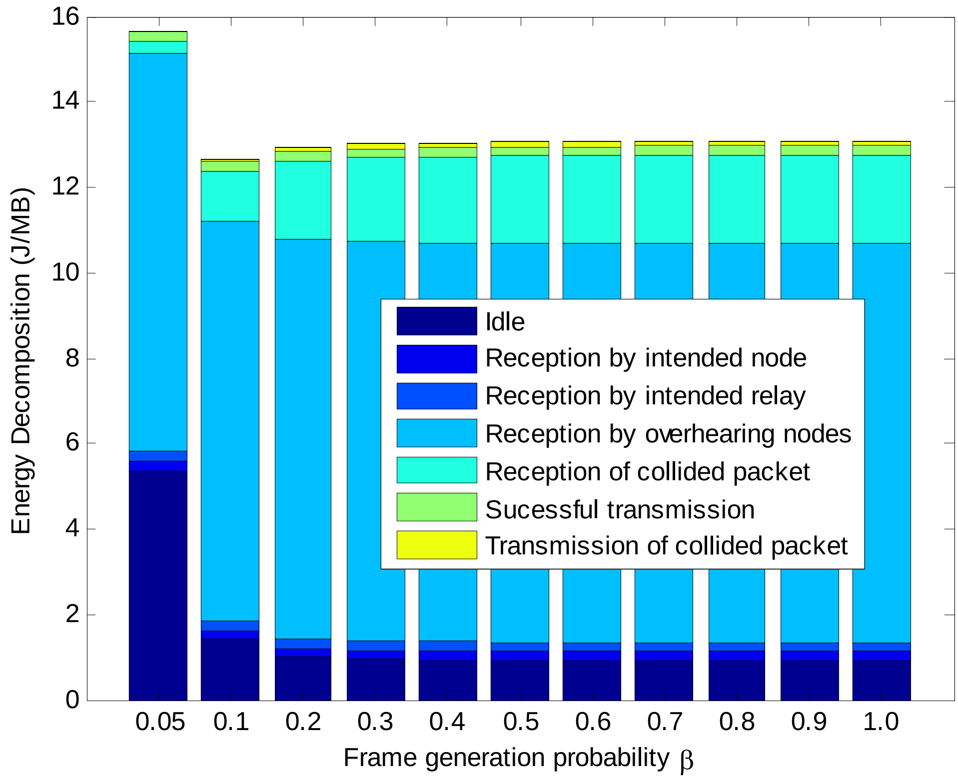


Figure 4.23: Non-saturated energy consumption of ErDCF(11, 5.5) in an ideal channel.

Fig. 4.22 shows the non-saturated packet delay in an ideal channel. We observe that impact of non-saturation on packet delay is not as significant as packet delay. This is related to successful transmission and is exclusive of the delay time for a packet drop due to the expiry of retry limit.

In Fig. 4.23, non-saturated decomposition of energy consumed by ErDCF(11, 5.5), at n = 50 nodes, in ideal channel is shown. As seen from the figure with increasing β the energy consumed in staying idle decreases where as the energy consumed in receiving collided packets increases. This is due to fact that when more packets are available the nodes are not idle and more transmissions increase the possibility of collision. The energy consumed in overhearing remains constant as expected.

4.5 Conclusions

In this chapter, we have proposed ErDCF protocol for ad hoc networks which achieves higher throughput, lower delay and energy consumption by using dual-hop relay based transmission. ErDCF yields higher throughput gain as compared to rDCF by using short preamble for relay based dual-hop transmission. As shown in the results, most energy is wasted in listening to ongoing transmission. ErDCF is more energy efficient as compared to rDCF due to 1) short preamble and 2) the ability to conserve energy (by avoiding unnecessary overhearing) when transmission duration is known. At the same time ErDCF is able to avoid the collision of data packet from relay's neighbor nodes.

We have further evaluated the throughput, delay and energy of ErDCF for different rate combinations in the presence of the transmission errors. This analysis is important as most of the MAC protocols show the performance in ideal or non realistic channel environment. We have used low error probability to show acceptable throughput degradation. It is interesting to see that the throughput gain of ErDCF is maintained because of the use of short preambles and relays, although throughput degradation depends on the link quality and distance.

In addition, we have shown the average packet delay and average packet drop time performance of ErDCF for different rate combinations in an ideal channel and channel with transmission errors. It is again interesting to see that the average delay greatly depends on transmission errors and is an increasing function of number of nodes and packet length. In the presence of transmission errors, average packet delay reduces. This is a result of increase in probability of failure (due to collisions and transmission errors) which in turn reduces probability of successful transmission. As a result of lower average delay we experience increase in the average packet drop time which reflects a reduction in throughput. Finally, we have also shown some results for the non-saturation throughput, delay and energy in an ideal channel.

Chapter 5

MrMAC: Multiple relay Medium Access Control Protocol

5.0 Introduction

As mentioned earlier in Section 2.3.2, broadcast based relay protocols can be classified as single relay and multiple relay protocols. The majority of the existing literature is focused on the single relay domain. This is mainly due to the complexity involved in relay selection, defining maximum number of relays, multiple relay coordination and handling of additional overheads.

Though from physical layers perspective, researchers have found that multiple relays results in higher gains in terms throughput and outage probability. However, these results do not include overheads in coordination of multiple relays. Simply, using more than one relay may not result in higher performance gain at MAC layer. One such example is given below from AHN or WLAN (where users share common wireless medium) perspective where coordination overheads due to multiple relays and the transmission time will be approximately twice when compared to a single relay

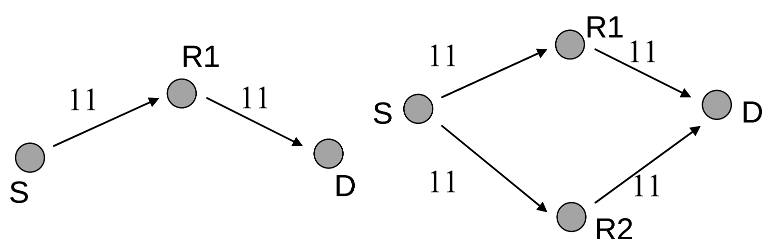


Figure 5.1: Single and Two relay (with 11 Mbps links) scenario in an ideal environment.

scenario, thus resulting in significantly lower throughput. In light of above example, it is necessary to devise clever solutions which will overcome the coordination overhead and transmission time losses. One such proposed technique is described in later sections, whereas the strategies used in current literature are summarized below.

In addition to the classification of the cooperative MAC protocols in Chapter 2, it is possible to sub divide the multiple relay MAC protocols based on the antenna structure used:

1. Multiple relay MAC protocols with omni-directional antennas.
2. Multiple relay MAC protocols with directional antennas.
3. Multiple relay MAC with multiple beam antennas.

Currently there is not much literature on multiple relays from MAC layer perspective. However, one notable contribution reported is [48]. This scheme uses two relays to form the virtual antenna array and makes use of the physical layer network coding technique to achieve the throughput gain. The assumption in this work is that nodes are equipped with omni-directional antennas and therefore each node can only communicate with one node at a time. An alternative to omni-directional antennas is directional or multiple beam antennas. In [81, 82], authors have proposed a multi-relay MAC protocol with directional antennas. The main idea is to use directional antennas to allow parallel transmissions. In this protocol two relays are selected and the parallel transmission takes place from the first relay to the destination and from the source to the second relay. Compared to traditional omni-directional antennas, the use of directional antennas can give rise to hidden terminal or node deafness problems due to different antenna gains [83, 84].

To reduce the above mentioned problems, Korakis [85] proposed a protocol that introduces a circular directional transmission of the RTS control packet to spread information about the following data transmission. The nodes receiving the directional RTS defer their transmission toward the beams that could harm the ongoing communication. In this way, the proposed protocol takes advantage of the benefits of directional transmissions because they increase spatial reuse and coverage range. In addition, the improper channel separation between directional antennas which allows parallel transmission may lead to throughput degradation. Further, a measurement study [86] conducted to entail the impact of directional antennas on 802.11 based systems. It shows that the achievable throughput is highly dependent on the antenna orientation, placement and channel separation.

In another recent work by [87], this prevailing assumption of omni-directional antennas is loosened by assuming multiple beam antennas which, unlike the omni-directional antennas, can use the multiple beams to communicate with multiple nodes simultaneously. The idea behind this notion of multiple beam antennas is to enable parallel transmissions. This works show significant improvement in the system throughput by increasing spatial reuse, reducing collisions and avoiding co-channel interference. However, this assumption of directional or multiple beam antennas leads to compatibility issues as the existing IEEE 802.11 MAC protocol and devices have no support for directional antenna or multiple beam antennas. In future, MAC protocols would require major modifications and hardware support to enable these features. The main issues faced by multiple relay MAC protocols are as follows:

- **Relay Selection:** Selection of the relay out of a number of potential relays is a critical issue in distributed wireless networks which do not have a centralized controller. The choice of relay will eventually impact the overall throughput.
- **Maximum number of relays:** The increasing number of relays involved in a transmission results in diminishing returns. Therefore, it is important to find out the number beyond which there is no gain. Increasing the number of relays is thus directly linked to the complexity and delay faced by the whole system.
- **Multiple relay coordination:** Another issue worth consideration in multiple relay MAC is the coordination between the relays. Lack of coordination may lead to higher system delays, higher overhead and increase in the blocking time of the other nodes. Smooth coordination results in lower delay and efficient transmissions.
- **Overheads:** Transmission and coordination overheads are associated with multiple relays. More relays lead to more overheads and if not utilized efficiently may result in no gains. To achieve maximum gain it is important to minimize the overheads.
- **Energy Consumption:** Higher overheads and blocking time result in high energy consumption. To realize the gain affectively in energy critical scenarios, it is important to evaluate the energy consumption and restrain it to the minimum.
- **Hidden and exposed terminal problems:** With the coverage expansion due to the relays, the possibility of hidden terminals, exposed terminals and deaf nodes increases. Control packets have been shown to reduce the impact of the above mentioned issues to some extent; however, sensible use of controls packets is

required. Unnecessary control packets will increase the overhead and would result in uncalled-for delays.

- **Compatibility:** Compatibility with existing standards such as 802.11 is a key issue due to wide proliferation of 802.11 products. Some solutions in the literature presented above are not compatible with 802.11 and require significant changes.

The above mentioned issues and the lack of literature in this area have led to the motivation for this work. The proposed protocol is designed keeping in mind the compatibility requirements. The next section describes the proposed protocol in detail.

5.1 Protocol Description

In the standard 802.11 DCF protocol, control packets are used to avoid collisions. In our scheme we make use the control packets to coordinate relay based transmission and avoid collisions. Our proposed protocol Multiple relay MAC (MrMAC) is compatible with standard DCF and makes use of it for direct transmissions. In Fig. 5.2, three modes of transmissions available in the proposed protocol are shown.

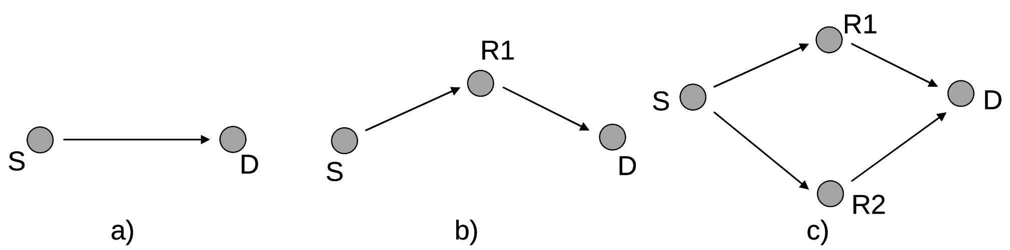


Figure 5.2: Modes of transmission: a) Direct transmission, b) Single relay transmission and c) Multiple relay transmission.

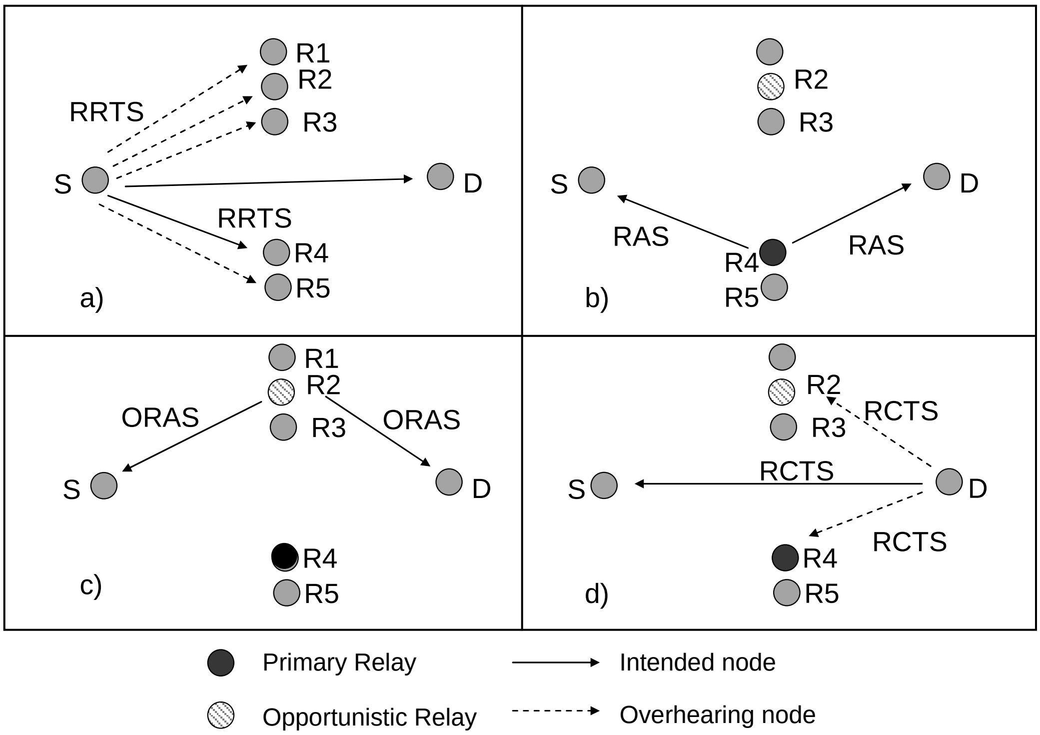


Figure 5.3: An illustration of the handshake in MRMAC.

The first mode is the direct transmission (Fig. 5.2a) which is same as the 802.11 DCF, second mode of transmission is single relay transmission (Fig. 5.2b) which is similar to ErDCF and the third mode of transmission is multiple relay transmission (Fig. 5.2c) where more than one relay is used. In MrMAC protocol a handshake of control packets similar to the RTS/CTS mode of 802.11 DCF is used. This handshake in the protocol to coordinate relays is shown above in Fig. 5.3:

a. When a source node has a data packet to send via a preselected primary relay it senses the medium. Primary relay is selected based on the entries in the relay table maintained by the source. If the medium is busy, the source waits or else it initiates the transmission with a Relay Request-to-send (RRTS) packet. Fig. 5.3a shows the transmission of RRTS from source to primary relay which is overheard by other potential relay nodes.

b. Primary relay node on receiving the RRTS, generates a control packet called Relay-Agrees-to-Send (RAS). In case, the primary relay is not available to forward the data packet, the direct mode of transmission is used. The control packet RAS is received at both the source and destination and overheard by potential relays. Fig. 5.3b depicts the transmission of RAS from primary relay to source and destination, which is also overheard by other potential relay nodes. After RAS the protocol allows time for the opportunistic potential relays to acquire the medium.

c. When an opportunistic relay gets access to the medium after the relay selection mechanism, it transmits an Opportunistic-Relay-Agrees-to-Send (ORAS) packet to source and destination. This packet is also meant for other potential relays to end the contention to win access to the medium. Fig. 5.3c reflects this scenario. Detail of primary and opportunistic relay selection is given in a later section.

d. Finally, the destination receiving RCTS, RAS and ORAS decides whether to choose multiple relay, single relay or direct transmission. This decision is conveyed to other nodes by sending out RCTS or CTS control packets shown in Fig. 3.3d. The RCTS means relay based transmission and it shows the number of relays where as CTS is for a direct transmission.

After the successful relay coordination through the handshake of control packets, the next step is transmission of data packets. The source starts the transmission of packet DATA1 of length L bytes at rate R_1. This packet is received at both primary relay and secondary opportunistic relay. The primary relay forwards the packet DATA2 of length L bytes at transmission rate R_2 to the destination which is also received at the secondary relay. The secondary relay now combines the source's data packet DATA1 with its own data packet by a simple XOR operation to keep the length of the packet same. Later secondary relay transmits the data packet DATA3 of length *L* bytes at transmission rate R_3 and waits for the acknowledgment. The transmission of data packets is shown in Fig. 5.4.

In [88] the relay node encapsulates its data packet and source's data packet and sends both to the destination. In a similar way AR-MAC [89] also combines the source and relays data in a single relay transmission but both these result in increased packet length and there is no diversity or combining gains.

In MrMAC at the destination node, the received packets are DATA2 and DATA3. The destination can retrieve a copy of DATA2 by a simple XOR operation. The advantage of the carrier sensing scheme is that the overhearing nodes are only blocked for the transmission duration unlike 802.11 DCF where the RTS packet reserves the medium till the end of transmission. The durations in the control and data packets of MrMAC are shown in Table 5.1. The control and data frame formats of the proposed MrMAC are shown in Fig. 5.5. To reduce the overheads XOR operations are used in RCTS and ACK frames for the relay address and relay rate fields.

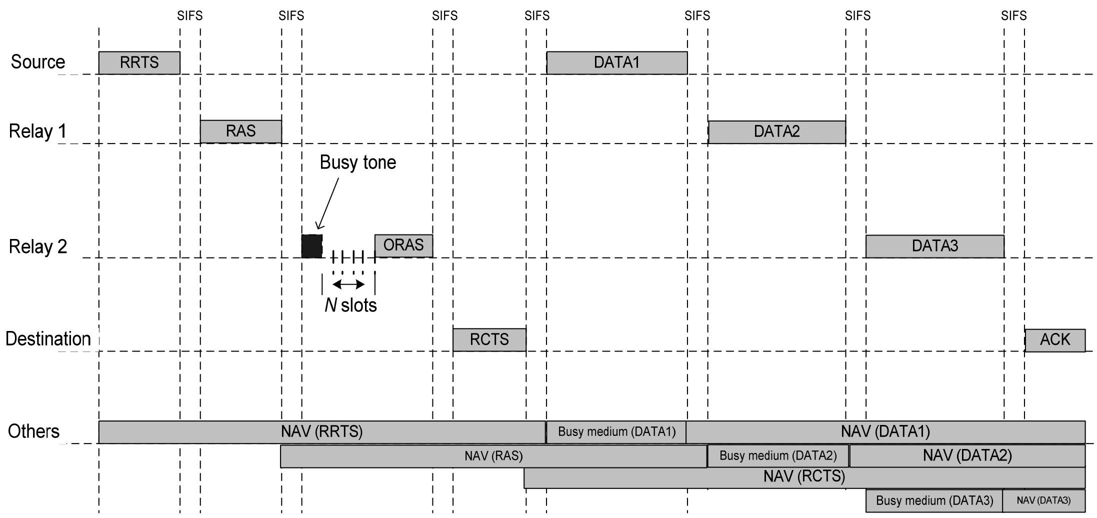


Figure 5.4: MrMAC carrier sensing scheme.

Table 5.1: Duration field of Control and Data packets in MrMAC.

	MrMAC [duration]
RRTS	[RAS+ORAS+RCTS+4SIFS+4SIFS(Secondary relay selection]
RAS	[ORAS+RCTS+4SIFS+4SIFS(Secondary relay selection]
ORAS	[RCTS+2SIFS]
RCTS	[DATA(L,R_1)+ DATA(L,R_2)+ DATA(L,R_3)+ACK+4SIFS]
DATA1	[DATA(L,R_2)+ DATA(L,R_3)+ACK+3SIFS]
DATA2	[DATA(L,R_3)+ACK+2SIFS]
DATA3	[ACK+SIFS]
ACK	[0]

a) RRTS format

Frame Control	Duration	DA	SA	BSSID	Address4 RA	FCS
2	2	6	6	6	6	4

b) RAS format

Frame Control	Duration	R_1	DA	SA	BSSID	RA1	FCS
2	2	0.5	6	6	6	6	4

c) ORAS format

Frame Control	Duration	R_3	DA	SA	BSSID	RA2	FCS
2	2	0.5	6	6	6	6	4

d) RCTS format

Frame Control	Duration	$RA1 \oplus RA2$	$R_1 \oplus R_2$	$R_1 \oplus R_3$	FCS
2	2	6	0.5	0.5	4

e) DATA format

	0 -2302	4
MAC header	Frame Body	FCS

Frame Control	Duration	HCS	DA	SA	BSSID	Sequence Control	Address4
2	2	0.5	6	6	6	6	4

f) ACK format

Frame Control	Duration	$RA1 \oplus RA2$	FCS
2	2	6	4

Figure 5.5: Control and Data frames for proposed MrMAC.

5.1.1 Relay Selection

It is a well known fact that the gain of multiple relays start to diminish when the maximum number of relays is reached. Chou [90] defined a limit to the number of relays to be 5 beyond which there is no significant gain. The two relays requiring selection in this scheme are: primary relay selection and secondary opportunistic relay selection.

The primary relay is always selected based on the table (information about potentials relays) maintained by the source node. After the primary relay confirms its participation with the RAS packet, the secondary relay selection is initiated. In this protocol the main aims are to reduce the blocking time for other nodes and reduce contention. Therefore, the secondary relays are selected based on a subset of potential relays which can hear RRTS and RAS and have data packets intended for the destination mentioned in the RRTS. In order to reserve access to the medium the opportunistic relay sends out a busy tone similar to [90]. The opportunistic relay selection duration is equal to four times the SIFS interval. The busy tone is equal to a SIFS interval. The selection of secondary relay is again based on the lookup table kept by the relays. The relays with the best data rates are selected as potential relays. These relays will perform random backoff as reported in [49, 91]. Finally, the best relay will start a busy tone as shown in the carrier sensing figure to reserve the medium. This busy tone is followed by an ORAS packet from the same relay which defines the NAV and rate information.

The idea behind limiting the relay selection to only relays with data packets for the destination is that at the secondary relay the source's data is combined with the secondary relay's data and sent to the destination. The destination now receives the source's data via the primary relay and the combined source and relay data via the secondary relay. The destination now receives two data packets in a single transmission.

At the same time secondary relay is able to send its data to the destination without contending to access the medium, thus reducing the contention. Though participation of secondary relay increases the transmission time, at the same time we are able to transmit twice as much data, reduce transmission overhead and reduce contention for other nodes. The increase in transmission time compared to time spent in scheduling a fresh transmission of data packet after contention and exchange of control packets is much less.

5.1.2 Advantages of MrMAC

The advantages of the proposed scheme are that we are able to receive multiple data packets (which are equal to the number of participating relays) in a single transmission. Overall contention is reduced as an opportunistic node was able to send its own data while supporting the source.

5.2 System Model

Consider a wireless network of n nodes based on IEEE 802.11 MAC that can support multiple transmission rates and allow multiple relay based transmissions. The wireless medium is shared among multiple contending nodes, i.e. a single physical channel is available for wireless transmission. The control packets are used to solve the hidden terminal problem, coordinate multiple relays and improve the system performance. Another assumption in this model is that the collision can only take place at the initializing control packet. For the performance evaluation, a saturated network where nodes always have packets to transmit is assumed. In addition to this, it is assumed that there are always relays available to help. All nodes are capable of relaying data for other nodes. The relay nodes simply forward the data packets or add their own data packet to the source's data. The idea is to reduce the overall transmission time via dual-hop transmission at higher data rates. Relays are not required to compete for the access as once a source node acquires the medium the transmission is carried out via the relay. The control packets are also used for the coordination of multiple relays.

For MrMAC, the equations for the average times the channel is sensed busy for successful transmission and for collision respectively are:

$$\begin{aligned} T_s^{MrMAC} &= T_{RRTS} + T_{RAS} + T_{ORAS} + T_{RCTS} + T_{ACK} + T_{DATA(L,R_1)} \\ &+ T_{DATA(L,R_2)} + T_{DATA(L,R_3)} + 7T_{SIFS} + 8\delta + T_{DIFS} + 4T_{SIFS} \end{aligned} \quad (5.1)$$

$$T_c^{MrMAC} = T_{RRTS} + T_{DIFS} + \delta. \quad (5.2)$$

T_s and T_c are times the channel is sensed busy for successful transmission and for collision. Here RRTS, RAS, ORAS and RCTS are control packets for coordinating multiple relay transmission in MrMAC. In the above equations, T_{RRTS}, T_{RAS}, T_{ORAS} T_{RCTS} and T_{ACK} are the transmission times for RRTS, RAS, ORAS, RCTS and ACK, respectively. T_{SIFS} and T_{DIFS} are inter-frame times and δ is the propagation delay. $T_{\mathrm{DATA(L,R_1)}}$ and $T_{\mathrm{DATA(L,R_2)}}$ are the times for the data packets of length L bytes at rates R_1 and R_2 respectively. Similarly $T_{\mathrm{DATA(L,R_3)}}$ is the time for the transmission of the packet by opportunistic relay at rate R_3. The MrMAC chooses from 11 and 5.5 Mbps to make different rate combinations for relaying.

5.2.1 Performance Evaluation

For the performance evaluation of MrMAC we compare it against the single relay ErDCF of Chapter 4 and low data rate 802.11 DCF. The scenario considered for MrMAC uses $R_1 = R_2 = R_3 = 11$ Mbps and for ErDCF $R_1 = R_2 = 11$ Mbps. The low rate 802.11 DCF uses data rates of 2 Mbps. Ideal channel conditions are assumed. Table 5.2 shows the parameters for MrMAC.

In Fig. 5.6, saturation throughput of MrMAC, ErDCF and 802.11 DCF is shown for comparison. As per the expectation we can observe that MrMAC results in the highest throughput followed by the single relay ErDCF and low data rate 802.11 DCF. The use of dual-hop multiple relay significantly improves the saturation throughput of the networks.

Table 5.2 MrMAC Specification.

Physical Characteristic	IEEE 802.11 b DSSS
$CW_{\min}$	32
m	6
m'	5
DIFS	50 µs
SIFS	10 µs
Slot	20 µs
MAC header	272 bits
PHY header	192 µs
RRTS	256 bits/control rate + PHY header
RAS	228 bits/control rate + PHY header
ORAS	228 bits/control rate + PHY header
RCTS	168 bits/control rate + PHY header
ACK	112 bits/control rate + PHY header
Control Rate	2 Mbps
Propagation Delay	1 µs

In Fig. 5.7, throughput gains of MrMAC and ErDCF over 802.11 DCF are shown for n = 5. This scenario uses the same rates as in the earlier figure. We observe a throughput gain of 2.84 and 2.24 for MrMAC and ErDCF respectively at 2500 bytes. In a similar fashion at 1000 bytes we observe a gain of 2.27 and 1.87 for MrMAC and ErDCF respectively. It is interesting to observe that throughput gain is an increasing function of the packet length. The use of dual-hop multiple relay is always advantageous compared to dual-hop single relay ErDCF in terms of throughput gain. However, we still need to justify the use of multiple relays from the delay and energy perspectives.

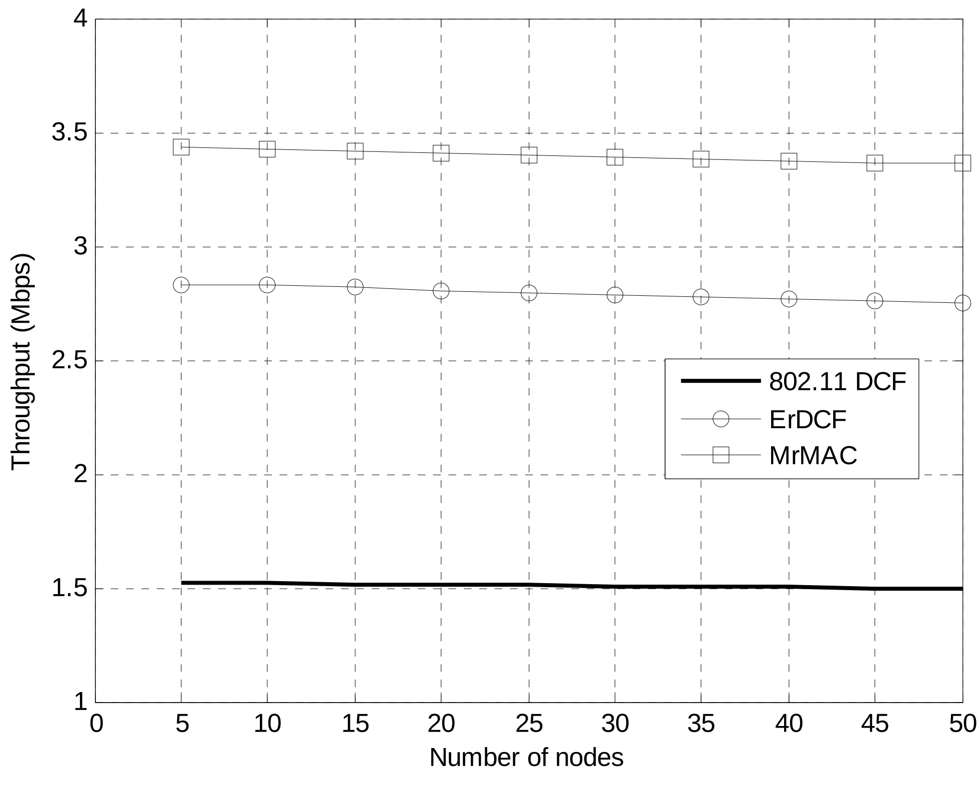


Figure 5.6: Saturation Throughput of MrMAC, ErDCF and 802.11 DCF.

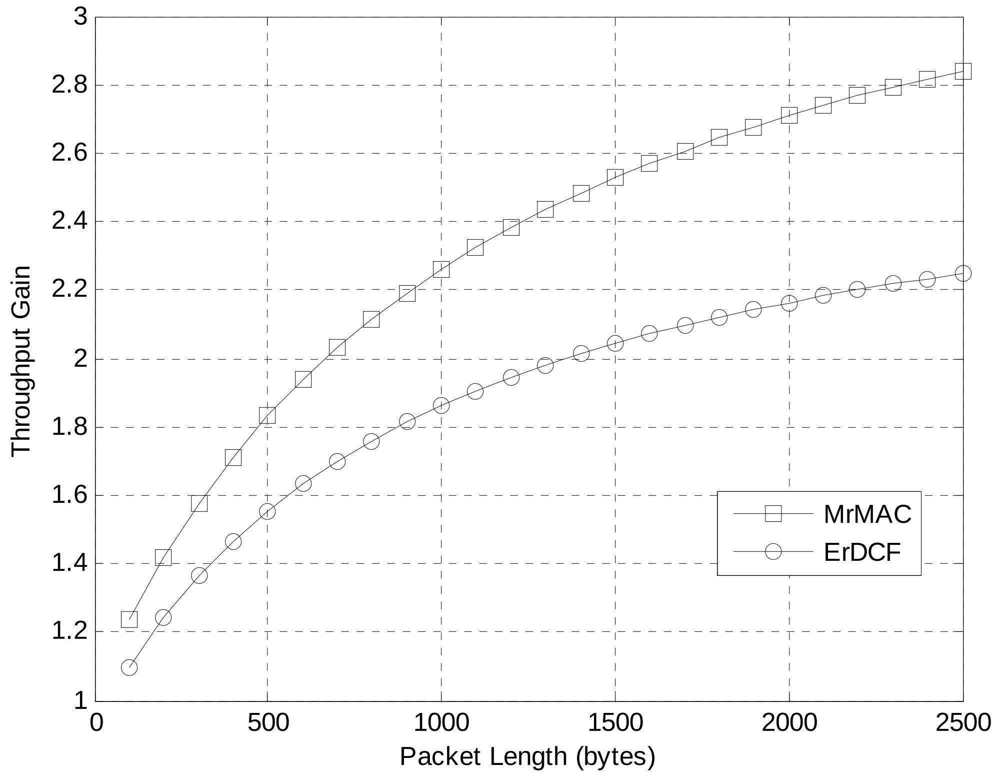


Figure 5.7: Throughput gain of MrMAC and ErDCF over 802.11 DCF for different packet lengths.

Table 5.3: Throughput Comparison.

	Throughput (Mbps) at 5 nodes	Throughput (Mbps) at 50 nodes
MrMAC	3.43	3.36
S-MrMAC	1.716	1.68
ErDCF	2.82	2.75
802.11 DCF	1.51	1.49

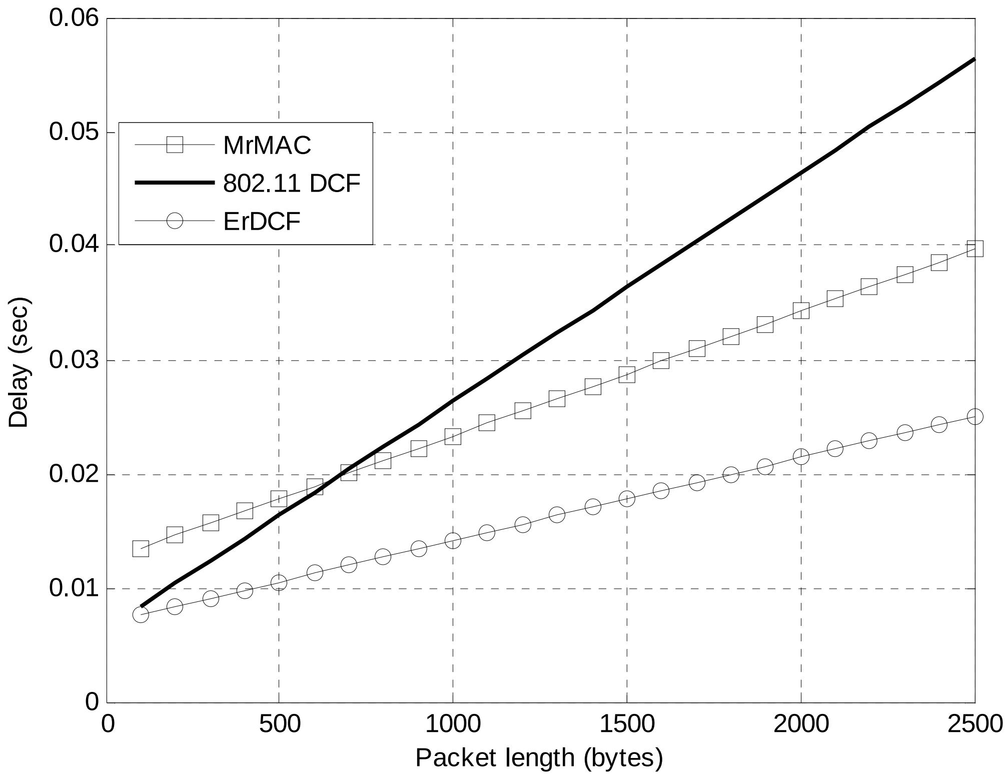


Figure 5.8: Delay of MrMAC, ErDCF802.11 DCF and 802.11 DCF for different packet lengths.

Table 5.3 shows throughput comparison of MrMAC, ErDCF, 802.11 DCF and S-MrMAC. Here S-MrMAC is multiple relay without data from the second relay. We observe that S-MrMAC performs close to 802.11 DCF and worse compared to ErDCF. This is due to the fact that as opposed to MrMAC, S-MrMAC only transmits source's data with out adding data packet opportunistically at the relay. S-MrMAC results in same delay and energy consumption as MrM.AC.

In Fig. 5.8, delay of MrMAC, ErDCF and 802.11 DCF are shown for $n = 5$. Again the results are for the same data rates as in earlier figures. It is interesting to observe that delay is an increasing function of packet length. The use of dual-hop single relay is always advantageous compared to 802.11 DCF at a low rate. However, due to the overhead associated with a multiple relay scenario it is not justified to use multiple relays for shorter packet lengths. We can see that for packet lengths approximately below 700 bytes, MrMAC results in higher delay compared to 802.11 DCF. Further to this, delay is also an increasing function of number of nodes.

From the above results we can easily conclude that it is advisable to use the multiple relays for the throughput gain. For the delay we can see that it is not feasible to use the multiple relays for packets shorter than a certain length. This defines the optimum packet length beyond which it is feasible to use the multiple relays.

For multiple relay MAC protocols, modelling of energy consumption is very important. It is important to have a feeling of the gain of multiple relays in terms of energy consumption. This may make it more suitable for energy critical applications and energy critical environments (such as sensor networks).

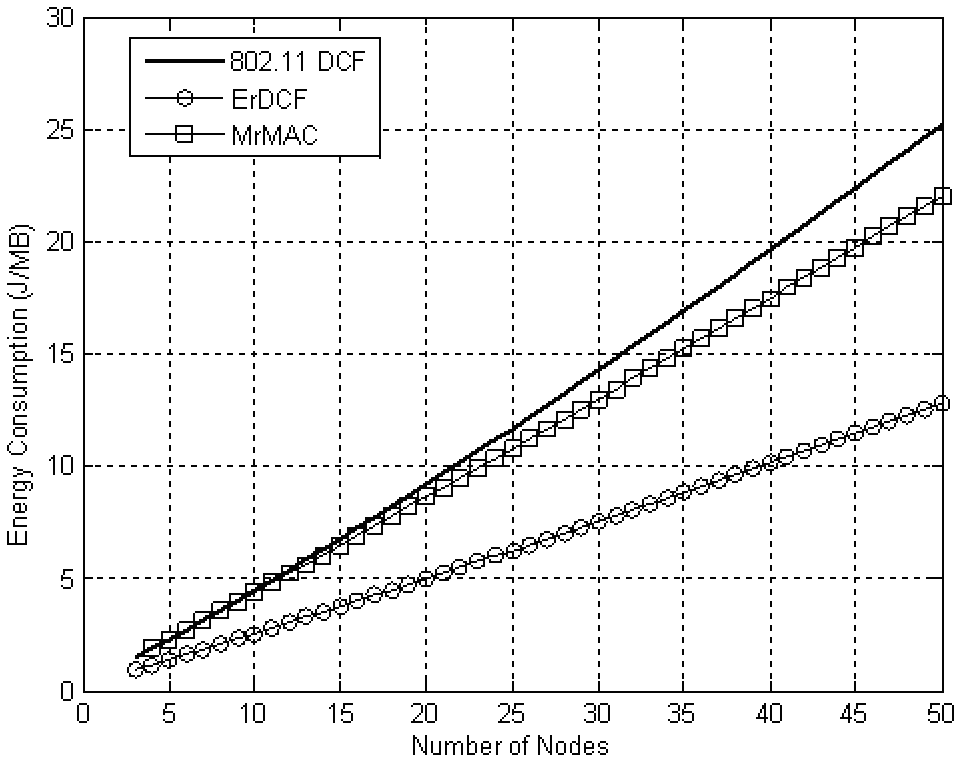


Figure 5.9: Energy consumption of MrMAC, ErDCF802.11 DCF and 802.11 DCF.

Fig. 5.9 shows the energy consumption of MrMAC, ErDCF and 802.11 DCF. It is interesting to observe that, with multiple relays and high overhead, MrMAC is still more energy efficient compared to 802.11 DCF, which makes it feasible for higher throughput and energy consumption as well. The single relay ErDCF is the most energy efficient of all three schemes. It is expected that MrMAC with some energy saving mechanism or overhead optimization may show even better performance.

5.3 Conclusion

In this chapter, we have proposed a multiple relay MAC protocol MrMAC for ad hoc networks which achieves higher throughput and lower and energy consumption by using multiple dual-hop relay based transmission in ideal channel conditions. Multiple relays result in higher overheads which show that in terms of delay it is not feasible to use MrMAC for shorter packet lengths. From the above results, we can further conclude that there is no gain for more than two relays due to the high overhead involved in coordinating relays.

MrMAC yields higher throughput gain as compared to ErDCF by using multiple dual-hop relay transmission. In future, we plan to optimize the control frames and devise an energy conservation mechanism for the MrMAC. It is worth mentioning here that throughput gain of MrMAC can be further improved with diversity or combining gains. This requires performance analysis of the protocol in channel with transmission errors.

Chapter 6

Conclusions and Future Work

6.0 Introduction

The future wireless communications demand higher throughput, lower delay as well as lower energy consumption to meet the increasing user requirements for high bandwidth. This drive has focused current research towards making the user experience pleasant. Cooperative networking technology aims at providing higher network resilience to enhance system capacity and reduce power consumption. Cooperative networking is now widely used in ad hoc networks which form an important component of the next generation networks. In this dissertation, performance analysis for cooperative relay based MAC protocols is addressed. A summary of the main contributions and findings of the dissertation is presented in this chapter. Section 6.1 discusses the main conclusions derived from previous chapters. This is followed by a sketch of open research issues outlined in Section 6.2.

6.1 Summary and Conclusion

The focus of the work in this dissertation has been on the performance analysis of cooperative relay based MAC protocols for ad hoc networks. The thesis is in three main parts:

1. A review of the state of the art in cooperative networking: Chapters 1 and 2.
2. The first major contribution: Chapter 3.
3. The second and third major contributions: Chapters 4 and 5 respectively.

Chapter 1 introduced the area, research motivation and the social impacts of the research. This chapter also highlighted the main contributions derived from this work and outlines the thesis. **Chapter 2** illustrated the basic concepts of Ad hoc and cooperative networks in detail and presented an overview of ad hoc networks and MAC layer issues. This led to IEEE 802.11 which is the most common standard for ad hoc networks. An introduction to Markov chain model used for the modeling of 802.11 DCF was given in order to help the readers understand the analytical models in later chapters. This chapter further presented a review on the state-of-the-art of cooperative networking. This part of the thesis concluded with a detailed classification of the cooperative MAC protocols along with a tabular comparison. This classification and comparison can be used as a valuable resource for new researchers in this area.

In **Chapter 3**, an analytical method for energy consumption analysis was presented. This chapter highlighted the importance of energy consumption analysis for MAC protocols developers while in design phase. It further illustrated the integration of existing and next generation networks where efficient energy consumption will play an important role. This method is able to model the energy consumption in ideal and non-ideal channel conditions. Finally, it exemplified the energy consumption of the existing rDCF in ideal and non-ideal channels. From this chapter we can conclude that energy consumption is an important issue in today's world, it is important for the existing networks, NGNs and the co-existence of existing networks and NGNs. The energy consumption model for relay based MAC protocols is a useful aid for MAC protocol developers for protocol optimization and devising energy saving mechanisms. The detailed analytical model is capable of showing energy decomposition, thus helpful in identifying key energy critical operations. In conclusion, we were able to identify the energy critical operations in rDCF such as reception by overhearing nodes, reception of collided packets and idle period.

In **Chapter 4**, ErDCF was presented to overcome the shortcomings of the rDCF protocol. The main idea of ErDCF is to introduce dynamic preamble, energy saving, gain for variable packet lengths and it also addresses the issue of collision of second data packet (from relay to destination). This chapter analyzed the saturation performance of the ErDCF in terms of throughput, delay and energy consumption. The analysis of throughput, delay and energy is modified to incorporate the relay based transmission, transmission errors and non-saturation. It is appealing to see that ErDCF results in higher throughput, lower energy consumption and lower delay when compared with both 802.11 DCF and rDCF. We can further conclude that ErDCF is resilient to the channel conditions as the throughput gain of ErDCF can be maintained even in the presence of errors. Energy consumption of ErDCF identifies the energy critical operations and we were able to obtain significant reductions in energy.

Finally, in **Chapter 5,** MrMAC - a multiple relay MAC protocol aimed at achieving gain from use of multiple relays - was presented. The advantages of MrMAC are: reception of multiple data packets (based on the number of relays involved) in a single transmission, and reduced contention and blocking time for other nodes. The performance evaluation of MrMAC confirmed its usefulness. MrMAC showed significant throughput gain compared with ErDCF. From this chapter, we could conclude that multiple relays do have a significant throughput advantage, but at the cost of higher overhead. Therefore, it is important to achieve an optimum trade-off between overhead, delay and throughput. Further it is important to analyze diversity gain for the source's data packets which increases its reliability in a non-ideal channel, Overall, this thesis has highlighted the gains associated with relay based MAC protocols and their role in NGNs. On the other hand, the work in this thesis also raises a number of open issues which require further investigation. These are shown in the next section.

6.2 Open Research Issues and Future Directions

This thesis has addressed a number of significant issues such as energy consumption analysis and performance of effective single and multiple relay based MAC protocols. Many other key issues have also been identified during the course of this work but have not been covered in this dissertation. Some of these issues are listed below and require further investigation.

- Introduction of power control and rate adaptation in relay based MAC protocols to increase spatial reuse, reduce interference and improve energy efficiency.
- The focus of the thesis was on MAC layer perspective of relaying. However, cross layer solutions should greatly benefit cooperative networks. To yield the gain, the cross layer approach should integrate the physical layer, MAC layer and network layer. This can result in reduced overheads. Potential benefits and challenges in cooperative networking by using a cross-layer approach should be studied in future work.
- Current relay based MAC protocols neglect user mobility which can be true in practice (e.g. cooperative vehicular networks). Further investigation is needed in this area.
- Current relay selection is based on the available rates only and may result in reuse of the same relay again and again. This would drain the energy of this relay thus lose a potential cooperative partner. This requires the design of efficient and fair relay selection algorithms that can select the potential relays

based on energy consumption and network throughput together. This would result in network lifetime maximization and fairness.

- Relay selection by itself is a vast research area which can benefit from efficient multiple relay selection algorithms.
- Relay based MAC protocols can find applications in energy critical sensor networks and require modification according to the energy and overhead requirements of sensor networks.
- Joint framework to combine ARQ mechanism into the MAC protocol.
- Interference analysis of the cooperative MAC protocols is an interesting area. An analytical model to predict interference can lead to potential interference mitigation techniques.

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Appendix A

Equations for Packets in Error

Here we have shown the extended equations from Chapter 3 (by replacing (3.25) – (3.28) by (A.1) – (A.4)) for the error averaged over all packets and used in Figs. 3.12 and 3.13:

$$
\begin{aligned}
J_e^{tx} = {} & \rho_{tx}T_{RRTS1} + \rho_{\sigma}(T_{EIFS} + \delta) + \rho_{tx}T_{RRTS1} + \rho_{rx}T_{RRTS2} \\
& + \rho_{\sigma}(T_{EIFS} + T_{SIFS} + 2\delta) + \rho_{tx}T_{RRTS1} + \rho_{rx}T_{RRTS2} \\
& + \rho_{\sigma}(T_{RCTStimeout} + T_{DIFS} + T_{SIFS} + 3\delta) + \rho_{tx}(T_{RRTS1} \\
& + T_{DATA(L,R1)}) + \rho_{rx}(T_{RRTS2} + T_{RCTS}) \\
& + \rho_{\sigma}(T_{EIFS} + 4\delta + 3T_{SIFS}) + \rho_{tx}(T_{RRTS1} + T_{DATA(L,R1)}) \\
& + \rho_{rx}(T_{RRTS2} + T_{RCTS} + T_{DATA(L,R2)}) \\
& + \rho_{\sigma}(T_{EIFS} + 4T_{SIFS} + 5\delta) + \rho_{tx}(T_{RRTS1} + T_{DATA(L,R1)}) \\
& + \rho_{rx}(T_{RRTS2} + T_{RCTS} + T_{DATA(L,R2)}) \\
& + \rho_{\sigma}(T_{ACKtimeout} + T_{DIFS} + 4T_{SIFS} + 6\delta)
\end{aligned}
\tag{A.1}
$$

$$
\begin{aligned}
J_e^{rx}(l) = {} & \rho_{rx}T_{RRTS1} + \rho_{\sigma}(T_{EIFS} + \delta) + \rho_{rx}(T_{RRTS1} + T_{RRTS2}) \\
& + \rho_{\sigma}(T_{EIFS} + T_{SIFS} + 2\delta) + \rho_{rx}(T_{RRTS1} + T_{RRTS2}) \\
& + \rho_{\sigma}(T_{RCTStimeout} + T_{DIFS} + T_{SIFS} + 3\delta) \\
& + \rho_{rx}(T_{RRTS1} + T_{DATA(L,R1)} + T_{RRTS2} + T_{DATA(L,R2)}) \\
& + \rho_{tx}T_{RCTS} + \rho_{\sigma}(T_{EIFS} + 5\delta + 4T_{SIFS}) \\
& + \rho_{rx}(T_{RRTS1} + T_{RRTS2} + T_{DATA(L,R1)} \\
& + T_{DATA(L,R2)}) + \rho_{tx}T_{RCTS} \\
& + \rho_{\sigma}(T_{ACKtimeout} + T_{DIFS} + 4T_{SIFS} + 6\delta)
\end{aligned}
\tag{A.2}
$$

$$\begin{aligned} J_e^{rx}(r) = {} & \rho_{rx}T_{RRTS1} + \rho_\sigma(T_{EIFS} + \delta) + \rho_{rx}T_{RRTS1} + \rho_{tx}T_{RRTS2} \\ & +\rho_\sigma(T_{EIFS} + T_{SIFS} + 2\delta) + \rho_{rx}T_{RRTS1} + \rho_{tx}T_{RRTS2} \\ & +\rho_\sigma(T_{RCTStimeout} + T_{DIFS} + T_{SIFS} + 3\delta) \\ & +\rho_{rx}(T_{RRTS1} + T_{DATA(L,R1)} + T_{RCTS}) \\ & +\rho_{tx}(T_{RRTS2} + T_{DATA(L,R2)}) + \rho_\sigma(T_{EIFS} + 5\delta + 4T_{SIFS}) \\ & +\rho_{rx}(T_{RRTS1} + T_{DATA(L,R1)} + T_{RCTS}) \\ & +\rho_{tx}(T_{RRTS2} + T_{DATA(L,R2)}) \\ & +\rho_\sigma(T_{ACKtimeout} + T_{DIFS} + 4T_{SIFS} + 6\delta) \end{aligned} \tag{A.3}$$

$$\begin{aligned} J_e^{rx}(\sim l) = {} & \rho_{rx}T_{RRTS1} + \rho_\sigma(T_{EIFS} + \delta) + \rho_{rx}(T_{RRTS1} + T_{RRTS2}) \\ & +\rho_\sigma(T_{EIFS} + T_{SIFS} + 2\delta) + \rho_{rx}T_{RRTS1} + \rho_{rx}T_{RRTS2} \\ & +\rho_\sigma(T_{RCTStimeout} + T_{DIFS} + T_{SIFS} + 3\delta) \\ & +\rho_{rx}(T_{RRTS1} + T_{DATA(L,R1)} + T_{RRTS2} + T_{DATA(L,R2)}) \\ & +\rho_{rx}T_{RCTS} + \rho_\sigma(T_{EIFS} + 5\delta + 4T_{SIFS}) \\ & +\rho_{rx}(T_{RRTS1} + T_{RRTS2} + T_{DATA(L,R1)} + T_{DATA(L,R2)}) + \rho_{tx}T_{RCTS} \\ & +\rho_\sigma(T_{ACKtimeout} + T_{DIFS} + 4T_{SIFS} + 6\delta) \end{aligned} \tag{A.4}$$