An Energy Efficient Dynamic Directional Power Control Protocol for Ad hoc Networks

by

Carlos Quiroz Perez
B.Sc, Universidad de las Americas, 2001

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Electrical and Computer Engineering

University of Victoria

An Energy Efficient Dynamic Directional Power Control Protocol for Ad hoc Networks

by

Carlos Quiroz Perez

B.Sc, Universidad de las Americas, 2001

Supervisory Committee

Dr. T. A. Gulliver, Supervisor (Dept. of Electrical and Computer Engineering)

Dr. M. Sima, Department Member (Dept. of Electrical and Computer Engineering)

Supervisory Committee

Dr. T. A. Gulliver, Supervisor (Dept. of Electrical and Computer Engineering)
Dr. M. Sima, Department Member (Dept. of Electrical and Computer Engineering)

ABSTRACT

The use of directional antennas bring many benefits to wireless ad hoc networks, a collection of mobile nodes that communicate directly with each other. Directional antennas increase spatial reuse of the wireless channel, reduce the number of hops to a destination, reduce interference, limit energy waste in unnecessary directions, and increase the transmission range towards a specific direction. Since directional antennas radiate most of their power to a specific direction, a transmitter with a directional antenna might reach a far away destination in one hop. On the other hand, a transmitter with an omnidirectional antenna may instead need the routing services of intermediate nodes to reach the same destination. This is because omnidirectional antennas radiate equally in all directions limiting the transmission range. However, when focusing the total energy in some direction, directional antennas can provide a range on the order of kilometers. If a destination node is only 250 meters from the transmitter, some of the power used in this direction will be wasted. This wasted energy reduces the battery life of the transmitter.

Because most mobile nodes are operated using batteries, protocols which conserve energy are of interest. The Dynamic Directional Power Control Protocol (DDPC) is a protocol that dynamically varies the energy used in directional transmission to increase the battery life of the transmitter without sacrificing connectivity with the receiver. The advantage of DDPC is that it takes into account the remaining battery power of a node before changing its transmission power. DDPC can achieve a higher network lifetime when compared to a network where nodes use a fixed transmit power level. Meanwhile DDPC dynamically

reduces the energy consumed by a node in transmission. It can also reach nodes far from the transmitter by using directional antennas.

Table of Contents

Abstract iii

Table of Contents v

List of Tables vii

List of Figures viii

List of Abbreviations xii

Acknowledgement xiv

Dedication xv

1 Introduction 1

1.1 Contributions and Organization of the Thesis 5

2 Background 6

2.1 Overview 6

2.2 Mobile Ad Hoc Networking 6

2.3 Omnidirectional Antennas 9

2.4 The IEEE 802.11 Protocol 10

2.4.1 The IEEE 802.11 PHY layer 11

2.4.2 The IEEE 802.11 MAC Layer 11

2.4.2.1 Problems in Wireless Ad hoc Networks 13

2.5 A Wireless Ad hoc Network using the 802.11 MAC Protocol 16

2.6 Directional Antennas in Ad hoc Networking 18

2.6.1 Advantages of Directional Antennas 22

2.6.1.1 Increased Spatial Reuse 23

2.6.1.2 Increased Transmission Range and Energy Savings . . . 23

2.6.2 Disadvantages of Directional Antennas 24

2.6.2.1 Deafness 25

2.7 Energy Efficiency in Mobile Ad hoc Networks 25

3 Review of Previous Work **28**

4 The Proposed Protocol **34**

4.1 Dynamic Directional Power Control (DDPC) Protocol 34

4.2 Impact of Directional Antennas on Transmission and Reception 35

4.3 Problem Formulation 37

4.4 Design and implementation of DDPC 40

4.5 Simulation Environment 48

4.5.1 Metrics 49

4.6 Performance Evaluation 52

4.6.1 Varying B_{init} and α in DDPC Approach $\#1$ 52

4.6.2 Finding an Efficient α with the DDPC Approaches 53

4.6.3 Static Scenarios: Single Transmissions 55

4.6.4 Static Scenarios: Simultaneous Transmissions 59

4.6.5 DDPC Performance with Mobility 62

5 Conclusions and Future Work **97**

5.1 Conclusions 97

5.2 Future Work 99

Bibliography **102**

List of Tables

Table 4.1 Simulation Parameters 51
Table 4.2 Static scenario performance with two flows using a Dtx-Drx (90 ° beamwidth antennas) communication link with a separation distance of 250m. 61
Table 4.3 Static scenario performance with two flows using a Dtx-Drx (90 ° beamwidth antennas) communication link with a separation distance of 600m. 62

List of Figures

Figure 1.1 Inefficiency of the four handshake process in nodes using omnidirectional antennas [12]. 3

Figure 2.1 An example of a mobile ad hoc network. 7

Figure 2.2 Ad hoc network classification. 8

Figure 2.3 The radiation pattern of a node using an omnidirectional antenna. . . 9

Figure 2.4 Interframe spacing relationships in IEEE 802.11. 13

Figure 2.5 The "hidden node" problem. 14

Figure 2.6 The "exposed node" problem. 15

Figure 2.7 RTS/CTS process. 15

Figure 2.8 NAV in virtual carrier sensing. 16

Figure 2.9 MAC protocol with an omnidirectional RTS/CTS mechanism. 17

Figure 2.10 The radiation pattern of a node using a directional antenna with a single main lobe [17]. 19

Figure 2.11 The radiation pattern of a node using 4 directional antennas [17]. . . 20

Figure 2.12 Four nodes transmitting simultaneously in the same neighborhood using directional antennas. 22

Figure 2.13 Spatial reuse with omnidirectional and directional antennas [34]. . . 23

Figure 2.14 Range with omnidirectonal and directional antennas [34]. 24

Figure 2.15 An example to illustrate the deafness problem [17]. 25

Figure 2.16 An example of spatial reuse with power control: (a) without power control and (b) with power control [17]. 27

Figure 3.1 Antenna power performance using omnidirectional antennas on IEEE 802.11 and P-CON with [$\alpha = 0.4$ and $\alpha = 0.7$]. 32
Figure 3.2 Throughput using omnidirectional antennas on IEEE 802.11 and P-CON with ($\alpha = 0.4$ and $\alpha = 0.7$). 33

Figure 4.1 Dtx-Orx communication between two nodes. 36
Figure 4.2 Dtx-Drx communication between two nodes. 36
Figure 4.3 A comparison between Dtx-Orx communication and Dtx-Drx communication. 38
Figure 4.4 Efficient and inefficient transmission ranges of a node when using a directional antenna. 39
Figure 4.5 Efficient transmission range when a node uses a directional antenna with power control. 40
Figure 4.6 The Dynamic Directional Power Control (DDPC) algorithm layer implementation with the IEEE 802.11 structure. 42
Figure 4.7 Functional flow diagram of the Dynamic Directional Power Control (DDPC) algorithm. 44
Figure 4.8 The impact of positive α on the transmitted power of a node. 45
Figure 4.9 The impact of negative α on the transmitted power of a node. 46
Figure 4.10 The transmit power variation under different power control mechanisms: a) P-CON, b) DDPC Approach $\#1$, c) DDPC Approach $\#2$, d) DDPC Approach $\#3$. 48
Figure 4.11 Transmit power with DDPC Approach $\#1$ using $\alpha = 20$ and different battery capacities (10J, 25J, 50J, 100J and 200J) at the source node. . . 64
Figure 4.12 Transmit power with DDPC Approach $\#1$ using a constant battery capacity of 100 Joules and various α at the source node. 65
Figure 4.13 Consumed energy for different values of α with DDPC Approach $\#1$. 66
Figure 4.14 Throughput for different values of α with DDPC Approach $\#1$. . . . 67

Figure 4.15 Consumed energy for different values of α with DDPC Approach $\#2$. 68

Figure 4.16 Throughput for different values of α with DDPC Approach $\#2$. . . . 69

Figure 4.17 Consumed energy for different values of α with DDPC Approach $\#3$. 70

Figure 4.18 Throughput for different values of α with DDPC Approach $\#3$. . . . 71

Figure 4.19 Energy consumption with a Dtx-Orx communication link and a 90° (4 beams), directional antenna at a distance of 250m. 72

Figure 4.20 Energy consumption with a Dtx-Drx communication link and a 90° (4 beams), directional antenna at a distance of 250m. 73

Figure 4.21 Throughput with a Dtx-Orx communication link and a 90° (4 beams), directional antenna at a distance of 250m. 74

Figure 4.22 Throughput with a Dtx-Drx communication link and a 90° (4 beams), directional antenna at a distance of 250m. 75

Figure 4.23 Energy consumption with a Dtx-Orx communication link and a 90° (4 beams), directional antenna at a distance of 600m. 76

Figure 4.24 Energy consumption with a Dtx-Drx communication link and a 90° (4 beams), directional antenna at a distance of 600m. 77

Figure 4.25 Throughput with a Dtx-Orx communication link and a 90° (4 beams), directional antenna at a distance of 600m. 78

Figure 4.26 Throughput with a Dtx-Drx communication link and a 90° (4 beams), directional antenna at a distance of 600m. 79

Figure 4.27 Energy consumption with a Dtx-Orx communication link and a 60° (6 beams), directional antenna at a distance of 250m. 80

Figure 4.28 Energy consumption with a Dtx-Drx communication link and a 60° (6 beams), directional antenna at a distance of 250m. 81

Figure 4.29 Throughput with Dtx-Orx and Dtx-Drx communication links and a 60° (6 beams), directional antenna at a distance of 250m. 82

Figure 4.30 Energy consumption with a Dtx-Orx communication link and a 60° (6 beams), directional antenna at a distance of 600m. 83

Figure 4.31 Energy consumption with a Dtx-Drx communication link and a 60 ° (6 beams), directional antenna at a distance of 600m. 84
Figure 4.32 Throughput with a Dtx-Orx communication link and a 60 ° (6 beams), directional antenna at a distance of 600m. 85
Figure 4.33 Throughput with a Dtx-Drx communication link and a 60 ° (6 beams), directional antenna at a distance of 600m. 86
Figure 4.34 Energy consumption with a Dtx-Drx communication link (flow 1) and a 90 ° (4 beams), directional antenna at a distance of 250m. 87
Figure 4.35 Energy consumption with a Dtx-Drx communication link (flow 2) and a 90 ° (4 beams), directional antenna at a distance of 250m. 88
Figure 4.36 Throughput with a Dtx-Drx communication link (flow 1) and a 90 ° (4 beams), directional antenna at a distance of 250m. 89
Figure 4.37 Throughput with a Dtx-Drx communication link (flow 2) and a 90 ° (4 beams), directional antenna at a distance of 250m. 90
Figure 4.38 Energy consumption with a Dtx-Drx communication link (flow 1) and a 90 ° (4 beams), directional antenna at a distance of 600m. 91
Figure 4.39 Energy consumption with a Dtx-Drx communication link (flow 2) and a 90 ° (4 beams), directional antenna at a distance of 600m. 92
Figure 4.40 Throughput with a Dtx-Drx communication link (flow 1) and a 90 ° (4 beams), directional antenna at a distance of 600m. 93
Figure 4.41 Throughput with a Dtx-Drx communication link (flow 2) and a 90 ° (4 beams), directional antenna at a distance of 600m. 94
Figure 4.42 Energy efficiency of two nodes in motion with speeds 1m/s, 2m/s, 5m/s, 10m/s, 20m/s, and 50 m/s. 95
Figure 4.43 Packet delivery ratio of two nodes in motion with speeds 1m/s, 2m/s, 5m/s, 10m/s, 20m/s, and 50 m/s. 96

List of Abbreviations

ACK	Acknowledgment
AODV	Ad hoc On-Demand Distance Vector
AP	Access Point
CBR	Constant Bit Rate
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
DCF	Distributed Coordination Function
DDPC	Dynamic Directional Power Control Protocol
DIFS	Distributed Inter-Frame Space
DMAC	Directional Medium Access Control
EIFS	Extended Inter-Frame Space
ESS	Extended Service Set
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
NAV	Network Allocation Vector
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
NS-2	Network Simulator-2
PCON	Power Control Protocol
PHY	Physical Layer
PS	Power Save

RF	Radio Frequency
RREP	Route Reply
RREQ	Route Request
RTS	Request to Send
SA	Source Address
SIFS	Short Inter-Frame Space
SYNC	Synchronize
UDP	User Datagram Protocol
Wi-Fi	Wireless Fidelity
B_{init}	Initial Battery Power
B_{rem}	Remaining Battery Power
$CurrTx$	Current Transmission
D-tx	Directonal Transmission
D-rx	Directional Reception
$MaxTx$	The Maximum (Initial) Transmission
$MinTx$	The Minimum Transmission
O-tx	Omnidirectional Transmission
O-rx	Omnidirectional Reception

Acknowledgement

I want to start by thanking God who is the source of my strength to accomplish my goals.

This thesis would not have been possible unless the support and guidance of my supervisor, Dr. Aaron Gulliver. His experience and genius conveyed my research to have a mixture of logic, innovation and passion.

I would like to thank my examination committee members, Dr. Sima and Dr. Coady, whose revision and examination of my research helped me to refine my thesis. I also thank Vicky Smith, for her kind assistance.

It is a pleasure to acknowledge to some of my friends and colleagues who have been there to offer their help in key moments, T.J. Umar, Yihai Zhang, Khalid Almuzaini, Amer Abdel and Abolfazl Ghassemi. In particular, I am thankful to Yousry Abdel Hamid whose friendship and support enlightened the path to knowledge. In addition, I thank my good friend Behzad Bahr, whose enthusiasm and friendship filled my dull days of joy.

I would like to show my respect and gratefulness to Jeremy Kominar for providing me with the needed time to complete crucial parts of my thesis. His kind understanding allowed me to honor my duties and defend my thesis as scheduled. It is fair to mention Lee Manchur for his interest in my research. I also want to mention the PKI Team, who bravely defended the fortress in my absence.

I owe my deepest gratitude to my parents, Maria Del Socorro Perez (Soco) and Eduardo Fernando Quiroz, who have provided much moral and material support during the long years of my education. Their sacrifice, patience and faith in me were the fuel for my mind and soul. I would like to mention also my siblings Fernando, Maria Guadalupe and Carmen Quiroz, who were an invisible presence during the composition of these pages.

A very special thank you to Yu Zhang, my muse, for accompanying me during the hard moments of my graduate student life. Her support, patience, encouragement, care and love made me a better man in many ways and motivated me to achieve this goal.

Dedication

Dedicated to my mother, Soco. She is my own ”soul out of my soul”. Without her lifting me up when this thesis seemed interminable, I doubt it would ever have been completed...

Chapter 1

Introduction

Wireless technology, has brought great achievements and advancements, but it has also created new problems that have to be solved. Even though wireless communications technologies are widespread and used around the world, traditional ways of networking in wireless environments may be inadequate to meet new challenges. Providing long transmission ranges in wireless connections without losing connectivity is an important issue. A desirable goal is to maintain connections for longer times. These and other challenges have to be addressed.

Wireless networks such as the IEEE 802.11 Wireless Ethernet [37] offer two distinct advantages over wired networks, mobility and flexibility. For instance, by using Wi-Fi hotspots, mobile devices such as laptops and WiFi phones can access the Internet in coffee shops, malls, universities, airports and other public gathering spots. Wireless Access Points (WAPs or APs) are connected, on one side, to a wired network and, on the other side, to wireless devices allowing communication between them. Because APs are connected to a wired network, wireless nodes can relay data from a wireless node to a wired node. Wi-Fi hotspots are APs which provide either commercial or public access to the Internet. Wireless networks are flexible since they do not require additional infrastructure to add and connect new mobile users. Whether one user or several users want to be connected, the infrastructure side of a wireless network is the same. It is just a matter of authorizing the new user or users to have access to the wireless network.

If an AP is not available, a mobile ad hoc network can be employed. Mobile ad hoc networks, or MANETs [19] are wireless networks where mobile neighbors within the network function as routers, finding a route to the destination node. In other words, mobile nodes themselves provide the extension and connectivity of the ad hoc network. Ad hoc networks can be used for rescue operations, vehicular networks, disaster recovery operations, and many other applications.

There is a complexity of tasks in communication between two mobile devices, therefore, it is necessary to divide such tasks into a series of stages or layers. There are five layers in a hierarchical order that define the process of end-to-end communication between two mobile users, these are: the physical (PHY) layer, the Medium Access Control (MAC) layer, the network or routing layer, the transport layer and the application layer.

The antenna and wireless medium form the physical layer (PHY). The MAC layer senses the wireless channel (medium used to transmit information) using the CSMA/CA, *Carrier Sense Multiple Access with Collision Avoidance*, procedure. CS (Carrier Sense) for ad hoc networks is performed through virtual mechanisms. Virtual Carrier Sensing mechanisms consist of overhearing control signals (RTS and CTS), which contain the duration of time of the current data packet and corresponding ACK packet [35]. If the channel is idle, the sender sends a RTS (Request To Send) packet to the destination node. Then, the destination sends a CTS (Clear To Send) packet back to the sender. This process is required to reserve the wireless channel between the sender and receiver. Then, the transmitter sends data packets to the destination, the destination checks the received information for corruption and answers the receiver with an ACK (Acknowledgment) packet. The four-handshake process is then completed. The routing layer finds a route from the sender to the destination. This route is used by the destination to acknowledge the data sent by the transmitter. The transport layer and application layer have functionality similar to those in wired networks [21] [37].

Wireless devices commonly use omnidirectional antennas [21]. Omnidirectional antennas radiate signals in all directions resulting in a circular transmission/reception pattern. The signal is received by all nodes within its range. Since the sender intends to send infor-

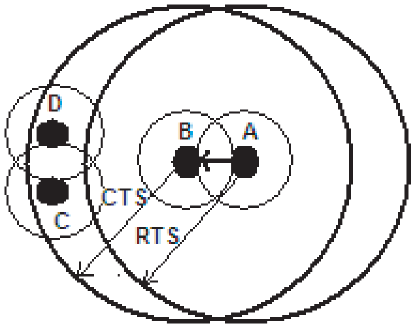


Figure 1.1. *Inefficiency of the four handshake process in nodes using omnidirectional antennas [12].*

mation to just a specific receiver, it is not necessary for all neighboring nodes to receive the signal. As a consequence, the wireless channel is not efficiently used and the receiver gets only a small part of the energy. Figure 1.1 illustrates the inefficiency of omnidirectional antennas in ad hoc networks. Node A uses its maximum transmission power to send the RTS control packet to B. Then, node B replies with a CTS control packet, at this point B is reserving a circular area around it, which may affect subsequent communication between nodes C and D. Both communications, between A-B and C-D, can take place at the same time if the nodes can control their transmission powers appropriately. Another problem in Figure 1.1 occurs when sender A is transmitting with its full power, and receiver B is very close to it. This situation causes two drawbacks with omnidirectional antennas; one, node A wastes energy in communicating with B; two, this waste of energy shortens the lifetime of the communication between A and B.

One solution is to use a type of antenna able to focus its energy towards the receiver to allow other nodes, around the area, to establish their communications. Such antennas are called Directional Antennas.

Some of the benefits of utilizing directional antennas are:

1) Higher gain which provides a longer communication range. This also improves routing performance (for route discovery or for data delivery) [3].

2) Greater spatial reuse which improves the ad hoc network capacity [13].

3) Reduction of interference [3].

With directional antennas, a transmitter can concentrate most of its power towards the destination, hence, it is able to reach the destination even if the destination is relatively far from the sender. However, if the receiver is close to the sender, energy from the transmitter is wasted. Therefore, the transmission power needs to be controlled so that it is sufficient to reach the destination without causing too much interference to neighboring nodes. By controlling the power level from the transmitter, it is possible to increase battery life [5], which will increase the lifetime of the network [6].

According to [7], controlling the power at the transmitter is very complex since the variation of power affects many stages of the network. For instance, the power level at the transmitter impacts the received signal at the destination node. Changing the transmission power of the directional antenna will determine the range of transmission. Changing the antenna power also changes the interference to other users. Power control affects the physical, network and transport layers of a wireless network. Connectivity of the network is also affected by varying the transmission power, thus, the delivery of packets to the destination is affected as well. An inappropriate choice of power level at the transmitter affects the throughput of the network. The number of hops to reach a destination can vary drastically when the transmit power level is changed at a node. Finally, energy consumption at the transmitter is affected by the transmit power used. Therefore, to achieve the benefits of directional antennas with intelligent power control, it is necessary to design a protocol to dynamically regulate the transmission power of a node equipped with directional antennas.

This thesis will present the design and implementation of an efficient and dynamic power control protocol, Dynamic Directional Power Control (DDPC), using directional antennas in mobile ad hoc networks. Performance results are presented to show the benefits of using DDPC. This protocol allows a longer transmission range while saving battery life and causing less interference to other nodes than omnidirectional antennas.

1.1 Contributions and Organization of the Thesis

This thesis is organized as follows:

CHAPTER 2: Chapter 2 presents an overview of Mobile Ad hoc NETworks (MANET). Then, the omnidirectional antenna model is described and a summary of the IEEE 802.11 protocol is given with a particular attention to the MAC layer. The characteristics, advantages and disadvantages of directional antennas in ad hoc networks are also discussed. Finally this chapter introduces "energy efficiency" in ad hoc networks and identifies the effects of varying the transmit power level at the transmitter in ad hoc networks.

CHAPTER 3: Chapter 3 discusses related work on transmit power control protocols to increase the lifetime of ad hoc networks. In particular, this chapter briefly describes the Residual Battery Power Based Power Control (P-CON) protocol. We present a comparison between P-CON and IEEE 802.11.

CHAPTER 4: Chapter 4 addresses the problem of energy efficiency in transmission using directional antennas. Then the Dynamic Directional Power Control (DDPC) protocol is proposed. Emphasis is given to the design and implementation of DDPC. Furthermore, we discuss the simulation environment and present some simulation results.

CHAPTER 5: Chapter 5 contains the conclusions and future work that can be undertaken to extend this thesis.

Chapter 2

Background

2.1 Overview

Mobile ad hoc networking is introduced in this chapter. Since omnidirectional antennas are widely used in mobile ad hoc networks, the omnidirectional antenna model is briefly described. Ad hoc networks can be implemented using IEEE 802.11 technology, which is the protocol for wireless networks. The IEEE 802.11 standard specifies both the Medium Access Control (MAC) layer and the Physical (PHY) layer. This chapter presents the IEEE 802.11 protocol with particular attention given to the MAC layer. Given the focus of this thesis, directional antenna basics and features are summarized as well. The advantages of directional transmission in relation to omnidierectional transmission are identified. Finally, this background chapter examines energy efficiency in ad hoc networks.

2.2 Mobile Ad Hoc Networking

A Mobile Ad hoc NETwork (MANET) is a system of wireless mobile nodes that dynamically self-organize in arbitrary and/or temporary network topologies [21]. Therefore, we could say that ad hoc networks are “infrastructureless” networks without a centralized entity or Access Point (AP). This means that the wireless nodes do not require all traffic to be routed through an AP, instead wireless nodes can communicate directly with each other in an ad hoc network [37]. Wireless nodes are connected by relatively low-bandwidth

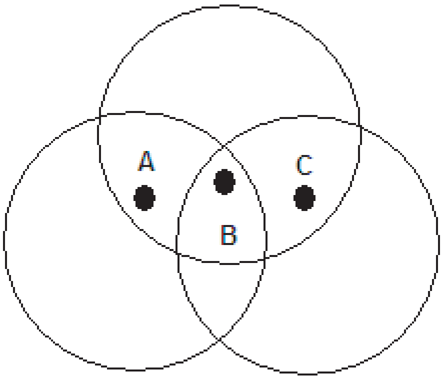


Figure 2.1. *An example of a mobile ad hoc network.*

wireless links. In order to establish communication, wireless nodes must be within communication range, typically (100-200m) [43]. The communication range between two wireless nodes is denoted as a single-hop. In larger topologies, multi-hop ad hoc networking may be required. Multi-hop networking involves the implementation of routing mechanisms at wireless nodes to forward packets beyond the transmission range [37][43].

Since wireless nodes are free to move arbitrarily, multi-hop topologies change rapidly in a MANET. If a wireless node wishes to send information to a distant host, there is a risk that not all packets will reach the intended host. To provide more reliable communication through the entire network, a source to destination path should be determined with the help of intermediate nodes [18]. In Figure 2.1, nodes A and B are within each other's transmission range, so they can communicate directly with each other. However, nodes A and C are not within each other's communication range. To establish communication between A and C, node A can first forward information to node B and then B can route the information to node C [19].

In the previous example, intermediate node B routes traffic not related to its own use to C. Therefore, a source node can send data to a distant destination through the help of one or more intermediate nodes. Initially to create a communication path, the source node needs to advertise to the neighboring nodes its willingness to communicate to a specific destination.

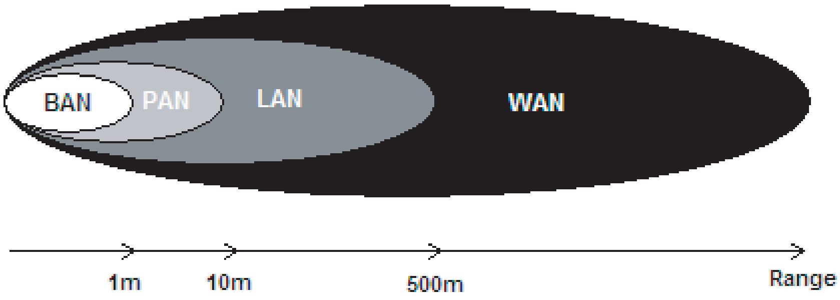


Figure 2.2. *Ad hoc network classification.*

This is important since the source node does not know exactly where the destination node is. In mobile ad hoc networks, there are three basic algorithms to find and route data to a destination. A naive approach is to simply flood the network. Every node receiving a message floods it to a list of neighbors. Flooding a network acts like a chain reaction that can result in exponential growth. A proactive approach is to precompute paths to all possible destinations and store this information in routing tables. To maintain an up-to-date database, routing information is periodically distributed throughout the network. A third approach is to create paths to other hosts on demand. This is based on a query-response mechanism or reactive multicast (the delivery of information to a group of destinations simultaneously). In the query phase, a node explores the environment. Once the query reaches the destination, the response phase starts and establishes the path [25].

Ad hoc networks can be classified depending on their coverage area as : Body (BAN), Personal (PAN), Local (LAN), or Wide Area Networks (WAN) [18]. This is illustrated in Figure 2.2. Body, personal and local networks are typically single-hop wireless ad hoc networks. They constitute the building blocks to construct small multi-hop ad hoc networks that extend the range over several radio hops. Wide area ad hoc networks are mobile multi-hop wireless networks. These networks represent a challenge in addressing, routing, managing, and securing the wireless network [23].

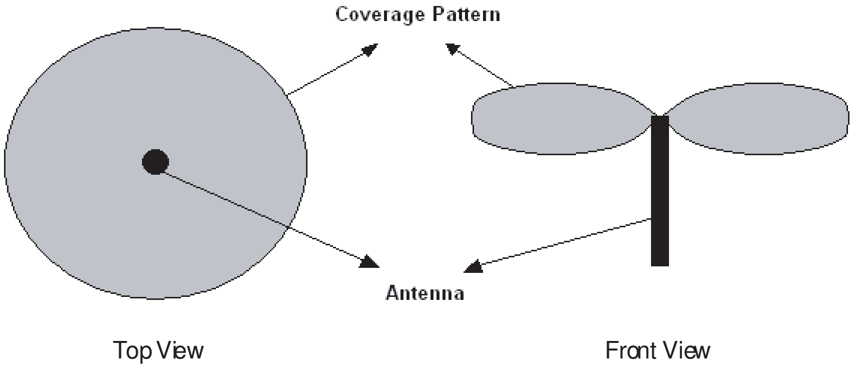


Figure 2.3. *The radiation pattern of a node using an omnidirectional antenna.*

2.3 Omnidirectional Antennas

There are many types of antennas and they can be classified depending on their use [33]. In the case of wireless networks, there are two important types of antennas: omnidirectional and directional antennas (discussed in Section 2.6). According to [19], omnidirecional antennas are commonly used in wireless nodes in ad hoc networks. Omnidirectional antennas, also called isotropic antennas, radiate and receive uniformly in all directions. Figure 2.3 illustrates the radiation pattern of a node using an omnidirectional antenna. The antenna in Figure 2.3 is capable of transmitting and receiving 360° around the node. This particular radiation shape is called donut-shaped [33]. The gain of an omnidirectional antenna is denoted as G_0, which is the unity gain ($0dB$) isotropic antenna [32]. The term *isotropic antenna* refers to an ideal antenna which radiates equally well in all directions, it is used as a reference for specifying antenna gain.

For a given power, an omnidirectional antenna can transmit within a specific range. Therefore, we can vary the range of transmission of an omnidirectional antenna by changing its power [34].

2.4 The IEEE 802.11 Protocol

Wireless Local Area Networks are also referred to as wireless Ethernet or IEEE 802.11 networks. IEEE stands for the Institute of Electrical and Electronics Engineers. The IEEE 802 family is a series of standards for LAN technology. The IEEE 802 group covers Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wireless LANs (WLANs). The second number in IEEE 802.11, refers to the 11th working group which deals with WLANs [21].

The goal of the IEEE 802.11 standard is to offer wireless connectivity to nodes within a local area and standardize access to one or more frequencies bands [37]. IEEE 802.11 provides a Physical (PHY) layer and a Medium Access Control (MAC) layer specification for wireless devices. The PHY layer controls the details of transmission and reception. The MAC layer is a set of conventions or regulations that indicate to the system and the nodes how to access the medium and how to send data [21].

According to [43], IEEE 802.11 operates at a maximum data transmission rate of 2Mbps. One of the data transfer services supported by IEEE 802.11 is asynchronous data transfer [37]. Asynchronous data transfer is used for traffic that is relatively susceptible to time delay, where the delay in data transmission may be caused by the wireless medium congestion [35]. Ad hoc networks are suitable to asynchronous data transfer, where wireless nodes with data to transmit have an equally fair chance of accessing the wireless medium [37].

In IEEE 802.11 *carrier sense* is performed through *physical* (by air interface, PHY) and *virtual* (by overhearing control packets that contain the duration of time the medium is reserved to transmit the current data packet, MAC) mechanisms. *Physical carrier sensing* is described in the next section, Section 2.4.1, and *virtual carrier sensing* is explained in Section 2.4.2.1.

2.4.1 The IEEE 802.11 PHY layer

The Physical Layer (PHY) consist of the hardware technologies to transmit raw bits (converted to a physical signal) over the wireless medium to connect wireless nodes. The PHY layer also defines the electrical and mechanical interface to send a signal over the wireless medium [37].

In IEEE 802.11, *Physical carrier sensing* is performed in two ways. Physical carrier sensing detects the presence of other wireless nodes by analyzing all detected packets. Physical carrier sensing also detects activity in the wireless medium through the signal strength from other transmitting nodes [37]. According to [21], it is difficult (complex circuitry), and expensive to build physical carrier sensing hardware since such hardware requires complex design of transceivers (devices that have both a transmitter and receiver) capable of transmitting and receiving signals at the same time. Moreover, with hidden nodes (Section 2.4.2.1), physical carrier sensing cannot provide all the necessary information.

2.4.2 The IEEE 802.11 MAC Layer

The 802.11 MAC layer is responsible for the resolution of contention to access the wireless medium, core framing operations and error checking [37]. The MAC layer offers a fundamental access method, the Distributed Coordination Function (DCF), to support asynchronous data transfer for ad hoc networks. In other words, DCF permits interaction among wireless terminals without central control [21].

DCF provides a multiple access mechanism called *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA). CSMA/CA is used to determine if the medium is available for transmission and to reduce the probability of collisions on the channel [21]. The CSMA part refers to listening to the physical medium to detect any ongoing transmissions [43]. The CA portion refers to reducing the probability of collisions on the wireless medium by deferring transmission for a random interval when the channel is sensed busy

[37].

In CSMA/CA, when a wireless node wants to transmit a data packet, first the wireless node must sense the medium to check whether any other node is transmitting. If the medium is idle (no active transmitters) for an interval longer than the *Distributed Inter-Frame Space* (DIFS), the wireless node gets temporary possession of the wireless medium and starts transmitting data. On the other hand if the medium is busy (an active transmitter), the initial attempt to transmit is deferred until the end of the ongoing transmission [43]. Then, it starts a *contention period.* The contention period is the random period when all nodes contend for access to the wireless channel. The contention period statistically allows every node in the network equal access to the wireless medium [37]. If the wireless medium is idle after the contention period, the node can start transmitting its information. Otherwise, the node defers to transmit until the ongoing transmission stops and repeats the contention period until it gets a free channel [43].

The contention period is divided in slots of time, these can be referred to as *contention window*. Each slot length is medium dependent; for instance, higher-speed PHY layers requires shorter slot times [21]. During a contention window period, the node selects a *backoff time* (random slot). A *backoff timer* is set with the backoff time selected. Then every time the medium is sensed as idle, the backoff timer is decreased. The backoff timer stops when a transmission is detected on the medium, and reactivates when the medium is idle for more than DIFS. When the backoff timer reaches zero, the node is allowed to transmit on the wireless medium [21]. If collisions or transmission errors are detected through erroneous packets, a node must remain idle for at least an *Extended Interframe Space* (EIFS) interval before it reactivates the backoff timer [43].

To ascertain the successful reception of a data packet, it employs a positive Acknowledgment (ACK) scheme. After the destination node has successfully received a data packet, it will return an ACK packet to the transmitter after a time interval called the *Short Inter-Frame Space* (SIFS). In order to give priority to the receiving node over other nodes wanting to transmit, SIFS is shorter than DIFS. If the receiver has not received any packet or received a packet with errors, the receiver will NOT respond (there is no NACK). If the ACK is not received by the source node, the sender node will retry to transmit the packet (since the data packet is assumed to have been lost), until either a successful reception of ACK or the operation is stopped due to an excessive number of retries [43].

Interframe spacing, illustrated in Figure 2.4, helps in coordinating access to the wireless medium. Different interframe spacing indicates priority levels for different types of traffic. Once the SIFS has elapsed, the high-priority packets (RTS, CTS and ACK), are transmitted. When high-priority transmissions begin, the medium becomes busy. The DCF Interframe Space (DIFS) is used for contention-based services. If the medium has been unoccupied after a period longer than the DIFS, a node may start transmitting packets [18].

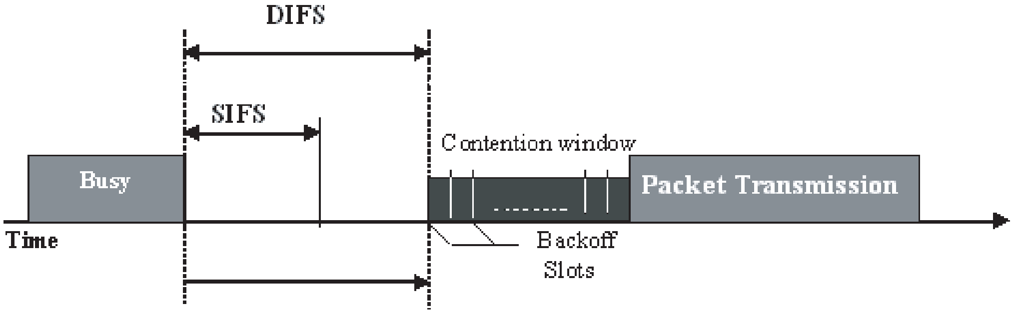


Figure 2.4. *Interframe spacing relationships in IEEE 802.11.*

2.4.2.1 Problems in Wireless Ad hoc Networks

Mobile ad hoc networks that rely upon the IEEE 802.11 CSMA/CA scheme experience complex phenomena caused by the wireless medium characteristics, such as the *hidden node* and the *exposed node* problems.

Figure 2.5 presents the *hidden node* problem. Node B is in the transmission range of A and C, however A and C cannot hear each other. In this scenario, A is transmitting to B. If C wants to transmit to B, C will sense that the medium as free since it is not able to hear the transmission of A. As a consequence, C will start transmitting packets but this transmission will result in collision at the destination node B.

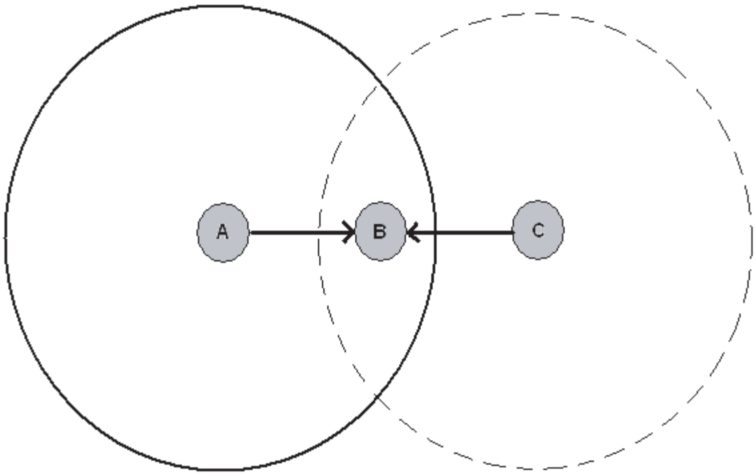


Figure 2.5. *The “hidden node” problem.*

Figure 2.6 shows the *exposed node* problem. Nodes A and C can hear the transmission of node B, but A cannot hear transmissions from C. B is transmitting packets to A. Node C wishes to transmit data packets to D. However, C senses the medium as busy because of the transmission of B. As a result, node C abstains from transmitting to D even though this transmission would not cause collision at A. The *exposed node* problem reduces throughput [43].

The *hidden node* problem can be alleviated by implementing *virtual carrier sensing* mechanisms based on two *control signals* to clear out an area. Such control packets are, *Request To Send* (RTS) and *Clear To Send* (CTS). Before transmitting a data packet, the source node sends an RTS control packet to the destination. By sending an RTS packet, the source announces the upcoming packet transmission. After the destination receives the RTS packet, it replies with a CTS packet to indicate that it is ready to receive data packets from the source node [43]. Figure 2.7 illustrates the RTS/CTS process.

The total duration of the transmission is contained in the RTS and CTS packets, thus the information can be read by any node within the transmission range of the source or destination. Such nodes within the transmission range use the information from the RTS and CTS packets to set up a timer called *Network Allocation Vector* (NAV). The NAV is a

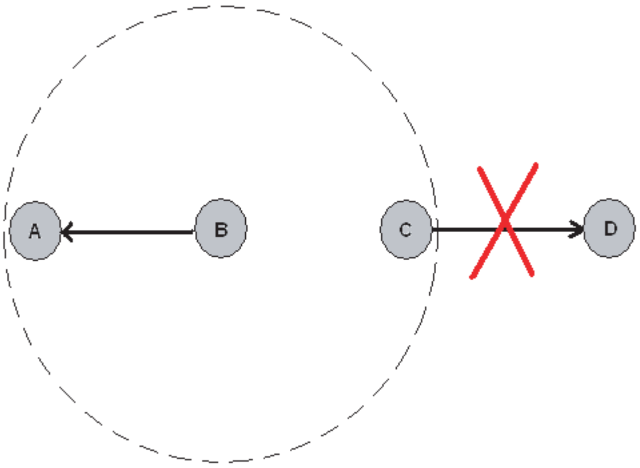


Figure 2.6. *The “exposed node” problem.*

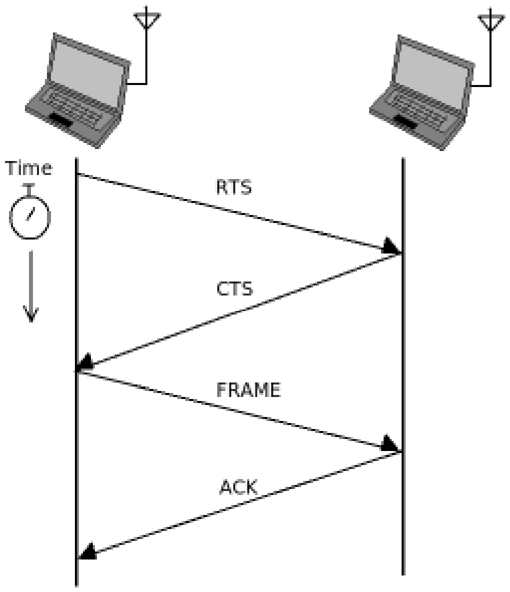


Figure 2.7. *RTS/CTS process.*

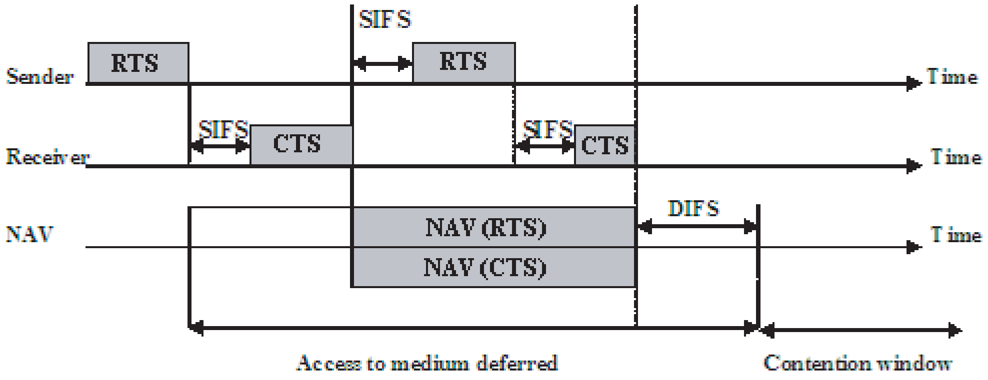


Figure 2.8. *NAV in virtual carrier sensing.*

timer that tells the MAC the amount of time the wireless medium will be reserved. This is the necessary time to transmit all the required packets to complete the transmission. Nodes count down from the NAV to 0. A number different from 0 means that the medium is busy. Once the NAV reaches 0, the medium is idle. The NAV is transmitted in the packet headers on the RTS and CTS packets. By using the RTS/CTS scheme, wireless nodes can be aware of transmissions from hidden nodes and how long the medium will be occupied for transmission [21]. Figure 2.8 shows NAV on a time line.

2.5 A Wireless Ad hoc Network using the 802.11 MAC Protocol

A network model using MAC protocol with an omnidirectional RTS/CTS mechanism is considered.

The following assumptions are made:

1) All hosts in a region share a wireless channel and communicate on that shared channel.

2) Each host is assumed to be equipped with an omnidirectional antenna.

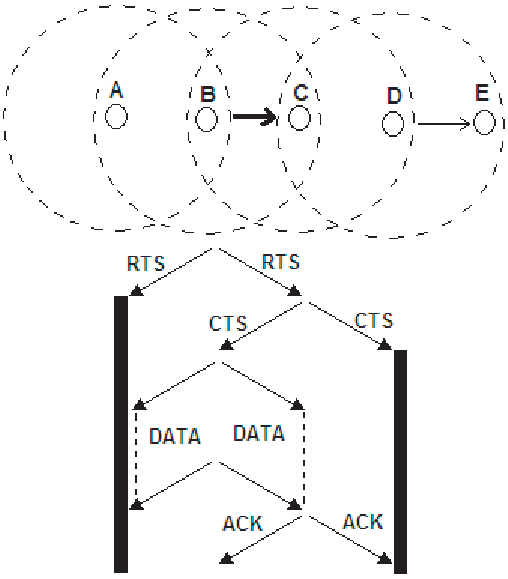


Figure 2.9. *MAC protocol with an omnidirectional RTS/CTS mechanism.*

3) Simultaneous transmissions by the same node in different directions are not allowed.

4) Each host has a fixed transmission range and two hosts are said to be neighbors if they can communicate with each other over a wireless link. Each node knows the location of its neighbors as well as its own location.

5) Any node that wishes to transmit data must send an RTS packet before it can start data transmission.

Figure 2.9 shows the IEEE 802.11 MAC protocol for omnidirectional antennas using RTS and CTS control messages [15]. In Figure 2.9, the circle centered at each node shows the transmission range of the node. In the lower half of the figure, time progresses from top to bottom. The figure shows messages sent by various nodes. Black bars indicate that these nodes are not allowed to transmit in the duration covered by the bars (to avoid interference with the transfer from B to C).

In this example, node B transmits an RTS packet for its intended receiver, node C. If C receives the RTS successfully, it replies with a CTS packet so that B can start transmitting a data packet upon receiving the CTS. After receiving the data packet from B, C sends an

ACK to B. All nodes within radio range of B and C will hear one or both of these control packets. In this case, nodes A and D must wait for the data transmission to end before they can transmit. Therefore, the area covered by the transmission range of both B and C is reserved for the data transfer from B to C, to prevent collisions. Thus, the RTS/CTS mechanism overcomes the *hidden node* problem. However, this mechanism consumes a large portion of the network capacity by reserving the wireless medium over a large area. For instance, even though node D has data packets for node E while B and C are communicating with each other, node D has to defer the transmission to E until the transmission from node B to C is completed [21].

It is clear that the use of omnidirectional antennas with the IEEE 802.11 protocol limits spatial reuse of the wireless channel by silencing all nodes in the vicinity of the transmitter and receiver. On the contrary with directional antennas, two pairs of nodes located in each other's vicinity can establish communications simultaneously if their directional transmissions are directed properly [15]. The following section will describe the advantages of using directional antennas in ad hoc networks.

2.6 Directional Antennas in Ad hoc Networking

In ad hoc networking, omnidirectional antennas are typically assumed for all nodes. However, there is a major drawback in using omnidirectional antennas, the fact that communication between two nodes requires all other nodes in the vicinity to stay silent. In addition, the lower antenna gain with omnidirectional antennas increases the number of hops a sender needs to reach a far away destination. It is possible to solve the above issues by using directional antennas [16].

When a wireless node uses a directional antenna either for transmission or reception, all its packets are transmitted/received in a specific direction. This is because a directional antenna concentrates the transmitted/received power in that direction. Therefore, instead of spreading the signal power uniformaly as with omnidirectional antennas, directional

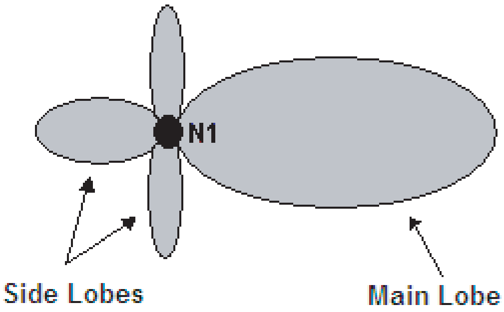


Figure 2.10. *The radiation pattern of a node using a directional antenna with a single main lobe [17].*

antennas spread most of the signal power in its main lobe, and the rest of the power in its side lobes. In Figure 2.10, a high gain main lobe is aimed in the direction of the target and the low gain side lobes are in other directions [17]. These side lobes represent lost energy. Hence, a good antenna design should minimize the energy in these lobes [17].

A node equipped with N directional antennas can have N beam patterns. The main lobe of each beam spans an angle of $\frac{2\pi}{N}$ radians. For instance, if a wireless node has four directional antennas, the conical radiation pattern of one of its beams will span an angle of $\frac{\pi}{2}$ radians ($90\,^{\circ}$). This angle is referred to as beamwidth (in degrees). The beamwidth of the antenna is a measure of its directivity [17]. Figure 2.11 illustrates a node with 4 directional antennas, each antenna beam has a beamwidth of $90\,^{\circ}$.

In wireless networks, a node using directional antennas can select only one of its beams with a main lobe gain of G_d. The gain of the antenna is inversely proportional to the beamwidth, the narrower the beamwidth the higher the gain. This offers a greater transmission range, but with a reduced coverage angle. Antenna gain is given in units of dBi, dB gain with respect to an isotropic source [3]. The relationship between gains in directional and omnidirectional antennas is $G_d \geq G_o$ [3]. Based on [46], we used (2.1) to calculate the gain of the antenna.

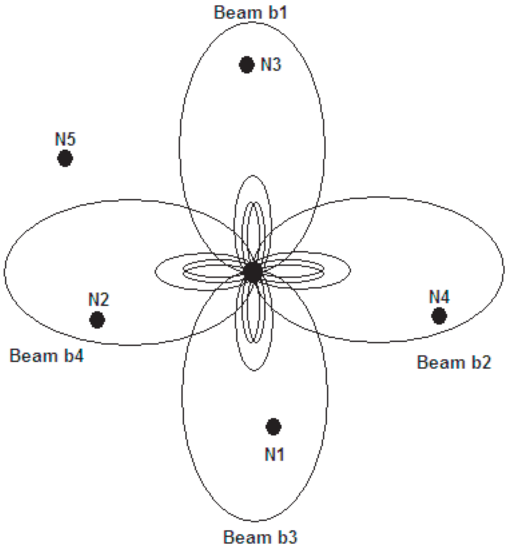


Figure 2.11. *The radiation pattern of a node using 4 directional antennas [17].*

$$G = \frac{2}{1 - cos(\frac{\pi}{180} * \frac{beamwidth}{2})} \tag{2.1}$$

For instance, to determine the omnidirectional gain, G_o, of an antenna using (2.1) we have,

$G_{0_{360^\circ}} = 0dB$

Now, if we use a directional antenna with beamwidth of 90° we get the next gain,

$G_{d_{90^\circ}} = 8.34dBi$

Narrowing the directional antenna beamwidth to 60°, we obtain the following gain,

$G_{d_{60^\circ}} = 11.74dBi$

Antennas are passive devices that do not provide any added power to the signal. Instead, antennas only redirects the power it receives from the transmitter. The receive power is given by,

$$P_R = \frac{P_T * G_T * G_R}{L_P * L_O} \tag{2.2}$$

$$L_P = (\frac{4 * \pi * d}{\lambda})^2 \tag{2.3}$$

Where P_T is the transmit power. The term L_O is an additional path loss factor to account for atmospheric absorption and ohmic losses. L_P is called free space loss, and is due to the spreading of the transmitted waves. λ is the wavelength of the transmitted signal and d is the physical distance between the transmitter and receiver [14]. By replacing L_P in (2.2) we have

$$P_R = \frac{P_T * G_T * G_R}{L_O} * (\frac{\lambda}{4 * \pi * d})^2 \geq \Omega \tag{2.4}$$

Because of path loss, the received power P_R at distance d from a node transmitting with transmit power P_T should be larger than the receiver sensitivity threshold Ω for correct reception [1]. For notational simplicity, we set $\Omega * (\frac{4 * \pi}{\lambda})^2 = 1$ and $L_O = 1$ so that the minimum required transmit power for correct reception at a distance d can be expressed as:

$$P_t = G_T^{-1} * G_R^{-1} * d^2 \tag{2.5}$$

Therefore, the effective communication distance between two nodes is proportional to the product of the transmission and reception gains. Consequently, directional antennas provide range extension. For example, if two nodes transmit and receive with omnidirectional antennas, the product $G_T * G_R$ may not be large enough for communication between them. On the other hand, if one node uses a directional antenna in the direction of the other node, which has an omnidirectional antenna, the new product $G_T * G_R$ may be large enough to allow direct communication [14]. Therefore, the type of antenna determines the maximum communication distance between two nodes.

To understand better the effects of directional antennas in wireless ad hoc networks, it is convenient to examine the advantages and disadvantages of directional antenna systems.

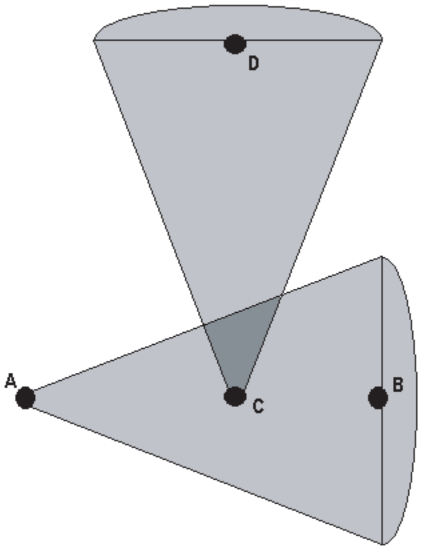


Figure 2.12. *Four nodes transmitting simultaneously in the same neighborhood using directional antennas.*

2.6.1 Advantages of Directional Antennas

Directional antennas provide many improvements over omnidirectional antennas. These are listed below:

* Directional antennas have higher spatial reuse than omnidirectional antennas.

* Since directional antennas have higher gains than omnidirectional antennas, the connectivity is higher with directional antennas.

* Because directional antennas focus power in a specific direction, interference to nodes in the vicinity is reduced (except in the direction of the receiver). Figure 2.12 shows four nodes transmitting simultaneously in the same neighborhood. Such communication is possible when directional antennas are used for transmission.

In the following subsections, these advantages are examined through examples.

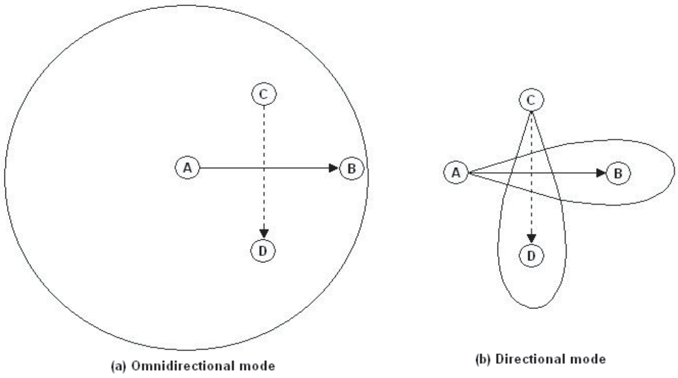


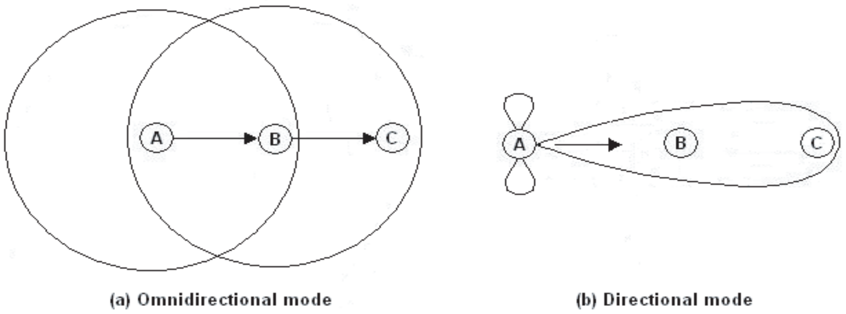
Figure 2.13. *Spatial reuse with omnidirectional and directional antennas [34].*

2.6.1.1 Increased Spatial Reuse

Figure 2.13(a) illustrates the poor spatial reuse with omnidirectional antennas. When node A attempts to communicate with node B, A reserves the medium around it with an RTS control signal. If C wants to communicate with D, the RTS signal from A will prevent C from sending data packets to D. This is because the data transfer between C and D might interfere with the communication between A and B. On the other hand, when A and C use directional antennas, the communication between C and D will not interfere with the communication between A and B. This is because A is only reserving the area that is covered by its directional antenna, a beam focused on B. The use of directional antennas allows multiple transmissions by different nodes in a limited area instead of a single transmission. Therefore Figure 2.13(b) shows an increase in spatial reuse.

2.6.1.2 Increased Transmission Range and Energy Savings

Transmissions between two nodes that are close to each other require only a single hop with omnidirectional antennas. However, when this distance exceeds the range, intermediate nodes must be used to route packets from sender to receiver. Thus, more than one hop is required to reach the destination node. This is illustrated in Figure 2.14(a). Node A wants to transmit to node C using an omnidirectional antenna. Since node C is beyond the range of



(a) Omnidirectional mode (b) Directional mode

Figure 2.14. *Range with omnidirectonal and directional antennas [34].*

A, node A needs to first send the intended packets to B, then node B forwards the packets to C. Transmission between two nodes is one hop, so in this example, transmission requires two hops A→B→C. However, with directional antennas the number of hops required to reach a destination can be less. In Figure 2.14(b), nodes A, B and C are the same distance apart, but now A is using a directional antenna. A can now reach node C in just one hop, without the routing services of B.

Figure 2.14(b) illustrates two main benefits, increased transmission range and energy saving. First, since a node with directional antennas can focus its beam in a specific direction, the directional signal can travel a larger distance than an unfocused omnidirectional signal. As a result, a sender can reach a destination farther away. At the receiver side, directional antennas can help recipient nodes listen to signals from senders further away. Second, the energy required to reach a destination at a distance d is less with a directional antenna than an omnidirectional antenna. This is true only if the power of the focused beam is directed towards the receiver [34].

2.6.2 Disadvantages of Directional Antennas

Even though directional antennas solve many issues with omnidirectional antennas, directional antennas give rise to a new problem, namely *deafness*.

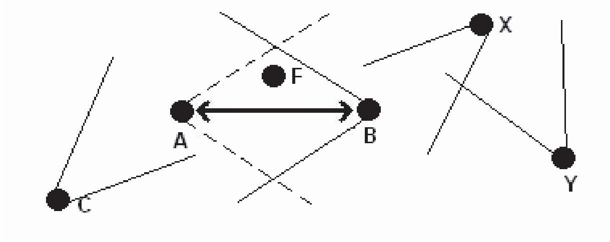


Figure 2.15. *An example to illustrate the deafness problem [17].*

2.6.2.1 Deafness

Deafness is defined as the portion of the neighborhood region from which a node cannot receive signals. *Deafness* can adversely affect protocol performance [17]. *Deafness* is explained using the scenario in Figure 2.15. Assume that C has packets to send to A. At a given time, if A is sending packets to B, C could be unaware of it (when using directional antennas), and may transmit an RTS meant for A. Since A is beamformed in the direction of B, A does not receive the RTS from C and consequently A does not respond with a CTS. Since C does not receive any response from A, C retransmits the RTS. This resending of RTSs continues until a limit of retries has been reached, wasting network capacity. This phenomenon is referred to as *deafness* since node A is “deaf” to the signals from C while it is beamformed in the direction of B [15].

An important point to consider when using directional antennas is determining the necessary transmit power to reach a destination, as this affects the energy efficiency of the network.

2.7 Energy Efficiency in Mobile Ad hoc Networks

Energy efficiency is critical to the wide deployment of wireless networks. Since wireless nodes lack a constant power supply, it is important to analyze mechanisms and protocols to optimize the use of battery power, as this can increase the network lifetime [6].

According to [22], battery capacity cannot be significantly improved. As a consequence, research should focus on designing energy-efficient software and hardware.

Research in energy efficiency can be classified into the following four fields:

(A) Sleeping mode [24]

(B) Power-aware route selection [23]

(C) Broadcast control [24]

(D) Transmission power control [12] [7] [8]

According to [25], in communications between two wireless nodes, the transmission operation consumes more energy than reception. For this reason, the focus of this thesis is energy efficiency in transmission. Energy efficiency in transmission requires power control at the transmitter. Power control involves tuning the transmission power to the proper range.

The power control issue is complex since it affects many aspects of wireless network operation [7]. For instance:

(1) The transmitted power of a wireless node determines the level of quality of the received signal at the destination.

(2) The transmitted power of an antenna determines the range of transmission.

(3) By controlling the transmit power, it is possible to control the interference to other receivers.

(4) Power control affects the MAC layer since contention depends on the number of nodes in range of the transmitter.

(5) Power control affects network connectivity.

(6) The transmitted power affects the throughput capacity of the network.

(7) The transmitted power affects the number of hops in a transmission; therefore, the end-to-end delay.

(8) The transmitted power affects the energy consumption of the sender.

(9) Adjusting the direction and level of transmission power of an antenna changes the network topology [7].

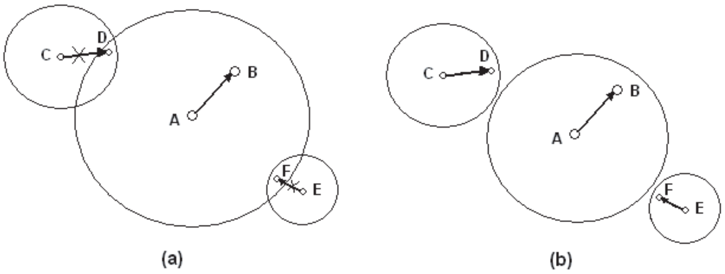


Figure 2.16. *An example of spatial reuse with power control: (a) without power control and (b) with power control [17].*

Figure 2.16 illustrates the advantage of using power control in ad hoc networks. In Figure 2.16(a), communications between nodes A→B, C→D, F→E is required simultaneously. However, communications between nodes C→D and F→E is delayed because A is using excessive transmission power. A is causing interference to nodes D and F. On the other hand in Figure 2.16(b), node A is using power control and as a result, A is not interfering with nodes D and F. All three communications, A→B, C→D and F→E can now occur simultaneously and successfully.

Chapter 3

Review of Previous Work

In [8], the authors purpose a power control MAC protocol for ad hoc networks using omnidirectional antennas. Their work is based on a granular variation of the transmit power level to save energy. The power variation at transmission occurs at the MAC layer by using different power levels for RTS-CTS, Data, and ACK. The maximum power level is used for the RTS and CTS packets. The minimum required transmit power is used for Data and ACK packets to conserve energy. This paper not only claims that its protocol saves energy but also that the protocol does not degrade throughput. The sender and receiver exchange RTS-CTS control packets with the highest power in order to reach neighbor nodes that can cause interference or collisions when the sender and receiver start communication. Then the receiver calculates the minimum necessary transmission power level for the Data packet based on the RTS received from the sender, the receiver power, and noise level at the receiver. The receiver specifies the minimum necessary transmission power in its CTS to the sender. The sender uses that information to transmit data packets. Periodically, the sender increases the power of the Data packet to prevent data collisions from nodes that become idle during its transmission. Finally, the receiver sends ACKs with the minimum power to conserve energy. The first problem with this approach is that there is an inefficiency in the spatial reuse when nodes use their highest power to transmit RTS-CTS packets. The second problem is that the energy saving is minimal since the energy saving happens only when ACK packets and Data packets are set at a low power level.

In [11], it is claimed that the optimal transmission power level in wireless ad-hoc networks depends on network conditions such as the number of nodes, the network grid area and the traffic load. This paper proposes two transmission power schemes, Common Power Control (CPC) and Independent Power Control (IPC). These power control algorithms adapt the transmission power according to the network conditions to improve network throughput. In the CPC approach, all nodes use the same transmission power. On the contrary, in the IPC approach nodes use independent transmission power. Nodes use two contention time (the time taken to successfully send a packet) thresholds to determine the optimal transmission power based on local conditions, using either CPC or IPC mode. These algorithms force the nodes to increase or decrease their transmission power when the contention time reaches the upper or lower thresholds, respectively. This approach does not take into account the residual battery power. As a consequence, nodes may run out of battery power sooner than other transmitters with a power control strategy that considers the remaining battery power.

The authors in [2] propose a power control (P-CON) protocol sensitive to the battery power. The idea is to vary the transmit power to increase network lifetime (when the first node runs out of energy), and to reduce end-to-end delay in wireless ad hoc networks. Before varying the transmission power of a node, P-CON takes into account the remaining battery power of the node. P-CON uses the residual battery power of a source as input and returns the transmission range at which the source should transmit data. The source node starts transmitting with a maximum (initial) transmission range, then the destination node selects a time interval (between 0 and *PC-time*) and invokes the P-CON algorithm periodically based on the selected time interval. When P-CON is invoked, the source node starts reducing its transmitted power gradually using a power control tuning parameter, α. If α is smaller than unity, the decreasing transmit power is less sensitive to the battery power changes of the node. If α is greater than 1, P-CON algorithm becomes over-sensitive to loss of battery power. Therefore, all nodes reduce their operating transmission range drastically. The transmitting node gradually reduces its power until it reaches a fixed *minimum transmission range*. Then, the transmitter node continues operating at this minimum until communication with the destination node is completed. The transmit power cannot go below the minimum transmission range, otherwise the probability of keeping connectivity with the destination node becomes very low. The minimum transmission range should be previously determined based on network size, number of nodes and node mobility. P-CON uses a minimum transmission range of 175m. Since P-CON gradually reduces the operating transmission range, the power control tuning parameter α should be less than unity. The authors of [2] purpose an α of 0.4 for low load traffic and 0.7 for high load traffic. The problem in P-CON is that it assumes the minimum closest distance between the source and destination is 175m. For example, consider the scenario where a source node is reducing its transmit power towards a destination located at 200m from the transmitter. The source will keep reducing its transmit power until it reaches the 175m of transmission range. As a consequence, the source node may not be able to detect the destination node at 200m (if P-CON has not yet been re-invoked). Another problem with P-CON is that it needs to know in advance network parameters such as the traffic load, the number of nodes in the network (and mobility if applicable), in order to efficiently save energy. Therefore, P-CON is not very dynamic.

The P-CON protocol assumes the use of omnidirectional antennas in ad hoc networks. Figure 3.1 shows a comparison of the *transmitted power performance* of the P-CON algorithm (using $\alpha = 0.4$ and 0.7) versus the IEEE 802.11 protocol. Figure 3.2 presents the *system throughput* comparison between P-CON (using $\alpha = 0.4$ and 0.7) and IEEE 802.11. The simulation parameters for both figures were based on those in[2]. Some important assumptions and parameters are given bellow:

1) A transmitter sends data to a destination. Both nodes use omnidirectional antennas. The sender and receiver are static. Nodes are separated by a distance of 175m.

2) The traffic model used is Constant Bit Rate(CBR) / UDP with packet sending rate of 4 packets/sec.

3) Three different cases are considered: IEEE 802.11, P-CON with $\alpha = 0.4$, and P-CON with $\alpha = 0.7$.

4) The initial battery level is 100 Joules.

5) The maximum (initial) transmission range is 0.28 Watts (250m) (the default constant transmission power for 802.11).

6) The minimum transmission range is 71.5×10^{-6} Watts (175m).

In Figure 3.1, it can be seen that P-CON outperforms IEEE 802.11 since the P-CON transmission lasts longer than the one with IEEE 802.11. P-CON reduces its transmit power smoothly until it reaches the minimum transmission range of 175m, when the sender and receiver are still connected. Figure 3.2 confirms the previous results by showing the throughput of the system. It is important to notice that P-CON with $\alpha = 0.4$ performs better than $\alpha = 0.7$ in this scenario where the traffic load is low.

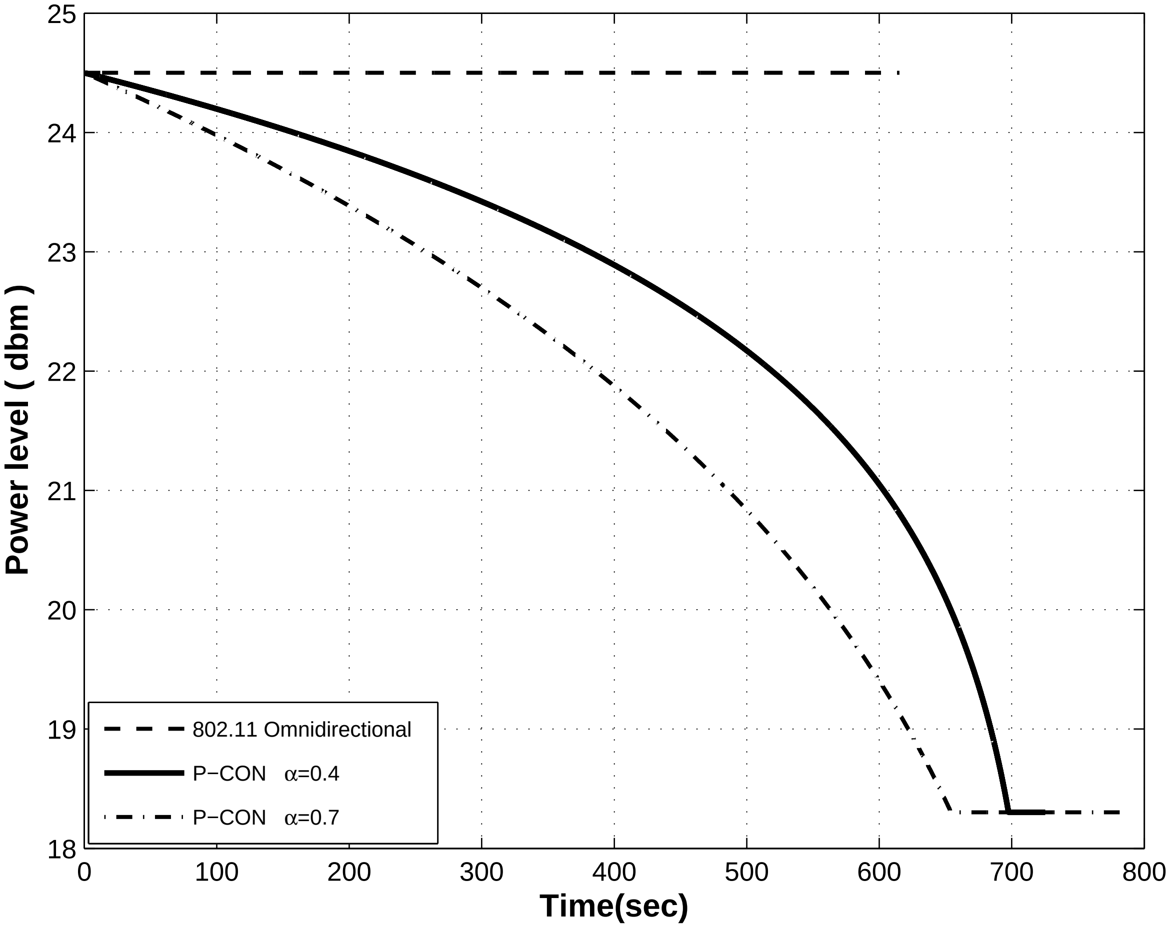


Figure 3.1. *Antenna power performance using omnidirectional antennas on IEEE 802.11 and P-CON with [*$\alpha = 0.4$ *and* $\alpha = 0.7$*].*

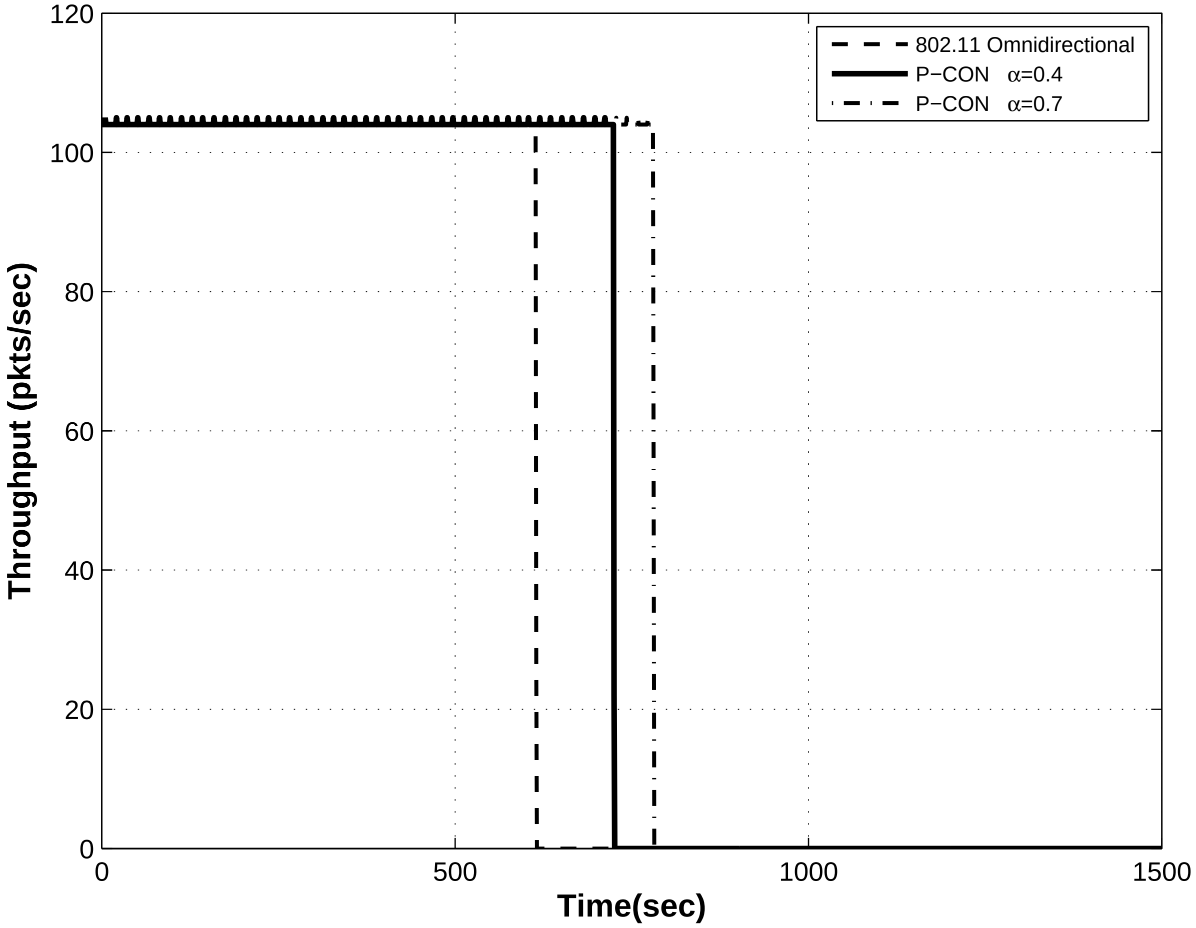


Figure 3.2. *Throughput using omnidirectional antennas on IEEE 802.11 and P-CON with ($\alpha = 0.4$ and $\alpha = 0.7$).*

Chapter 4

The Proposed Protocol

4.1 Dynamic Directional Power Control (DDPC) Protocol

In this chapter, we propose an efficient, dynamic and directional variable range transmission power control strategy called the *Dynamic Directional Power Control* (DDPC) protocol. DDPC allows transmitter nodes to increase their transmission range while saving battery life and causing less interference than with omnidirectional antennas. The power control strategy of DDPC does not require significant maintenance since the transmission power control tunning is dynamically performed to keep connectivity between source and destination nodes. The operating transmission range of a node first adjusts to the position of a receiver then if connectivity with the destination is lost, DDPC reacts in three different ways to restore connectivity while saving battery energy. The three different reactions of DDPC are according to the given circumstances if the destination node is static, if the destination node is static and in presence of interference, or if the destination node has mobility. An important characteristic of DDPC is that it takes into account the remaining battery energy before varying the transmit power of the node. DDPC is implemented with directional antennas to reach distant nodes, reduce node interference and increase the saving of battery energy.

4.2 Impact of Directional Antennas on Transmission and Reception

The use of directional communication brings two very important benefits, reduction of interference and extension of transmission range. As discussed in Section 2.6, signals are received with a gain of G_o when using omnidirectinal antenna. The directional antenna model we use is composed of N beam patterns. Each beam spans an angle of $\frac{2\pi}{N}$ radians. A node can select only one of its directional beams and beamforms with a gain of G_d to reduce interference. Due to higher gain ($G_d \geq G_o$), nodes using directional antennas have a greater range in comparison to nodes using omnidirectional antennas. This is true if we assume that both omnidirectional and directional transmissions operate at identical power levels [15].

According to [3], the distance between a transmitter and receiver in communication is proportional to the product of the transmission and reception gains. Therefore, the link-length (distance) between a directional transmitter and an omnidirectional receiver can be longer than between an omnidirectional transmitter and an omnnidirectional receiver. In this thesis, the communication established with directional transmission and omnidirectional reception is represented as *Dtx-Orx communication*. The communication where the transmission and reception are directional is denoted as *Dtx-Drx communication*. Dtx-Drx communication denotes a longer link-length than Dtx-Orx communication. Figures 4.1 and 4.2 illustrate the Dtx-Orx and Dtx-Drx transmission ranges.

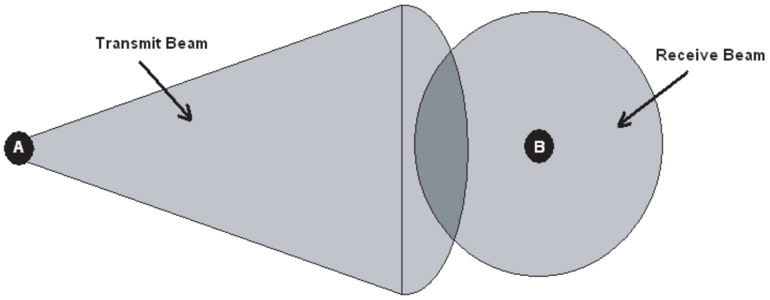


Figure 4.1. *Dtx-Orx communication between two nodes.*

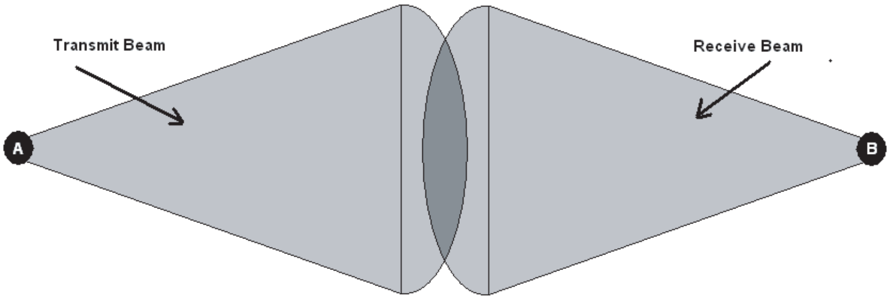


Figure 4.2. *Dtx-Drx communication between two nodes.*

Figures 4.1 and 4.2 show that the maximum distance at which two nodes can communicate depends on the type of antenna (Omnidirectional or Directional) used by the transmitter and receiver. Figure 4.3 gives a comparison of Dtx-Orx and Dtx-Drx communications between two wireless nodes using the IEEE 802.11 protocol. The sender uses a constant transmit power of $0.2818W$. The simulation in Figure 4.3 was conducted using NS-2 [45]. This figure shows the maximum separation distance where transmitter and receiver are still able to communicate versus beam width angles of the directional antennas. According to Figure 4.3, the narrower the directional beam, the longer the communication link-length. When a transmitter beamforms its signal with an angle of 90° to a receiver with an omnidirectional antenna, the link-length where both nodes can still communicate is approximately 1.2Kms. The impact of directional antennas is more obvious when the receiver beamforms as well with an angle of 90° as the maximum communication link-length is now approximately 2km.

In this thesis, the communication link-length is referred to as the *transmission range*. The transmission range of a wireless node is the range within which a transmitted packet can be received successfully [2].

4.3 Problem Formulation

Ad hoc networks offer unique challenges that distinguish them from other wireless networks. It is important to consider those challenges when new applications are designed and implemented. One of the major challenges considered in this thesis is the limitation of resources in ad hoc networks, such as battery energy. Improving battery energy use through software mechanisms or protocols is a good approach since it is harder and more complex to build batteries with better capacity to meet consumer demand for more energy.

Power use can be classified as transmission power required to send data, receive power required to receive data, and idle power when no data is being transferred. Transmission consumes most of the power because it includes the power required to drive the transmitter circuitry and the power transmitted from the antenna [11]. For this reason we consider power control mechanisms to reduce the energy consumption in transmission. This will improve node battery life, reduce interference in transmission and improve throughput [6].

A number of papers provide solutions to save energy in transmission. The authors of [8], [11], [5] and [2] propose saving energy through *transmission power control* mechanisms using omnidirectional antennas, so they cannot exploit the benefits of using directional antennas (Section 2.6). Directional antennas reduce the beam width angle to diffuse the radio transmission in one direction and therefore save energy [4]. Based on (2.5) we conclude that the larger the gain is, the smaller the required transmit power [1]. Hence, it is possible to save energy in transmission by adjusting the power from a directional antenna.

Figure 4.4 shows Dtx-Orx communication between nodes A and B. We assume node

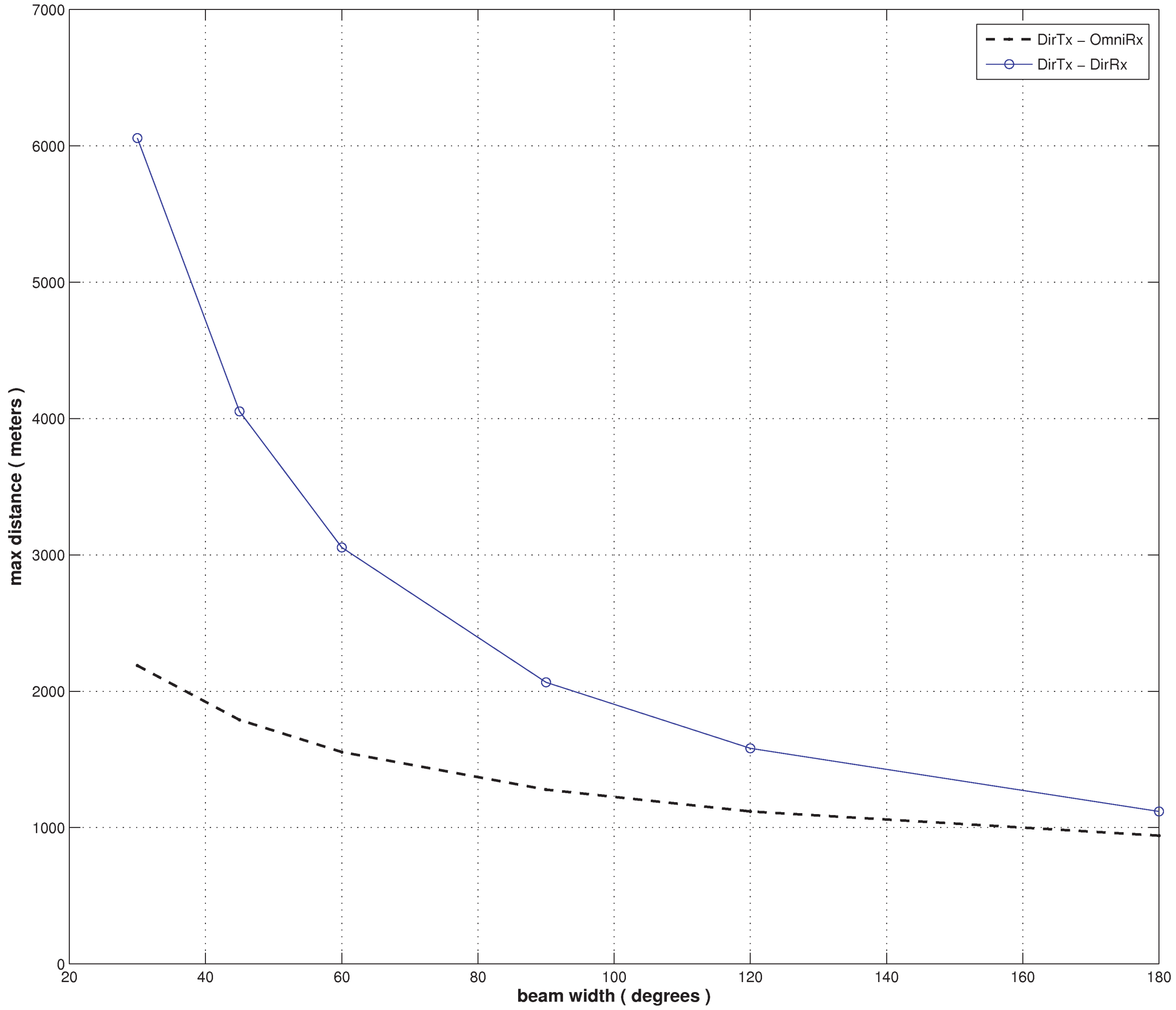


Figure 4.3. *A comparison between Dtx-Orx communication and Dtx-Drx communication.*

A beamforms towards B with a transmission range of 1.2Km (based on the analysis in Figure 4.3). We also assume that node B is located 1.0km from A. Since node A has a transmission range of 1.2Km when node B is only 1.0Km away, there is a waste of transmission range of 200m. We refer to this as *inefficient transmission range*.

By using power control mechanisms in transmission, it is possible to minimize or reduce the *inefficient transmission range*. Figure 4.5 shows the results after applying power control in transmission. In this case, node A has sufficient transmission range to keep connected with B without affecting the *throughput* (details in Section 4.5.1). The transmission range between A and B, in Figure 4.5, is referred in this thesis to as *efficient transmission range*.

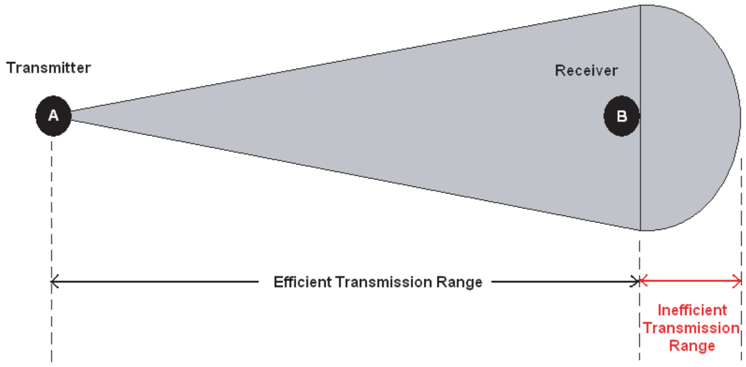


Figure 4.4. *Efficient and inefficient transmission ranges of a node when using a directional antenna.*

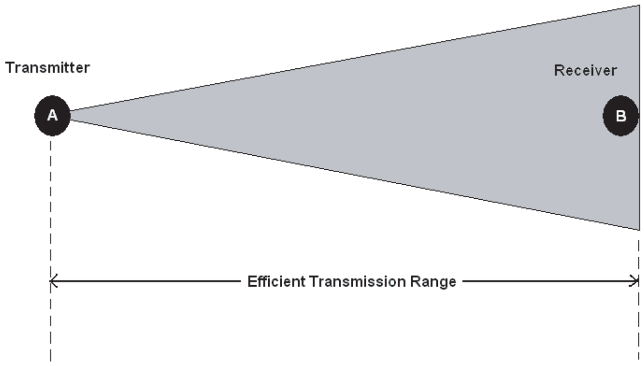


Figure 4.5. *Efficient transmission range when a node uses a directional antenna with power control.*

4.4 Design and implementation of DDPC

In this thesis, we propose a solution to control the transmit power of a node in order to vary the transmission range for energy efficiency purposes. We call this solution *Dynamic Directional Power Control* (DDPC). DDPC is only executed when a node is transmitting packets to a destination. In DDPC, we assume the use of directional antennas in transmission. DDPC has the following important characteristics:

* It dynamically controls the power during transmission.
* It provides long transmission ranges, so distant nodes can be reached with fewer hops.
* It reduces interference, allowing multiple simultaneous transmissions in the same neighborhood.
* It maintains connectivity between the transmitter and receiver during transmission.
* It takes into account the remaining battery energy before transmission.
* Three variations of the algorithm have been developed to save transmission power according to the network conditions.

DDPC shares some characteristics of the P-CON protocol [2] (discussed in Chapter 3).

However, DDPC improves certain aspects of the P-CON mechanism. Moreover, DDPC contains new features to make the power control more dynamic and efficient than the P-CON algorithm.

Figure 4.6 shows a block diagram of the DDPC algorithm in the IEEE 802.11 structure and its relationship with the MAC and PHY layers. In order to vary the transmission range through DDPC, it is necessary to change the transmission power at the PHY layer. Since the physical layer determines the transmit power, DDPC is implemented at the PHY layer.

DDPC borrows and extends the functionality of the *power control tuning parameter*, α, from P-CON. In P-CON, α determines the sensitivity of the power control strategy to changes in the residual battery energy at a node [2]. In DDPC, α determines not only the sensitivity of the power control mechanism based on the residual battery energy but also the power control direction (whether the transmit power should be increased or reduced at the antenna).

In order to keep an efficient transmission range, DDPC increases/reduces the node transmit power accordingly. Therefore, DDPC must know when the transmitter node loses connectivity with the receiver node during transmission. When a transmitter has not yet received an ACK control packet from the destination confirming that a packet has been received, the MAC layer (at the transmitter side) notes the absence of an ACK and retransmits the data packet. DDPC uses the absence/presence of an ACK at the MAC layer to increase or reduce the transmit power.

During transmission, a source node receives an ACK for every data packet that is sent, and the MAC layer notifies ($TxPower = 1$) DDPC that it is receiving ACK packets. As a consequence, DDPC sets a *positive* α, and the algorithm starts reducing transmission power. On the other hand, when a transmitter stops receiving ACK packets due to lost connectivity, the MAC layer informs ($TxPower = -1$) DDPC that connection to the destination has been lost. As a result, DDPC sets a *negative* α, and the algorithm starts increasing transmission power to recover connectivity with the destination.

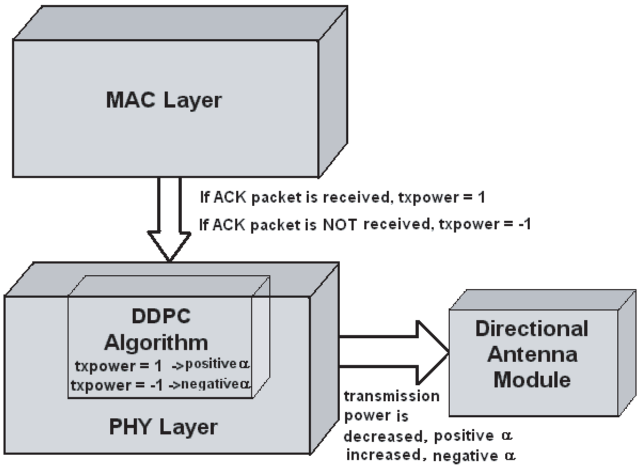


Figure 4.6. *The Dynamic Directional Power Control (DDPC) algorithm layer implementation with the IEEE 802.11 structure.*

Figure 4.7 depicts a functional flow diagram of DDPC in order to analyze in detail the transmit power saving mechanism. The DDPC algorithm employs a number of variables and constants which are defined below.

(1) B_{rem} is the remaining (available) battery energy of the node.
(2) B_{init} is the initial battery energy of the node.
(3) $MaxTx$ is the maximum transmission power of the node. This is a constant set to $MaxTx$ = $0.28W$ or $MaxTx \approx 24dbm$ [47].
(4) $CurrTx$ is the current transmission power of the node. At the beginning of a transmission ($t = 0$), $CurrTx$ = $MaxTx$. At any time ($t \neq 0$), $CurrTx$≤$MaxTx$.

$$CurrTx = MaxTx * \left(\frac{B_{rem}}{B_{init}}\right)^{\alpha} \tag{4.1}$$

(5) α is the power control tuning parameter. If α is *positive*, $CurrTx$ decreases. If α is *negative*, $CurrTx$ increases.

The proper selection of α is crucial for efficient transmission. Figures 4.8 and 4.9 show the impact of α on the transmission range of a node. Based on (4.1), at the beginning of the transmission the ratio of the residual battery energy to the initial battery energy $\left(\frac{B_{rem}}{B_{init}}\right)$, and the ratio of the current transmission power to maximum transmission power of a node $\left(\frac{CurrTx}{MaxTx}\right)$, are equal to $unity$. When α is $unity$, $\frac{B_{rem}}{B_{init}}$ is equal to $\frac{CurrTx}{MaxTx}$. Thus, changes in the residual battery energy will not affect the operating transmission range of the node. In Figure 4.8, assume $\frac{B_{rem}}{B_{init}}$ is 0.1. When α has a value of 2, $\frac{CurrTx}{MaxTx}$ is 0.02. Therefore, a higher value of α will reduce the operating transmission range of the node. When α is 0.3, $\frac{CurrTx}{MaxTx}$ is 0.5. Hence, smaller values of α will increase the operating transmission range of the node. Figure 4.9 shows the impact of a *negative* α in DDPC. When α is -1 with $\frac{B_{rem}}{B_{init}} = 0.1$, $\frac{CurrTx}{MaxTx}$ is 10. Therefore, to reduce the *inefficient transmission range* of a node, the DDPC algorithm uses positive values of α. To restore and maintain connectivity during transmission, the DDPC algorithm uses *negative* values of α. The selection of α is considered in Section 4.6.2.

Equation (4.1) shows that the residual battery energy, B_{rem}, of the node is an input of the algorithm. The reduction/increase in transmission range is based on $\frac{B_{rem}}{B_{init}}$ and B_{rem}. The output of the algorithm is the power level $CurrTx$, at which the node should operate. The wireless nodes adjust their transmitted power according to the power level of $CurrTx$ returned by the DDPC algorithm.

It is worth mentioning that one of the differences between P-CON [2] and DDPC is that DDPC does not use a *minimum transmission range*. Thus, DDPC is not restricted to a predefined *minimum transmission range* to reduce the probability of connectivity loss between a transmitter and receiver. The DDPC strategy of using the MAC layer to monitor connectivity gives DDPC more accuracy in varying the transmit power to maintain connectivity.

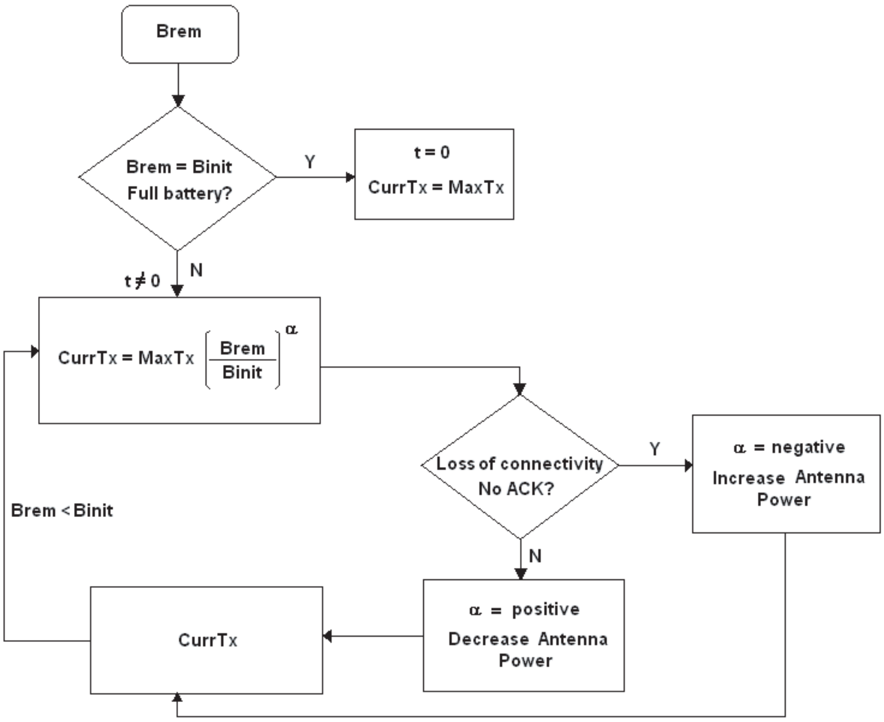


Figure 4.7. *Functional flow diagram of the Dynamic Directional Power Control (DDPC) algorithm.*

Based on Figure 4.7, the DDPC energy saving process is as follows. At the beginning of transmission, $t = 0$ and the remaining battery energy, B_{rem}, is equal to the initial battery energy, B_{init}. Based on (4.1), if $B_{res} = B_{init}$ then $CurrTx$ = $MaxTx$ at $t = 0$. Once a transmitter starts sending packets ($t \neq 0$), the DDPC algorithm starts reducing transmit power (α is always positive initially). The initial goal of DDPC is to reduce the *inefficient transmission range*. When $CurrTx$ is reduced to a point where the transmitter does not receive an ACK packet for the first time (loss of connectivity), α switches to a negative value to increase transmit power and recover connectivity. Thus DDPC dynamically varies the transmission range.

Three DDPC mechanisms have been developed (Approach $\#1$, Approach $\#2$, and Approach $\#3$) based on the network circumstances. Each approach is intended to perform better under particular network circumstances such as, static scenarios without interfer-

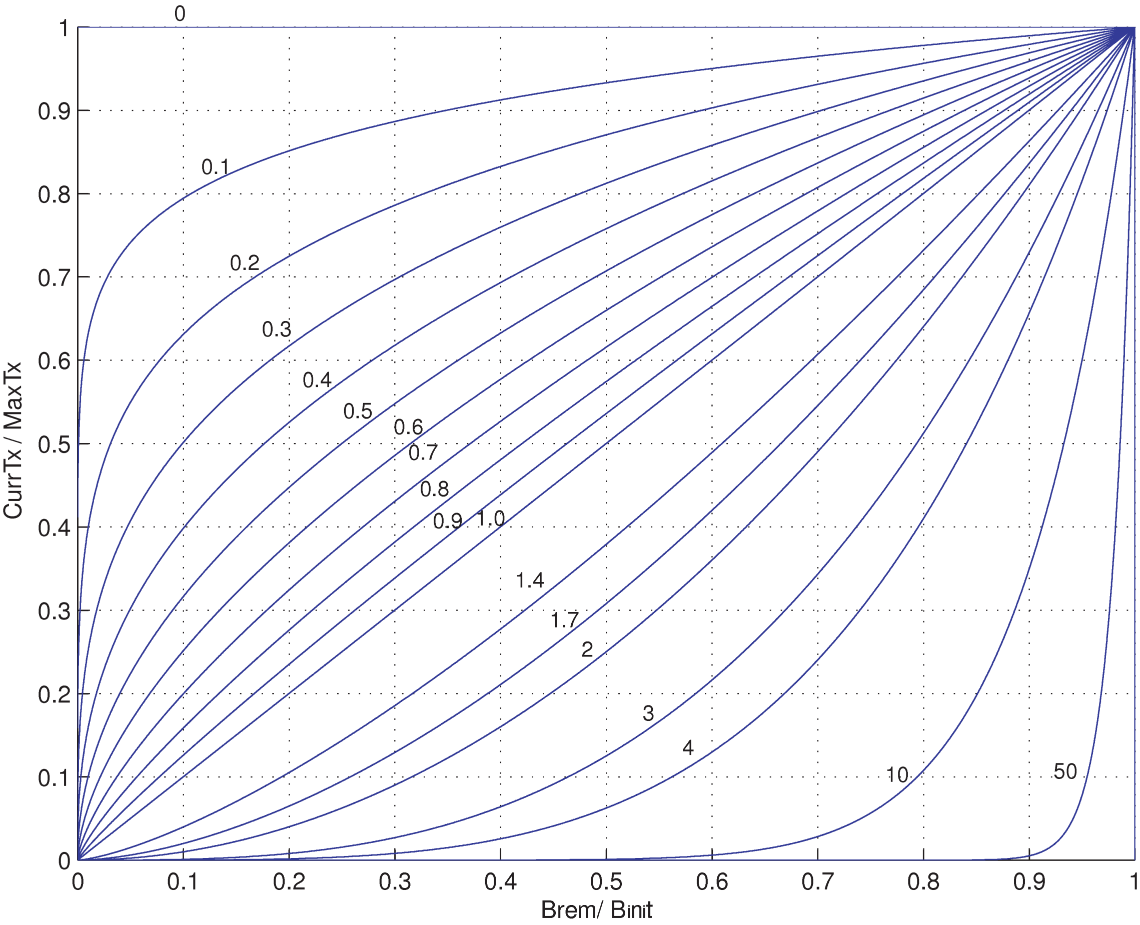


Figure 4.8. *The impact of positive α on the transmitted power of a node.*

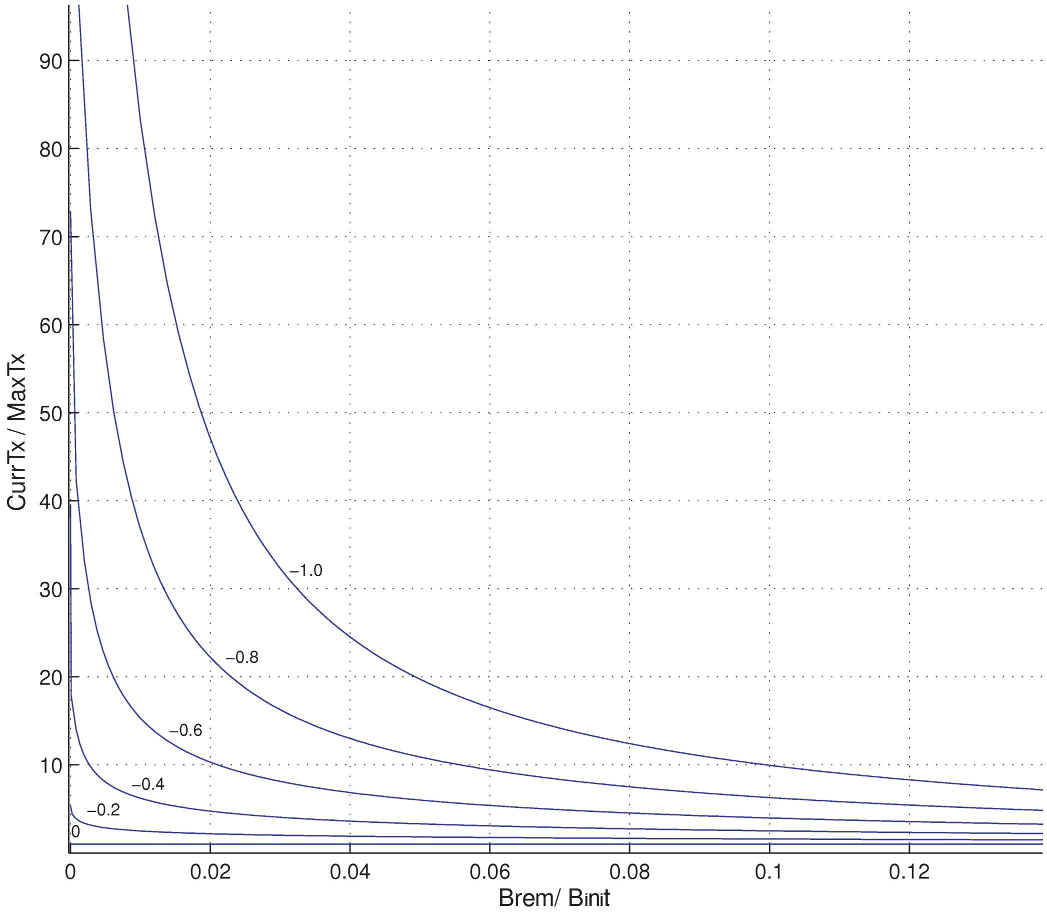


Figure 4.9. *The impact of negative α on the transmitted power of a node.*

ence, static scenarios with interference and scenarios with mobility. These approaches are implemented separately and independently on a node, so a node uses only one approach. Figure 4.10 shows the transmit power variation when P-CON and the three DDPC approaches are implemented on a node.

Figure 4.10a) shows that with P-CON, a node starts transmitting with a power of $MaxTx$. Then the node reduces the transmit power until it reaches a *minimum transmission range* of $Min - Tx$. This value might not be the lowest transmit power a node can reach before losing connectivity. Once reaching $Min - Tx$, the node continues to operate at $Min - Tx$.

DDPC Approach $\#1$, described in Figure 4.10b), shows a decrease in transmission power from a level of $MaxTx$. When the transmitter node detects an absence of ACK (NACK), it starts increasing transmission power until it reaches again a transmit power of $MaxTx$. This process is repeated until the end of the transmission.

DDPC Approach $\#2$ is illustrated in Figure 4.10c). This approach is similar to P-CON with the difference that instead of using $Min - Tx$, it uses an absence of ACK (NACK). Once DDPC detects the transmit power level corresponding to a NACK, DDPC increases the transmit power to a level high enough to recover connectivity. Then DDPC continues transmitting at this level, which corresponds to the *efficient transmission range*.

DDPC Approach $\#3$ is depicted in Figure 4.10d). This approach is similar to Approach $\#1$ with the difference that instead of gradually increasing power to $MaxTx$ once a NACK is received, Approach $\#3$ increases the transmit power to $MaxTx$. This process is repeated until the end of the transmission.

Since each approach in DDPC represents a different power control strategy, each approach uses different α values in their corresponding algorithm. Section 4.6.2 will present the process employed through simulation to find the most suitable α values for the three DDPC approaches.

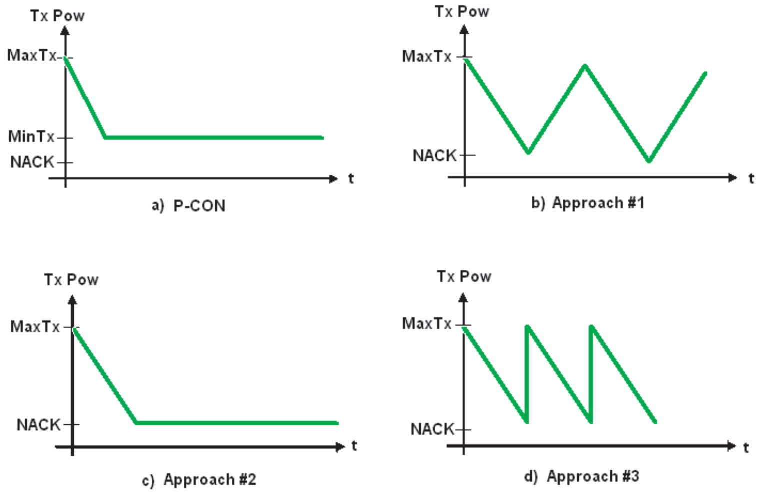


Figure 4.10. *The transmit power variation under different power control mechanisms: a) P-CON, b) DDPC Approach #1, c) DDPC Approach #2, d) DDPC Approach #3.*

4.5 Simulation Environment

To evaluate our protocol, we performed simulations using the *Network Simulator*, NS-2 [45]. NS-2 is a discrete event simulator widely used in the research community [42]. It was first developed at the University of California Lawrence Berkeley National Laboratory [47]. Then, it was extended at Carnegie Mellon University to integrate wireless extensions like IEEE 802.11 and ad hoc networking [42]. In wireless environments using IEEE 802.11, NS-2 enables the use of omnidirectional antennas for transmission and reception. In order to implement directional antennas in NS-2, we use *The Enhanced Network Simulator* (TENS) [46]. TENS is an extension of NS-2 to incorporate additional features such as directional antennas. We modified NS-2 to implement the DDPC protocol in the PHY layer. In our modification, we added a link between DDPC and the MAC layer.

In our simulations, we used the AODV routing protocol. AODV is an on-demand protocol without global periodic routing advertisements. Since AODV has low routing overheads, it consumes less network bandwidth [9]. AODV is loop-free, reliable, fast in fixing, and can repair routes with minor errors [10]. We focus only on energy consumption in transmission, and do not consider energy consumption in the idle state and during reception. Table 4.1 summarizes the simulation parameters used in studying DDPC. In the case of a Dtx-Orx communication link, we used directional antennas with 4 and 6 beams for transmission. Dtx-Drx communication links have directional antennas in transmission and reception.

In our simulations, we compare the DDPC approaches with the IEEE 802.11 and P-CON protocols. In order to compare these protocols, we use the same simulation parameters found in Table 4.1. For example in communications using Dtx-Drx links we also implement directional antennas with the P-CON and IEEE 802.11 protocols to compare with DDPC. However, we do not use any power control mechanism with the IEEE 802.11 standard. Based on the simulation parameters in [2], for P-CON we use α values of 0.4 and 0.7, and a $Min - Tx$ of 175m.

4.5.1 Metrics

We use the following metrics to evaluate the performance:

* **Data packet delivery ratio** ($\%$): This is the ratio of the number of packets generated at the source to the number of packets received by the destination. This metric reflects the network *throughput*, measured in packets per second.

* **Energy consumption** ($Joules$): This is a measure of the energy consumed.

* **Transmit power** (dbm): This is the power level that is transmitted from the antenna.

* **Average delay** (ms): Average delay is the average of packet delay, from the start of the packet being transmitted at the source to the end of the data packet being received at the destination.

* **Packet loss** ($\%$): Packet loss occurs when one or more packets fail to reach their destination.

* **Energy efficiency** ($packets/Joule$): We define Energy efficiency as the number of pack-

ets successfully received per Joule. The grater the number of packets per Joule, the better the energy efficiency achieved.

Simulation Parameters for DDPC		
Simulator	The Network Simulator - NS-2 Version 2.6	
	Network Size	1500 X 1500
	Time of Simulation	10000 seconds
Directional Antenna Package	The Enhanced Network Simulator - TENS Version 1.2	
	Beam Width Angle	Number of Beams
	90°	4 beams
	60°	6 beams
DDPC Parameters	$MaxTx$	0.2818W / ≈24.5dBm
	B_{init}	$10J$ (static), $100J$ (mobility)
	α	20, 100, 10
PHY Layer	Signal Propagation Model	Two-ray ground
MAC Layer	IEEE 802.11	
	Link Bandwidth	2 Mbps
	Interface Queue Length	FIFO, size 50
Routing Protocol	AODV	
Traffic Model	Constant Bit Rate (CBR), UDP	
	Data Packet Size	1000 Bytes
	Data Rate	740.0$kbps$
Communication Link-Length	Dtx-Orx and Dtx-Dtx	
Static Model	2 nodes	Distance = 250m / 600m
	4 nodes	Distance = 250m / 600m
Mobility Model	Type of Communication	Dtx-Drx
	2 nodes	Distance = 50m to 1000m
	Beam Width Angle	60°
	Node Speeds	[1, 2, 5, 10, 20, 50]m/s

Table 4.1. *Simulation Parameters*

4.6 Performance Evaluation

We considered three sets of results to evaluate the performance of the DDPC protocol. The first set of simulations shows the effect of α and B_{init} on the transmit power. For example, we use DDPC Approach $\#1$ with different B_{init} and α values. In this set of results, we also include the analysis to find the best α value for each DDPC approach. The second set of results are intended to evaluate the performance of DDPC in static scenarios with single and simultaneous transmissions. With single transmissions, we evaluate energy consumption and duration of transmission with the DDPC approaches. For simultaneous transmission, we also consider interference. The third set of results show the performance of DDPC with node mobility. We evaluate the connectivity with DDPC, and also the effects of node speed on energy efficiency and the packet delivery ratio.

4.6.1 Varying B_{init} and α in DDPC Approach $\#1$

In this section, we show the impact of the initial battery energy (B_{init}) and the power control tuning parameter (α) on DDPC. We selected Approach $\#1$ in this set of simulations since it better represents the transmit power variations due to changes in B_{init} and α. In this case, node A is transmitting to node B. Node A is using a directional antenna and node B is using an omniderctional antenna ($Dtx - Orx$ communication link).

In Figure 4.11, we show the power level during transmission using DDPC with a constant $\alpha = 20$ and different values of B_{init}, $10J, 25J, 50J, 100J$ and $200J$. From these results we can determine where the lowest and highest power levels occur with DDPC approach $\#1$. Most of the energy saving occurs at the bottom (below $0dbm$) peak areas of each transmit power curve, while most of the energy consumption occurs at the top (above $20dbm$) peak areas. For example, with $B_{init} = 10J$, a node will transmits below $0dbm$ for approximately 1000 seconds (bottom peak). On the other hand, the same node will transmit above $0dbm$) for approximately 800 second (upper peaks). Thus, a node using DDPC Approach $\#1$ will spend significant time (1000 seconds) transmitting at a low power level without significantly affecting connectivity. We observe the same pattern with $B_{init} = 200J$. In this case, the node's battery capacity is larger. As a consequence, the node will transmit below $0dbm$ for a longer time, 1400 seconds. The same situation occurs with the maximum power transmission at the top peak areas, above $0dbm$ for 1180 seconds. Therefore, using DDPC with different battery capacities will not significantly affect the DDPC power saving mechanism. However, from Figure 4.11, DDPC extends the energy consumption time by ≈50$\%$ for every increment of $100Joules$ in battery capacity.

The relationship between the power control tuning parameter, α, and the transmission power is investigated by measuring the transmitted power with different α values $(0, 15, 20,$ and $50)$ and a constant $B_{init} = 100J$. Figure 4.12 shows that smaller values of α produce longer transmission times at power levels below $0dbm$. As a result, transmissions might consume more energy before reaching $0dbm$. This is compensated by the negative value of α, where larger values produce longer times to reach reaching power levels above $20dbm$. With proper values of α, nodes should be able to transmit with low power levels (below $0dbm$) for longer times. It is crucial to choose the right value of α for each DDPC scheme in order to maximize energy savings in transmission. The following section considers the choice of α for each DDPC approach.

The previous figures showed the transmit power curves reaching the bottom peaks and top peaks several times. In order to show more variation in energy consumption, the simulation time is set large enough to allow consumption of most (or all) of the battery energy. In this way we can better determine the performance of DDPC. We use $B_{init} = 10J$ with a simulation time of $t = 10000$ for the rest of the simulations.

4.6.2 Finding an Efficient α with the DDPC Approaches

This section is dedicated to finding suitable α by measuring the *consumed energy* and *throughput* for each DDPC approach. Figure 4.13 shows the consumed energy with DDPC Approach $\#1$ and α = 5, 10, 15, 20, 25 and 30. For each curve, the transmitting node goes from a full battery state (consumed energy$= 0J$) to an empty battery state (consumed energy= $10J$). In this figure, we compare the time a node takes to consume its transmit energy. We observe that when the transmitter node uses $\alpha = 20$, transmission lasts longer than with the other α values. The first time each transmit power curve reaches the bottom peak, transmissions using DDPC with $\alpha = 5$ and 10 have consumed 50% and 70% of their total available energy, respectively. The reason is because very small positive values of α result in DDPC Approach $\#1$ operating at power levels between $20dbm$ and $0dbm$ for longer times. The other values of α conserve more energy when they reach low power levels. When transmit power curves reach high power levels, there is less energy consumption with large negative α values. Thus, negative α values of 30, 25, 20 and 15 still conserve more energy than α =5 and 10. However very large values of negative α will eventually cause significant energy consumption because the high power levels (top peaks) will occur more frequently. Therefore, α =20 is chosen as a good balance to conserve battery energy. In Figure 4.14, the throughput of the system is used as an indication of connectivity. This shows that DDPC Approach $\#1$ with α =20 maintains communications for almost 8000 seconds. According to this figure, α =20 lasts the longest.

Figure 4.15 show the consumed energy when a transmitter node implements DDPC Approach $\#2$ with α = 5, 10, 20, 50 and 100. With this approach, only positive values of α are used. Since the goal of this approach is to transmit data with the lowest power level at all times, it is more convenient to use large values of α to decrease the power quickly from the $MaxTx$ power level. In this figure, α =100 provides the lowest consumption of battery energy. Figure 4.16 shows that the transmitter and destination maintain communications for almost 4×10^4 seconds, with $\alpha = 100$. During this communication, the destination is receiving $95\ packets/s$.

Figure 4.17 shows the consumed energy when a transmitter node implements DDPC Approach $\#3$ with α = 5, 10, 15, 20, 25, and 30. This figure shows that DDPC Approach $\#3$ follows a consumption pattern similar to Approach $\#1$. Smaller positive α values result in a quick reduction of battery energy. This is because the node takes longer to transmit at low power levels (slow decrease of transmit power). Moreover, each connectivity loss makes the transmit power jump to the maximum power level, $MaxTx$. Large values of positive α produce power levels that reach the bottom peaks more frequently, which trigger transmissions at the maximum power level more often. However, small values of α consume more energy than larger values of α. When α =10, the node is able to transmit for the longest time. This is because this α provides a good balance in power variation to save energy. Figure 4.18 shows the corresponding duration of transmission information. With α =10, a transmitter using DDPC Approach $\#3$ is able to transmit $95 packets/sec$ to a destination for approximately 5400 seconds.

The best α values found above for each approach will be used in the remainder of the simulations in this thesis.

4.6.3 Static Scenarios: Single Transmissions

In this set of simulations we compare the performance of the DDPC schemes with P-CON and IEEE 802.11. Figure 4.19 shows the energy consumed by a node transmitting with directional antennas. The node can use only one of its N antenna beams. Hereafter, we denote 802.11 Directional and P-CON Directional with N antenna beams as 802.11 N-Directional and P-CON N-Directional, respectively. Similarly, we refer to DDPC with N antenna beams as N-DDPC. For example, 802.11 4-Directional refers to the IEEE 802.11 protocol simulated with 4 beam directional antennas. The beamwidth with 4 beams is $\left(\frac{2\pi}{4}\right)$, which is $90\,^{\circ}$. Signals are received at the destination using an omnidirectional antenna, so it is a Dtx-Orx communication link. The distance between the transmitter and receiver is 250 meters. In this figure we observe that IEEE 802.11 consumes its total energy fast since it transmits with a constant power level of $MaxTx$ (≈24.5dbm) during the entire transmission. P-CON consumes its energy in less time than IEEE 802.11, however, P-CON performs similar to IEEE 802.11 since it slowly decreases its transmit power (α=0.7). Moreover, P-CON never reaches transmit power levels below $0dbm$ in this case. According to (2.5), the closer α gets to unity, the less energy saving that occurs. From the results in this figure, the DDPC approaches perform better than P-CON and IEEE 802.11.

However, it is important to compare the performance of each DDPC approach. For the first 3000 seconds of the simulation, DDPC Approach $\#3$ consumes $3.6J$ more than Approach $\#1$. Nevertheless, Approach $\#1$ consumes $3J$ more than Approach $\#3$ for the next 1000 seconds. Then, Approach $\#3$ consumes $2.1J$ more than Approach $\#1$ for 1600 seconds. As a result, Approach $\#3$ consumes a total energy of $2.7J$ $(5.7J - 3J)$ more than Approach $\#1$. Therefore, Approach $\#1$ saves more energy than Approach $\#3$. However, during the entire transmission, DDPC Approach $\#2$ consumes less energy than the other approaches. This is because, Approach $\#2$ keeps the transmission power below $0dbm$ during the entire simulation time (10^4 seconds). Hence, Approach $\#2$ conserves battery energy the best.

Although P-CON and DDPC Approach $\#2$ show a similar transmit power behavior, DDPC Approach $\#2$ decreases its transmission range faster than P-CON. Moreover, DDPC Approach $\#2$ is more accurate in attaining the most *efficient transmission range*. Figure 4.21 shows the throughput at the destination. Since Approach $\#1$ consumes less energy than Approach $\#3$, the transmission between the sender and receiver will last longer (≈8000 seconds). However, a node using Approach $\#2$ will be able to transmit to the destination for the duration of the simulation (10^4 seconds), and have some battery energy remaining.

Implementing directional antennas at the receiver improves the energy saving in transmission. This is because with directional reception, the gains at the transmitter and receiver provide an increased product, $G_T * G_R$, compared to omnidirectional reception. Therefore, less power is required to transmit the same amount of information at the same distance from the receiver. In particular, if we use directional reception, the effective communication distance will be approximately three times larger than having only directional transmission.

Figures 4.20 and 4.22 show the performance of DDPC with directional reception. The transmitter and receiver use directional antennas (Dtx-Drx communication link) with 4 beams. The distance between the transmitter and receiver is 250 meters. In these figures, the transmitter require less power to transmit to the destination, so less energy is consumed. DDPC Approach $\#2$ still consumes the least amount of energy, and with Dtx-Drx communications most of its battery power remains when the simulation time ends. In fact, all three DDPC approaches stop transmitting at 10^4 seconds.

In Figures 4.23 and 4.25, we use a Dtx-Orx communication link with 4 directional antenna beams. In these figures, the separation distance between the transmitter and receiver is increased to $600m$. Since the separation between sender and receiver nodes is longer, the consumption of energy is faster than with shorter distances. The reason is that more power is required to transmit packets to a further destination. Equation (2.5) indicates that power is proportional to the square of the distance. In the figures we also observe that Approach $\#1$ conserves $2.5J$ of battery energy while Approach $\#3$ terminates transmission because of insufficient battery energy. This $2.5J$ allows Approach $\#1$ to transmit 440 seconds longer than Approach $\#1$. However, Approach $\#2$ has a longer transmission time since it consumes the least amount of energy. This approach uses the minimum effective power level in transmission.

In Figures 4.24 and 4.26 we use directional antennas at the transmitter and receiver (Dtx-Drx communication link) with 4 beams. The distance between the transmitter and receiver is $600m$. In these figures, we observe that the higher power transmission due to longer distances is reduced if directional antennas are used at the destination. The greater the communication distance, the more transmit power is required. However, directional reception requires less power to transmit the packets. In this figures, the DDPC approaches provide longer transmission times. Transmission using Approach $\#1$ lasts $\approx$300 seconds more than Approach $\#3$. However, Approach $\#2$ lasts the longest.

In Figures 4.27 to 4.29 we use directional antennas with 6 beams. Therefore, the beamwidth is $\left(\dfrac{2\pi}{6}\right)$, which is $60\,^\circ$. This is denoted by 802.11 6-Directional, P-CON 6-Directional and 6-DDPC. Signals are received at the destination using an omnidirectional antenna, so it is a Dtx-Orx communication link. The distance between the transmitter and receiver is 250 meters. In this figure, the narrower beamwidth increases the transmission gain ($G_{d_{90^\circ}} < G_{d_{60^\circ}}$), which improves the energy savings. However, it takes more time for the 6-DDPC approaches to find the appropriate *efficient transmission range* (the transmission range before losing connectivity). As a result, the consumed energy with the 6-DDPC approaches shows less variations. With Dtx-Orx communication links, Approach $\#1$ conserves $2J$ more than Approach $\#3$. However, Approach $\#2$ conserves $7J$ (energy remaining at the end of the simulation), more than Approach $\#1$. Thus, Approach $\#2$ lasts the longest. Note that P-CON still consumes more energy than the DDPC approaches.

Using a directional antenna at the destination increases the gain over the communication link. Hence, we do not see the transmit power curves reaching power levels below $0dbm$ within the specified simulation time ($t = 10000$). Although all approaches save more energy, DDPC Approach $\#2$ still saves the most. On the contrary, P-CON consumes its energy sooner than the other approaches as its battery energy is depleted after 250 seconds of simulation time.

Figures 4.30 and 4.32 show that the 6-DDPC approaches, using a Dtx-Orx communication link, reach the efficient transmission range during the simulation time. This is because the long separation distance ($600m$) between the transmitter and receiver is compensated by the extra gain provided by the 60° directional antenna at the transmitter. In this figure, Approach $\#1$ conserves $2J$ more than Approach $\#3$, but Approach $\#2$ contains $8J$ in battery energy when Approach $\#1$ has consumes all of its energy. Therefore, Approach $\#2$ still provides the longest transmission time, ≈3500 seconds. On the other hand, P-CON finishes its available battery energy after ≈200 seconds.

For the results in Figures 4.31 and 4.33, we use a Dtx-Drx communication link with 6 beams. The distance between the transmitter and receiver is $600m$. These figures show that implementing directional antennas at the destination improves energy savings, thus providing longer transmission times. The performance of the DDPC approaches is similar to that in the previous figures. Approach $\#1$ consumes $2.2J$ less than Approach $\#3$, and Approach $\#2$ consumes $7J$ less than Approach $\#1$. This pattern is constant in static scenarios because Approach $\#2$ transmits more often at a low power level. Conversely, P-CON transmits with a near constant power level, so the energy savings is poor. This is because P-CON was developed with an emphasis on keeping nodes connected by slowly decreasing transmit power.

P-CON is intended to be used in scenarios with mobility, and mobility will be considered later in this chapter. In the next section, we examine the performance of the DDPC approaches when there is more than one transmission in the same neighborhood.

4.6.4 Static Scenarios: Simultaneous Transmissions

We now evaluate the performance of DDPC when there are simultaneous transmissions in the same neighborhood. From Figure 2.12, we refer to the transmission from node A to B as *flow 1* and the transmission from node C to D as *flow 2*. The results of this section were obtained by using directional antennas with 4 beams at both the transmitters and receivers.

In this section, we focus on the effects of interference on the DDPC approaches. We start by comparing Figures 4.34 and 4.35 (with a separation distance between transmitters and receivers of $250m$), with previous results (with similar parameters but no interference). In these figures we observe that there is a major consumption of energy with all the approaches, and Figures 4.36 and 4.37 show a degradation of throughput. Since two simultaneous transmission occur in the same area, network performance is affected by packet loss caused by packet collisions. Table 4.2 shows that all DDPC approaches experience packet loss. In the event of packet loss, the transmitter automatically resends packets that have not been acknowledged. Retransmission of packets causes the throughput to decrease, and consequently greater energy consumption per received packet.

Analyzing flows $\#1$ and 2 from the table, we observe that P-CON is the most affected by interference. P-CON provides a packet delivery ratio of only 2.97% (successful packets from the total number of packets transmitted to the destination). In both flows, Approach $\#3$ provides the highest packet delivery ratio (92.38%) and the lowest packet loss (3.81%). The reason is because the transmit power in Approach $\#3$ constantly jumps to the $MaxTx$ power level every time there is a loss of connection. This provides more power to minimize the effects of interference. In this static scenario, Approach $\#2$ lasts the longest. However, Approach $\#1$ and Approach$\#3$ provide better packet delivery ratios than Approach $\#2$ in flow $\#1$. The reason is because Approach $\#2$ is more sensitive to the interference since it operates with a low power level. In flow $\#2$, the packet delivery ratio of Approach $\#2$ is slightly higher than in flow $\#1$ ($78.16\% > 67.88\%$). This is because flow $\#2$ transmissions started slightly before flow $\#1$. Similar results were obtained with the other approaches.

In this table, we also observe that transmitted packets experience delay in reaching the destination. Approach $\#2$ is the mechanism that shows the highest packet delay ($731.52ms$), followed by Approach $\#1$ (442.26ms) and Approach $\#3$ (238.10ms). This can be attributed to interference since transmissions with low power are more sensitive to interference. Approach $\#2$ decreases its power rapidly to transmit with a low level the rest of the transmission. Hence, the average delay is high. On the other hand, Approach $\#3$ transmits more often at a high power level (the absence of an ACK packet causes jumps to the $MaxTx$ power level). Thus, average delay in Approach $\#3$ is the lowest of the DDPC approaches. Approach $\#1$ transmits less often at the $MaxTx$ power level. Therefore, the packet delay in Approach $\#1$ is more than Approach $\#3$ and less than Approach $\#2$. With these observations, we can conclude that lower transmit power implies higher average delay. For instance, P-CON transmits mostly with high power levels. As a consequence, its average delay is the lowest (4.56ms) of all the approaches.

	Flow $\#1$			
DDPC Scheme	Approach$\#1$	Approach$\#2$	Approach$\#3$	P-CON
Packet Delivery Ratio	77.92$\%$	67.88$\%$	92.38$\%$	2.97$\%$
Average Delay	442.26ms	731.52ms	238.10ms	4.56ms
Packet Loss	11.04$\%$	16.06$\%$	3.81$\%$	97.12$\%$
	Flow $\#2$			
DDPC Scheme	Approach$\#1$	Approach$\#2$	Approach$\#3$	P-CON
Packet Delivery Ratio	77.95$\%$	67.92$\%$	92.47$\%$	2.98$\%$
Average Delay	440.22ms	634.53ms	237.68ms	4.58ms
Packet Loss	11.02$\%$	10.92$\%$	3.76$\%$	97.11$\%$

Table 4.2. *Static scenario performance with two flows using a Dtx-Drx (*90° *beamwidth antennas) communication link with a separation distance of 250m.*

Figures 4.38 to 4.41 show that a longer distance between the transmitter and destination ($600m$) increases the energy consumption. A long distance between the transmitter and receiver also makes the transmitters wait for ACK packets before they can send more data packets. As before, interference degrades network performance because of the retransmissions of lost packets. Table 4.3 shows the packet delivery ratio of the DDPC approaches and P-CON. The results in this table show that the battery life with all approaches is less than with a distance of 250m, but Approach $\#2$ is still transmitting for a longer time than the other approaches. Although Approach $\#2$ provides battery energy longer, it offers the lowest packet delivery ratio. The reason is because the low transmit power used by Approach $\#2$ is more susceptible to packet loss due to interference. As a consequence, Approach $\#2$ shows the highest rate of packet loss. Approach $\#3$ performs better than Approach $\#1$ because Approach $\#3$ uses the highest power level more frequently. Therefore, Approach $\#3$ is less affected by interference. As a result, Approach $\#3$ shows the lowest packet loss rate and the highest packet delivery ratio. Even though, P-CON uses a high power level most of the time, its packet delivery ratio is the lowest. The reason is that P-CON consumes all its energy faster than the other approaches. This leaves a very short time (200 $seconds$) to deliver packets to the destination. In this table, we observe a similar pattern in the average delay as in the previous table. Approach $\#2$ shows the highest average delay (890.45ms) since it uses the lowest power level during transmission. On the contrary, P-CON shows the lowest average delay (4.59ms) due to its transmissions with high power. This confirms that a low transmit power results in a higher average delay. We also notice from the results that the metric values are lower with the longer distance. The reason is that a longer distance with interference results in more lost packets and thus worse performance.

	Flow $\#1$			
DDPC Scheme	Approach$\#1$	Approach$\#2$	Approach$\#3$	P-CON
Packet Delivery Ratio	68.36$\%$	56.23$\%$	70.72$\%$	2.12$\%$
Average Delay	715.89ms	890.45ms	590.46ms	4.59ms
Packet Loss	31.64$\%$	43.77$\%$	14.60$\%$	97.88$\%$
	Flow $\#2$			
DDPC Scheme	Approach$\#1$	Approach$\#2$	Approach$\#3$	P-CON
Packet Delivery Ratio	68.10$\%$	56.11$\%$	70.95$\%$	2.14$\%$
Average Delay	716.03ms	890.38ms	587.87ms	4.48ms
Packet Loss	31.90$\%$	43.89$\%$	14.43$\%$	97.80$\%$

Table 4.3. *Static scenario performance with two flows using a Dtx-Drx (*90° *beamwidth antennas) communication link with a separation distance of 600m.*

4.6.5 DDPC Performance with Mobility

In this section, we evaluate the performance of the DDPC schemes with node mobility. In this case, the destination node is moving towards the transmitter node. When the destination node reaches 50m away, it stops moving. Then, when the simulation time is $t = 1000$ secs, the destination node start moving away from the transmitter. The destination node stop moving when the separation distance is $1km$. Simulation stops either when the time ends ($t = 2000$ secs) or when the node has consumed all its energy.

Figure 4.42 shows the energy efficiency of the DDPC approaches at different speeds. In transmissions with low speeds ($< 5m/s$), the destination node takes longer to reach the source. Therefore, the transmission is more exposed to network degradation due to long distances. Longer distances means more consumption of energy, and less energy efficiency. In transmissions with high speeds ($> 10m/s$), the energy efficiency improves. The reason is because the destination approaches the source faster, consuming less energy when the minimum separation distance is reached ($50m$). IEEE 802.11 and P-CON consume their battery energy faster than the DDPC approaches. As a result, they provide with the lowest energy efficiency at all speeds. DDPC Approach $\#1$ consumes less energy than Approach $\#3$. Approach $\#3$ maintains connectivity by jumping to the maximum power level with the absence of an ACK. Thus, Approach $\#3$ consumes more energy than Approach $\#1$. Approach $\#2$ provides higher energy efficiency since the minimal effective power used during transmission is enough to maintain connectivity efficiently.

Figure 4.43 show the packet delivery ratio with each approach when the destination is in motion at several speeds. It is interesting to see that the total data delivered per joule for IEEE 802.11 is low, however, its packet delivery ratio is the highest in this figure. Even though IEEE 802.11 consumes rapidly its battery energy, its constant high power allows it to deliver more packets at the destination. IEEE 802.11 can be applied to applications where information transmission is more important than efficiency. Since P-CON consumes more energy compared to the DDPC approaches, it provides lower data delivery per joule, but still provides a higher packet delivery ratio. This is because of the higher consumption of energy that makes P-CON better able to maintain connectivity.

The DDPC approaches achieve energy efficiency (conserve more energy) by sacrificing the packet delivery ratio. From the results, it is clear that as node speed increases, the packet delivery ratio decreases with the DDPC approaches. The reason is due to the loss of connectivity due to motion during DDPC. The tendency of DDPC to vary the transmit power can potentially compromise network connectivity in scenarios with mobility.

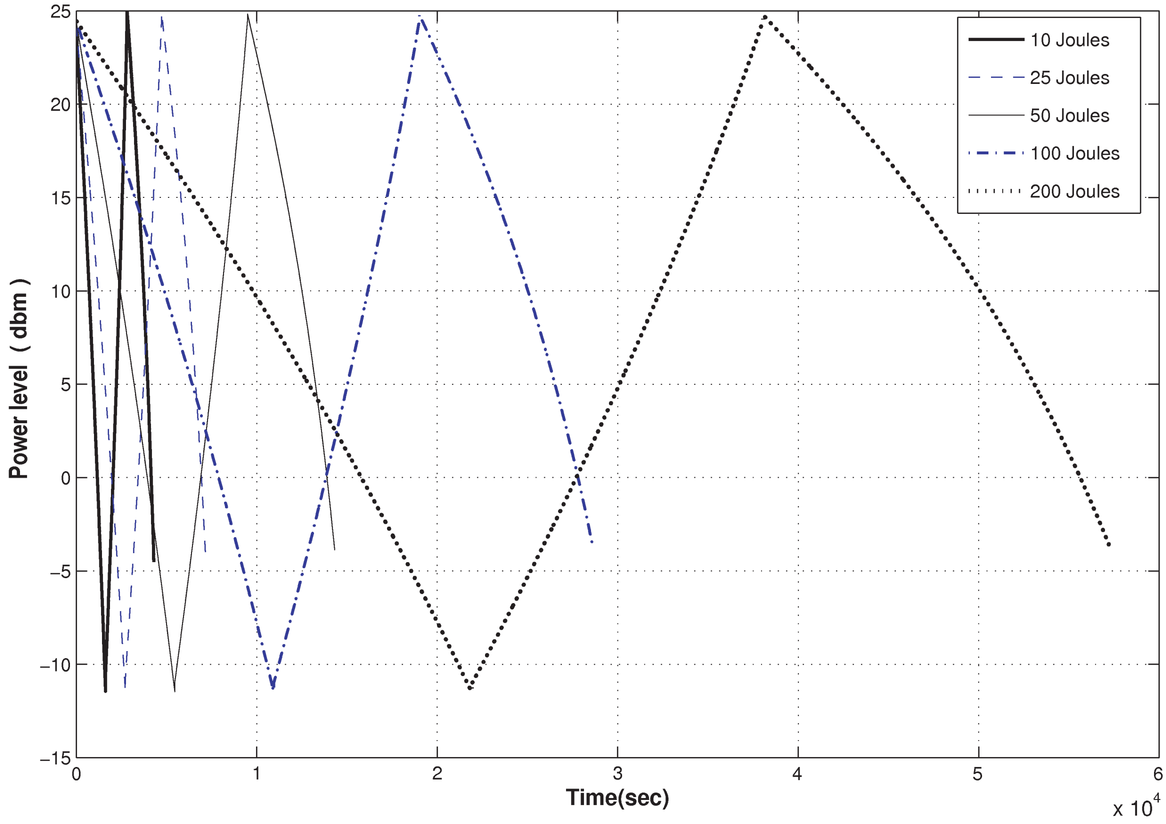


Figure 4.11. *Transmit power with DDPC Approach #1 using* $\alpha = 20$ *and different battery capacities (10J, 25J, 50J, 100J and 200J) at the source node.*

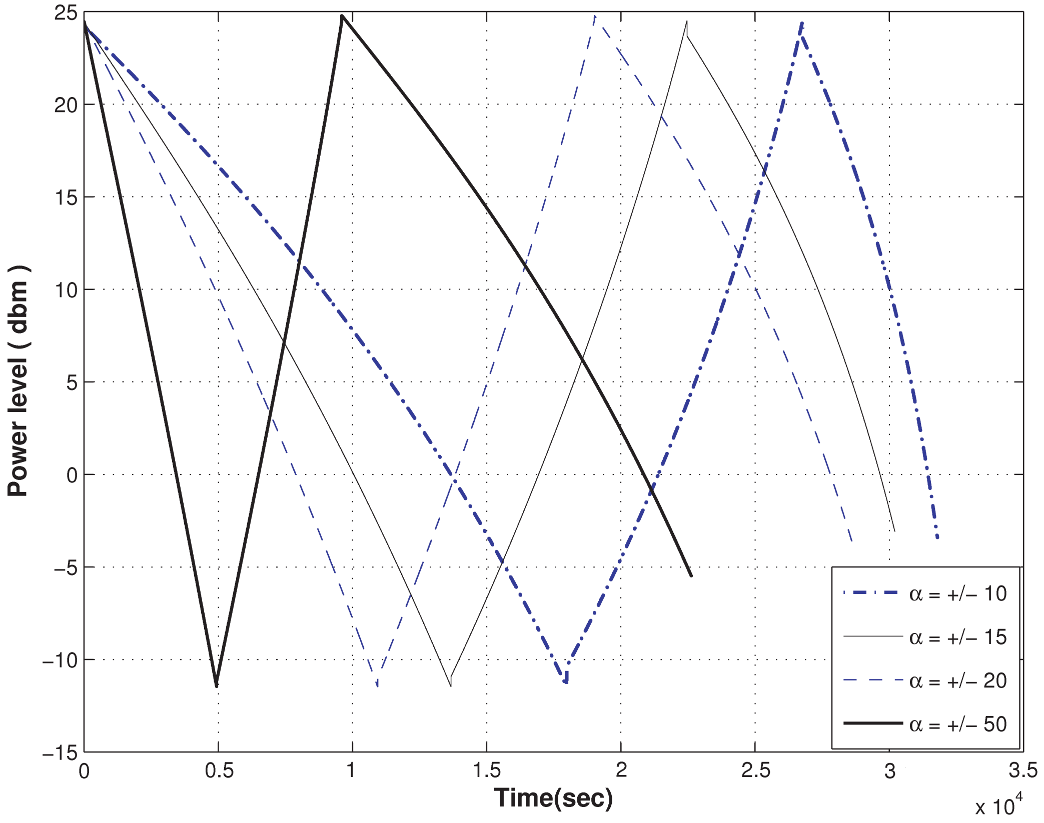


Figure 4.12. *Transmit power with DDPC Approach #1 using a constant battery capacity of 100 Joules and various* α *at the source node.*

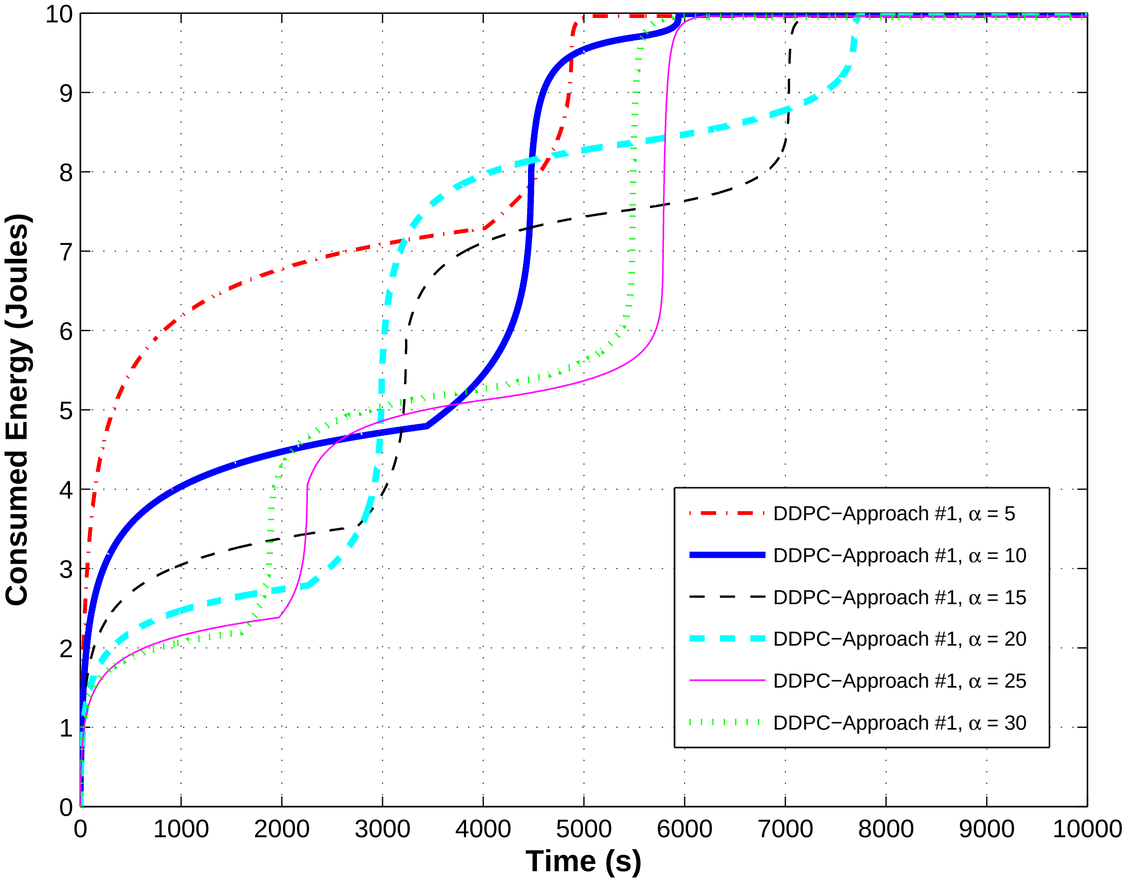


Figure 4.13. *Consumed energy for different values of* α *with DDPC Approach* $\#1$.

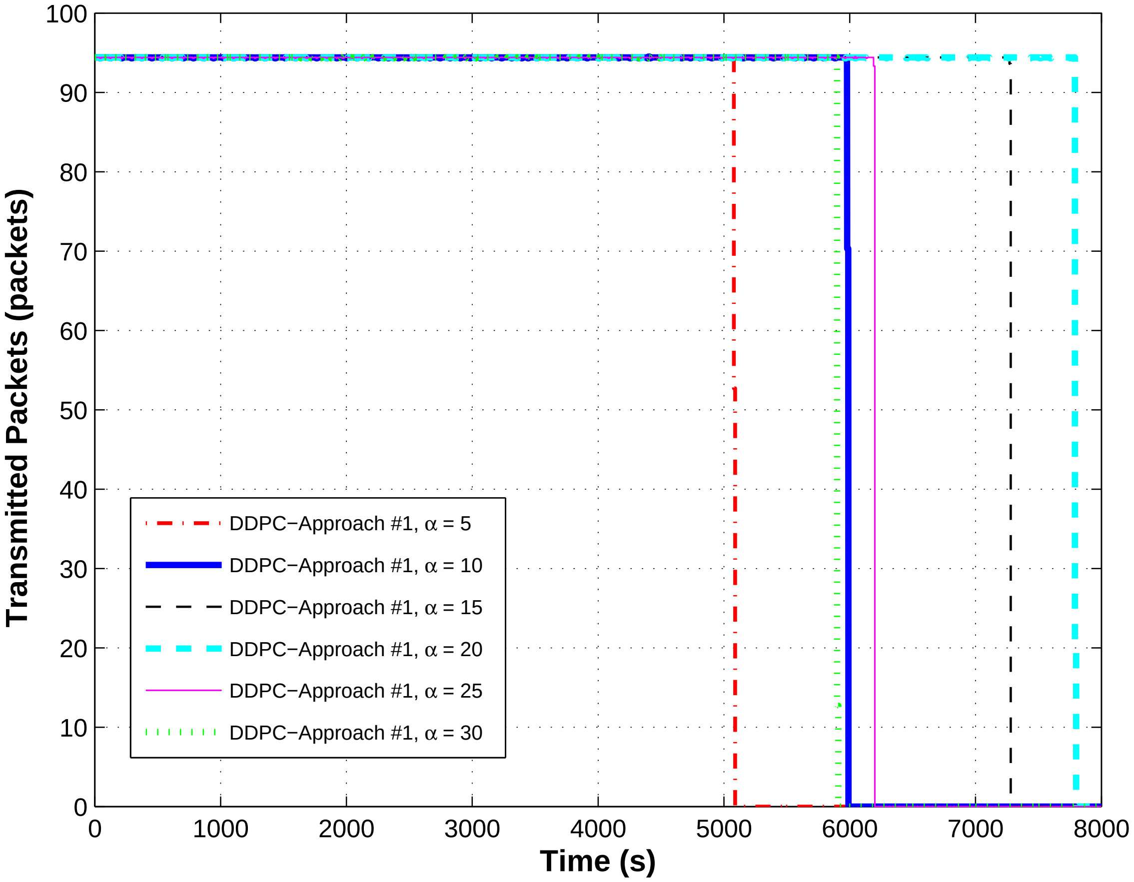


Figure 4.14. *Throughput for different values of α with DDPC Approach $\#1$.*

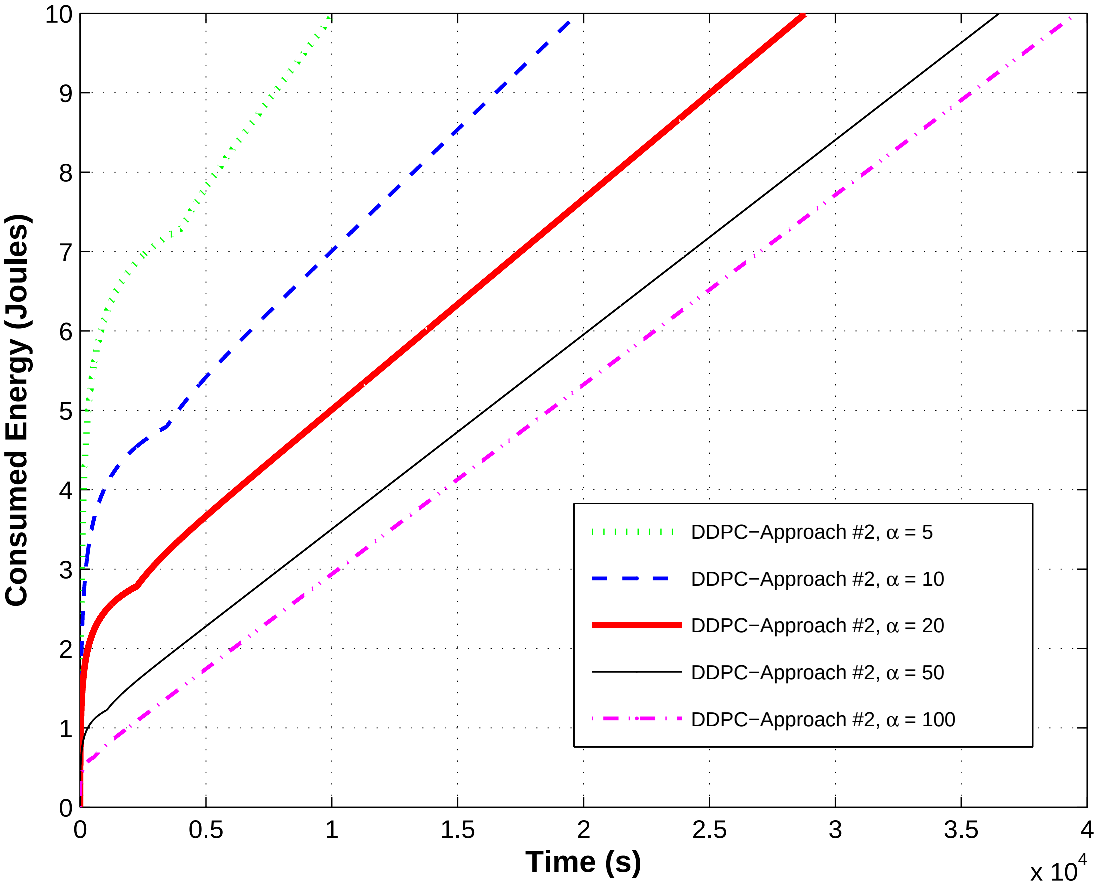


Figure 4.15. *Consumed energy for different values of* α *with DDPC Approach #2.*

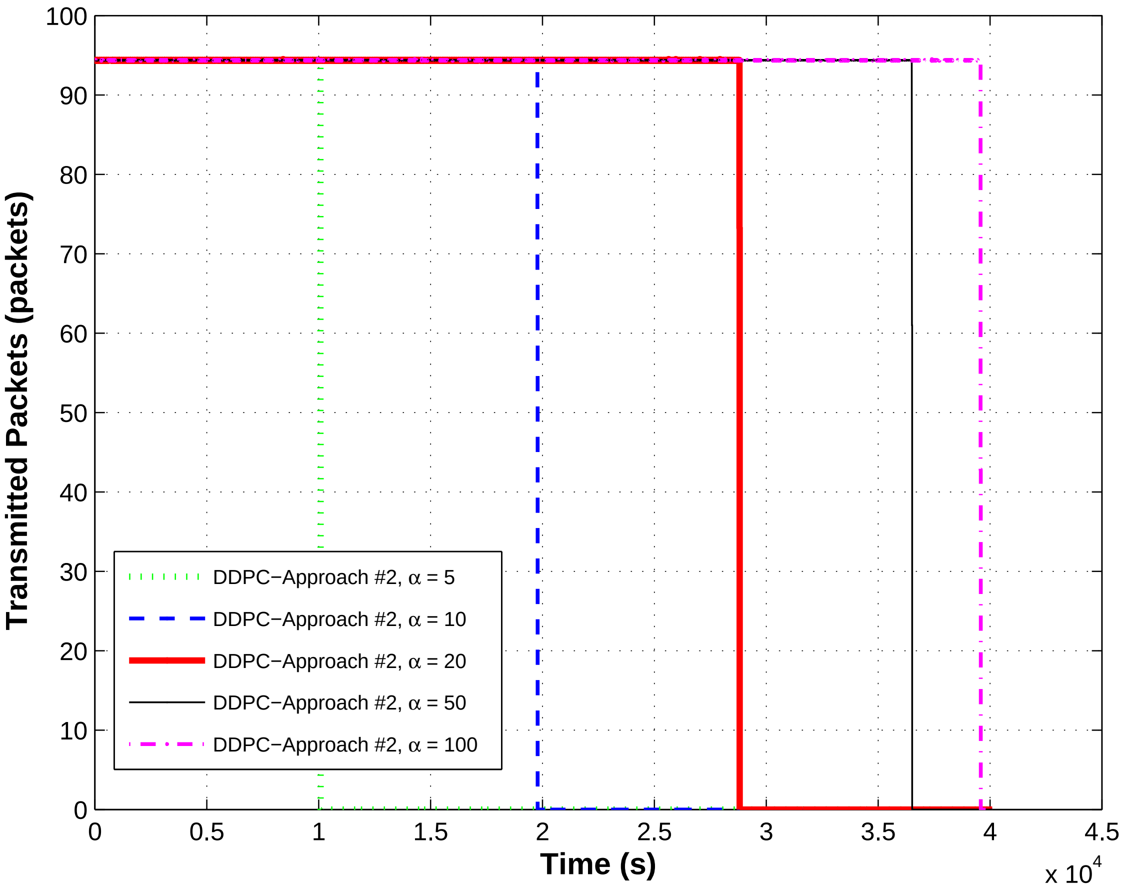


Figure 4.16. *Throughput for different values of* α *with DDPC Approach* $\#2$.

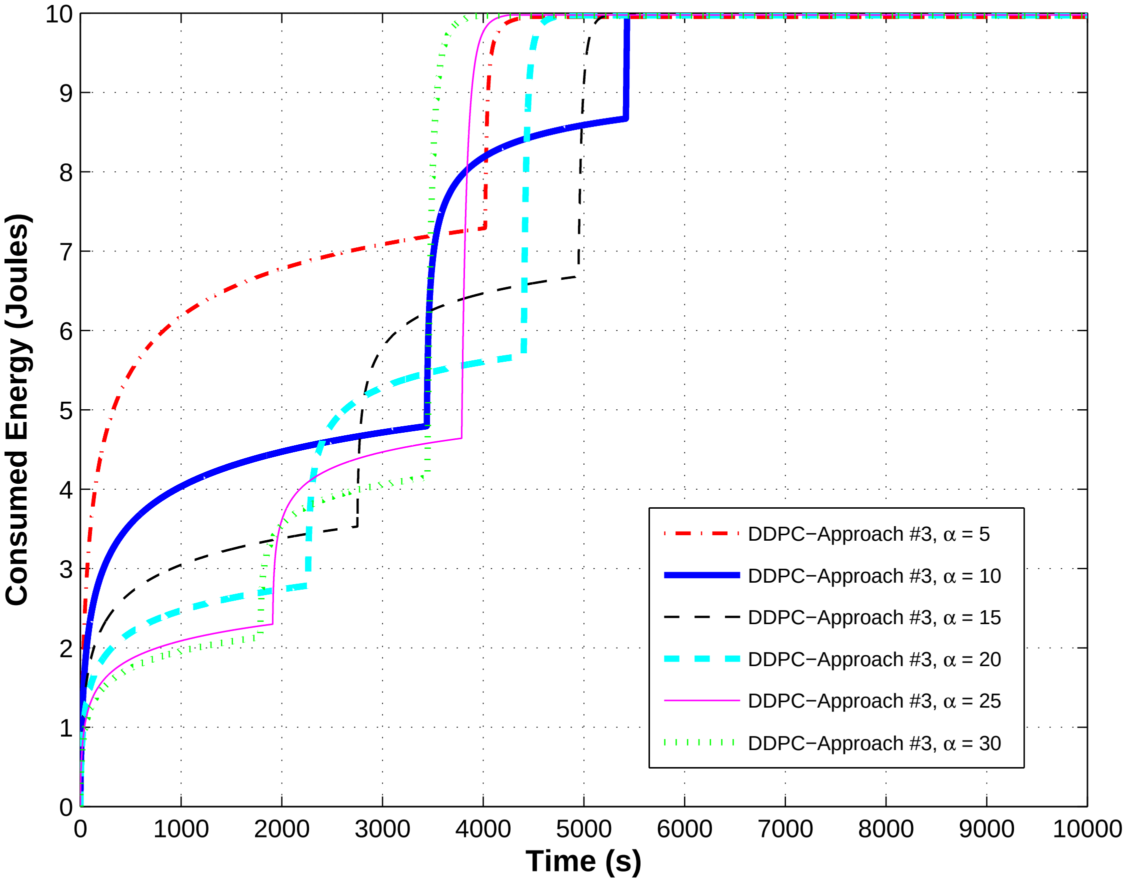


Figure 4.17. *Consumed energy for different values of* α *with DDPC Approach #3.*

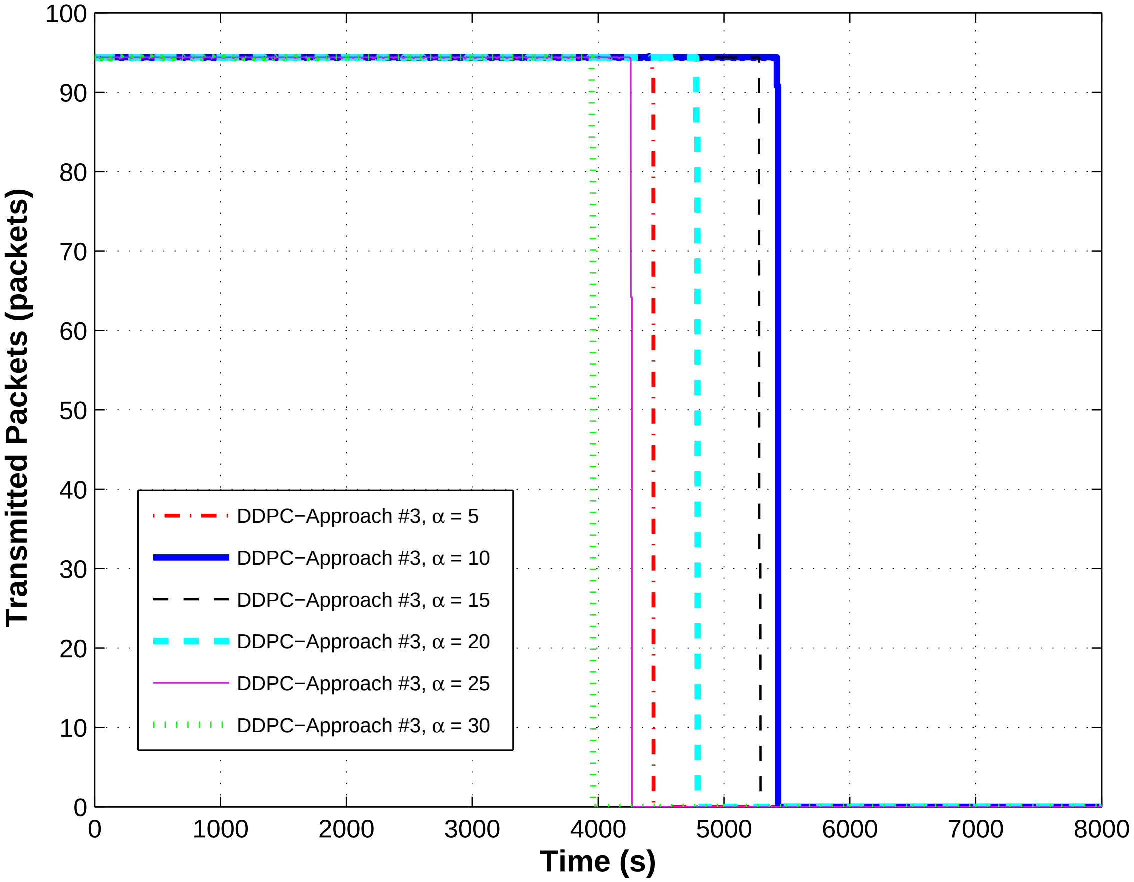


Figure 4.18. *Throughput for different values of* α *with DDPC Approach* $\#3$.

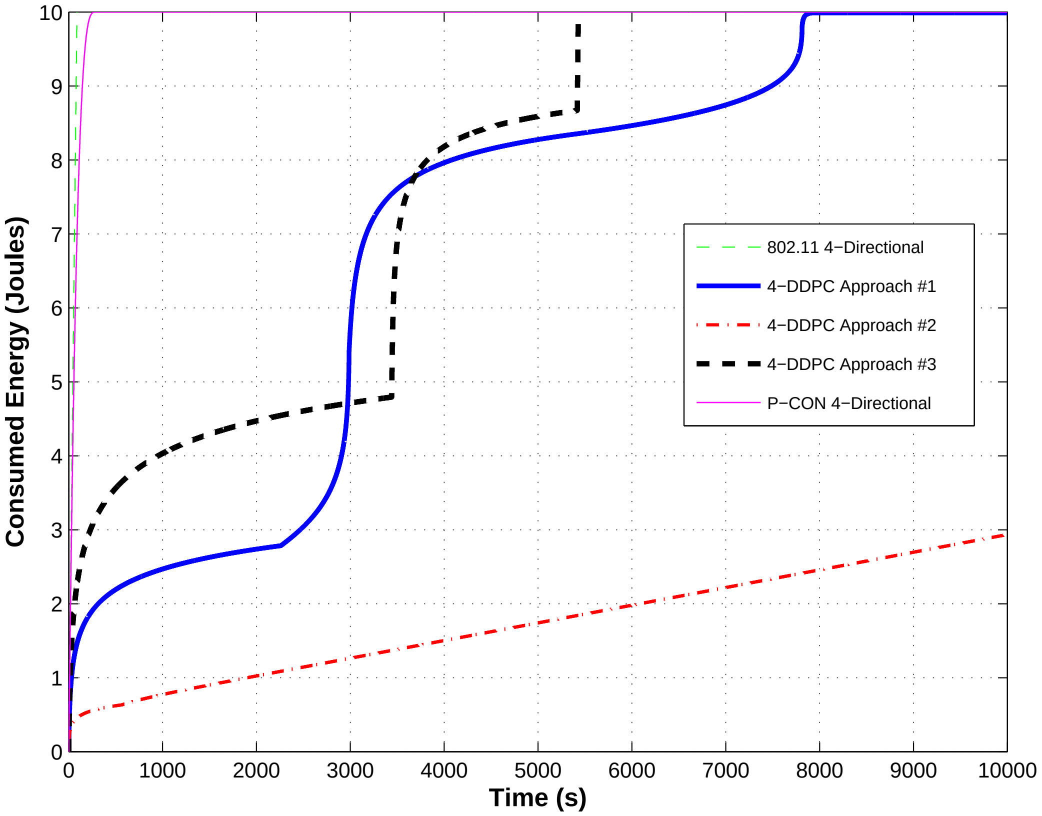


Figure 4.19. *Energy consumption with a Dtx-Orx communication link and a* 90° *(4 beams), directional antenna at a distance of 250m.*

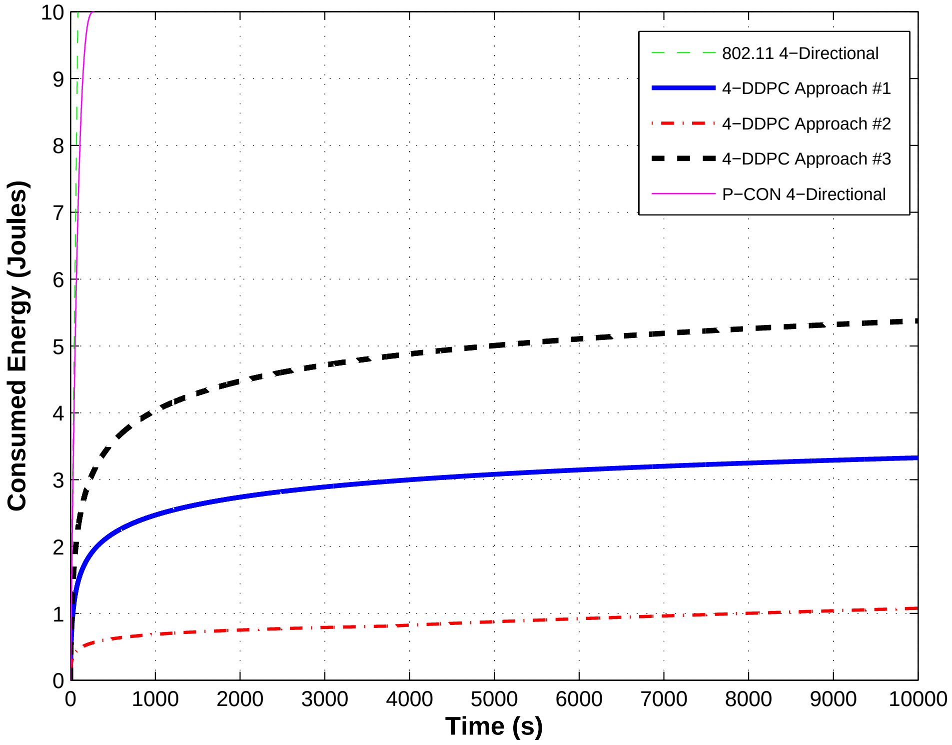


Figure 4.20. *Energy consumption with a Dtx-Drx communication link and a* 90° *(4 beams), directional antenna at a distance of 250m.*

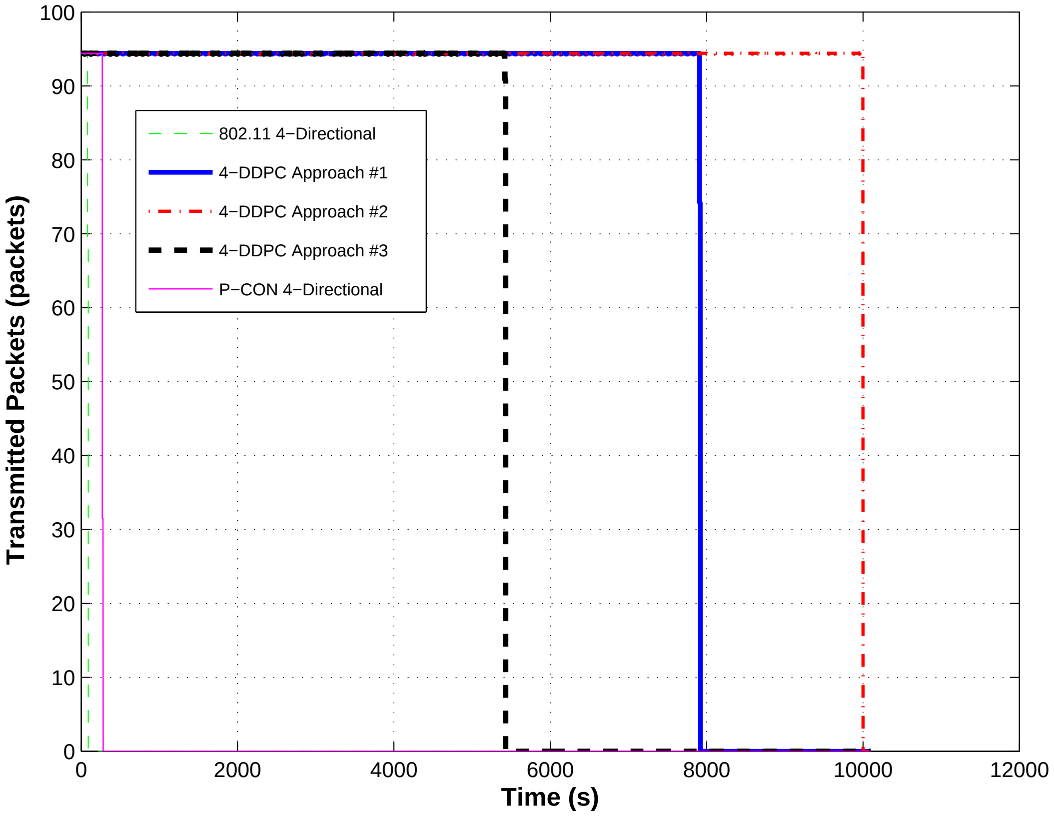


Figure 4.21. *Throughput with a Dtx-Orx communication link and a* 90° *(4 beams), directional antenna at a distance of 250m.*

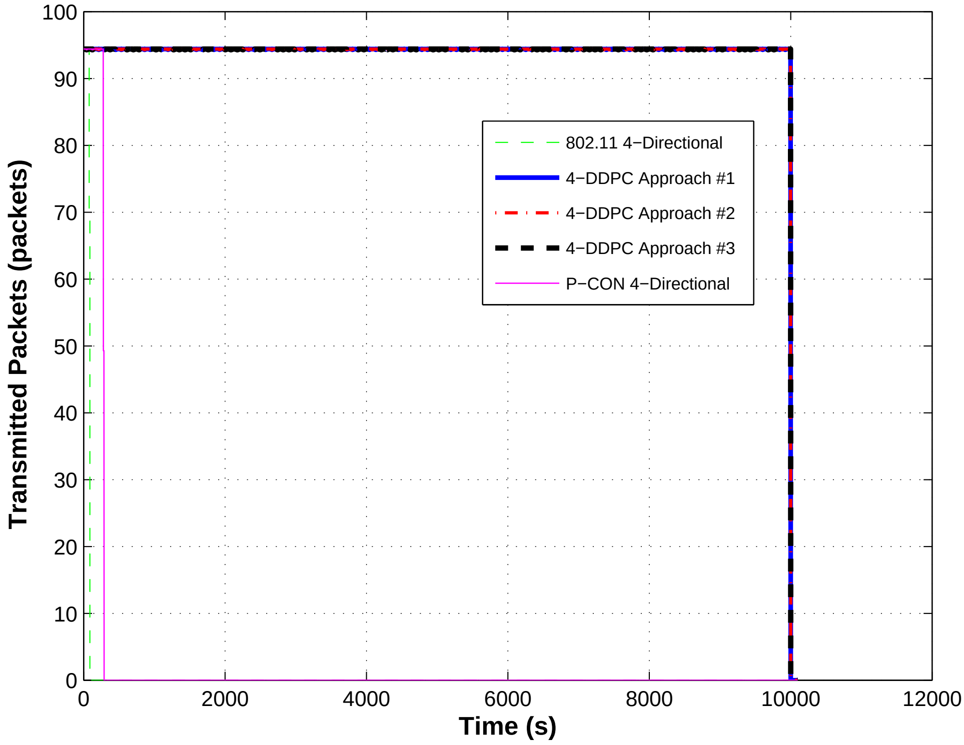


Figure 4.22. *Throughput with a Dtx-Drx communication link and a* 90° *(4 beams), directional antenna at a distance of 250m.*

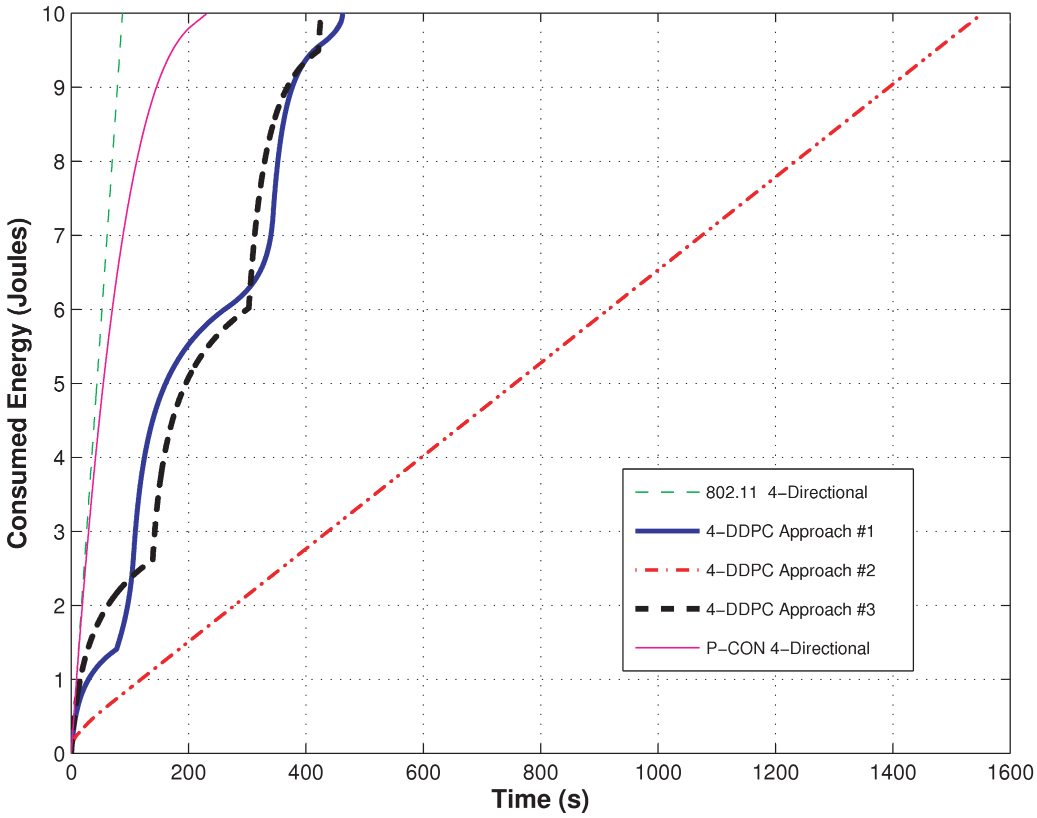


Figure 4.23. *Energy consumption with a Dtx-Orx communication link and a* 90° *(4 beams), directional antenna at a distance of 600m.*

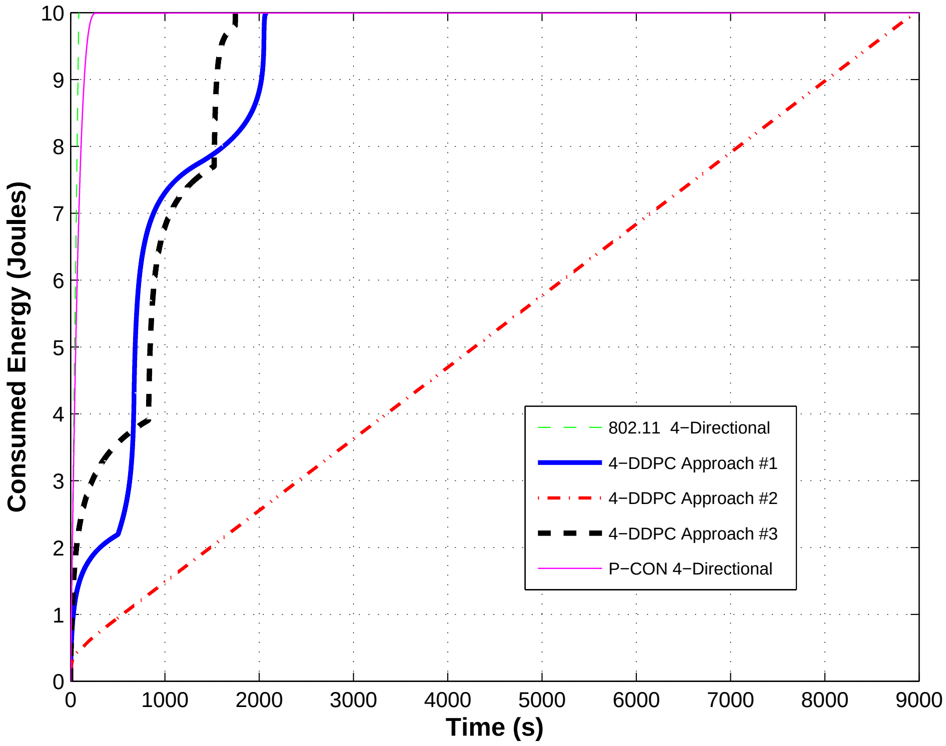


Figure 4.24. *Energy consumption with a Dtx-Drx communication link and a* 90° *(4 beams), directional antenna at a distance of 600m.*

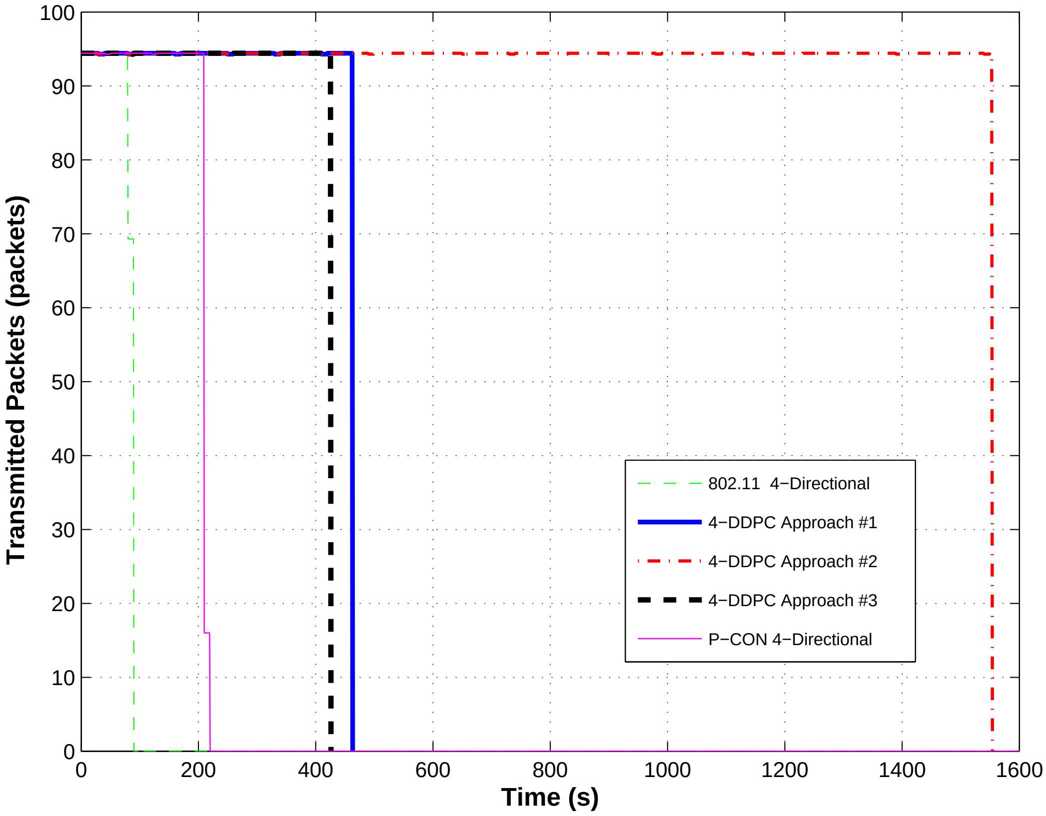


Figure 4.25. *Throughput with a Dtx-Orx communication link and a* 90° *(4 beams), directional antenna at a distance of 600m.*

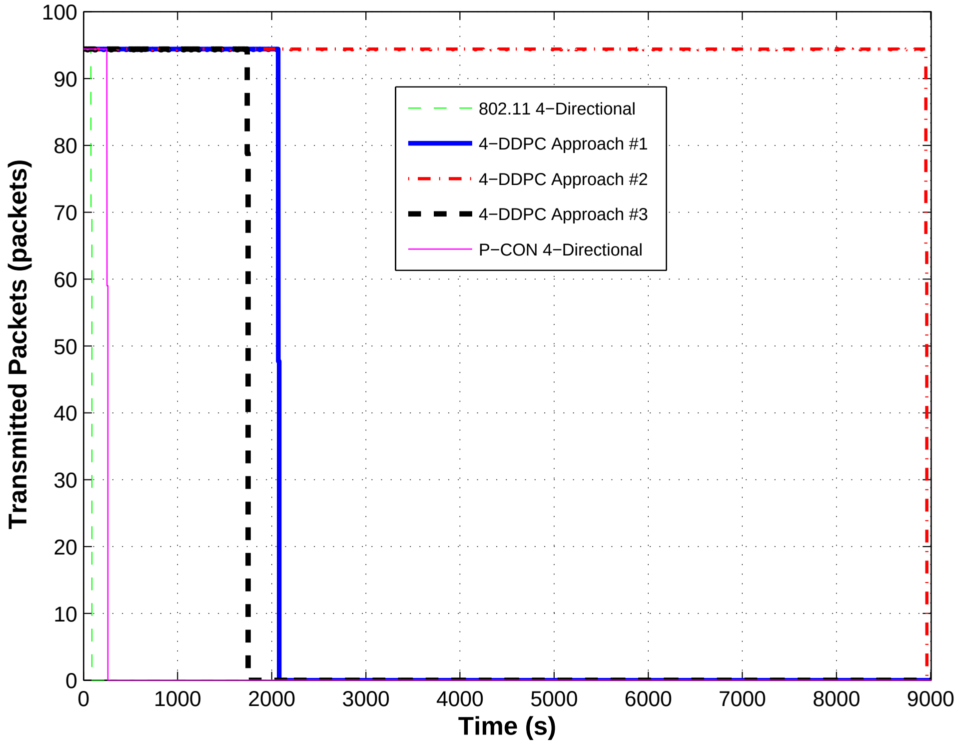


Figure 4.26. *Throughput with a Dtx-Drx communication link and a* 90° *(4 beams), directional antenna at a distance of 600m.*

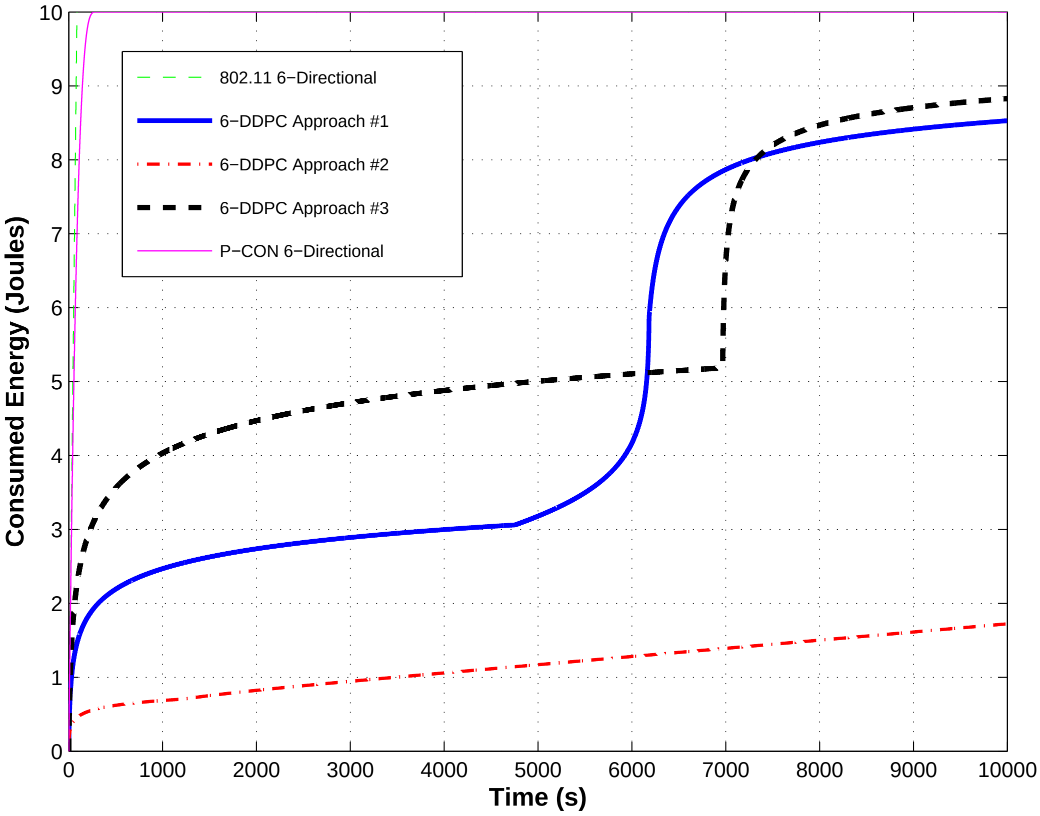


Figure 4.27. *Energy consumption with a Dtx-Orx communication link and a* 60° *(6 beams), directional antenna at a distance of 250m.*

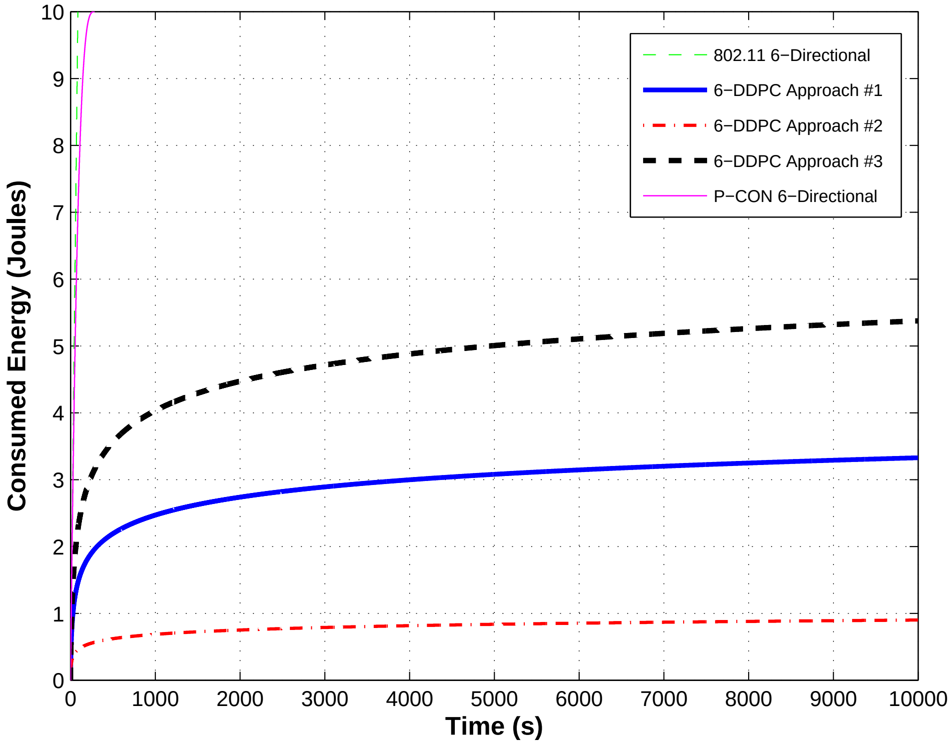


Figure 4.28. *Energy consumption with a Dtx-Drx communication link and a* 60° *(6 beams), directional antenna at a distance of 250m.*

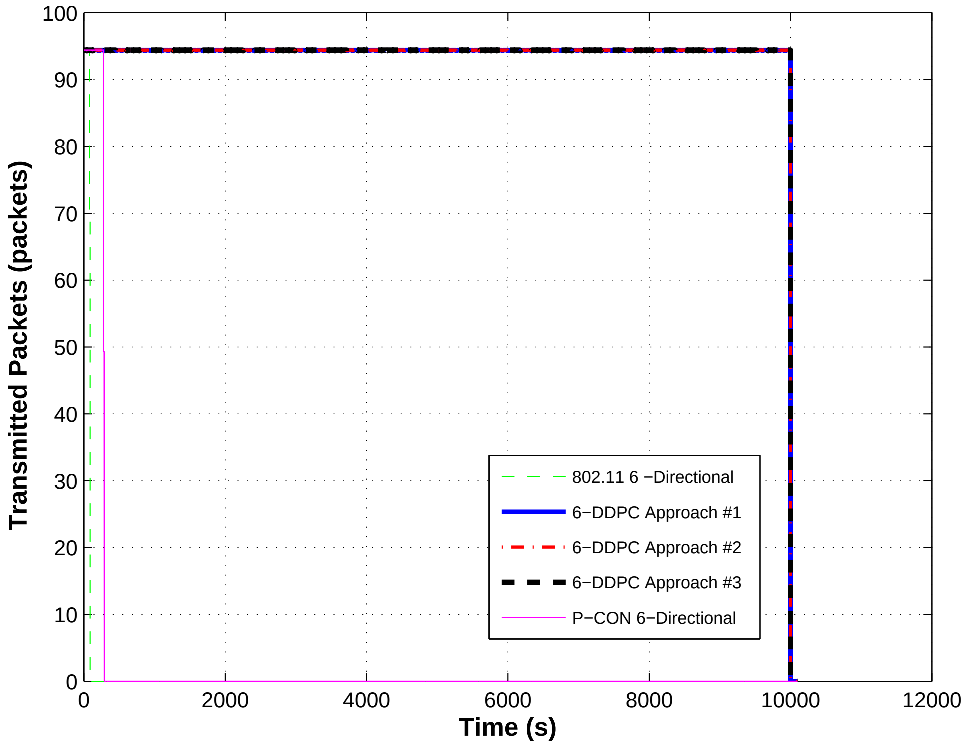


Figure 4.29. *Throughput with Dtx-Orx and Dtx-Drx communication links and a* 60° *(6 beams), directional antenna at a distance of 250m.*

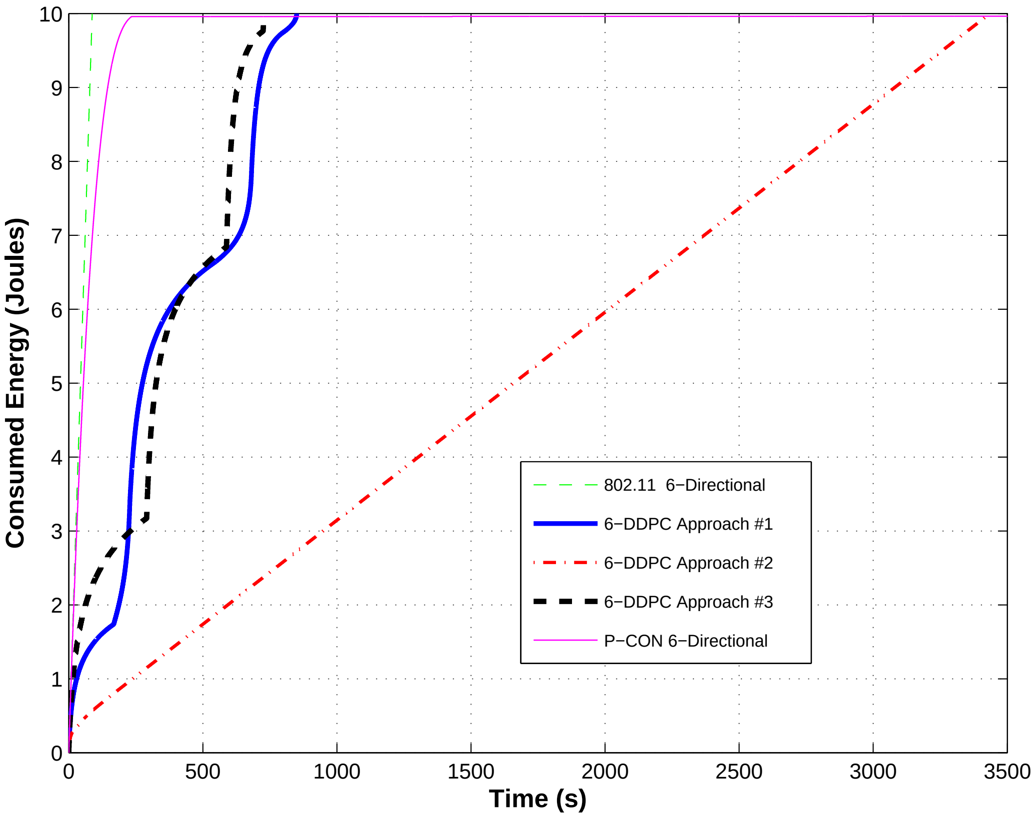


Figure 4.30. *Energy consumption with a Dtx-Orx communication link and a* 60° *(6 beams), directional antenna at a distance of 600m.*

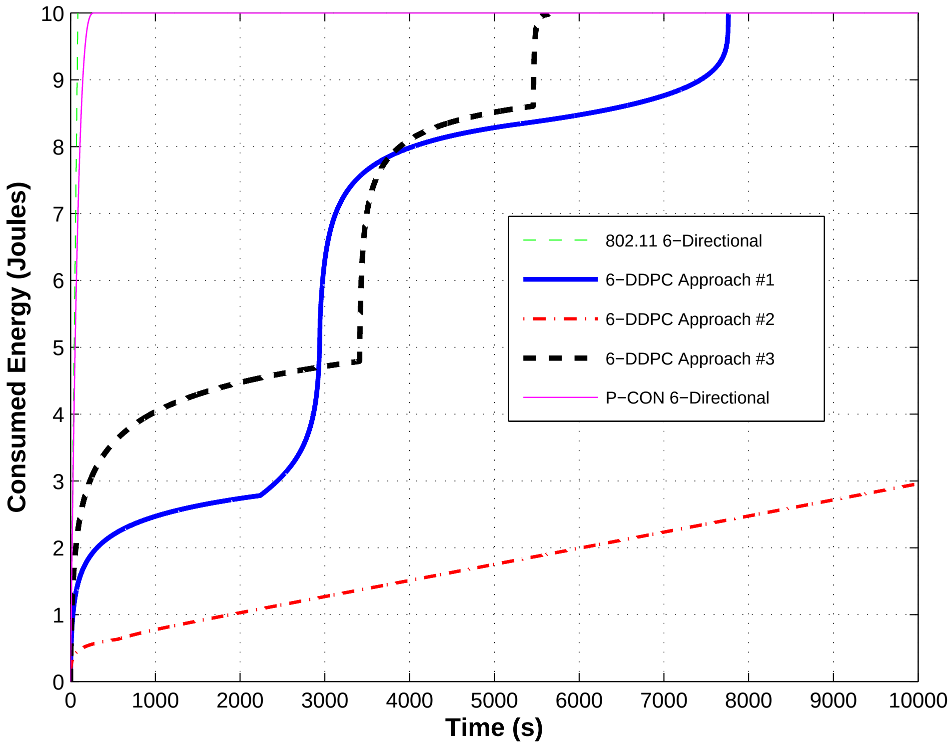


Figure 4.31. *Energy consumption with a Dtx-Drx communication link and a* $60°$ *(6 beams), directional antenna at a distance of 600m.*

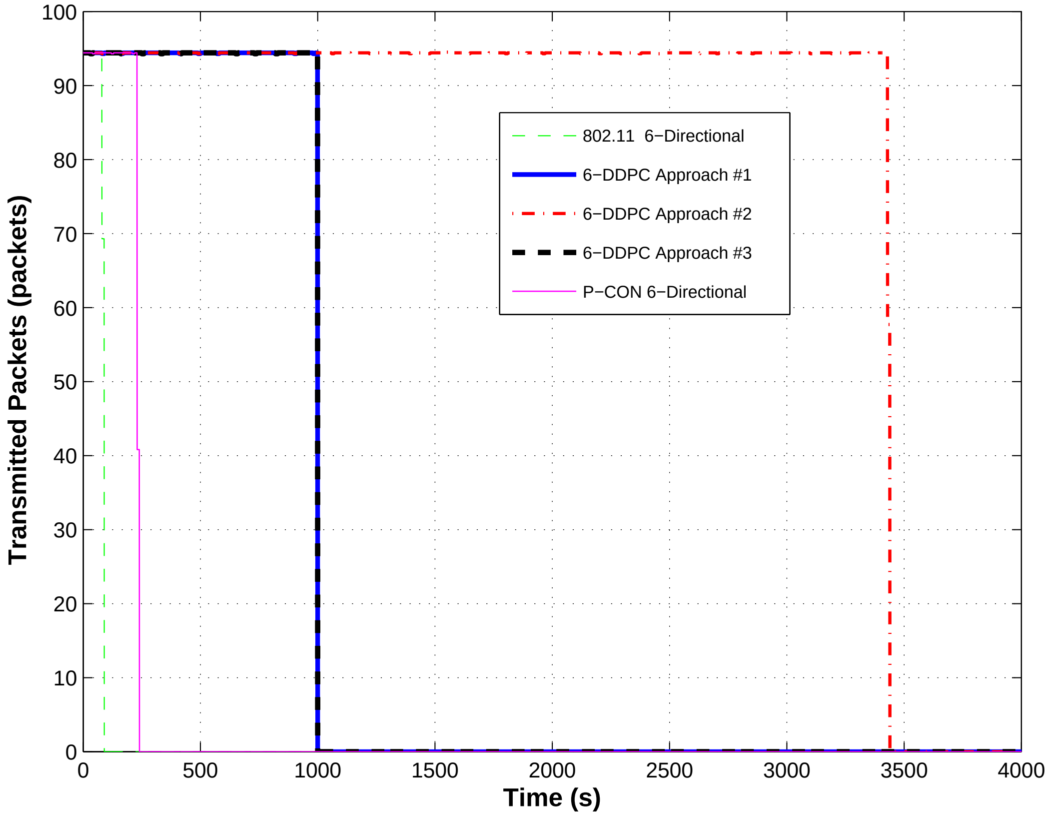


Figure 4.32. *Throughput with a Dtx-Orx communication link and a* 60° *(6 beams), directional antenna at a distance of 600m.*

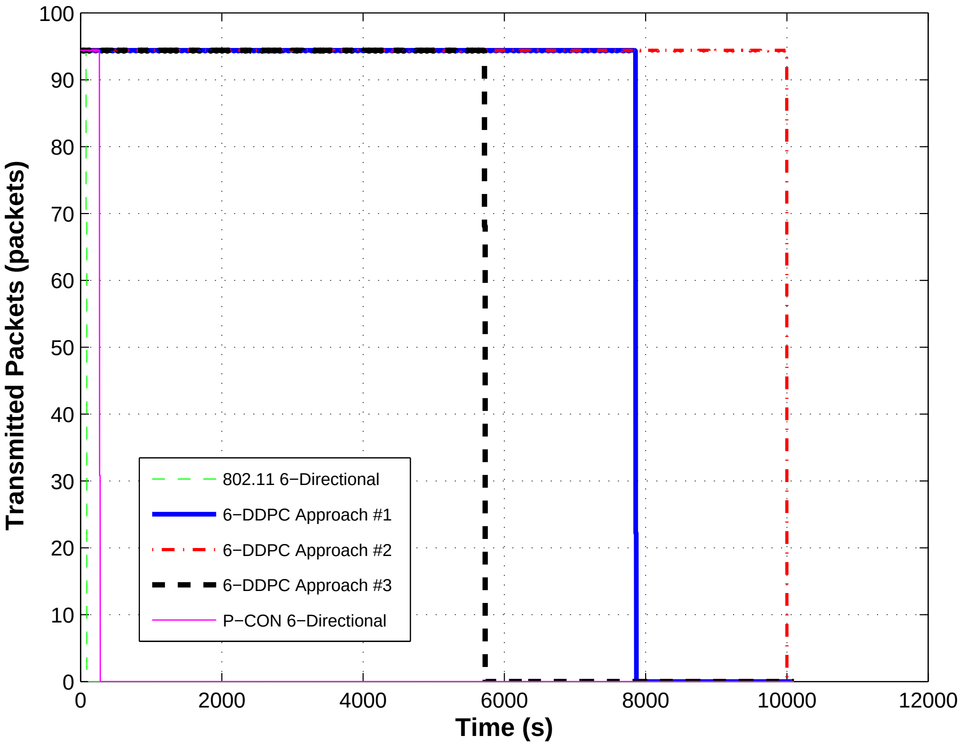


Figure 4.33. *Throughput with a Dtx-Drx communication link and a* 60° *(6 beams), directional antenna at a distance of 600m.*

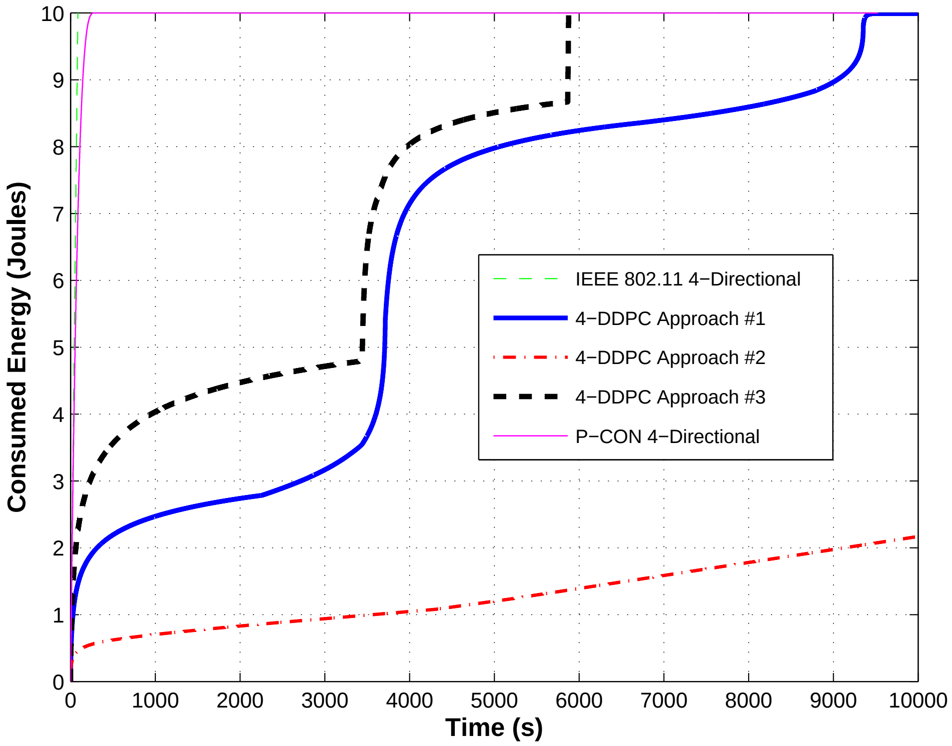


Figure 4.34. *Energy consumption with a Dtx-Drx communication link (flow 1) and a* 90° *(4 beams), directional antenna at a distance of 250m.*

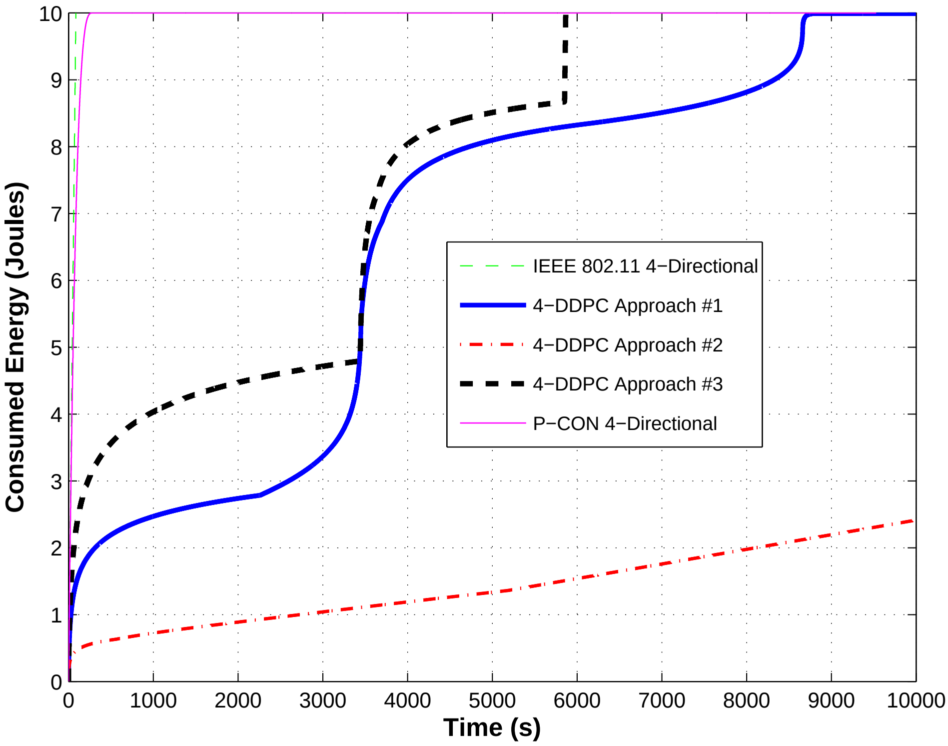


Figure 4.35. *Energy consumption with a Dtx-Drx communication link (flow 2) and a* 90° *(4 beams), directional antenna at a distance of 250m.*

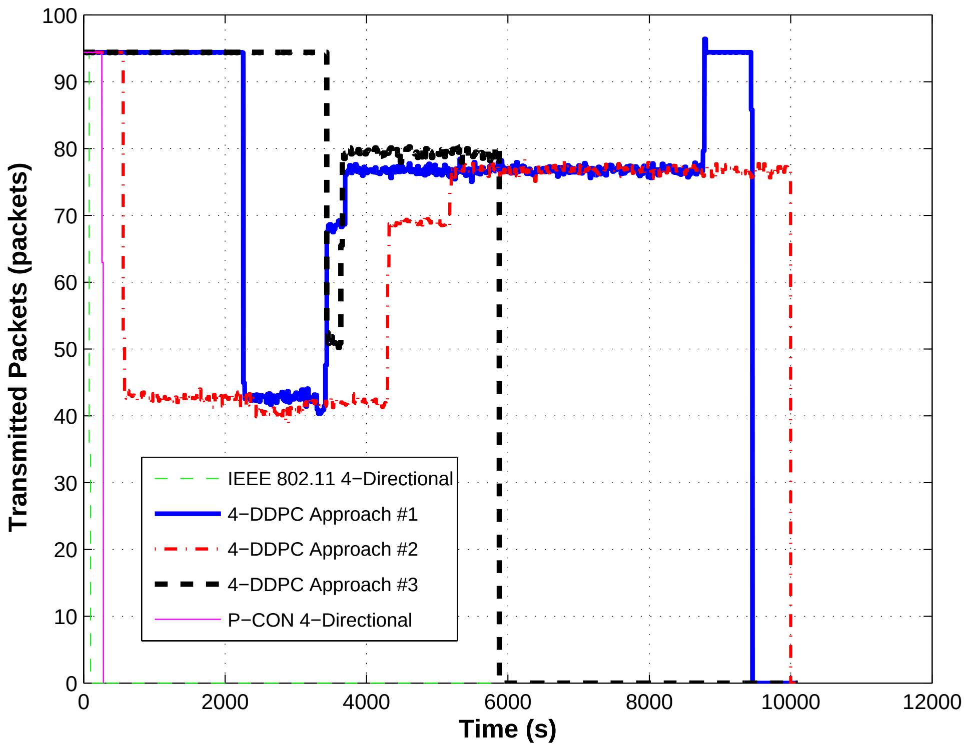


Figure 4.36. *Throughput with a Dtx-Drx communication link (flow 1) and a* 90° *(4 beams), directional antenna at a distance of 250m.*

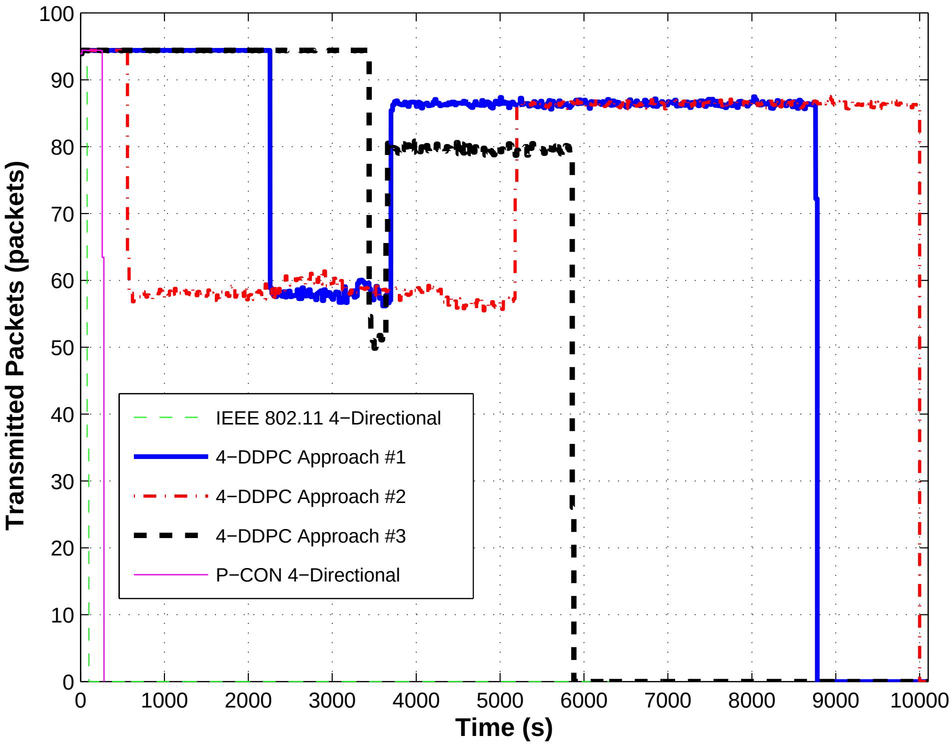


Figure 4.37. *Throughput with a Dtx-Drx communication link (flow 2) and a* 90° *(4 beams), directional antenna at a distance of 250m.*

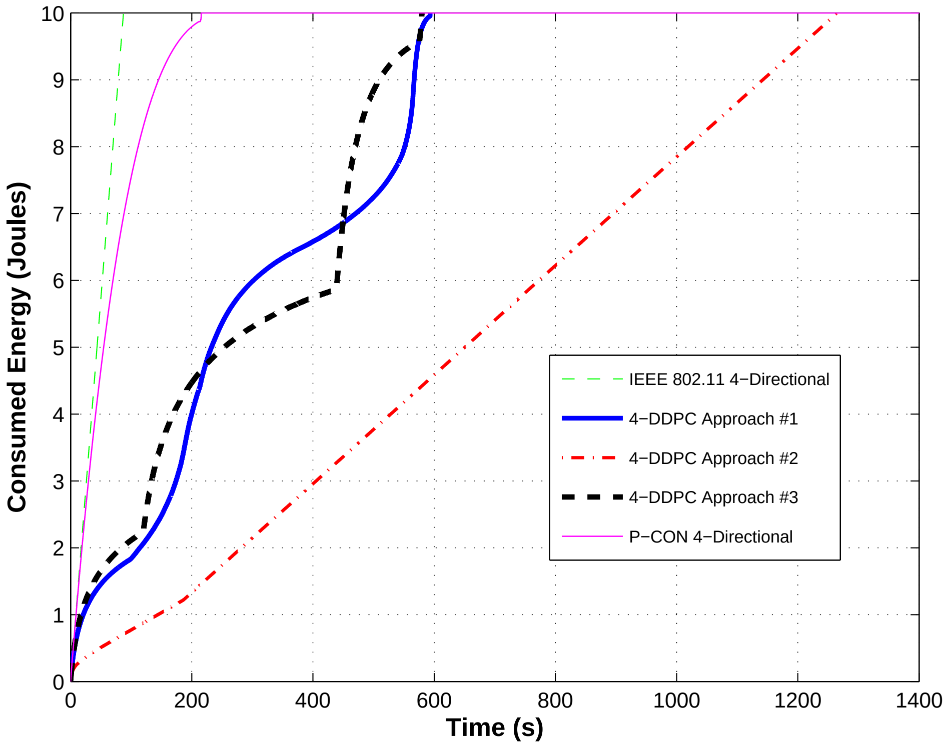


Figure 4.38. *Energy consumption with a Dtx-Drx communication link (flow 1) and a* 90° *(4 beams), directional antenna at a distance of 600m.*

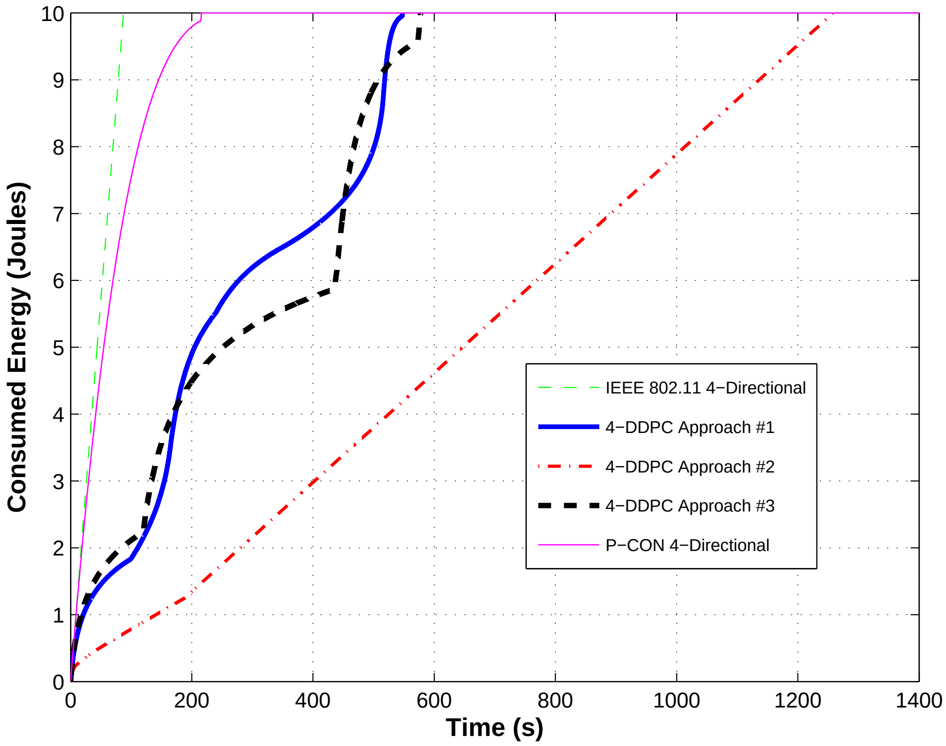


Figure 4.39. *Energy consumption with a Dtx-Drx communication link (flow 2) and a* 90° *(4 beams), directional antenna at a distance of 600m.*

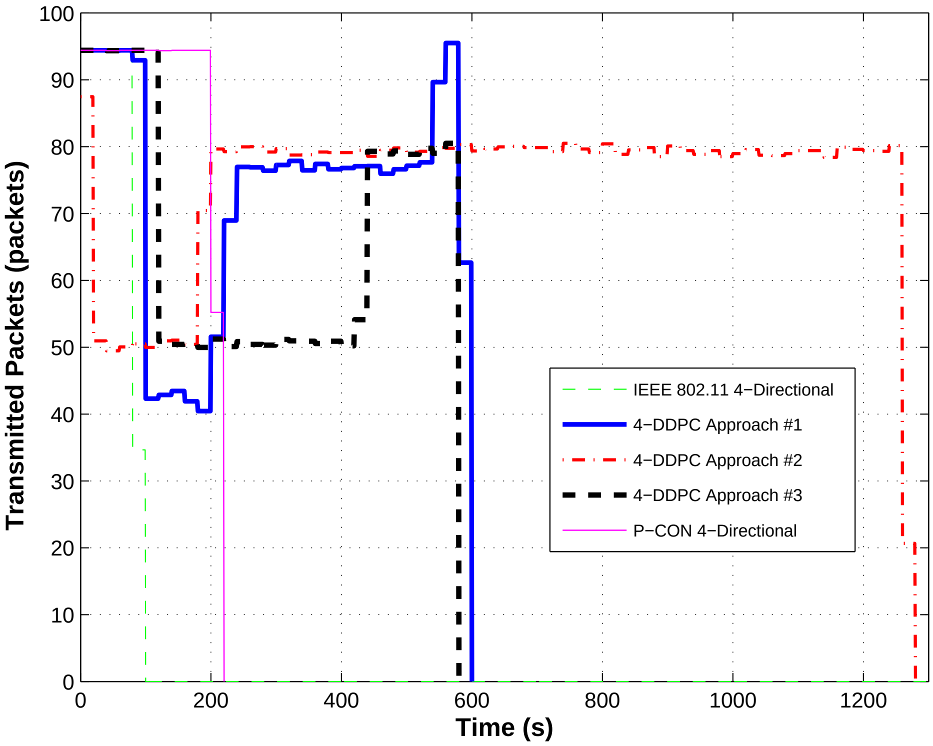


Figure 4.40. *Throughput with a Dtx-Drx communication link (flow 1) and a* 90° *(4 beams), directional antenna at a distance of 600m.*

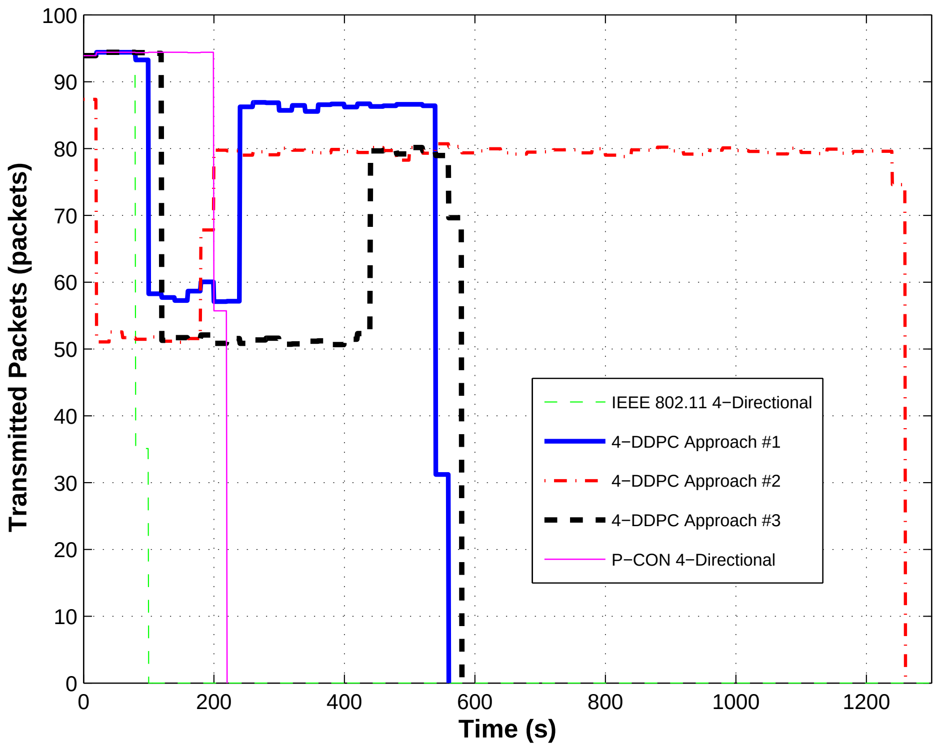


Figure 4.41. *Throughput with a Dtx-Drx communication link (flow 2) and a* 90° *(4 beams), directional antenna at a distance of 600m.*

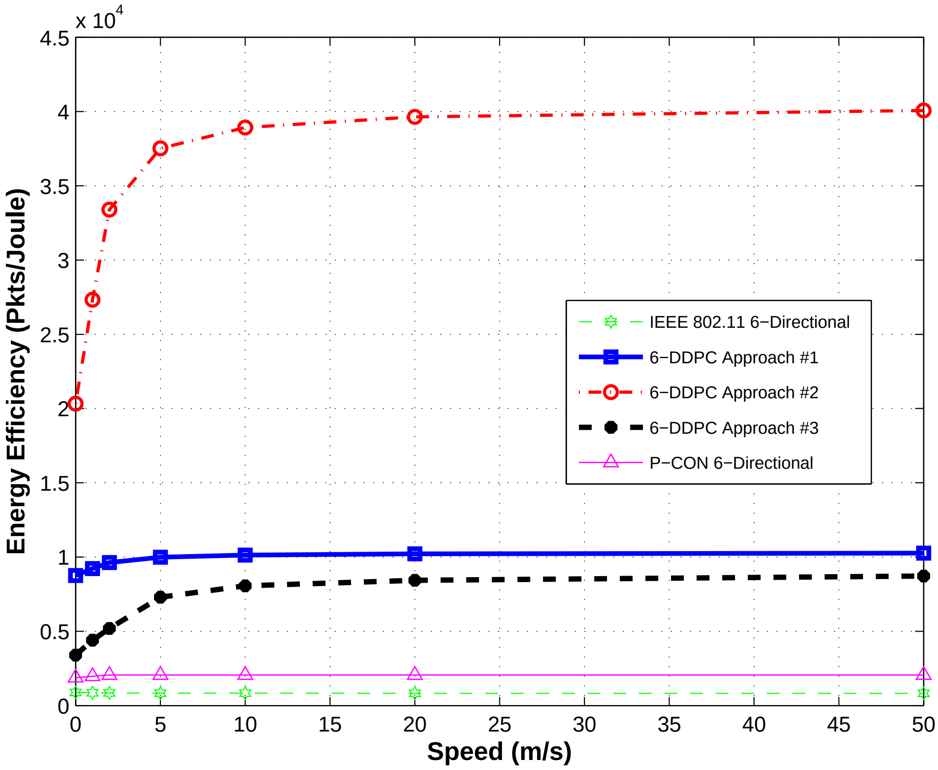


Figure 4.42. *Energy efficiency of two nodes in motion with speeds 1m/s, 2m/s, 5m/s, 10m/s, 20m/s, and 50 m/s.*

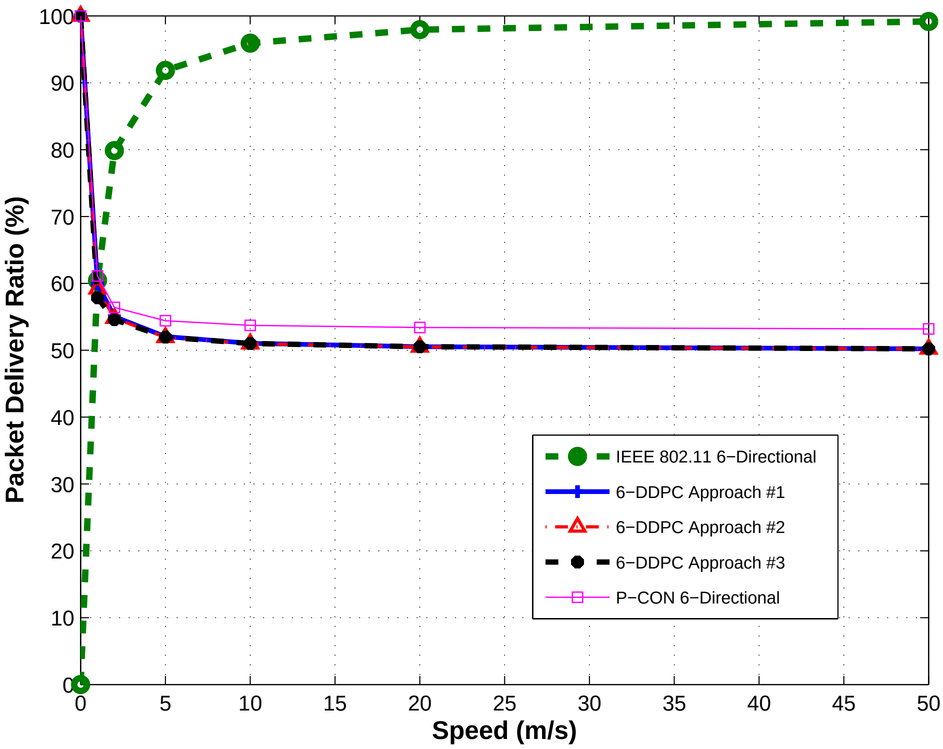


Figure 4.43. *Packet delivery ratio of two nodes in motion with speeds 1m/s, 2m/s, 5m/s, 10m/s, 20m/s, and 50 m/s.*

Chapter 5

Conclusions and Future Work

This chapter concludes the thesis and presents some directions for future research.

5.1 Conclusions

The growing success of wireless communications in ad hoc settings such as conferences, classrooms, or emergency scenarios is attracting unprecedented research interest [32]. A mobile ad hoc network (MANET) is an autonomous system of wireless mobile nodes that self-organize in a free and dynamical manner. MANETs allow wireless devices to connect and exchange data in areas without any preexisting communication infrastructure [19]. Ad hoc networks provide many advantages, however, they also present key challenges such as how to prolong the lifetime of nodes. The lifetime of a wireless network is limited by the battery energy of its wireless devices [6]. Batteries in wireless nodes have not improved as fast as wireless applications or memory storage capacity [4]. The energy consumption of battery-powered devices is an important matter that requires significant attention [6], thus it is critical to develop energy efficiency protocols for ad hoc networks. Using energy efficient protocols in wireless mobile nodes can increase the lifetime and improve the quality of wireless networks [12].

Energy efficient protocols based on *transmission power control* are of interest since the transmission power determines the energy consumed by a node and the range over which the signal can be received with good quality [12]. Reducing the transmission range reduces the energy required to deliver data packets to a destination, however, a reduction of transmission range increases the number of hops to reach a destination [12]. Since ad hoc networks typically assume the use of omnidirectional antennas at all nodes, using these antennas with transmission power control may increase the number of hops to a destination, reducing the connectivity of the network [9]. Therefore, transmission power control with omnidirectional antennas needs to be closely controlled to reach the desired destination while causing minimal interference to other nodes [13].

Energy saving in transmission motivates the development of a new protocol. In this thesis, we proposed the design and implementation of an energy efficient protocol able to minimize energy in transmission, control transmit power dynamically, reduce interference, provide long transmission ranges, maintain network connectivity, and adapt to different network environments. This new protocol is called the *Dynamic Directional Power Control* (DDPC) protocol. DDPC employs directional antennas because of their advantages over omnidirectional antennas. The characteristics of directional antennas and how they outperform omnidirectional antennas was presented in Chapter 2. In Chapter 2, we briefly described the IEEE 802.11 standard (ad hoc networks typically employ this protocol) and the benefits and effects of varying the transmit power of a node.

DDPC considers the remaining battery energy of a node before it selects the appropriate power level in transmission. Literature in the context of reducing consumed energy in transmission was examined in Chapter 3. This chapter considers one protocol in particular that takes into account the remaining battery energy of a node before changing its transmission power, called *residual battery power base transmission power control* (P-CON) [2]. In this chapter, P-CON was compared with the IEEE 802.11 protocol through simulations.

The characteristics, design and implementation of DDPC were presented in Chapter 4. Three approaches were considered for the DDPC protocol. Each approach was intended to perform better under particular network circumstances such as, static scenarios without interference, static scenarios with interference, and scenarios with mobility. In this chapter we used the *Network Simulator* (NS-2) [45] to find, through simulations, the most suitable *power control tuning parameter* (α) for each DDPC scheme. We also analyzed the performance of DDPC in static and mobility scenarios.

In the static scenarios without interference, we found that the *Dtx-Drx* communication links increase the effects of energy saving. We verified that Approach $\#2$ consumes the least battery energy. The packet delivery ratio in all cases was kept at a constant value of 94.4$\%$ since there was no interference. Thus, DDPC Approach $\#2$ performs the best in static scenarios with no interference.

In static scenarios with simultaneous transmissions (with interference) DDPC allows two pairs of nodes to communicate in the same vicinity. DDPC reduces the effects of interference by using directional antennas. In the presence of interference with short separation distances, Approach $\#3$ provides the best packet delivery ratio and lasts the longest. In addition, Approach $\#3$ consumes the battery energy faster than the other two approaches. However, when there is more interference, it is better to use Approach $\#3$. Approach $\#3$ also shows the lowest packet loss rate. In scenarios with interference where the separation distance between the transmitter and receiver is longer, Approach $\#2$ outperforms the other two schemes. In this case, the packet delivery ratio is much less since DDPC consumes more energy with longer distances.

With mobility, IEEE 802.11 and P-CON perform better than the DDPC approaches in situations when there are significant amounts of data to be transferred, and situations where connectivity during motion is important. However, DDPC offers more energy saving when nodes are in motion over short distances.

We conclude that DDPC protocol is well suited for static scenarios with and without interference since DDPC outperforms P-CON and IEEE 802.11.

5.2 Future Work

In this thesis, we proposed a protocol to provide energy efficiency in transmission in ad hoc networks. In an ad hoc network, wireless nodes run on batteries with a lifetime of perhaps a few hours of active lifetime. Our protocol improves this crucial factor by improving energy consumption at the node level, by controlling transmission power. However, there still exist more challenges, as there is no universal solution. Although we focused on saving energy in transmission, it is possible to implement *Energy Saving Mechanisms* in addition to DDPC. For instance, DDPC could be combined with an *energy saving management (sleep mode)* protocol. This will allow mobile nodes to switch to a low power sleep mode when they are inactive. Wireless nodes are in an awake state to transmit and receive (or in an idle state). During the awake state, nodes can save energy by using the DDPC protocol. With this new scheme, wireless nodes can save energy when they are inactive (sleep mode) or awake (DDPC protocol).

In regards to directional antennas, a MAC protocol can be developed which is suitable for such antennas. By modifying the IEEE 802.11 MAC protocol for directional antennas (DMAC), it is possible to have better control of directional transmissions. Upper layers are aware of the neighbors of a node, and this profile information can be sent to the DMAC layer. Then the DMAC layer can request the physical layer to beamform according to the profile information [15]. Thus transmission is more efficient and intelligent, increasing throughput, compared to MAC protocols with directional antennas. A DMAC protocol combined with DDPC will save more energy and increase throughput.

One can also consider extending the DDPC protocol to the MAC level so that transmit power levels can be varied on a per-packet basis. The idea is to use different power levels for RTS/CTS control packets and Data/ACK packets. A maximum power level of $MaxTx$ can be assigned to the RTS/CTS packets with different beamwidth transmissions. RTS packets can be sent directionally, and CTS packets can be sent omnidirectionally to reduce the effects of *deafness* when using directional antennas. Using a minimum power level, $MinTx$, to transmit Data/ACK packets can degrade network throughput. To avoid this situation, the DDPC protocol can be used only to transmit Data and ACK packets using a Dtx-Drx link.

The DDPC protocol can be improved by combining it with energy saving mechanisms at the network layer. AODV can be modified to work better with directional antennas, resulting in DAODV. The goal is to create paths (to a destination) to balance the energy consumption among nodes within a network and then prolong the lifetime of the network [9]. An effective communication route is established by selecting an average energy level for the directional transmission. This level is based on the ratio between the residual battery energy of the node and the network average energy. Then the average energy is recorded on the routing table of the current node at the time when the route is established. If the transmit energy lowers the average energy level, the source node has to rediscover a new route and find a new average energy level [9]. In order to reduce redundant route refreshing in DAODV, the effective communication route can be established using DDPC Approach #2. this approach can be modified to employ the next higher energy level (to keep nodes connected), when the transmitter loses connection. A new protocol based on DAODV and DDPC can increase the network lifetime while improving network performance.

The final suggestion for future work is the development of a more global automated DDPC which can dynamically switch from one approach to another depending on the network environment. In our approach, DDPC is configured to work with one specific scheme at a time. To extend this, a DDPC protocol could be developed to sense the network environment in order to switch automatically to an appropriate DDPC approach. This future research is definitely worth considering.

Bibliography

[1] I. Kang, R. Poovendran, and R. Ladner, “Power-Efficient Broadcast Routing in Adhoc Networks using Directional Antennas: Technology Dependence and Convergence Issues,” *Tech Rep. UWEETR-2003-0015, Dept. of EE, University of Washington*, pp. 2-4, 2003.

[2] N. Meghanathan and A. Farago, “Power Sensitive Power Control in Ad Hoc Networks,” *in Proc. ACM Southeast Conference*, pp. 18-20, Mar. 2005.

[3] R. Choudhury and N. H. Vaidya, “Impact of Directional Antennas on Ad Hoc Routing,” *in Proc. International LNCS Conference on Personal and Wireless Communication*, pp. 590-600, Sep. 2003.

[4] H. Xu, M. Jeon, L. Shu, W. Xiaoling, J. Cho, and S. Lee, “Localized Energy-Aware Broadcast Protocol for Wireless Networks with Directional Antennas,” *in Proc. IEEE International Conference on Embedded Software and Systems (ICESS)*, pp. 696-707, Dec. 2005.

[5] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar, “Power Control in Ad-hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW Protocol,” *in Proc. European Wireless Conference*, pp. 156-162, Feb. 2002.

[6] L. Kaddar and A. Mehaoua, “ESTREL: Transmission and Reception Energy Saving Model for Wireless Ad Hoc Networks,” *in Proc. IEEE Conference on Local Computer Networks*, pp. 784-785, Oct. 2007.

[7] V. Kawadia and P. Kumar, “Principles and Protocols for Power Control in Wireless Ad hoc Networks,” *IEEE Journal on Wireless Ad Hoc Networks*, pp. 76-88, Jan. 2005.

[8] E. Jung and N. H. Vaidya, “A Power Control MAC Protocol for Ad hoc Networks,” *in Proc. ACM/IEEE Annual International Conference on Mobile Computing and Networking (MOBICOM)*, pp. 36 - 47, 2002.

[9] C. Jie, C. Jiapin, and L. Zhenbo, “Energy-Efficient AODV for Low Mobility Ad Hoc Networks,” *International Conference on Wireless Communications, Networking and Mobile Computing (WiCom)*, pp. 1512 - 1515, Sep. 2007.

[10] X. Jing and M. Lee, “Energy-Aware Algorithms for AODV in Ad Hoc Networks,” *in Proc. of Mobile Computing and Ubiquitous Networking (ICMU 2004)*, Jan. 2004.

[11] S-J. Park and R. Sivakumar, "Load-Sensitive Transmission Power Control in Wireless Ad-hoc Networks," *in Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 42-46, Nov. 2002.

[12] M. Krunz, A. Muqattash, and S-J. Lee, "Transmission Power Control in Wireless Ad Hoc Networks: Challenges, Solutions, and Open Issues," *IEEE Network*, vol. 18, no. 5, pp. 8-10, Sep.-Oct. 2004.

[13] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 389-391, Mar. 2000.

[14] C. A. Balanis, "Smart Antennas for Future Reconfigurable Wireless Communication Networks," *IEEE Topical Conference on Wireless Communication Technology*, pp. 181-182, Oct. 2003.

[15] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "Using Directional Antennas for Medium Access Control in Ad Hoc Networks," *in Proc. ACM/IEEE Annual International Conference on Mobile Computing and Networking (MOBICOM)*, pp. 59-70, Sep. 2002.

[16] Y.-B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks," *in Proc. IEEE Conference on Computer Communications (INFOCOM)*, pp. 13-21, Mar. 2000.

[17] R. R. Choudhury and N. H. Vaidya, "Deafness: A MAC Problem in Ad hoc Networks when using Directional Antennas," *in Proc. IEEE International Conference on Network Protocols*, pp. 283-292, Oct. 2004.

[18] C. K. Toh, "Wireless ATM and Ad-Hoc Networks: Protocols and Architectures," *Kluwer Academic Publishers*, pp. 193-227, Jan. 1997.

[19] C. Perkins, Ad Hoc Networking, *Addison-Wesley Longman Publishing Co., Inc.*, pp. 173-184, Jan. 2001.

[20] J. G. Purdy, "Tri-Mode Wi-Fi: key to Enterprise IT," *MOBILITY: Mobile and Wireless Solutions for Today's Business*, pp. 16-23, Fall 2003.

[21] M. S. Gast, "802.11 Wireless Networks: The Definitive Guide," *O'Relly and Associates, Inc.*, Apr. 2002.

[22] Y-C. Tseng and T.-Y. Lin, "Power-Conservative Design in Ad Hoc Wireless Networks," in M. Ilyas, *The Handbook of Ad Hoc Wireless Networks, CRC Press*, pp. 2-3, 2003.

[23] A. M. Safwat, H. S. Hassanein, and H. T. Mouftah, "Power-Aware Wireless Mobile Ad Hoc Networks," in M. Ilyas, *The Handbook of Ad Hoc Wireless Networks, CRC Press*, pp. 2-5, 2003.

[24] H. Y. Youn, C. Yu, B. Lee, and S. Moh, "Energy Efficient Multicast in Ad Hoc Networks," in M. Ilyas, *The Handbook of Ad Hoc Wireless Networks, CRC Press*, pp. 5-7, 2003.

[25] I-P. Sheu, C.-T. Hu, and C.-M. Chao, "Energy-Conserving Grid Routing Protocol in Mobile Ad Hoc Networks," in M. Ilyas, *The Handbook of Ad Hoc Wireless Networks, CRC Press*, pp. 2-4, 2003.

[26] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "An Adaptive Energy-Efficient and Low-Latency MAC for Data Gathering in Wireless Sensor Networks," *in Proc. International Parallel and Distributed Processing Symposium*, pp. 224-231, Apr. 2004.

[27] L. Hu, "Topology Control for Multihop Packet Radio Networks," *IEEE Transactions on Communications*, vol 41, no. 10, pp. 1474-1481, Oct. 1993.

[28] Y. Chen, Q. Zhao, V. Krishnamurthy, and D. Djonin, "Transmission Scheduling for Sensor Network Lifetime Maximization: A Shortest Path Bandit Formulation," *in Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 145-148, May 2006.

[29] L. Yin, C. Wang, and G.E. Oien, "Energy Consumption Optimization in Data Transmission from Correlated Sensor Nodes," *in Proc. International Symposium on Wireless Communications Systems (ISWCS)*, pp. 26-30, Oct. 2007.

[30] T. Yang, L. Barolli, M. Ikeda, A. Durresi, and F. Xhafa, "Network Energy Consumption in Ad-Hoc Networks under Different Radio Models," *in Proc. International Conference on Parallel and Distributed Systems (ICPADS)*, pp. 1-8, Dec. 2007.

[31] A. Sheth and R. Han, "An Implementation of Transmit Power Control in 802.11b Wireless Networks," *Tech Rep. CU-CS-934-02, University of Colorado at Boulder*, pp. 5-9, Aug 2002.

[32] S. Taylor and M.P. Ferencczi, "How Wi-Fi Works," *PC Up-Grade: Wi- Fi A to Z*, vol. 6, no. 8, pp. 16-21, Fall 2003.

[33] S. Yi, Y. Pei, S. Kalyanaraman, and B. Azimi-Sadjadi, "How is the Capacity of Ad Hoc Networks Improved with Directional Antennas?," *in Proc. ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pp. 108-116, Mar. 2003.

[34] V. Kolar, "Challenges in Directional Antennas," *Masters Thesis, Binghamton University, State University of New York*, Mar. 2004.

[35] S. V. Heuvel and C. Blondia, "A survey of MAC protocols for Ad Hoc networks and IEEE 802.11," *PATS Research Group, University of Antwerp*, 2005.

[36] M. Gruteser, A. Jain, J. Deng, F. Zhao, and D. Grunwald, "Exploiting Physical Layer Power Control Mechanisms in IEEE 802.11b Network Interfaces," *Tech Rep. CU-CS-*

924-01, Department of Computer Science, University of Colorado at Boulder, pp. 4-10, 2001.

[37] S. V. Heuvel and C. Blondia, "IEEE 802.11 Wireless Local Area Networks," *IEEE Communications Magazine*, vol. 35, no. 9, pp. 116-126, Sep. 1997.

[38] A. Nasipuri, J. Mandava, H. Manchala, and R. E. Hiromoto, "On-demand Routing Using Directional Antennas in Mobile Ad Hoc Networks," *in Proc. International Conference on Computer Communications and Networks*, pp. 535-541, Oct. 2000.

[39] A. C. Ajay and J. O. Limb, "Wireless Medium Access Control Protocols," *IEEE Communications Surveys and Tutorials*, vol. 3, no. 2, pp. 2-15, Nov 2009.

[40] F. Dai and J. Wu, "Efficient Broadcasting in Ad Hoc Wireless Networks Using Directional Antennas," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, pp. 335-347, Apr. 2006.

[41] I. Caragiannis, C. Kaklamanis, and P. Kanellopoulos, "Power Consumption Problems in Ad-Hoc Wireless Networks," *In Proc. Meeting of the North American Chapter of the ACL*, pp. 252-255, Feb. 2004.

[42] J.-M. Dricot and P. D. Doncker, "High-Accuracy Physical Layer Model for Wireless Network simulations in NS-2," *in Proc. International Workshop on Wireless Ad-Hoc Networks*, pp. 249-252, June 2004.

[43] G. Anastasi, E. Borgia, M. Conti, and E. Gregori, "IEEE 802.11b Ad Hoc Networks: Performance Measurements," *Journal of Cluster Computing*, vol. 8, no. 2, pp. 135-145, July 2005.

[44] D. Groth and T. Skandier, "Network+," *Wiley*, pp. 107-109, 2005.

[45] S. McCanne and S. Floyd, "NS Network Simulator," *http://www.isi.edu/nsnam/ns/*

[46] B. Raman and K. Chebrolu, "The Enhanced Network Simulator (TENS)," *http://www.cse.iitk.ac.in/users/braman/tens/*

[47] L. Breslau, et al., "Advances in Network Simulation," *IEEE Computer*, vol. 33, no. 5, pp. 59-67, May 2000