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by
Qiaozhong Ke

School of Information Technology and Engineering

Submitted in partial fulfillment of
the requirements for the degree of
Master of Applied Science

Faculty of Graduate and Postdoctoral Studies
The University of Ottawa
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ABSTRACT

This thesis addresses the performance analysis and improvement of Wireless IEEE 1394 networks. Wireless IEEE 1394 appears to be the only existing QoS capable broadband wireless home networking solution that has been standardized. Our study investigates the performance of the original Wireless 1394 protocol. It also addresses protocol extensions that improve the original Wireless 1394 network, as well as add new useful functionalities. The performance analysis has taken into consideration the behaviour of the wireless channel through simple, yet effective and widely used model. The evaluation demonstrated the strong potential of Wireless IEEE 1394. They also uncovered some weaknesses, which our protocol extensions addressed successfully.

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1. Chapter 1

Introduction

1.1 Background Overview

In the past several years, we have seen the appearance of new paradigms in our information processing and networking technologies. A new era has appeared, becoming the successor of earlier technologies in mobile computing and distributed systems. This is the era of Pervasive Computing, where emphasis shifts from information and communication technologies to information and communication per se. Computers will become pervasive technology; that is, a technology more noticeable by its absence than its presence [1]. An increasing number of “Intelligent Appliances” are already available in the market, with more to come. Examples are Palm’s PDAs, RIM’s BlackBerry wireless Internet solutions [2][3], intelligent home appliances (“smart” refrigerators, coffeemakers, ovens etc.), new integrated cell phone / PDA devices etc. The development of new services and applications are being fueled by the increased capabilities of our wired, wireless and mobile networking technologies. The increasing reliability and capacity of our networks expands the horizons of these new technologies. While most of the existing devices are supporting services that are of narrowband nature and have minimal QoS requirements, it is expected that the picture will change in the not very far future. We will see devices supporting very crucial services in important sectors, such as health, security, transportation, structural safety, training, entertainment etc. Some of the applications will be of broadband nature (e.g. high quality video, interactive games and visualization etc.).

While there is no doubt that the new technologies will be used extensively by the main business organizations, it is expected that they will have a very significant impact in the residential and small business sectors, where penetration of modern information and networking technologies seemed to be relative weak in the past. Moreover, recent advances in transmission and broadband access technologies provide the abilities to bring the information superhighway to thousands of houses worldwide. The explosion of the

Internet, the emergence of the various smart consumer electronic devices and the availability of plenty in-home computing resources increase the demands for creating a networked home. Aiming at connecting PC devices, appliances, sensors, actuators, switches, controllers and user interfaces to exploit novel applications and to provide an infrastructure for multimedia distribution, the home system is obtaining significant attention from manufacturers ranging from consumer electronics to computers and communication networks [34].

Interestingly, the proliferation of home networks also has an influence on other sectors, such as in the real estate market. As pointed out in [34], home builders have learned that home networks are able to help them sell new houses. Also home owners begin to realize that a good home networking solution can keep the beauty of their houses, simplify and effectively manage all their household PC devices and electronics appliances, thus it will increase the value to their properties.

1.2 Wireless Home Networking Technologies

Home networks are not new. For years, telephone companies have installed telephone lines to transmit voice; cable companies have placed cables to provide television service; electric utilities have equipped power lines to distribute electric power in homes. Additionally, some newer homes possess some intelligent environmental control systems to manage the home security system, air conditioning and/or heating system, entertainment system, etc. Since each type of these technologies was implemented only for a specific purpose of service distribution. However, this lack of coexistence and interoperation is not the philosophy of nowadays networking solutions and needs of modern applications. Home networking solutions should be able to provide connectivity and support to different and diverse applications, such as audio, video, web surfing, e-mail, telemetry and control functions [35].

Home network is a Local Area Network (LAN), but it is different from the business LANs in a sense that home networks have more stringent requirements for

broadband applications such as video on demand and entertainment video. The capabilities of home network are expected to be beyond those of traditional LAN technologies. This is because the proliferation of consumer electronics devices and IP-based entertainment content and services not only calls for high-speed connectivity between computing platforms and between computing platforms and consumer electronics devices, but also requires technologies to offer real-time video entertainment and content distribution, as well as data networking. Therefore, the concept of home networking should go beyond the original concept of LAN, to a vision of delivering multiple streams of content such as HDTV-quality video and multimedia Internet content [40].

Moreover, home network solutions should be able to simplify the ease of use. This is due to the fact that most of the home users may not be the professional staff, thus they may not have the expertise to tackle the complicate network installation and initiate the configuration procedures. In addition, the cost to deploy the home network technology ought to be reduced to an affordable level with respect to the majority of the home users.

A variety of networking technologies have been developed the past several years that are suitable for use in the residential and small business environment. Basically, they can be classified into two domains, wired based and wireless based home networking technologies. The examples of wired based technologies are IEEE 1394 [24], Phoneline [30], Powerline [31,32], Coax [33], USB, etc. Due to the fact that these wired based networking strategies require wire based infrastructure when establishing the network and are not capable of supporting mobility, they constrain themselves from being widely deployed. Opposite to these, the wireless home networking techniques allow easy deployment and expansion, thus becoming a more suitable solution for providing integrated services at the home environment. Based on this fact, we focus our research in the direction of wireless networks, specifically on the Wireless IEEE 1394, which is the first wireless broadband, yet simple LAN solution, with well defined QoS-support capabilities.

Typical wireless home networking schemes include IEEE 802.11 [36], Bluetooth [37], HomeRF [38], HiperLAN [39], Wireless IEEE 1394 [9] and so on. Among them, IEEE 802.11 is the most popular and widely used technology in wireless LAN. It was originally designed to function as an enterprise network, however it is now making its way to the home environment. IEEE 802.11b [52], operating at 2.4 GHz is the current version, providing maximum transmission speed of 11Mbps. IEEE 802.11a [53], operating at 5GHz band, using OFDM [45] technology at the physical layer, is able to provide transmission speed up to 54Mbps. IEEE 802.11g provides speeds of 54 Mbps as well, operates at 5 GHz and uses as physical layer technology identical to IEEE 802.11b (spread spectrum). The first IEEE 802.11b products appeared only recently in the market. Bluetooth was designed for short range personal networking and is now being extended for longer range. HomeRF is a member of the family of wireless LAN technologies particularly designed for home network. The current version of HomeRF is operating at the 2.4 GHz with peak speed of 1.6 Mbps. HiperLAN is a member of the family of ETSI standards for wireless LANs. The differences between HiperLAN and 802.11 families are that HiperLAN includes QoS and the support of ATM (Asynchronous Transfer Mode) and Ethernet. Wireless IEEE 1394 is a strong candidate for broadband wireless home networking with the abilities to provide dual mode (isochronous and asynchronous) transmission. It is the extension of IEEE 1394, one promising wired home networking technology, to the wireless domain. Its peak speed at the 5 GHz band is 40 Mbps, with technology operating at 25, 40, and 60 GHz band, offering higher transmission speeds under development.

1.3 Motivation and Thesis Objectives

Among the considerable diversities in terms of characteristics and capabilities (e.g. range of coverage, capacity, reliability, quality and guaranties etc.) provided by various wireless home networking strategies, Wireless IEEE 1394 appears to be superior to the other solutions because of the combination of its QoS support capability, broadband nature and its relatively less complex technology.

Since to the best of our knowledge there is no work in the open literature analyzing in detail the performance of the Wireless 1394 protocol, our objective in this thesis is to analyze the performance of this promising technology, as well provide modifications that improve its performance and increase its capacity further.

1.4 Thesis Contributions

As a novel wireless home networking technology, a variety of open issues in Wireless 1394 network are very worthwhile to be researched. Being at the beginning of a fruitful research, we were able to propose some new protocols and algorithms. We also came up with questions and directions for future research. In summary, our contributions are the following. We proposed the combined use of virtual sensing and polling to countermeasure the shadowing effect, which has been observed as been responsible for creating conditions of packet collisions in the (otherwise collision-free [5]) IEEE 1394 protocol [4]. As the home environment tends to be shadowing-prone, use of the proposed technique is proven quite beneficial. Furthermore, in [6] we pointed out a solution of how to dynamically select a Wireless 1394 compatible device to assume the role of Hub station. The choice is made based on the existing network conditions and assists to operate the network reliably even under very poor conditions. how to maintain the normal operation of the network in the error prone wireless home environment. The proposed technique ensures that the network has always a workable Hub station. The Hub station plays a vital role in the Wireless 1394 network, because it regulates all the other stations' communications and manages the system's resource. [7] proposed a solution to optimize the packet relay functionality in Wireless 1394 in terms of the selection of the relay station. This is motivated by the fact that the existing scheme used to relay traffic is only based on the received signal strength indicator station obtained, which is not accurate and good enough to bypass the traffic when the direct communication between any pair of leaf stations fails. [8] presented a new service discipline in Wireless 1394 network that provides a more fair distribution of network recourse.

1.5 Thesis Organizations

The remaining of the thesis is organized as follows. In chapter 2, serving as a background, a brief description of the ancestor of Wireless 1394, IEEE 1394, is provided first. Then the-state-of-the-art Wireless 1394 technology will be elaborated in detail. We also provide a comparison between Wireless 1394 and the other wireless home networking technologies and point out the deployment challenges when implementing Wireless 1394. Chapter 3 presents the performance analysis of the conventional Wireless 1394 protocol. In chapter 4 we provide the details of the protocol extensions we proposed for Wireless 1394, followed by the performance evaluation of techniques in chapter 5. Finally, chapter 6 draws the conclusions and makes recommendations for our future work.

2. CHAPTER 2

Wireless 1394

In this chapter, we begin with the brief overview of the IEEE 1394 standard, the ancestor of the Wireless 1394 technology. Then, we elaborate on the specification of Wireless 1394 protocol. This paves the way for us to see the advantages of Wireless 1394 when compared to its counterparts, the other wireless home networking technologies such as Bluetooth, HomeRF and IEEE 802.11. We proceed by revealing the deployment challenges when implementing this technology. Moreover, relevant work which has already been done to tackle those challenges in the open literature is reported concisely. Its advantages and deficiencies are pointed out.

2.1 IEEE 1394

IEEE 1394 is one of the popular wired home network technologies [18, 19,20,21] and has already been standardized by IEEE. It is also known as “FireWire” or “i. Link”. It is an international digital interface standard which is able to provide simple, low-cost and high bandwidth isochronous and asynchronous data transmission and unify all the communications among consumer electronics devices and computer and its peripherals, such as Digital TV, Digital VCR, DVD, digital cameras, PCs, printer, etc. The basic IEEE 1394 specification was standardized in 1995, in the IEEE 1394-1995 specification [24]. Additional improvements have been conducted by the IEEE 1394 TA (Trade Association) and other related working groups. The drafts on P1394a and P1394b for high speed up to 3.2 Gbps, P1394.1 for bridging and longer cable (more than 50 meters) are currently underway.

IEEE 1394 can operate over both copper and fiber cables. It does not require the deployment of different wires from those used in today’s home network appliances. Using a single cable to connect home network devices, IEEE 1394 avoids the need of any

terminators, device IDs, or complex setup procedures. The protocol stack of IEEE 1394 system is showed in Figure 2.1.

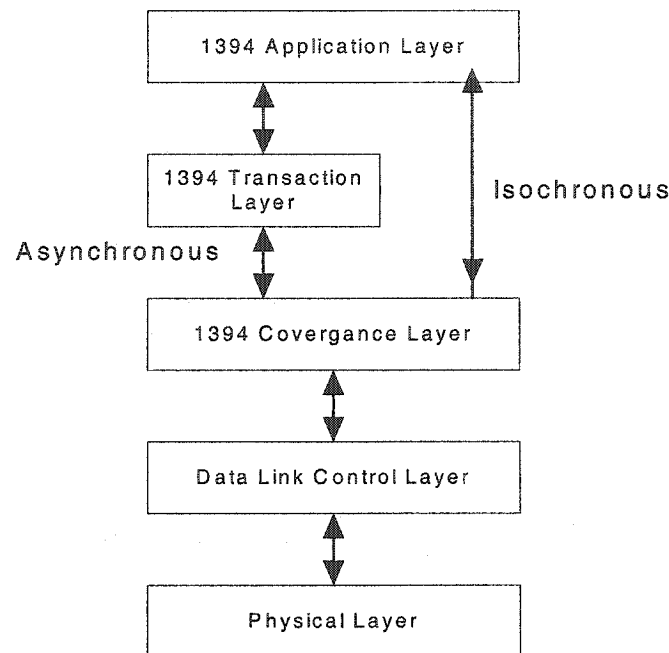


Figure 2.1 IEEE 1394 Protocol Stack

The merits of IEEE 1394 technology can be summarized as follows [24,25,26]:

- High-speed data transmission

IEEE 1394 is able to transmit data at the speed of 100, 200, or 400 Mbps. Now, the IEEE working group is conducting the research and development of IEEE1394b, which is capable of supporting data transmission at the speed of 3200Mbps.

- Real-time feature

IEEE 1394 can provide two kinds of data transmission, namely isochronous and asynchronous data transmission. Isochronous transfer mode guarantees constant transmission speed, which is important for the transmission of time crucial multimedia traffic to ensure the just-in-time delivery. Asynchronous transfer mode uses a best-effort communication strategy and guarantees data reliability, where data requested is sent to a

specific address and an acknowledgement is returned. As illustrated in Figure 2.2, 125 μsec is one IEEE 1394 cycle. Isochronous communication is a time controlled manner of communication and has priority over asynchronous communication. It uses a channel scheme where nodes transmit over a numbered channel and receive by listening on the receiver channels [16,17].

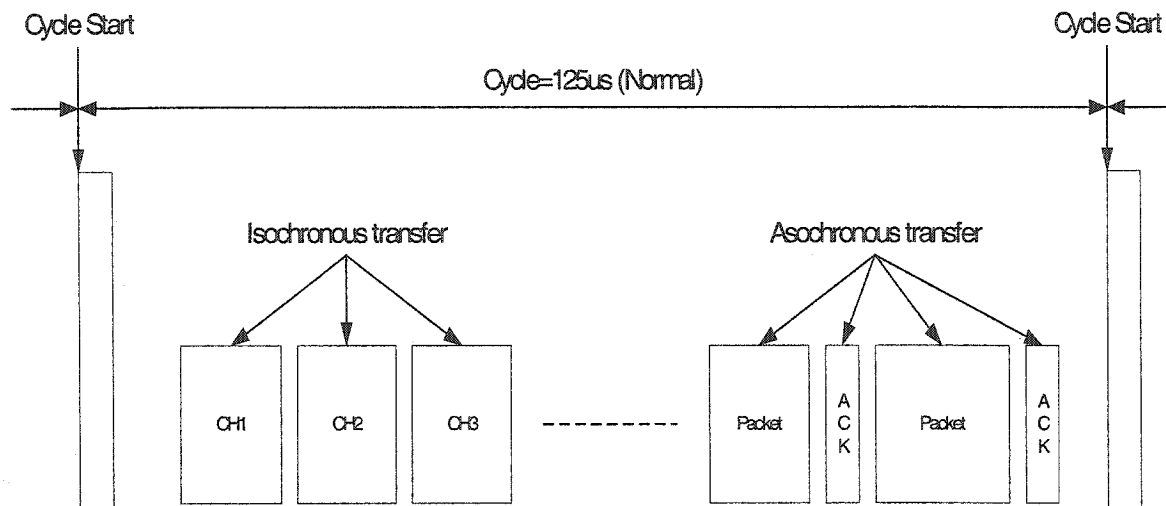


Figure 2.2 IEEE 1394 Cycle Structure

- Flexible topology

IEEE 1394 supports true peer-to-peer communications with daisy chaining and node branching. It is able to link different nodes in a certain geographic area which is named Bus [25]. Then, with the help of a Bridge, the IEEE 1394 network can be further extended [26]. These are indicated in Figure 2.3.

- Plug and play

When users add a new IEEE 1394 compatible device or when a device is disconnected, the IEEE 1394 bus can recognize it automatically. That is, users can add or remove IEEE 1394 devices with the IEEE Bus active.

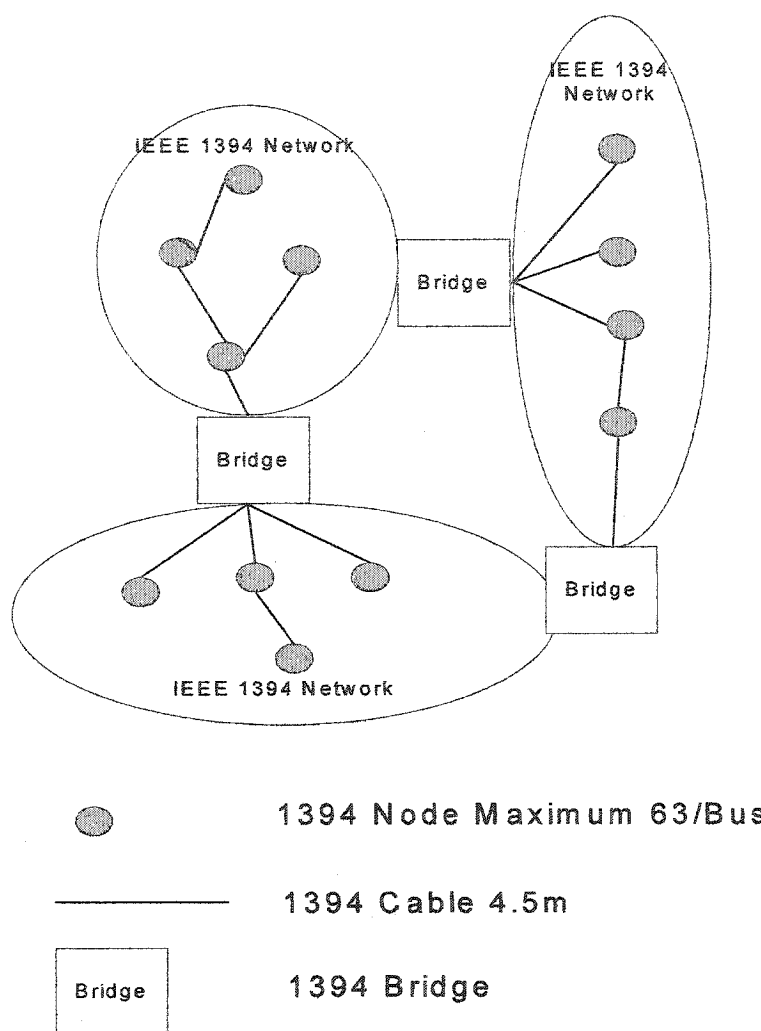


Figure 2.3 IEEE 1394 Network Architecture

The differences between IEEE 1394 and the other wire based home networking technologies such as PowerLine, HomePNA, USB (Universal Serial Bus), IEEE 802.3 can be summarized in Table 2.1, where IEEE 1394 appears to be superior to the others in terms of transmission speed and ability to support real time applications.

Table 2.1 Comparison of Wire Based Home Networking Technologies

	Powerline	HomePNA	USB	IEEE802.3	IEEE1394
Peak data rate	11 Mb/s	10 Mb/s	480 Mb/s	1 Gb/s	400 Mb/s
Real-time feature	No	No	Yes	No	Yes
Application	Electronic device control, low data rate transmission	Phone, low data rate transmission	PC peripherals	IP data transmission	Audio, Video, IP data transmission

2.2 Wireless 1394

As mentioned above, IEEE 1394 has a number of merits that make it a formidable networking solution for the home environment, networking technology, however it has some disadvantages as well, that limit its popularity. IEEE 1394 requires a wired infrastructure, which results in substantial infrastructure costs when the deployment has not been done prior to the completion of the structure, or extensions are made to increase capacity or coverage. In addition, IEEE 1394 does not support roaming with portable devices, which becomes a serious limitation in today's highly mobile user. The popularity of cordless phones is a very good indication how important mobility is to the modern user. The appearance of new mobile computing devices only increases the user's dependency in mobility. To avoid the drawbacks of IEEE 1394 and at the same time inherit its benefits, Wireless 1394 was proposed in this context; as the extension of IEEE 1394 into the wireless domain.

2.2.1 Overview of Wireless 1394

As mentioned earlier, Wireless 1394 supports two kinds of data transmission modes, namely isochronous transfer mode, which guarantees a fixed data rate at regular intervals, and asynchronous transfer mode, which guarantees data reliability while providing a best-effort service. A station having time-critical data such as voice and video uses the isochronous transfer mode that is based on the Time Division Multiplexing (TDM) scheme. The station employs a polling method to transmit non-real-time traffic.

In the Wireless 1394 specification, the wireless bus replaces the role nominal cable 1394 bus plays in IEEE 1394. As exhibited in Figure 2.4, a wireless bus, the basic communication unit in Wireless 1394 system, is formed by one hub station and several leaf stations (up to 15) in a star topology manner. A Wireless Bridge can be used to connect the Wireless 1394 bus with other cable or Wireless 1394 buses. Hub station and

leaf station are two key components in the Wireless 1394 network. Under normal conditions, the hub station takes charge of the network control. Particularly, the hub station is responsible for bandwidth distribution in the system. It assigns bandwidth to stations in isochronous transfer mode before allocating resource to station operating in asynchronous transfer mode. It administers media access control among stations by distributing transmission rights through polling packets to leaf stations. The Station ID of the leaf station that is granted the transmission permission is defined in the polling packet. Only the leaf station polled by the hub station can start to transmit. Additionally, the hub station performs real-time monitoring of all the communications in the subnet. The leaf stations communicate with other leaf stations directly after the transmission rights have been passed to them by the hub station with the resource specified by the hub station. In other words, data flow is conducted through peer-to-peer direct communication in a fully decentralized ad-hoc mode among leaf stations. Exceptionally, when the direct communications between any pair of transmitting station and receiving station fail, hub station or another leaf station will be involved to perform the data relay function [9].

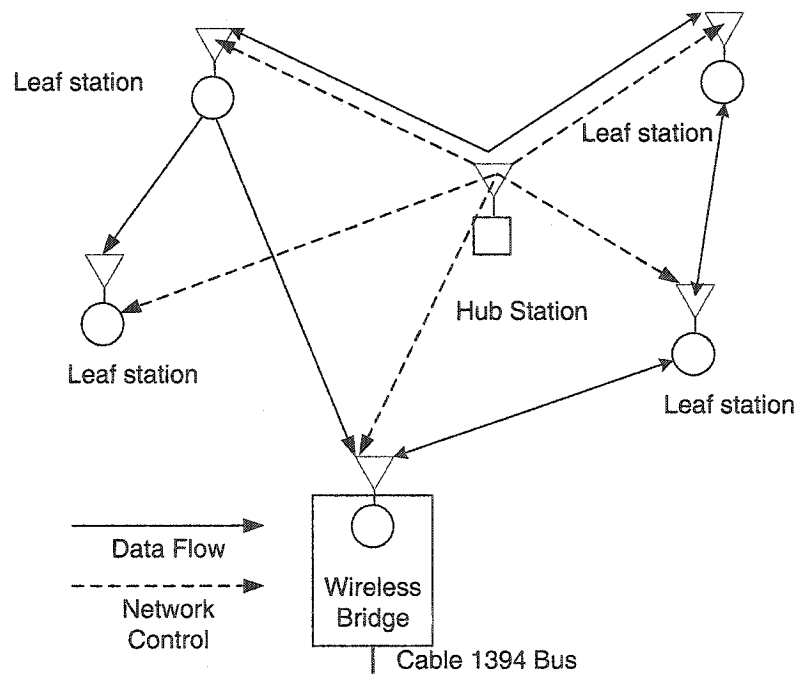


Figure 2.4 Wireless 1394 Network Topology

Current research and development in Wireless 1394 focuses on its operation in the 5.2 GHz band, while further extensions of Wireless 1394 with higher transmission rates, operating at 25, 40, 60 GHz band respectively are under investigation.

In general, the applications of Wireless 1394 home networking will include the following perspectives [9]: making video and data networking at home possible by unifying the communications among the A/V (Audio/Video) devices, multi-PCs, PC peripherals and the other digital appliances; high speed accessing of the Internet from anywhere in or around the home with portable display devices; delivering and broadcasting stored A/V entertainment data (e.g. on-demand A/V programming) from home servers, etc. Recently, the deployment and use of Wireless 1394 as an intra-vehicle network has been considered [42]. Figure 2.5 proves an example of a Wireless 1394 home network.

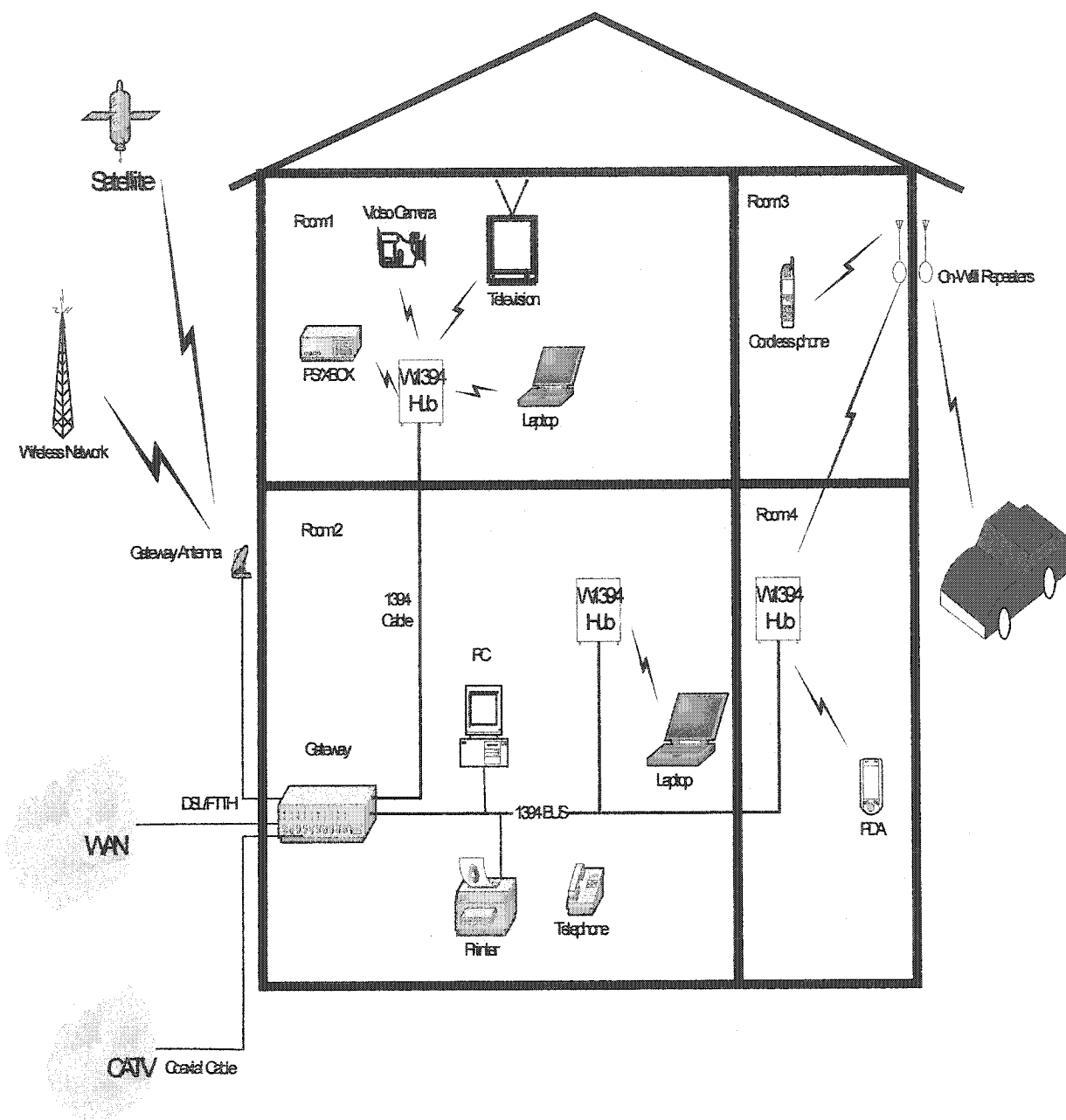


Figure 2.5 Wireless 1394 Home Networking Example

The basic protocol stack of Wireless 1394 is depicted in Figure 2.6. As mentioned earlier, Wireless 1394 supports two data transfer services, asynchronous and isochronous data transfer. The asynchronous data transfer service provides a packet delivery protocol for variable in length packets to a specific address, expecting that an acknowledgement is

returned. Asynchronous service starts at the Wireless 1394 Transaction Layer. On the other hand, the isochronous data transfer provides a broadcast packet delivery protocol for variable in length packets, which are transmitted at regular intervals. Isochronous service is triggered at the Application Layer.

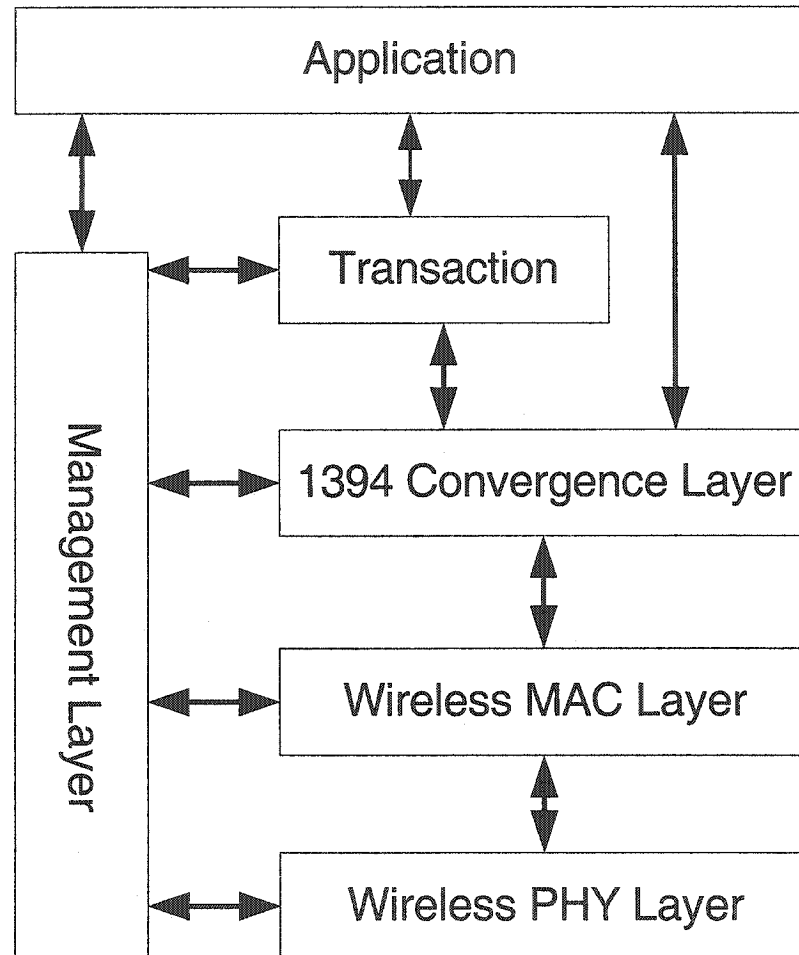


Figure 2.6 Wireless 1394 Protocol Stack

The detailed specification of Wireless 1394 will be reviewed layer-by-layer from the bottom to the top of the protocol stack in the following sections [41].

2.2.2 Physical Layer of Wireless 1394

The main characteristics of Wireless 1394 RF system can be summarized as follows:

- 4 channels with 20MHz spacing in the 5.15 – 5.25GHz band
- Real-time high bit rate transmission up to 40Mbps with higher data rates, for instance 70Mbps, as an option
- EIRP (Equivalent Isotropic Radiation Power) is 10mW/ MHz with maximum value of 200mW
- OFDM (Orthogonal Frequency Division Multiplexing) as modulation scheme
- Coverage range of 10-15m in indoor environment
- Carrier sense scheme is used to eliminate interference

Among those functions provided by the Wireless 1394 Physical Layer, the following ones need special attention to be paid.

- RSSI (Receive Signal Strength Indicator): Each station measures the received power of a packet transmitted from the other stations.
- Synchronization detection: It refers to the function of detecting the synchronization timing from the Preamble (placed at the beginning of a packet) transmitted from the Hub station or the other leaf stations. The synchronization timing provided by Frame Start Packet transmitted from the Hub station is used to maintain the frame synchronization. The other synchronization timing transmitted from the leaf stations is used to demodulate packets.

The specific services provided by the interface between the PHY layer and higher layers, the layers involved and the purpose to use the services are showed in Table 2.2 and Figure 2.7.

Table 2.2 Wireless 1394 Physical Layer Services

Service	Layer involved	Purpose
PHY_CONTROL.req	Provided by Bus management, For MAC Layer	Controls PHY-Layer operations
PHY_CONTROL.conf	Provided by Bus management, for MAC Layer	Confirms PHY_CONTROL.req
PHY_CLOCK.ind	Provide for MAC Layer	Provides PHY-Layer's clock of 20MHz for MAC Layer
PHY_FRAME.ind	Provided for MAC layer	Notifies MAC Layer that PHY Layers has detects the beginning of the FRAME
PHY_DATA.req	Provided by MAC Layer	Transmits a single MAC packet to PHY Layer
PHY_DATA.conf	Provide for MAC Layer	Confirms PHY_DATA.req
PHY_DATA.ind	Provided for MAC Layer	Transmits a single MAC packet to MAC Layer

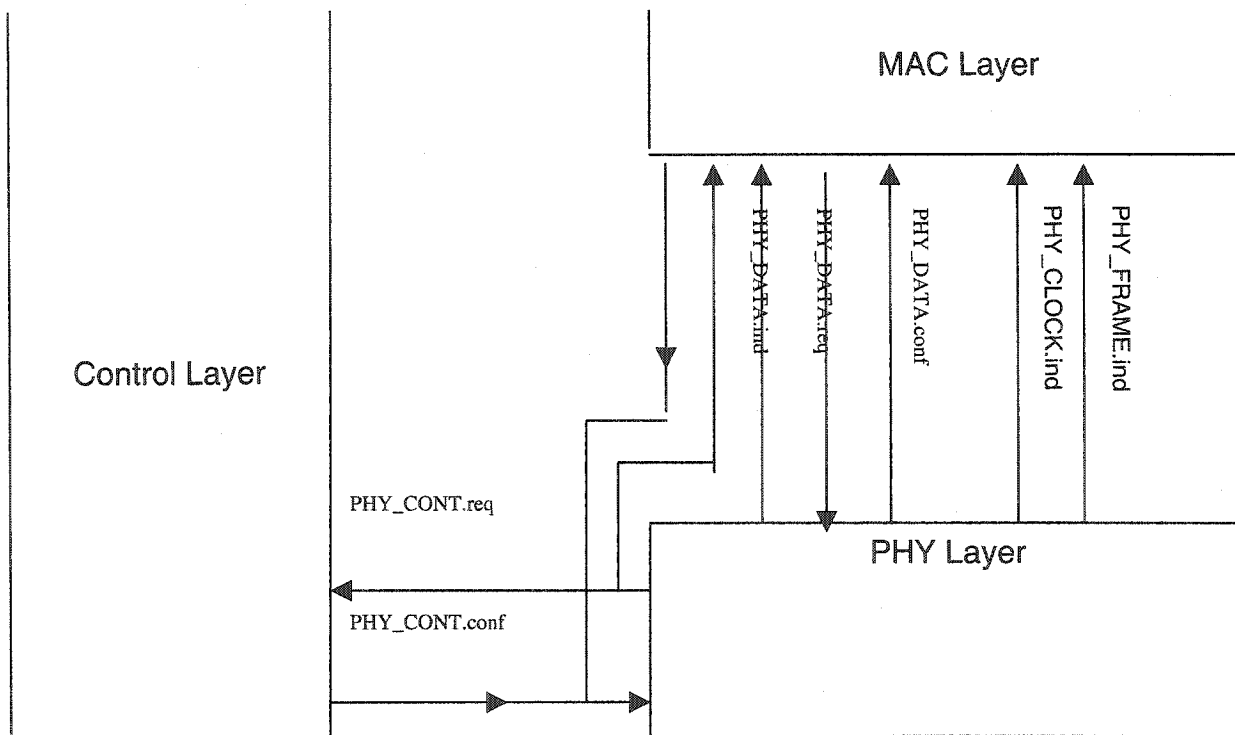


Figure 2.7 Wireless 1394 Physical Layer Services

The modulation scheme used for Wireless 1394 employs OFDM (Orthogonal Frequency Division Multiplexing) in order to take advantage of the diversity of a wideband radio channel and counteract the frequency selective fading. Table 2.3 depicts the major parameters of Wireless 1394 OFDM symbols.

Table 2.3 Parameters of Wireless 1394 OFDM Symbol

Function	Value
Data Scramble	m-sequence of Period 127
Convolutional Encoding	K=7, R=1/2, 9/16, 2/3, 3/4, 7/8
Subcarrier Modulation	BPSK, QPSK, 16QAM, 64QAM
Guard Interval (Note2)	8 samples (points) 800nsec (16 points) (Including ramp)
No. of sub-carriers	52
No. of data-carriers	48
No. of pilot-carriers	4
Sub-Carrier Frequency Spacing	312.5kHz
Effective OFDM Symbol Period	3.2 μ s
OFDM Symbol Duration	3.6 μ s

Table 2.4 Modulation Parameters

Data rate [Mbps]	Modulation	Coding rate	NCBPS	NDBPS	NBPS C	Remarks
6.66	BPSK	1/2	48	24	1	Essential
10	BPSK	3/4	48		1	Essential
13.3	QPSK	1/2	96	48	2	Essential
20	QPSK	3/4	96	72	2	Essential
26.7	16QAM	1/2	192	96	4	Essential
40	16QAM	3/4	192	144	4	Essential
46.7	16QAM	7/8	192	168	4	Option
40	64QAM	1/2	288	144	6	Option
53.3	64QAM	2/3	288	192	6	Option
60	64QAM	3/4	288	216	6	Option
70	64QAM	7/8	288	252	6	Option

NCBPS Number of Coded Bits per Symbol

NDBPS Number of Data Bits per Symbol; NBPS C Number of Bits per subcarrier

2.2.3 Wireless 1394 MAC Layer

Wireless 1394 MAC layer controls access using the physical layer operating at 5GHz.

2.2.3.1 Wireless 1394 MAC Layer Functions

In Wireless 1394, MAC layer provides the following main functions:

- Transmission of management information

It refers to the transmission of FSP (Frame Start Packet), CRP (Cycle Report Packet) and SSP (Station Synchronization Packet). If a station is a hub station, the station transmits FSP. If a leaf station is the cycle reporter, the station transmits CRP. Every station transmits SSP.

- Reception of management information

If a station is a hub station, and another station is defined as the cycle reporter, the hub station would receive CRP. Every station will receive SSP from the other stations.

- Frame synchronization

If a station is specified as a hub station, the station shall receive information of frame lengths from the 1394 CL (Convergence Layer) in order to control the FSP transmission timing. If a station is defined as a leaf station, the station shall synchronize with the FSP transmission timing provided by the hub station, and inform 1394CL of that synchronization timing.

- Cycle Time

Sets and updates counters for Cycle Time. The Cycle Time counter shall be updated at the same cycle as that for frame synchronization.

- Asynchronous packet transmission

Receives MAC packets from the 1394CL and performs the processes of fragmentation, MAC header attachment and CRC calculation and attachment.

- Asynchronous packet reception

Receives PHY packets from the PHY layer, and performs the following processes: CRC check, ACK response processing for received packets, defragment processing, MAC header check and MAC packet distribution to 1394 Convergence Layer.

- Isochronous packet transmission (no re-transmission)

Receives MAC packets from the layer and performs the processes of Reed Solomon encoding and Interleaving. Reed Solomon encoding is a means of accomplishing FEC (Forward Error Correction) in order to compensate for error bursts created in data transmission. Interleaving is a technique used to randomize the errors appearing in a sequence, in order to make error correction codes capable of correcting more effectively random errors rather than error bursts perform better when dealing with error-burst environments, as the wireless channels tend to be. [41].

- Isochronous packet reception (no re-transmission)

Receives the PHY packet from the PHY layer and performs the processes of de-interleaving and Reed-Solomon decoding (error correction).

2.2.3.2 Wireless 1394 MAC Layer Services

MAC Layer services are provided by the interfaces between the MAC layer and higher layers, as shown in Table 2.5 and Figure 2.8. The services can perform actions that are prescribed in higher layers. They can conduct transmissions using parameters whichever the parameters are related to MAC layer's actions.

These MAC Layer services can be classified into the following three groups. MAC-Layer Services for Control Layer include MAC_CONTROL.req, MAC_CONTROL.conf and MAC_EVENT.ind. The Asynchronous Data Services provided by

the MAC Layer for CL involve MAC_DATA.req, MAC_DATA.conf, MAC_DATA.ind and MAC_DATA.res. The Isochronous Data Services for CL consist of MAC_ISO.req, MAC_ISO.ind, MAC_FRAME.req and MAC_FRAME.ind.

Table 2.5 Wireless 1394 MAC Layer Services

Service	Layer involved	Purpose
MAC_CONTROL.req	Provided by Bus management	Requests for MAC layer control
MAC_CONTROL.conf	Provided for Bus management	Confirms MAC_CONTROL.req
MAC_EVENT.ind	Provided for Bus management	Informs Bus management of events that the MAC layer has detected
MAC_DATA.req	Provide by 1394CL	Transmits a signal MAC asynchronous packet
MAC_DATA.conf	Provide for 1394CL	Confirms MAC_DATA.req
MAC_DATA.ind	Provided for 1394CL	Indicates that a single MAC Asynchronous packet has been received
MAC_DATA.res	Provide by 1394CL	Responds to MAC_DATA.ind
MAC_ISO.req	Provided by 1394CL	Transmits a single MAC Isochronous packet
MAC_ISO.ind	Provided for 1394CL	Indicates that a single MAC Isochronous packet has been received
MAC_FRAME.req	Provided by 1394CL	Sets a value for the next frame counter
MAC_FRAME.ind	Provided for 1394CL	Indicates that frame has begun

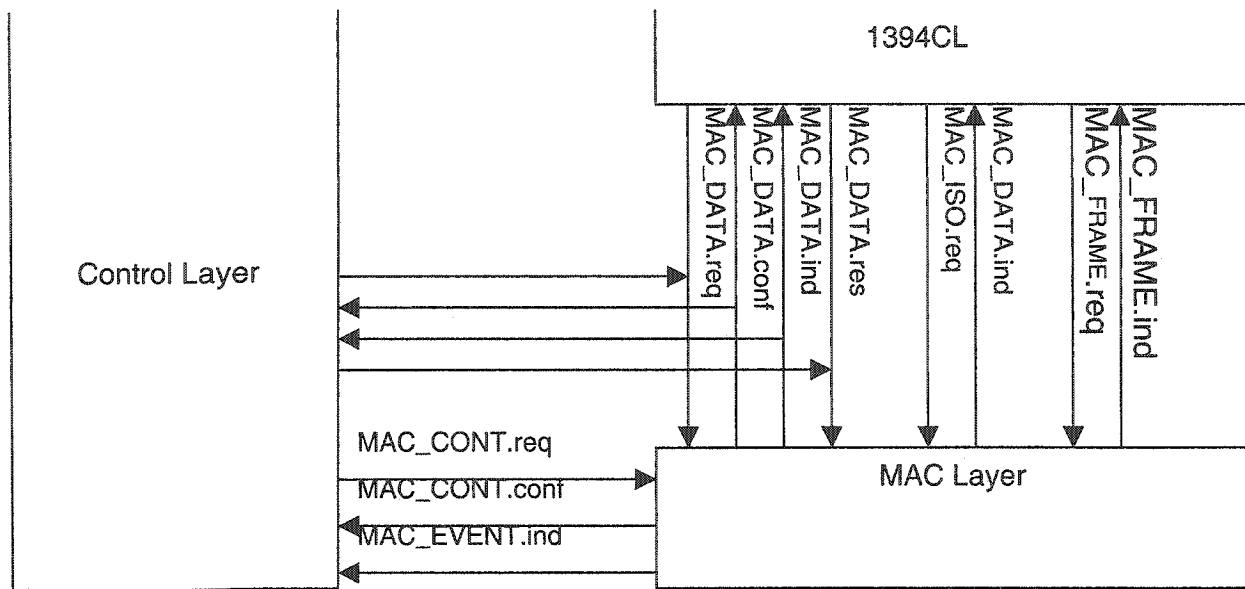


Figure 2.8 Wireless 1394 MAC Layer Services

2.2.3.3 Wireless 1394 Frame Structure

The basic structure of Wireless 1394 MAC layer comprises a sequence of MAC frames of equal length with 4ms duration. This corresponds to 32 times the length of one IEEE 1394 cycle (125 μ s). Shown in Figure 2.9, each frame is composed of a Management area, a Data area, a Reserved area and a Frame Gap. The Management area is a domain for communications between leaf stations and the hub station, which is used for the management of frame structure, verifying transmission quality between stations, association, and handling controls related to the Sleep mode. The Data area is a domain for data transmissions between all stations. It can handle both isochronous transfer, which accommodates a fixed data rate at regular intervals (e.g. real-time transfer such as video stream), and asynchronous transfer, which does not require real-time performance. The Reserved area is provided at the end of Data Area.

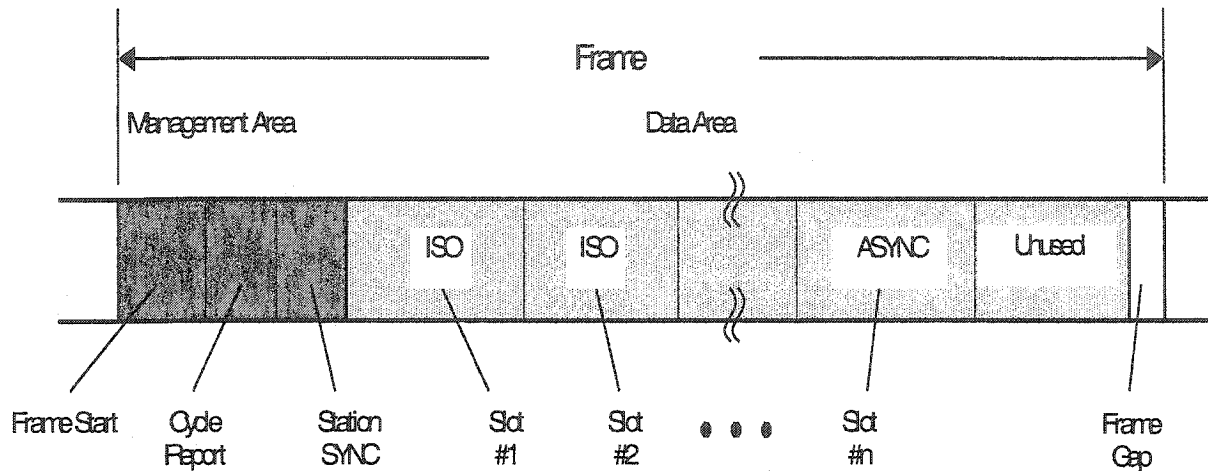


Figure 2.9 Wireless 1394 Frame Structure

- *Management area*

The Management area consists of a Frame Start, Cycle Report, and Station Sync. In Wireless 1394, the hub station plays a vital role in managing all the stations in the system. In particular, the hub station maintains frame structure and sends cycle time information; monitors the working status of all stations in the system; indicates the assignment of Data Area, identifying the isochronous and asynchronous domains; reports quality of communications among stations; controls medium access among the stations.

a) *Frame Start*

As shown in Figure 2.10, Frame Start is divided into two parts. CRC is attached to both parts. The first part is a fixed length, while the last is variable. The size of the last part is indicated by information provided in the first part, which is indicated in Figure 2.11.

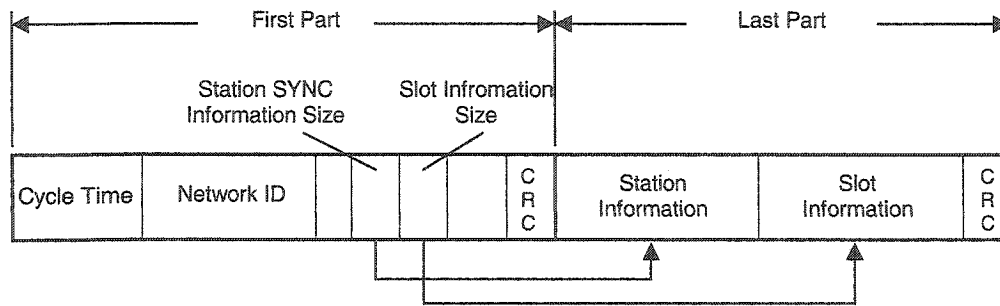


Figure 2.10 Frame Start

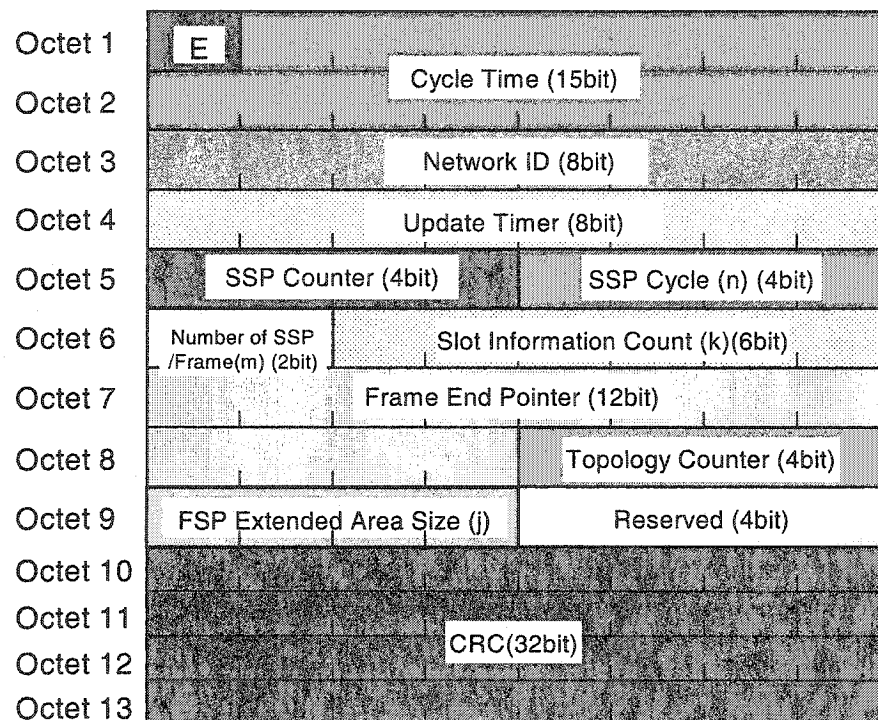


Figure 2.11 First Part of Frame Start

Among those fields in Figure 2.11, the field of Slot Information Count shows how many Slot Information Areas are contained in the last part of Frame Start. The value defined directly indicates the numbers of Slot Information areas. The allowable maximum value is 17. The 4-bit SSP Cycle informs how many frames are required to complete SSP transmission by all stations. The allowable value for Station SYNC Cycle is 1 to 16. Each station transmits SSP at least once in 16 frames.

The last part of Frame Start is shown in Figure 2.12. In this part, station information, slot information, and the FSP Extended Area field are transmitted.

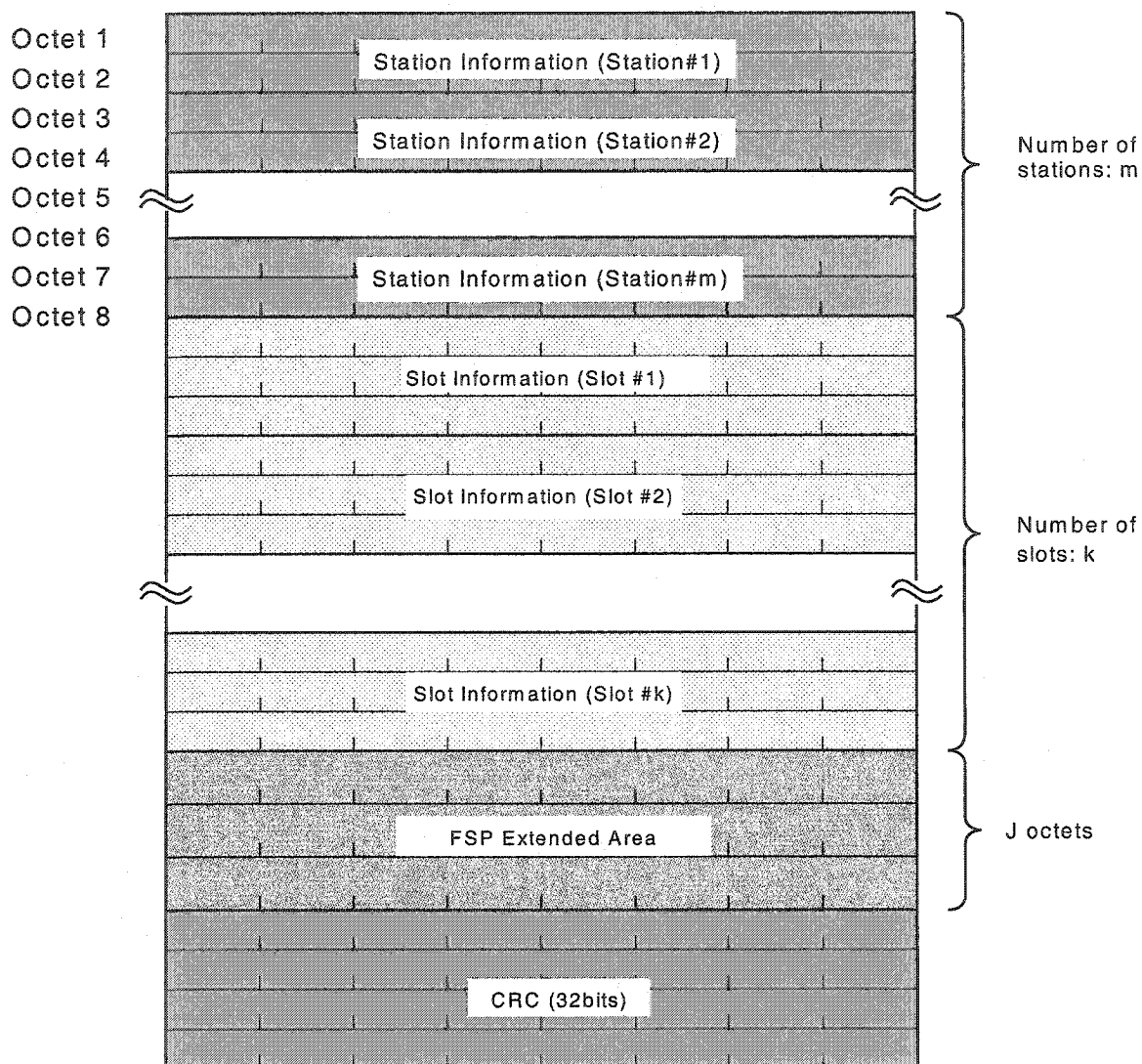


Figure 2.12 Last Part of Frame Start

In Figure 2.12, the 16-bit field of Station Information is provided for each station's Station SYNC. Shown in Figure 2.13, it includes Station Number, Station SYNC Indication, and Station SYN Status. The allowable maximum number of stations is 16.

Slot Start Pointer: 12 bits

Indicates the amount of time period between the frame boundary and the beginning of each slot. The unit is 0.5 OFDM symbol.

Slot type: 10 bits

0 to 63: Isochronous slot. Channel number is set.

64: Asynchronous slot

65 and above: reserved

Update Subject Flag: 1 bit

0: Update subject

1: NOT update subject

Reserved: 1 bit

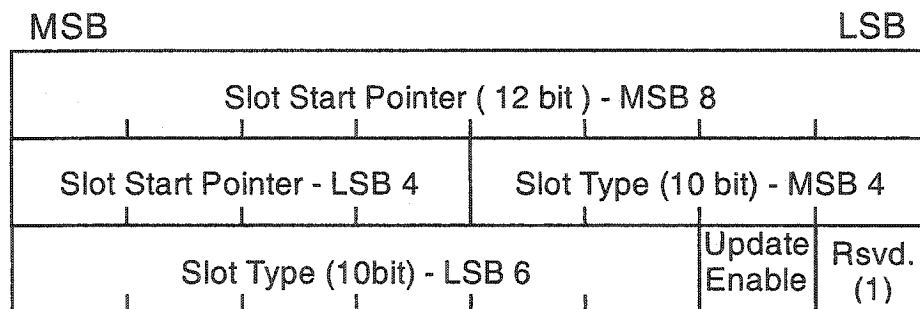


Figure 2.14 Slot Information

b) Cycle Report

Cycle Report indicates the time lag between timing of transmitting Frame Start (by the hub station) and when other stations receive Cycle Start from the node of IEEE1394.

c) *Station SYNC*

Using Station SYNC, each station transmits the status (or Rx automatic gain) of its corresponding station, sleep mode request, active mode request, polling priority (when needed), and the MAC Packet Destination Station Bitmap used for determining transmitting parameters (relay information, modulation schemes, and coding rates).

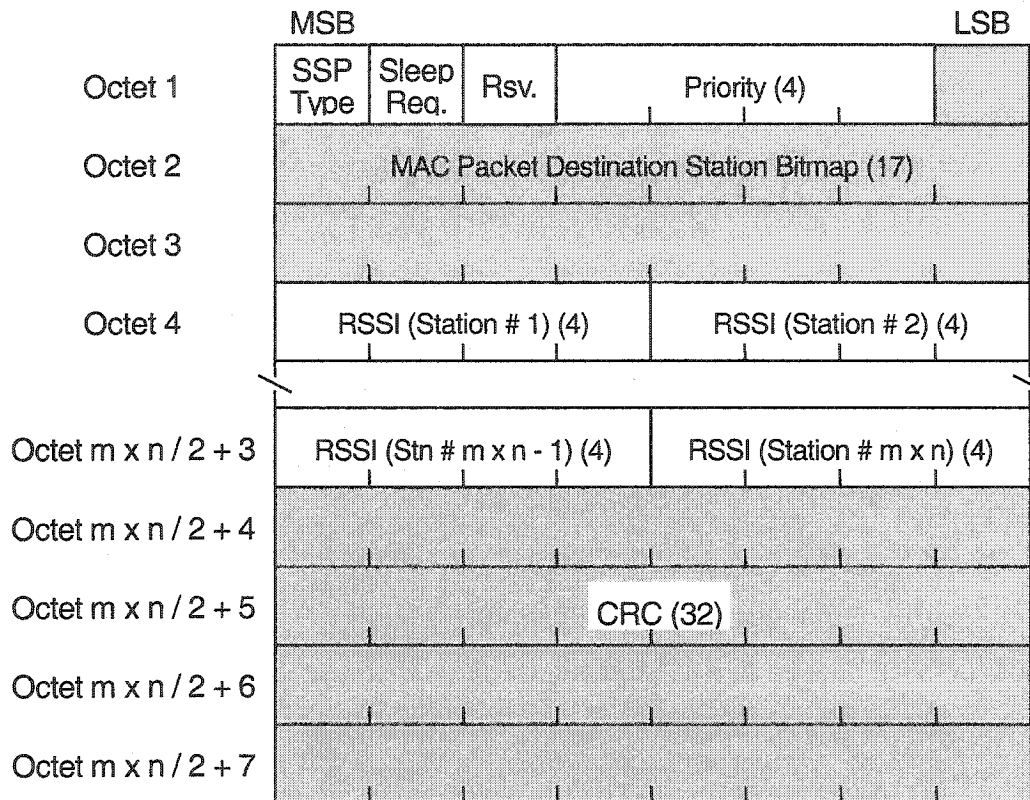


Figure 2.15 Station SYNC in normal operation

SSP Type: 1bit

Indicates a normal SSP or a new SSP. "0" is set in normal operation.

Sleep-Mode Request: 1 bit

Before a station goes into the sleep mode, the station shall inform the hub station of this request by setting this bit. Then the hub station updates the applicable Station SYNC Status field in Station Information of Frame Start.

Polling Priority: 1 bit

If a leaf station wishes to transmit Control packets or Asynchronous packets, the leaf station provides the hub station with a transmission request by setting a proper value in the Priority field. (Priority types are assigned as shown in Table 2.6). In addition, the leaf station can request that the hub station determines relay information, a modulation scheme, and a coding rate by specifying a destination station using the MAC Packet Destination Station Bitmap.

Table 2.6 Priority Type

Value	Type
0000	No packet transmission
0001	Asynchronous Data Packet Transmission Request
0010	Asynchronous Data Packet Transmission Request (Re-transmission)
0011	Asynchronous ACK Packet Transmission Request
0100	Asynchronous Packet (Relay Packet) Transmission Request
0101	Control Packet Transmission Request
0110	Control Packet Transmission Request (Re-transmission)
Others	Reserved

MAC Packet Destination Station Bitmap: 17bits

When a leaf station requests that the hub station determines relay information, a modulation scheme, and a coding rate, the station specifies a destination station for a MAC packet using the MAC Packet Destination Station Bitmap. The format of the MAC Packet Destination Station Bitmap is shown in Figure 2.16. If a MAC packet (to be transmitted) includes broadcast packets, “1” is set for Broadcast Bit. If a MAC packet (to be transmitted) includes unicast packets, “1” is set for each applicable Station ID, which indicates its destination Station. Multiple destinations can be specified. If a leaf station has no request, “0” is set for all station ID fields.

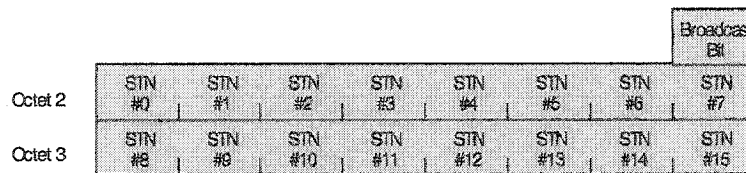


Figure 2.16 MAC Packet Destination Station Bitmap

RSSI value: 4bits per station

When leaf stations receive Station SYNC from other stations, they measure reception quality (or Rx automatic gain), and report the results to the hub station. The hub station also measures reception quality (or Rx automatic gain) and transmits SSP. The RSSI field is provided octet by octet. If the number of stations that report their results is odd, "0" is padded in the last 4 bits. Each station shall set "0000" for its own RSSI Value field. The hub station also transmits SSP. The relation between RSSI values and actual received input levels are shown in [41].

- Data Area

Data Area consists of one or more slots. Figure 2.17 shows an example of the Data area containing three isochronous data areas and one Asynchronous data area. Starting positions of these areas and their types are indicated by the last part of Frame Start.

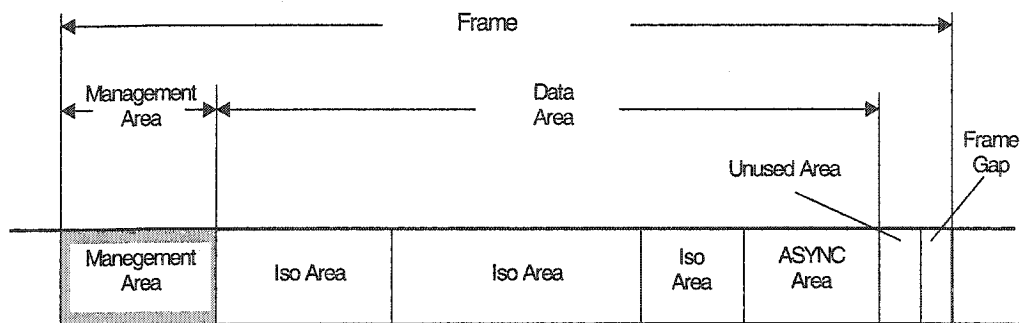


Figure 2.17 Example of Data Area

In the Data area, isochronous areas are continuously placed first and the remaining area can be used for asynchronous transmission. After isochronous transmission is completed, the slot is released; unoccupied areas are temporarily scattered before asynchronous area as described in the middle sample area in Figure 2.18. This is solved by slot reallocation.

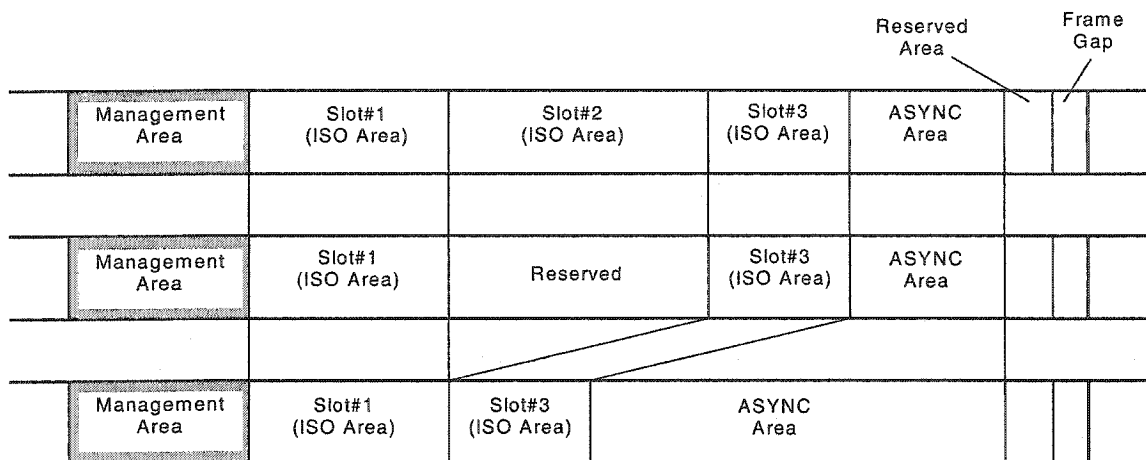


Figure 2.18 Slot Reallocation Example

- *Reserved Area*

An asynchronous transmission slot is placed at the end of the Data area of each frame. A Reserved Area is usually placed after the Asynchronous slot area. That area is not used in the Wireless1394 system. It is provided for allowing for other systems' use. In high-speed transmission such as DV-data transmission, the hub station can reduce or delete this area. The Reserved area begins just after the end of the Data area (which is indicated by Frame End Pointer in the first part of Frame Start) and ends just before the Frame Gap field. All "0" of Frame End Pointer indicates that Reserved Area has been deleted.

- *Frame Gap*

Frame Gap is provided in order to avoid signal collision on the boundary of frames. The frame period of the Wireless1394 system is adjusted to the cycle of Cable 1394 by controlling the timing of transmitting each Frame Start at the end of each frame.

2.2.3.4 Frame Synchronization

- *Frame Boundary*

Frame boundary is defined as the boundary between Frame Gap and the Gap which appears right before the Frame Start Packet. (See Figure 2.19.)

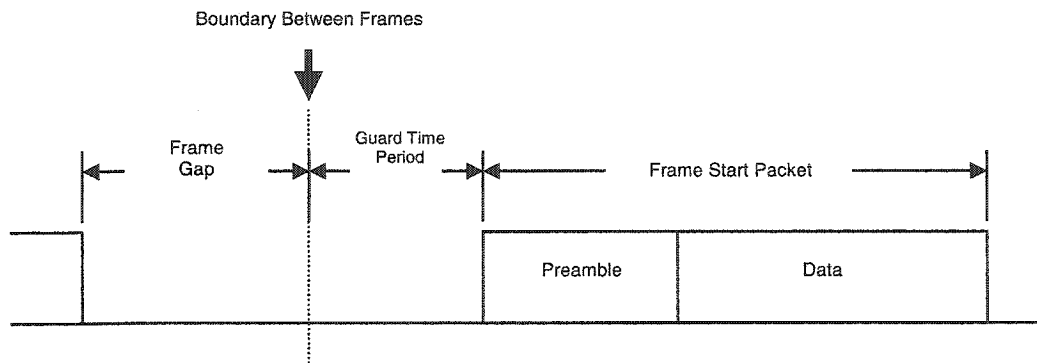


Figure 2.19 Frame Boundary

- *Frame Synchronization Continuity by Hub Station*

The hub station maintains 4ms-period frame continuity. The frame period is determined by any of the following situations:

- If the hub station is a net cycle master, the frame period must be counted by the clock of the hub station. In this case, the hub station does not adjust the frame period.
- If the IEEE1394 system connected to the hub station is a net cycle master, the hub station adjusts the frame period so that it will synchronize with the cycle start of the IEEE1394 system.
- If the IEEE1394 system connected to a leaf station contains a net cycle master, the leaf station compares the cycle start of IEEE1394 with the time when Frame Start Packet is transmitted by the hub station, and then reports the time lag to the hub station. Then the hub station adjusts the frame period.

- *Frame Synchronization by Leaf Stations*

Frame synchronization for every leaf station shall synchronize its frame synchronization with the timing of receiving Frame Start Packet transmitted by the hub station.

- a. Leaf stations shall adjust the frame period within the Frame Gap period.
- b. The amount of timing adjustment by any leaf stations must be one clock of the 20MHz-clock or less per frame.

2.2.3.5 MAC Packet

This section describes packets' structures for the MAC layer and the procedures for transmitting and receiving packets.

- *Asynchronous Packet*

The Asynchronous packet structure for the MAC layer is shown in Figure 2.20. The packet consists of a MAC Header, a Payload, and a CRC. There are four packet sizes, which are depicted in Table 2.7. The MAC Header size and CRC size are fixed at 7bits and 4 bits, respectively.

Table 2.7 MAC Asynchronous Packet Sizes (unit: octet)

Packet Sizes	MAC Header	Payload	CRC
35	7	24	4
107	7	96	4
215	7	204	4
323	7	312	4

According to the recommended values for the packet sizes, 35 bytes packet cannot be used for fragmentation. When several MAC packets are transmitted at a single transmission, sizes of all packets must be the same; the recommended combination of a modulation scheme and a coding rate is limited as shown in Table 2.8.

Table 2.8 Recommended Rates for Each MAC Packet Size

Packet size	Recommended rate (RATE*)
35	"0000"
107	"0000" to "0011"
215	"0010" to "0110"
323	"0100" to "1010"

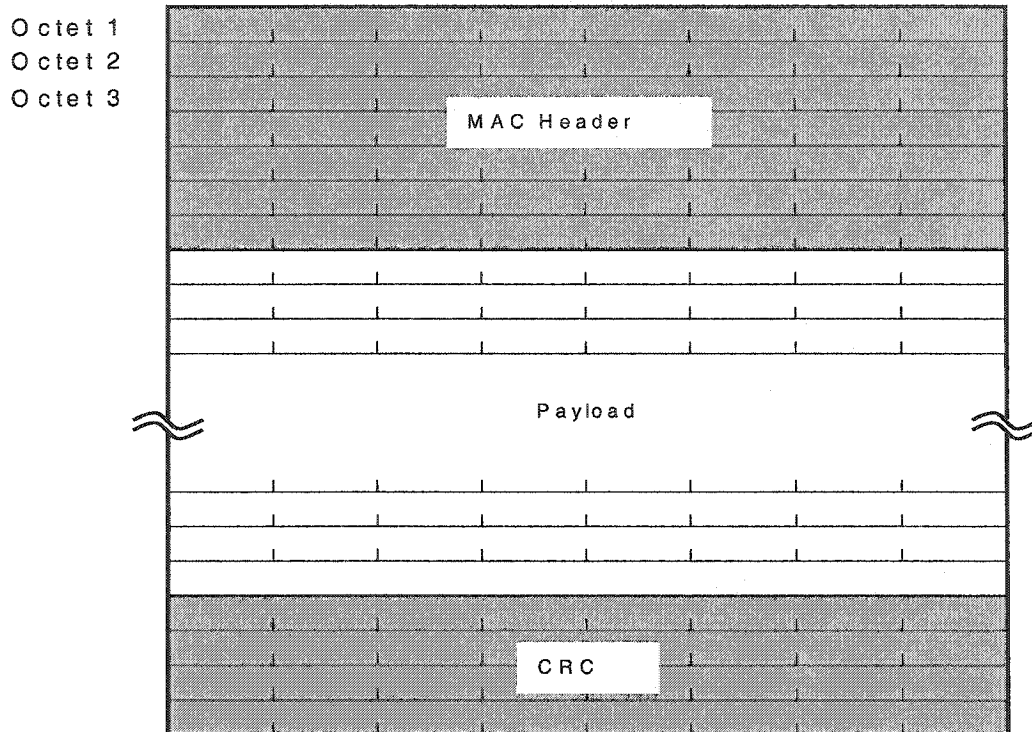


Figure 2.20 MAC Asynchronous Packet Structure

a. *MAC Header*

The format of MAC Header, which is added to the MAC of each asynchronous packet, is shown in Figure 2.21. The MAC Header consists of a Packet Type field, a Source Station ID field, a Destination Station ID field, a Relay Station ID field, a B/E Flag field, a Sequence Number field, and a Length field.

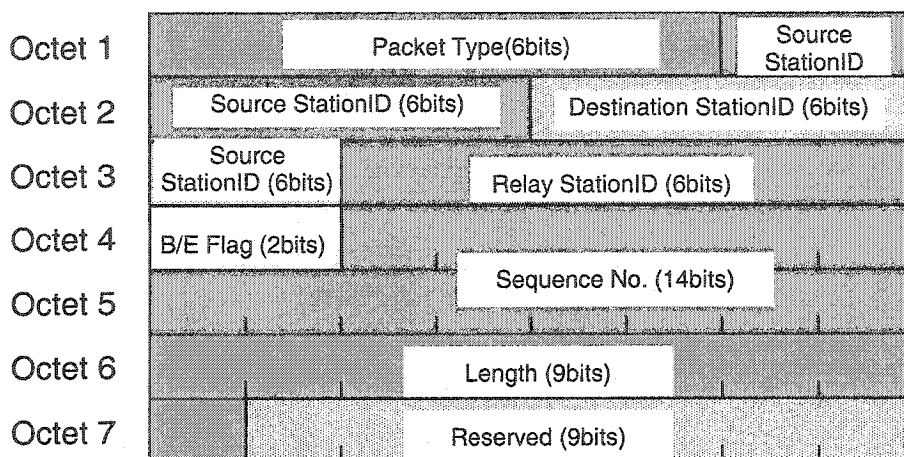


Figure 2.21 MAC Header

In Figure 2.22, the Packet Type field indicates the MAC Packet type. The relation between packet names and allocated values is shown in Table 2.9.

Table 2.9 Packet Types

Purpose	Identifier	Packet Type Name
Asynchronous transmission	000000	Asynchronous Polling Packet
	000001	Asynchronous Data Packet
	000010	Asynchronous ACK Packet
	000011	Reserved
	000100	Asynchronous Busy Packet
	000101	Asynchronous Ready Packet
	000110	Asynchronous Sequence Number Reset Packet
	000111	Asynchronous Sequence Number Reset ACK Packet
Isochronous Transmission	-	Exclusive format (Described separately)
(Reserved)	0010000 to 001111	
Network Management	010000	Topology Control
	010001	Registration Mode
	010010	Registration Info Share
	010011	Association/Disassociation
	010100 to 010111	Reserved
	011000 to 011010	Isochronous Resource Management
	011011	Reserved
	011100	Hub Information

b. Payload

Asynchronous Packet data is transmitted in the Payload field.

c. CRC

CRC applies parity checking to detect errors in the received data.

d. Polling Control for MAC Asynchronous Packet

The Wireless1394 system employs the Polling method in which the hub station provides transmission rights to a certain leaf station. This is done by placing the Station ID of the applicable station in the Polling Packet. Leaf stations wishing to transmit packets in asynchronous mode, they do so after receiving the Polling Packet with the ID indicated. If leaf stations do not have packets to transmit, they do not have to respond to such Polling Packet.

The polling order is controlled by the hub station. The hub station recognizes what station is currently in operation and controls the order of packet transmission through Polling. If a station is in the “Sleep” mode, the hub station removes such station from the Polling list. When the hub station receives transmission requests by leaf stations (using Priority of SSP), it determines an appropriate order to transmit Polling packets. If destination stations are indicated in the MAC Packet Destination Station Bitmap, the hub station determines proper relay information, a modulation scheme, and a coding rate.

Operations at hub station can be summarized by the following steps. The hub station first checks if an applicable frequency channel is available by using the Carrier Sense function, and then transmits a Polling Packet in which the Station ID of the leaf station, which has the right to transmit is indicated. If the hub station has received transmission requests through SSP, it generates a Polling packet and transmits it as Priority Polling. When there is no transmission request or if Priority Polling is completed, the hub station transmits a normal polling packet to all leaf stations.

The hub station checks if the leaf station (which has the right to transmit) transmits an Asynchronous packet within `poll_resp_time` after the hub station transmits the Polling Packet. If the leaf station transmits an Asynchronous Packet, the hub station receives the packet, obtains its length from PHY Header, and predicts when to transmit the next Polling packet. If the PHY Header cannot be received for some reason, but signal through Carrier Sensing can be detected, the next Polling Packet is transmitted after an applicable channel is released.

If the hub station does not detect any signal from the leaf station within `poll_resp_time` after the Polling Packet transmission, it transmits the next Polling Packet to the next leaf station.

If it is not enough time left in a frame for transmitting a Polling Packet, the Polling Packet is withheld, but can be transmitted in the Asynchronous area of the next frame.

`poll_resp_time` in Figure 2.22 refers to the time period between the end of a Polling Packet transmitted by the hub station and the Guard Time placed in the beginning of an Asynchronous packet. The minimum interval for transmitting Polling Packets (the interval between the end of a Polling packet and the beginning of the next Polling packet) is $34.2\mu\text{s}$.

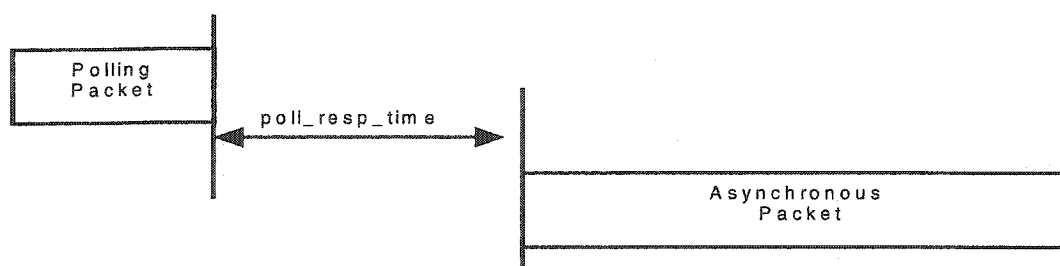


Figure 2.22 `poll_resp_time`

Operation at the leaf stations is as follows (assuming the leaf stations have data to be transmitted).

The leaf station can report Priority using the SSP, the priority level depending on the packet type. If the leaf station requests that the hub station decides on relay information, a modulation scheme, and a coding rate, it sets the destination station information into the MAC Packet destination Station Bitmap for the MAC packet.

The leaf station receives a Polling Packet from the hub station and checks out which station is given the right to transmit.

If the leaf station is the station given the right, it transmits an Asynchronous Packet after responding to the Polling Packet. If the Polling Packet is given in the response to a request, "Priority Polling" is set for Polling Type. If the Relay-Required Destination Station Bit Map indicates relay transmission is required, the hub station requests that applicable stations relay MAC packets by using the MAC packet Relay Station ID field. In addition, each Polling packet contains RATE Set indicating a recommended modulation scheme and coding rate. Mac Packets can be transmitted according to this RATE Set information or by using other parameters regarding RATE Set information as recommendation.

If the leaf station is not the station given the right, the leaf station starts to receive an Asynchronous packet.

If the leaf station has the right to transmit, but it does not have enough time to transmit an Asynchronous packet within a single frame, the asynchronous packet transmission is prohibited. If the leaf station has multiple Asynchronous packets, and if it cannot transmit all of them before the end of the frame, only allowable amount of packets can be transmitted.

e. Transmission Control for MAC Asynchronous Packet

Unlike the Unicast case, acknowledgement return and packet re-transmission cannot be performed in Broadcast Transmission.

In Wireless 1394, relay control ought to be performed when a direct communication link cannot be established between the source station and the target station.

- *Isochronous Packet*

- a. *Isochronous Packet*

In the Wireless1394 system, the Wireless 1394 Convergence Layer binds a Cable1394 isochronous Packet [16,17] every 32 cycles into a packet because its frame period is 4ms. If the 32-cycle Cable1394 data is shorter than a Wireless1394 Isochronous Block, "0" is padded into the remaining area (Figure 2.24 shows that the data can be divided 239 octets by 239 octets). Each portion is called Isochronous Payload.

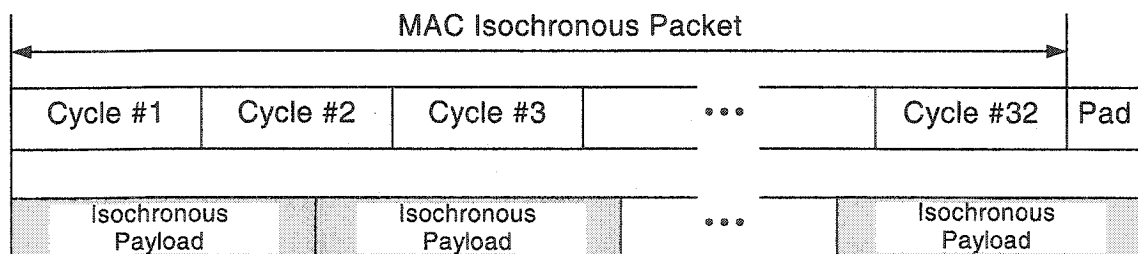


Figure 2.24 MAC Isochronous Packet and Isochronous Payload

- b. *Isochronous Block*

For Isochronous transmission, Reed-Solomon encoding and interleaving are performed. The Reed-Solomon code is calculated and added to each Isochronous Payload. Four sets of a Isochronous Payload field and a Reed-Solomon field are grouped

into a MAC Isochronous Block. Every MAC Isochronous Block is interleaved individually (See Figure 2.25).

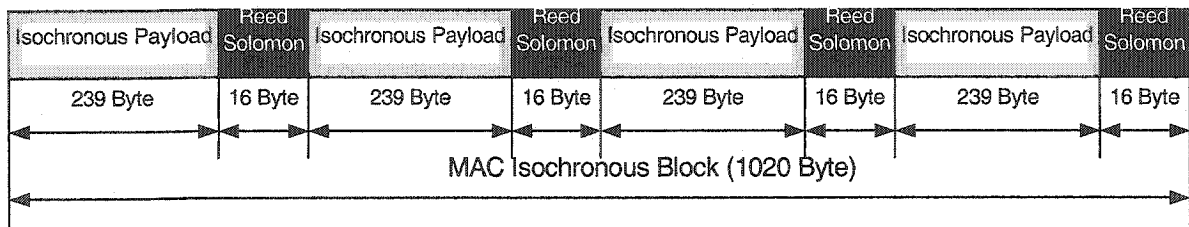


Figure 2.25 MAC Isochronous Block

c. *Isochronous Packet Transmission*

This part describes the process that prepares the data sent to the PHY layer.

The 1394CL data is divided into 239-octet Payloads, then calculates the Reed Solomon code for each Payload. 4 sets of a Payload and its corresponding Reed Solomon extension are grouped into a single Isochronous Block (for the description of the Isochronous Block please see below). The Isochronous Block is interleaved, and is finally passed to the PHY layer. (See Figure 2.26)

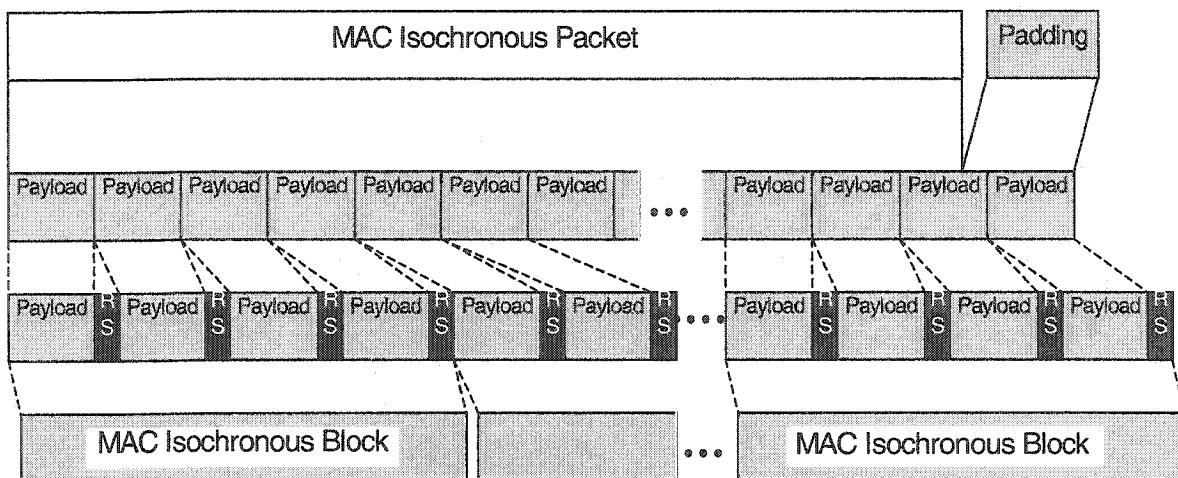


Figure 2.26 Isochronous Packet Processing at Source Station

d. *MAC Isochronous Packet Reception*

The MAC layer divides the PHY data into Isochronous Block (1020 bytes), and de-interleaves them. In addition, the MAC layer identifies the Reed-Solomon Blocks (255 bytes). It detects errors, and corrects them. "0"-padded area is removed from the error-corrected data. Finally, the MAC Isochronous Packet is passed upwards to 1394CL.

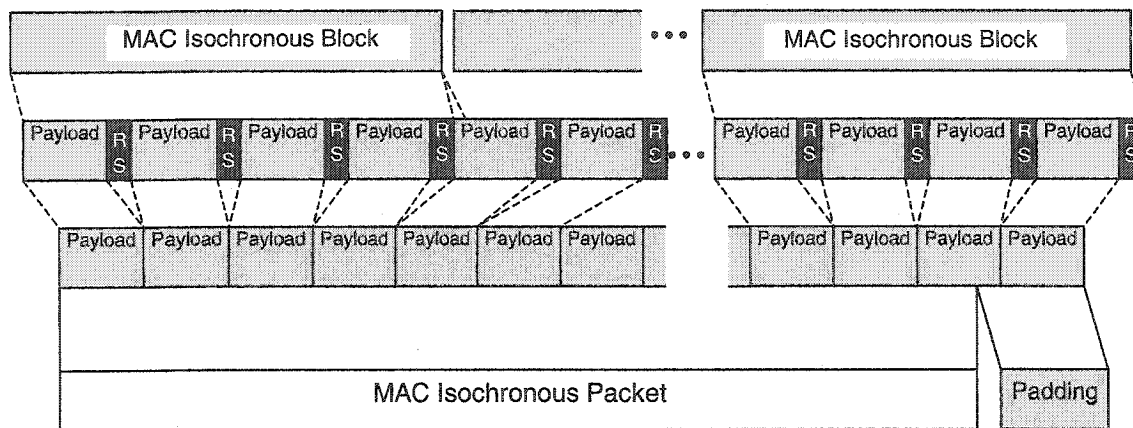


Figure 2.27 Isochronous Packet Processing at the Destination Stations

- *MAC Packet Format*

This section describes the detailed MAC Packet format.

a. *Polling Packet*

By using Polling Packets, the Station ID of a station that has the right to transmit and the information requested by SSP are provided. Figure 2.28 shows an example of the Polling Packet structure. Since the Polling Packet is important, BPSK and convolutional encoding rate of $R=1/2$ are used. To uniform packet structures, the Polling packet employs 7-byte MAC Header and 4-byte CRC. The MAC packet length is 14 bytes long, or 5 OFDM symbols. Please note that the following four sizes are defined as MAC Packet sizes for regular (information transporting) packets: 35 bytes, 107 bytes, 215 bytes and 323 bytes. However, since the length of 35 bytes is still too long for a Polling Packet, an irregular size (14 bytes - 5 OFDM symbols) is employed. "0's" are set into each bit of the Length field in PHY Header so that the PHY layer can

recognize Polling Packet. Such Polling Packets include the information, as shown in the figure below (the remaining area is filled with “0”):

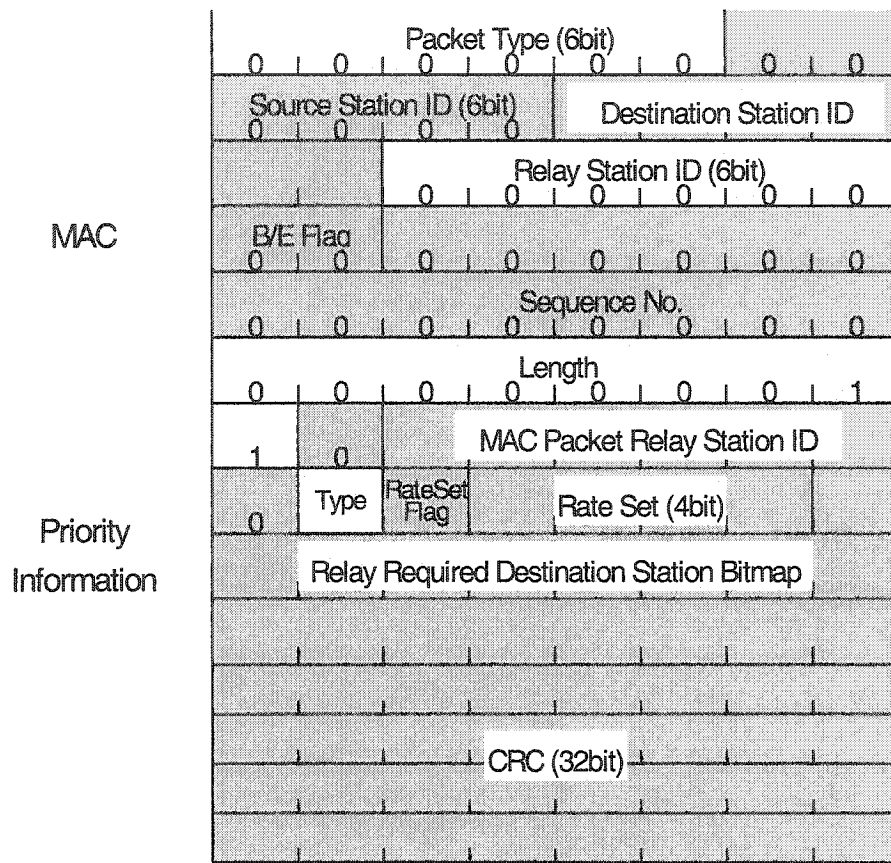


Figure 2.28 Polling Packet

Different polling types are indicated by different codes, which are summarized in Table 2.10.

Table 2.10 Polling Types

Code	Name	Description
0	Normal Polling	Polling that is automatically transmitted; that is, the trigger is NOT leaf stations' requests.
1	Priority Control Polling	Polling that is transmitted by leaf stations' requests. That is, this polling is regarded as response to leaf stations' transmission request.

b. *Data Packet*

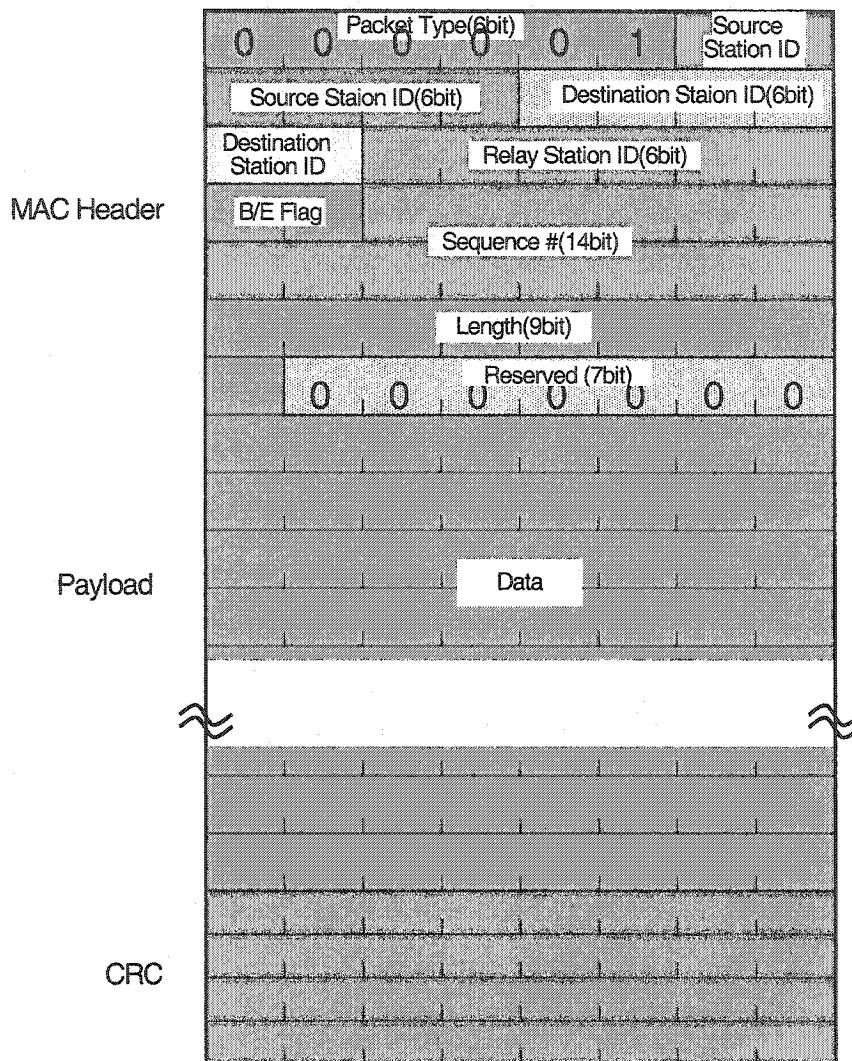


Figure 2.29 Data Packet

c. *Ack Packet*

ACK Packet consists of a MAC Header (7 bytes), a Payload, and a CRC (4 bytes). Up to 12 areas of ACK Information can be stored into a 35-byte-long packet: 48 for the 107-byte-long packet; 102 for the 215-byte-long packet; 156 for a 323-byte-long packet.

Since the B/E flag and Sequence# located in the MAC Header are not used, all "0" are put into those areas. Length shows the number of ACK Information in this packet (see Figure 2.30).

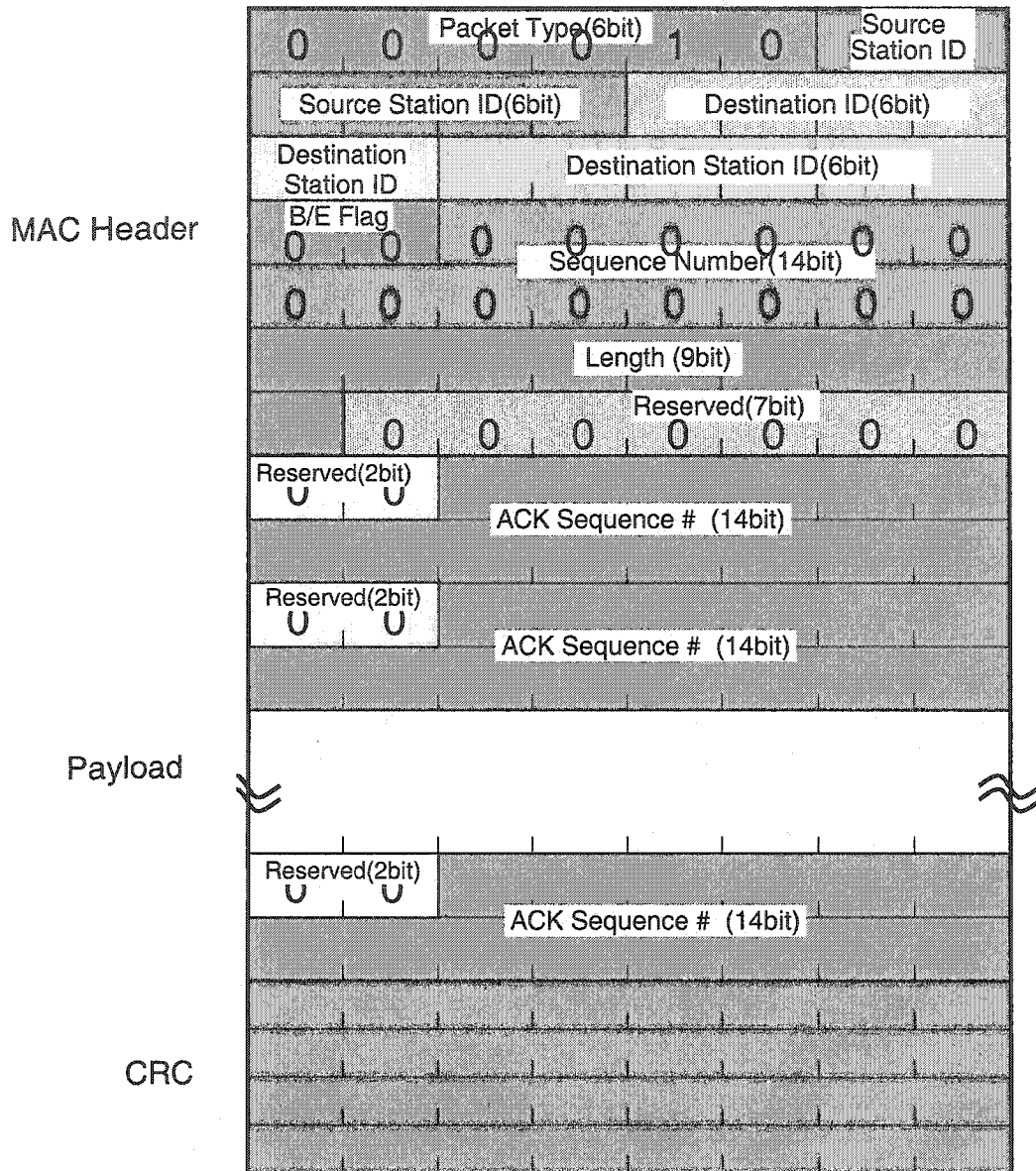


Figure 2.30 ASYNC ACK Packet

2.2.4 Wireless 1394 Convergence Layer

The Wireless 1394 Convergence Layer (CL) acts as an interface between the MAC layer used to control the wireless 1394 bus and the cable 1394 link layer. In reference to the upper layers, the Wireless 1394 CL provides the same level of services as the IEEE 1394 link layer does. Parts of the functions performed by the Wireless 1394 CL are performed cooperating with the Wireless 1394 bus manager.

As shown in Table 2.11, Wireless 1394 CL services are provided through the interface between the Wireless 1394 CL and the upper layers.

Table 2.11 Wireless 1394 Convergence Layer Services

Service	Layer communicating with	Purpose of service
CL_CONTROL.req	from bus management	1394CL control
CL_CONTROL.conf	to bus management	Confirm CL_CONTROL.req
CL_EVENT.ind	to Bus management	Indicate event detection by 1394CL
CL_DATA.req	from transaction layer	Cause MAC layer to send a primary asynchronous packet
CL_DATA.conf	to transaction layer	Confirm CL_DATA.req
CL_DATA.ind	to transaction layer	Indicate reception of a primary asynchronous packet
CL_DATA.res	from transaction layer	Respond to CL_DATA.ind
CL_BUS.ind	to transaction layer	Indicate bus event
CL_ISO_CONTROL.req	from application	Select radio channel
CL_CYCLE.ind	to application	Indicate starting isochronous cycles of local bus
CL_ISO.req	from application	Cause 1394CL to send a primary isochronous packet
CL_ISO.ind	to application	Indicate reception of a primary isochronous packet

Two kinds of subactions are defined in the Wireless 1394 Convergence Layer. They are the asynchronous and isochronous subactions respectively. Asynchronous arbitration is employed for those stations that do not require a guaranteed high bandwidth or low latency or a precise timing reference. Polling control is the access method to transmit the asynchronous data. In the isochronous subaction, accesses are performed within the bandwidth guaranteed to be available for use in the wireless 1394 system. In contrast to this, the asynchronous subaction uses only the remaining available bandwidth. In isochronous data transmissions, source stations transmit isochronous packets to Wireless 1394 CL immediately after a “cycle start indicate” is indicated by the Wireless 1394 CL. Then Wireless 1394 CL will transmit them to the MAC layer. The MAC layer will transmit data to those reserved slots controlled by the hub station. In the wireless 1394 system, every leaf station should first copy the cycle master of the hub station into

its own cycle master register, and then update it every time the Frame Start is transmitted by the hub station. This approach makes possible for all the leaf stations to synchronize with the hub station in the specific time duration.

2.2.5 Wireless 1394 Transaction Layer

Wireless 1394 Transaction Layer defines a complete request-response protocol to perform the bus transactions required to support the CSR (Command / Status Register Microcomputer Bus) architecture, which is the operation of read, write and lock. Please note that the Transaction Layer does not add any services for isochronous data, but it does provide a path to get some bus management services.

In Transaction Layer, data is transferred among Wireless1394 stations by three different transaction types:

- Read – data at a particular address within a responder is transferred back to a requester.
- Write – data is transferred from a requester to an address within one or more responders.
- Lock – data is transferred from a requester to a responder, processed with data at a particular address within the responder, and then transferred back to the requester.

Transactions consist of four service primitives:

- Request – the primitives used by a requester to start the transaction.
- Indication – the primitives used to notify the responder of an incoming request.
- Response – the primitives used by the responder to return status and possibly data to the requestor.
- Confirmation – the primitive used to notify the requester of the arrival of the corresponding response.

Relations between these primitives and data flow is shown in Figure 2.31.

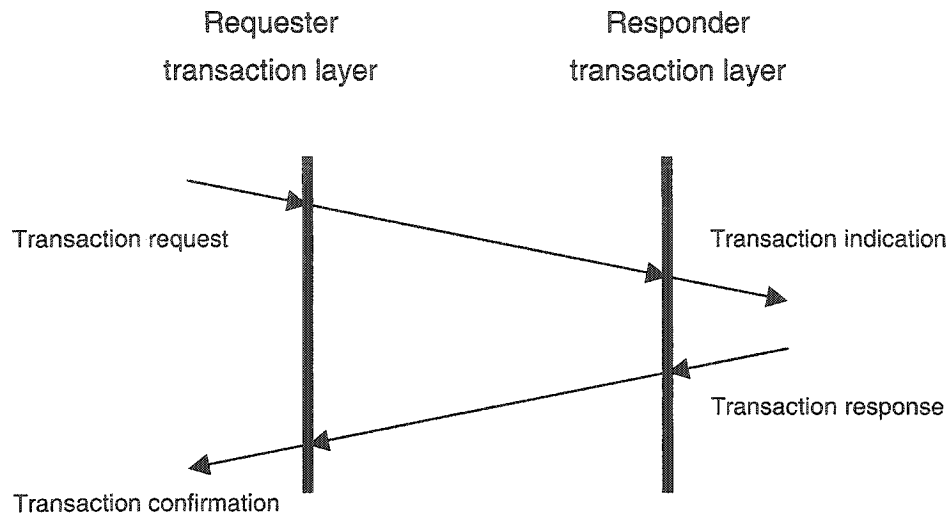


Figure 2.31 Transaction Services

2.2.6 Wireless 1394 Bus Management

The management layer provides isochronous resource management, network topology management and station association /network ID management, etc. There are two management entities in the Wireless1394 bus environment, isochronous resource manager and bus manager respectively, which are managed by the hub station. Bus manager services include station association and management, topology map maintenance and management as well as relay control. Isochronous resource manager assigns necessary resources to individual stations, allocating and deallocating isochronous resource, channels and bandwidth in a proper order.

2.3 Comparison of Wireless 1394 and Relevant Technologies

In order to see the differences among those wireless home networking technologies, Table 2.12 provides a comparison between various technical aspects. As depicted in this table, it is evident that Wireless 1394 appears to be the only Quality of Service (QoS) capable, yet simple broadband wireless home networking technology. These abilities (of possessing broadband communication and QoS support incorporated in the protocol) make Wireless 1394 an ideal scheme to be used in residential networks.

This is due to the fact that the current home network requires networking technology that does not solely support the TCP/IP based data transmission and simply to provide wireless network connectivity at home. Recent home networks are been requested to support bandwidth-intensive and delay-stringent applications, examples been audio and video data (which require QoS provisioning). This will turn out to be ever more urgent when plenty of digital multimedia enriched devices for audio and video content become available.

Table 2.12 Comparison of Wireless Home Network Technologies

	Bluetooth	HomeRF	IEEE802.11a	Wireless 1394
Operation Spectrum	2.4GHz(ISM band)	2.4GHz(ISM band)	5.2GHz	5.2GHz
Peak raw data rate	720kb/s	0.8-1.6Mb/s	54Mb/s	70Mb/s
Modulation	FHSS: 1600 hops/s	FHSS 50hops/s	OFDM	OFDM
Range	<10m	<50m	About 50m	10-20m
Connection Topology	Peer-to-peer Master-Slave	Peer-to-peer MS-to-BS	MS-to-BS	Peer-to-peer multihop
Broadband Nature	No	No	Yes	Yes
QoS Capability	Yes	Yes	No	Yes
Application	Mobile Phone, Portable Terminal	PC, Portable Terminal	IP data transmission	Home device (audio video, IP data transmission)

2.4 Deployment Challenges of Wireless 1394

The normal operation of Wireless 1394 protocol is based on the use of a controlling hub station, which is assumed to always be able to maintain perfect communications with all leaf stations, as well as be able to overhear the communications among leaf stations in the system all the time. Since the primary deployment environment of Wireless 1394 technology is the home environment, in this surrounding, the presence of shadowing, multipath fading, station mobility and temporary or permanent network failures will not allow these conditions to hold all the time. On the other hand, the use of low power

devices of personal and pervasive nature (e.g. PDAs, sensors and controllers in the household) makes this deviation from perfect conditions of operation even more possible.

To the best of our knowledge, only one published work [10] addressed the behaviour of shadowing in Wireless 1394. In [10], no detailed enough information was provided to allow for the accurate modeling of the Wireless 1394 channel and the measurements are based on a limited set of experiments with a specific (horn) type of antennas. The results provided information regarding average losses. There was no information relates second order statistics or the frequency selectivity of the channel. In any case, the results demonstrated that attenuations in excess of 20 dB are common and such fades occur around or more than 10% of the time. Since there is no adequate knowledge, we decided to follow a more “generic” and thorough approach. We consider that the channel could be blocked for several reasons (shadowing, fading, mobility, failure, etc.) and it follows an ON-OFF behavior. ON provides reliable communications, while OFF indicates unreliable communications. When the system is in the ON state, we are assuming that all packets are delivered correctly. When in the bad state, we are assuming that packets are received erroneously, with probability P_E . The detail of our simulation model will be given in the next chapter.

3. CHAPTER 3

Performance Analysis of Wireless 1394

In this chapter, we will evaluate the performance of the conventional Wireless 1394 protocol. This will provide a good understanding of the capabilities of the protocol when operating in the asynchronous mode (not adequately covered in the existing open literature) as well as will provide the benchmark for comparison with the modifications to the protocol we propose, for the purpose of enhancing its capabilities further.

3.1 Description of Simulation Environment

The simulation platform we use is OPNET (OPTimized Network Engineering Tool) [46]. It is a discrete event based simulation, well accepted in the scientific and engineering community working on computer networks (it is the standard simulation platform for US Army and US Government). It uses an object-oriented technique, where each object can be defined as having configurable attributes. It implements a hierarchical approach (network level, node level and process level) to model any kind of communication network [47].

We use the network architecture, which is shown in Figure 2.4 of Chapter 2, to simulate a Wireless 1394 network. Among those stations in the network, station S_1 is assigned as a hub station. The remaining are leaf stations. Leaf stations are evenly located on the circumference of a circle with a radius of 2.5 meters in a 6.0 meters * 6.0 meters indoor environment [10].

Regarding the wireless channel model in the home environment, we follow the two-state Markov chain model approach [48, 49, 50], which is shown in Figure 3.1. We consider that the connection could be lost because of mobility, unit failure, shadowing or

fading. We assume that there is a binary process: the station can maintain reliable communications with another station (“hear” the other stations) or not. This allows us to use the ON-OFF model. For the N ($N \leq 16$) stations: $S_1, S_2, \dots, S_N$ in the subnet, each pair of stations $\{S_i, S_j\}$ is associated with an ON-OFF process. This process indicates when the pair can hear each other or not. The time the pair stays at the ON stage is exponentially distributed with average value $\overline{\tau}_{i,j}^{ON}$. The time it stays at the OFF state is $\overline{\tau}_{i,j}^{OFF}$.

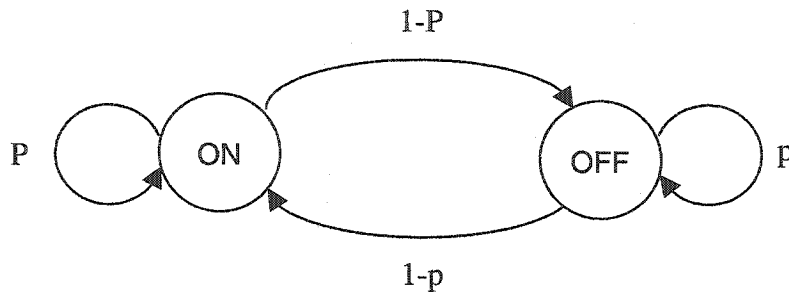


Figure 3.1 Two-State Markov Model

In the simulation, parameters to be monitored are the packet delivery ratio and average delay of delivered packets.

3.2 Simulation Results and Analysis

To reflect the performance of the original Wireless 1394 protocol accurately, we carry out the evaluation under both perfect and impaired conditions.

3.2.1 Results Under Perfect Conditions

The first set of evaluations will establish the effect of traffic volume and buffer size on the performance of the network. We run the following set of experiments, with Poisson packet arrival and fixed packet size (e.g. 1000 bytes) [10, 13].

The performance of the packet delivery ratio versus traffic load under ideal conditions is plotted in Figure 3.2. It conveys when the traffic load is low, the packet delivery ratio is high regardless of the size of the buffer. This is because the buffers are able to hold these packets (no packet lost) when the traffic volume is low. When the traffic volume is changing from low to high, the performance of the packet delivery ratio becomes dependent on the size of the buffer. The larger the buffer size is, the slower the dropping of packet delivery ratio (as the traffic increases) becomes. This is because large buffers are capable of absorbing bursts. When the size of the buffer is large (we use a buffer accommodating 10000 packets to emulate an infinite buffer), it is able to hold all the packets, thus no packets will be lost and these packets will be delivered eventually.

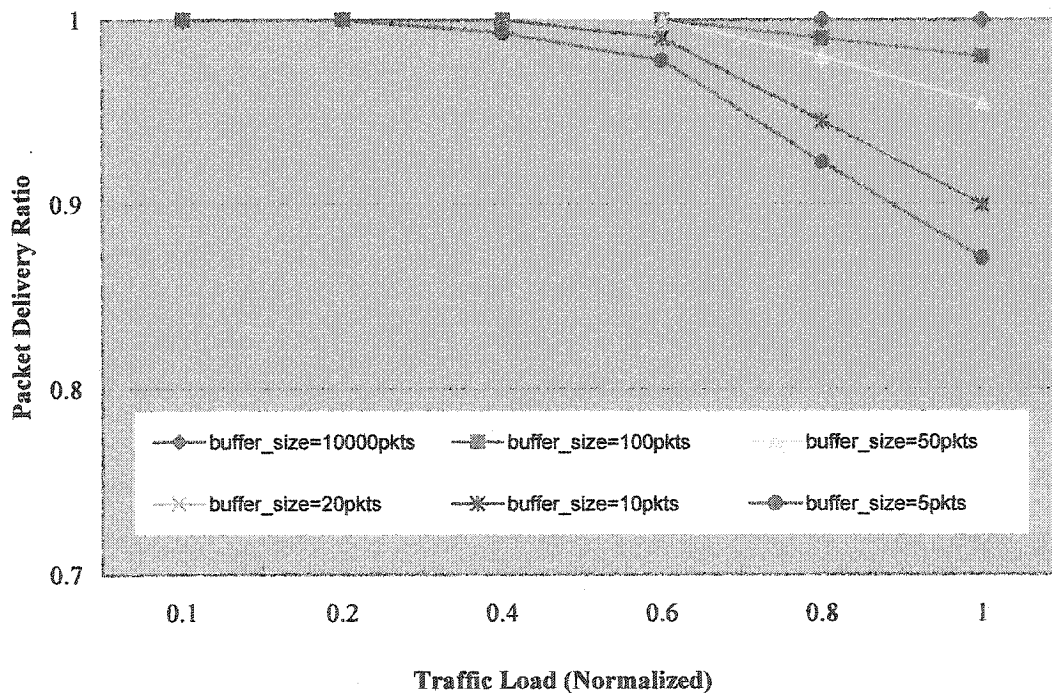


Figure 3.2 Packet Delivery Ratio vs. Traffic Load (Poisson traffic, perfect channel conditions)

The performance of the average packet delay versus traffic load under perfect condition is depicted in Figure 3.3. As one can see, in all cases of different buffer sizes, the higher the volume of the traffic is, the longer the average packet delay will be. Also, the average packet delay is on an upward trend as the buffer size increases. This is due to the fact the longer buffer will generate longer queuing delay (because it keeps more packets rather than dropping them, thus developing longer queues), which will eventually increase the time of packet delivery. The distance between the curves increases as the traffic load becomes higher.

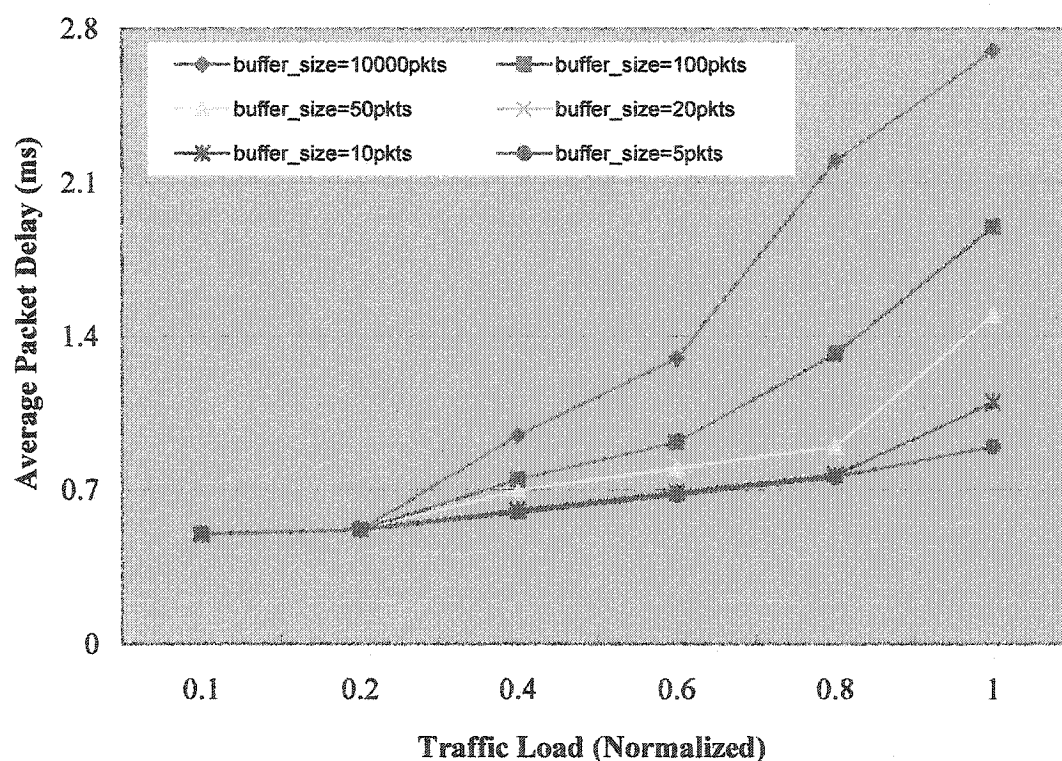


Figure 3.3 Average Packet Delay vs. Traffic Load (Poisson traffic, perfect channel conditions)

Figure 3.4 and Figure 3.5 provide results for the case where the traffic changes to Constant Bit Rate (CBR). The curves indicate that when the network traffic changes to Constant Bit Rate (CBR), the performance of the network improves as compared to Poisson traffic. The packet delivery ratio increases, whereas the average packet delay is reduced. This is because CBR traffic is not bursty.

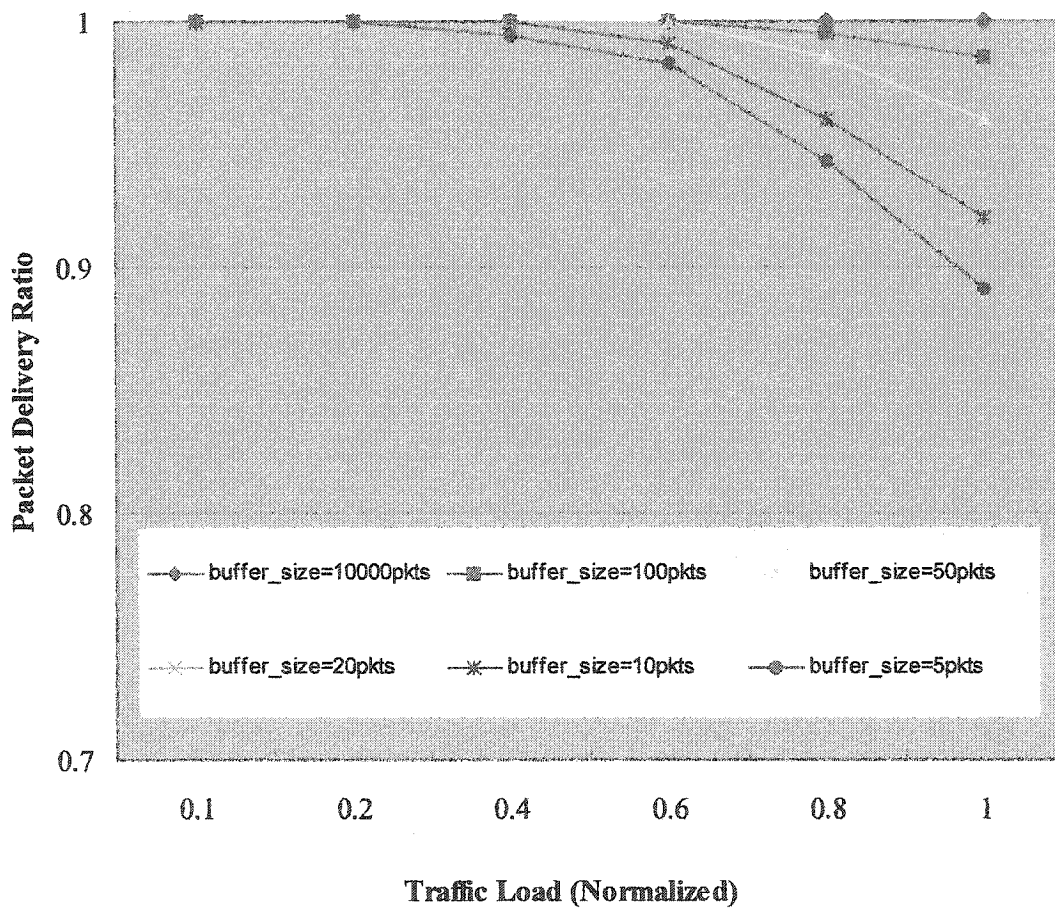


Figure 3.4 Packet Delivery Ratio vs. Traffic Load (CBR traffic, perfect channel conditions)

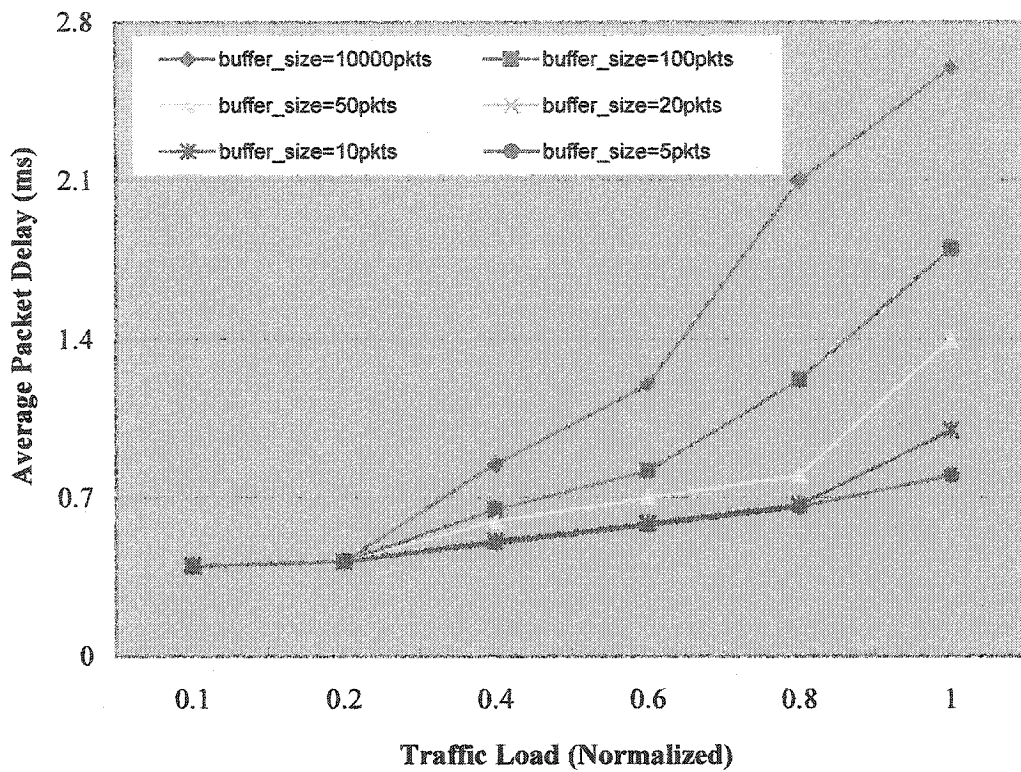


Figure 3.5 Average Packet Delay vs. Traffic Load (CBR traffic, perfect channel conditions)

3.2.2 Results Under Connection Failures

This section assess the effect of poor channel quality (resulting in loss of connectivity) among (the hub and leaf) stations in Wireless 1394 network due to mobility, unit failure, shadowing or fading. Each pair of stations $\{S_i, S_j\}$ is associated with an ON-OFF process. This process indicates whether the pair can hear each other or not. When the system is in the ON state, we are assuming that all packets are delivered correctly. When it is in the OFF (bad) state, we are assuming that packets are received

erroneously, with probability P_E (in the simulations, we assume that $P_E = 1$, i.e. no packets can be received correctly during OFF periods). The time the pair stays at the ON stage is exponentially distributed with average value $\overline{\tau}_{i,j}^{ON}$. The time it stays at the OFF state is $\overline{\tau}_{i,j}^{OFF}$.

In the following cases of the experiment, the status of the $\{S_i \rightarrow S_j\}$ and $\{S_j \rightarrow S_i\}$ channel is identical, which means that when the channel $\{S_i \rightarrow S_j\}$ is ON, channel $\{S_j \rightarrow S_i\}$ is ON too; when the channel $\{S_i \rightarrow S_j\}$ is OFF, channel $\{S_j \rightarrow S_i\}$ is OFF as well. Each pair of $\{S_i, S_j\}$ has $\overline{\tau}_{i,j}^{ON}$ and $\overline{\tau}_{i,j}^{OFF}$ identical. At the beginning of the simulation, we start with half stations at good state, half at bad state. However, we leave every pair to change state as the time progresses. We use buffer size of 100 packets. We have chosen values in the ON-OFF process that in average, a packet has 0.1 probability to be lost. We run the simulations for different $\overline{\tau}_{i,j}^{ON}$ (from 0.2msec to 20000msec) and $\overline{\tau}_{i,j}^{OFF}$ (from 0.02msec to 2000msec), however, in all cases, we maintain the ratio $\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON}$ equal to 0.1.

The performance of the packet delivery ratio versus traffic load (with $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) as parameter) is shown in Figure 3.6. It demonstrates that the packet delivery ratio will increase when the values of the $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) become higher. To understand this behaviour, let us consider two limiting cases: when the $\overline{\tau}_{i,j}^{ON}$

$(\overline{\tau}_{i,j}^{OFF})$ are very long and when they are very short to the point where the probability of delivery or failure for each packet is completely independent from those proceed or following it. As was mentioned above, each network layer packet is segmented to multiple link layer packets, which are delivered to the destination station, become reassembled forming the transmitted packet and deliver it to the link layer. Even if one of these link layer packets becomes lost, the network layer packet will be declared lost as well. It is clear that loss of one lost link layer packet results in loss of the entire network layer packet. When the ON-OFF periods are long, if the first packet goes through, then, there is almost certainty that the rest of the link layer packets will go through. However, this is not the case in the second scenario. Even if the first link layer packet goes through, the following one has a probability of 0.1 (in our case) to be lost, and the same holds for the third, forth etc. It is quite evident that in the second scenario, the probability of packet loss is higher. In a sense, the problem is similar to the case of TCP and ATM, where loss of one cell would damage the entire datagram. Thus, longer ON-OFF periods tend to provide a lower packet loss ratio. When the values of the $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) are large enough (as is the case where $\overline{\tau}_{i,j}^{ON} = 20000$ msec and $\overline{\tau}_{i,j}^{OFF} = 2000$ msec), the packet delivery ratio is the highest.

We also observe that when the traffic load becomes higher, especially when the traffic volume reaches or surpasses 60% of the capacity, the packet delivery ratio will drop dramatically. This can be explained as follows. As the traffic load increases, the chances to experience network congestion increase as well (the buffer size is fixed to 100 packets in these experiments).

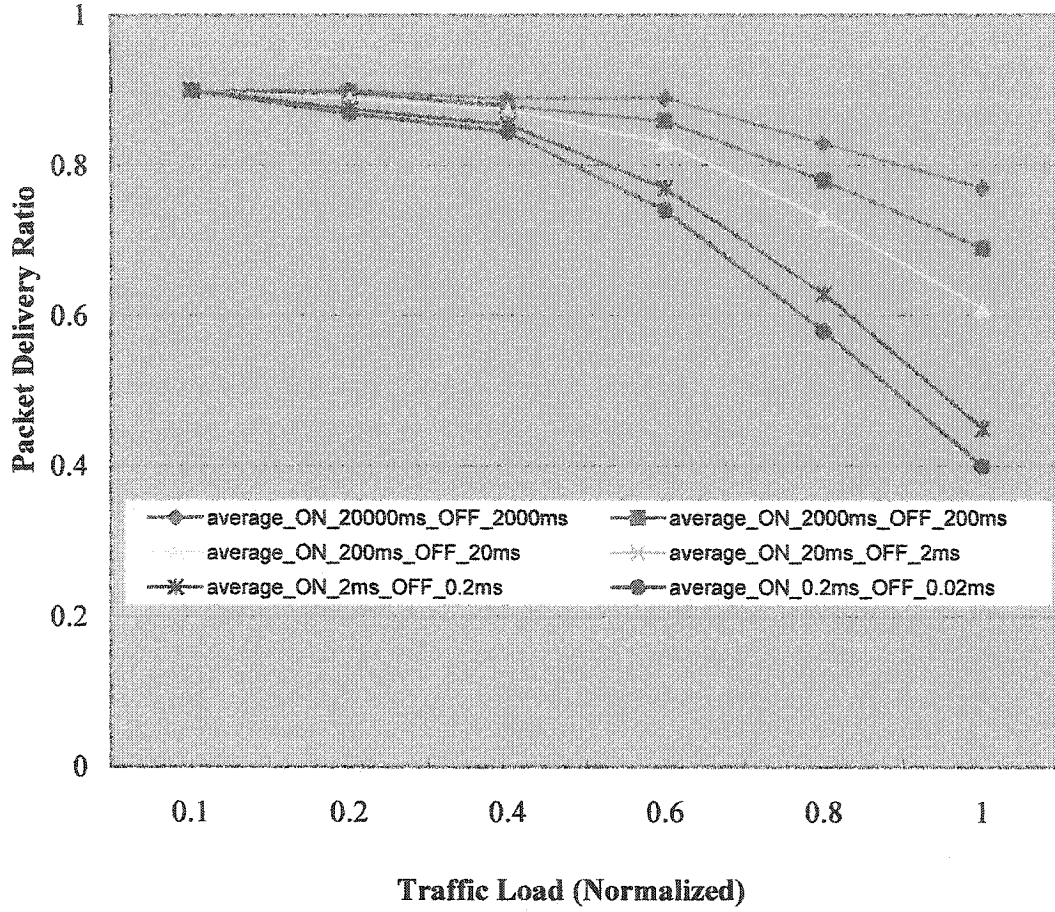


Figure 3.6 Packet Delivery Ratio vs. Traffic Load (with $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) as parameter)

Figure 3.7 depicts the performance of the average packet delay versus traffic load with $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) as parameter. It indicates that the faster the channel fluctuations are, the longer the delays become. This can be attributed to the fact that under faster channel condition fluctuations there are more random losses of link layer packets. Loss of one of these packets forces the receiver to wait for its retransmission, thus holding the remaining correctly receiving link layer packets, delaying the delivery of

the packet to the network layer. It is also evident that the increase of traffic volume affects the delays.

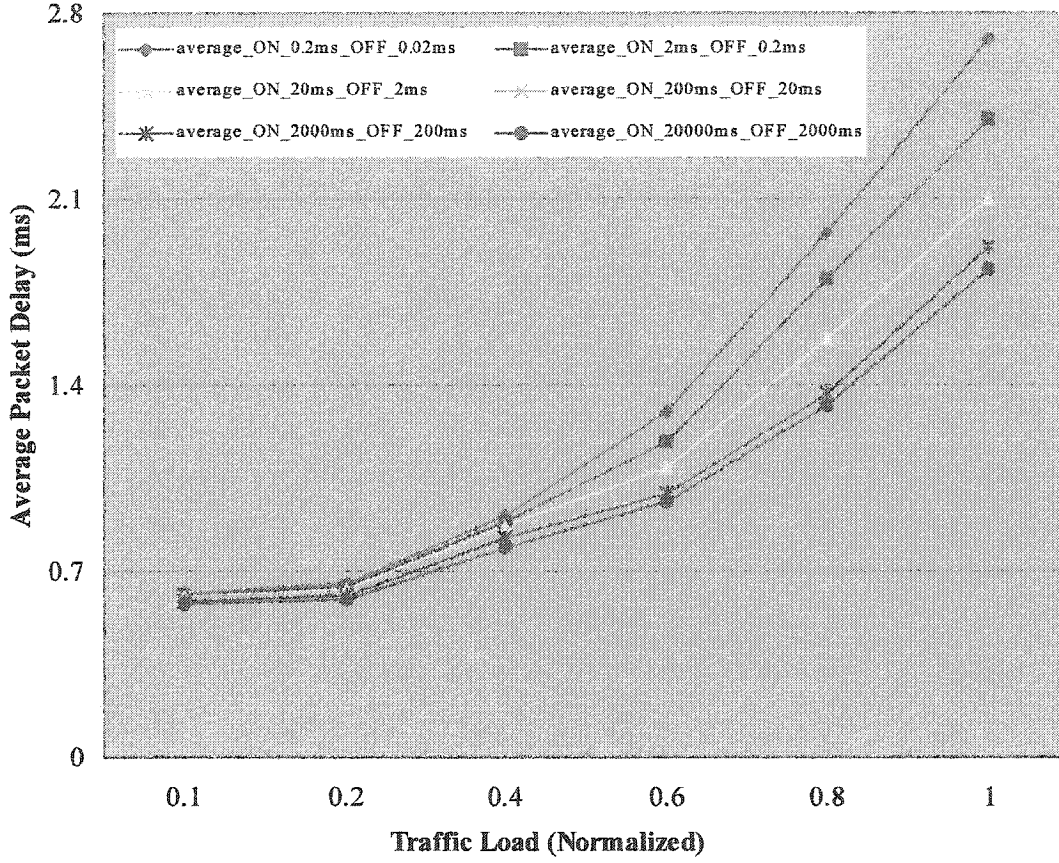


Figure 3.7 Average Packet Delay vs. Traffic Load (with $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) as parameter)

The following set of simulations will assess the effect of different ratio of $(\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON})$. We keep using 100 packets buffer size. We assume that the status of the $\{S_i \rightarrow S_j\}$ channel and $\{S_j \rightarrow S_i\}$ channel are identical. $\overline{\tau}_{i,j}^{ON} = 200$ msec,

$\overline{\tau}_{i,j}^{OFF} = \alpha * \overline{\tau}_{i,j}^{ON}$ msec, where different values of α (e.g. 0.0001, 0.001, 0.01, 0.1 and 1) have been investigated.

The performance of the packet delivery ratio versus traffic load with α as parameter is illustrated in Figure 3.8. It is evident that the lower the value of the probability of loss ratio ($\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON}$) is, the higher the packet delivery ratio becomes. This is according to the expectations. When the time the channels remain in poor conditions decreases, the system has the opportunity to pass more packets without losses and retransmission related delays, thus, the overall network performance improves. For instance, when $\alpha = 0.0001$, the performance of the packet delivery ratio with respect to different traffic volumes approaches to the one of perfect connections, shown in Figure 3.2. It is interesting to see that when $\alpha = 1$, the packet delivery ratio is very low (close to zero). The link condition is so poor for extensive period of times that link layer packets experience many (in many cases failed) retransmissions, thus taking away resources. Of course this level of poor performance is extreme, not expected under most of real-life cases.

It is also evident from Figure 3.8 that for a certain value of α , when the traffic load is increasing, especially to a high level (reaching or surpassing 60% of capacity), the packet delivery ratio is on a downward trend. This is due to the fact that the higher the traffic volume is, the bigger the chances of the network congestion will be (the buffer size maintains at 100 packets in the set of simulation). Therefore, the packet loss rate will be higher.

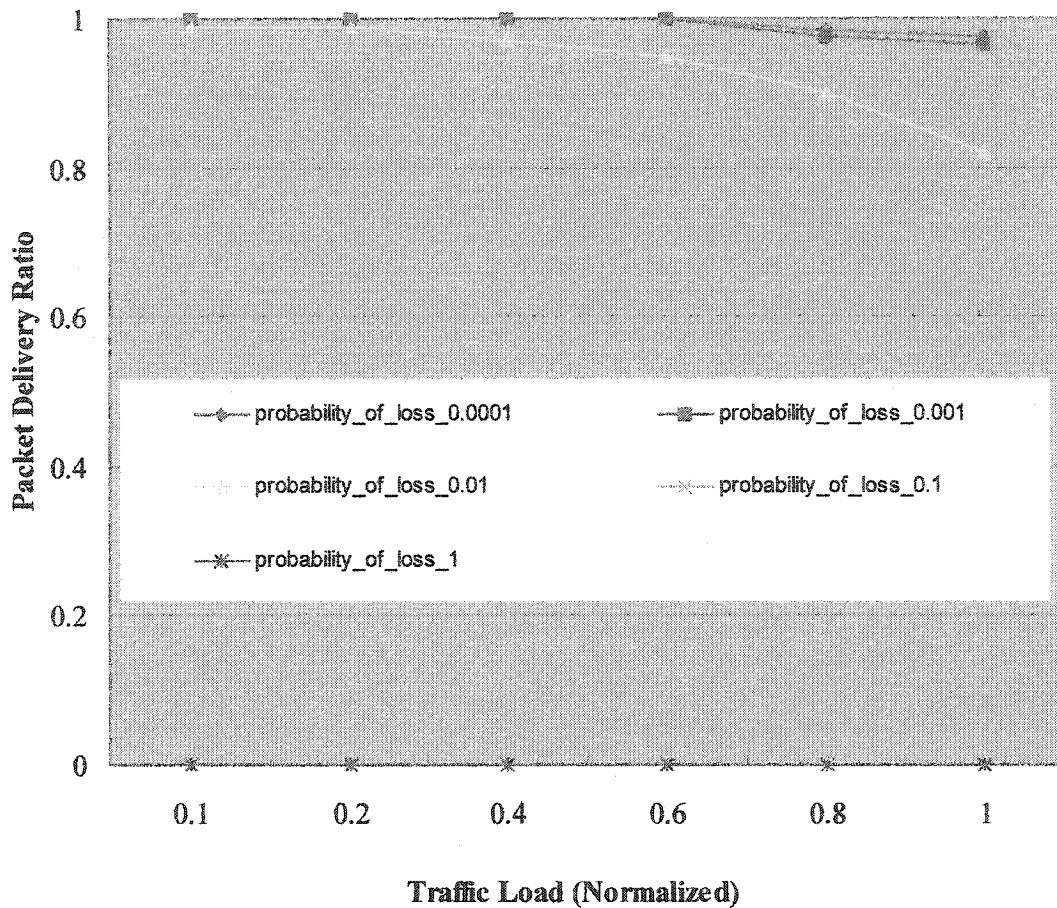


Figure 3.8 Packet Delivery Ratio vs. Traffic Load (with α as parameter)

The performance of the average packet delay versus traffic load with α as parameter is pictured in Figure 3.9. It conveys the fact that the higher the value of α is, the higher the average packet delay becomes. This is associated with the fact that longer fading periods produce more losses and retransmissions of link layer packets, thus delaying the time a network layer packet can be reassembled and pass to the network layer at the destination side. Moreover, when the traffic load increases, the average packet delivery time increases accordingly.

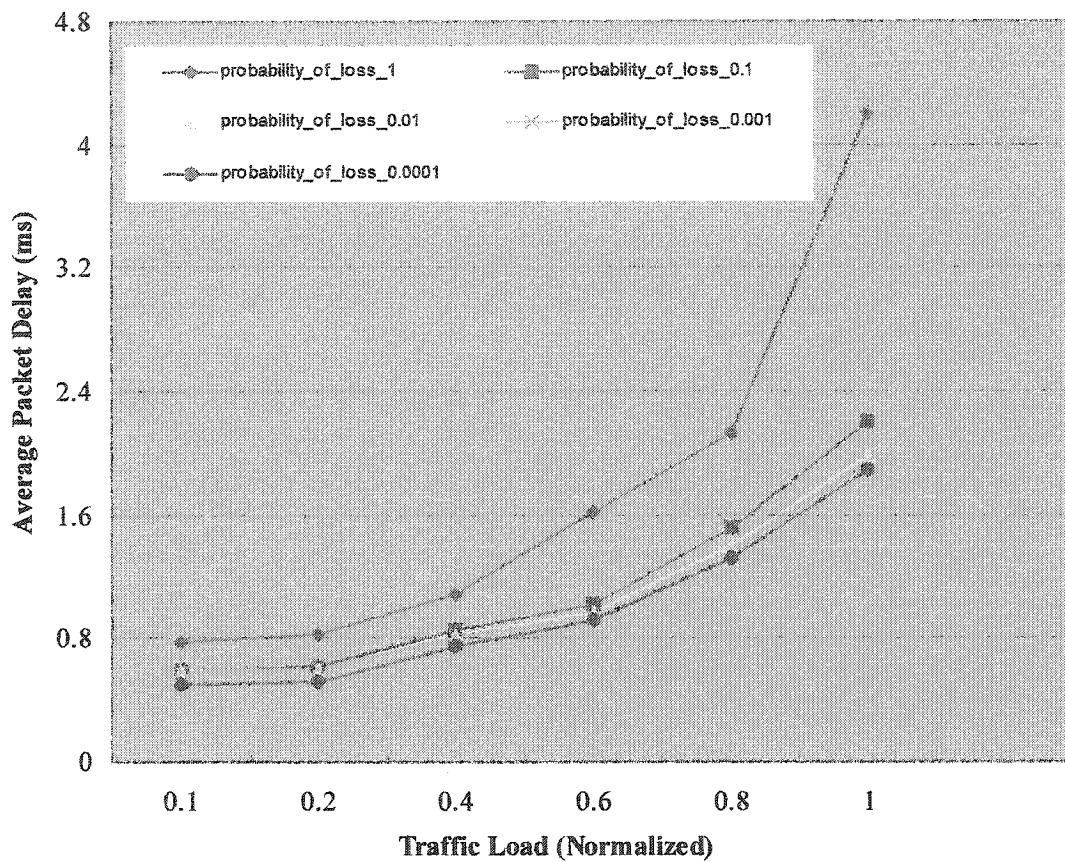


Figure 3.9 Average Packet Delay vs. Traffic Load (with α as parameter)

3.3 Summary

In this chapter, the performance of the original Wireless 1394 protocol has been evaluated both under perfect and impaired channel conditions. In addition to understand the performance of Wireless 1394, the information provided in this chapter allows us to set the benchmark for the comparison with the improved schemes we are proposing and describe in Chapter 4.

4. CHAPTER 4

Protocol Extensions and Improvements to the Original Wireless 1394 Technology

In this chapter, we will elaborate the protocol extensions and enhancements we propose to the conventional Wireless 1394 technology.

4.1 Applying Virtual Sensing and Polling in Wireless 1394

Since both IEEE 1394 and Wireless 1394 have been developed to operate as collision free protocols [5,10], it is necessary to ensure that all scenarios of practical deployment of Wireless 1394 networks should generate collision free conditions. After observing the possible packet collision problem existing in the asynchronous transmission mode of the original Wireless 1394 protocol, we came up with the solution of applying a virtual sensing and polling method to resolve this [4]. Interestingly, we find out this solution is also able to improve the system's performance when the channel conditions among the hub station, transmitting station and receiving station are of poor quality.

4.1.1 Problems Existing in the Traditional Wireless 1394 Asynchronous Transfer Mode

The primary deployment of Wireless 1394 is for the home network. Due to the fact that the quality of the wireless link in the home environment is time and location dependent, the conditions of the forwarding channel and the reverse channel between the transmitting station and the receiving station cannot always be thought as the same. A good wireless forwarding channel does not always imply the existence of a good wireless reverse channel. This is exactly the case when taking the low energy nature of some

emerging smart devices, such as PDAs, sensors and actuators into consideration. Depicted in Figure 2.24 of Chapter 2, the original Wireless 1394 asynchronous transmission has already defined that the polled leaf station has to acknowledge the polling to the hub station prior to its packet transmission. However, acknowledgements transmitted from the receiving station could be lost due to the poor reverse channel condition, and might not be captured by either the hub station or the transmitting station in the Wireless 1394 network. Such scenario is quite possible when the types of antennas (e.g. horn antenna [12], multiple-sectored antenna [12], omni-directional antenna [15], sleeve antenna [42]) and power transmission between the transmitter and the receiver are different, allowing one station to be able to pass its message to the corresponding station, whereas the corresponding station is not able to do so. The result of the loss of acknowledgement will further lead to the occurrence of packet collision in the network. An example will be demonstrated in Figure 4.1. Other possible occurrences of packet collision and packet loss when deploying Wireless 1394 can be attributed by shadowing and multipath fading, occurring frequently in the wireless home environment [10,12,15,42,51]. The reason is that the proximity of stations and the objects inside a home, for instance human bodies, furniture, various appliances, may shadow the communication path and block or reflect the transmitted signals, thus having significant negative effects on the system's performance.

Figure 4.1 illustrated how packet collision will occur either because of the loss of response (referring to leaf station's acknowledgment to the polling of the hub station) or due to the obstructed acknowledgment caused by shadowing and multipath fading. In Figure 4.1, we have a hub station, and leaf stations 1 and 2. Following the rule of asynchronous transmission of the original Wireless 1394, the hub station polls the leaf station 1 then leaf station 2. Let us concentrate on the case when the hub station fails to receive the response from the polled leaf station 1. One possible cause is the diversity of the wireless home networking devices in terms of their characteristics and capabilities. For example, the type of antennas, power transmission and receiver capabilities of the hub station and leaf station 1 might be different, allowing the hub station to be able to pass its message to the leaf station 1,

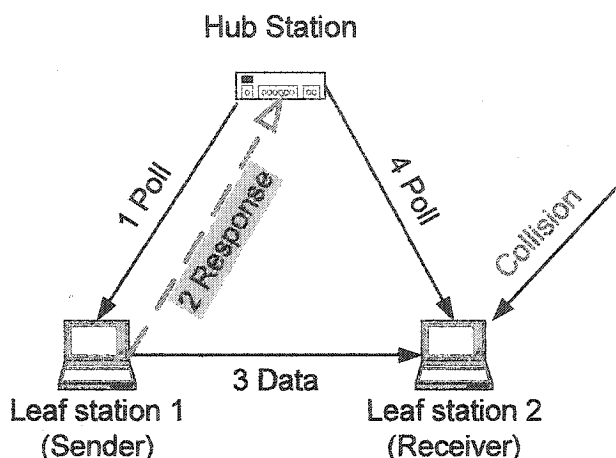


Figure 4.1 Packet Collision Occurrence in Poor Quality Sender-Hub Station Channel

whereas the leaf station 1 is not able to do so. Other possibilities include different shadowing / multipath fading conditions in the forward and reverse paths, that might prevent the hub station from receiving the response correctly. Since leaf station 1 has been given the transmission right, it can transmit its data to its target leaf station 2 after sending out the response to be polling message. We assume station 1 has one 215 or 323-byte [41] packet to send. It will take $57.3 \mu\text{s}$ ($215 * 8 \text{ bits} * 4/3 / 40 \text{ Mbps}$) or $129.2 \mu\text{s}$ ($323 * 8 \text{ bits} * 2 / 40 \text{ Mbps}$) to complete the transmission. (For data rate, modulation scheme and code rate please refer to [9].) Since the hub station is unaware of leaf station 1's ongoing transmission because it failed to receive the response, it cannot perceive the status of leaf station 1 and treats it as unreachable. After polling time out (a period of $34.2 \mu\text{s}$ counting between the end of the previous polling packet transmission and the beginning of the next polling packet transmission), it will issue a new polling packet to the next station, leaf station 2 in this example. Since the interval for the hub station to generate a polling packet is shorter than the total time for leaf station 1 to send the response to the hub station and finish its data transmission, (ignoring the propagation delay as it is extremely small due to the short distance among stations in home environment,) station 2 will be polled by the hub station prior to the completeness of data reception. That is, leaf station 2 receives two signals simultaneously, the polling packet from the hub station and the data packet from the leaf station 1, and hence it fails to

understand either of the two transmissions because of the occurrence of packet collision. This is especially the case when leaf station 1 has large amount of data (e.g. multiples of 215 or 323-byte packets [41]) to transmit to the leaf station 2, leading the network to a higher congestion level.

4.1.2 Proposed Virtual Sensing and Polling Method in Wireless 1394 Asynchronous Transfer

The above scenario indicates that the conventional Wireless 1394 asynchronous transfer mechanism might experience serious problems generated by packet collision, packet loss and network congestion. Bearing in mind that Wireless 1394 has been developed to operate as a collision free protocol [10], it is important that a solutions is provided, to enable the protocol to cope with the wireless environment.

To answer this challenge, we propose use of a pair of RTS (Request-To-Send) and CTS (Clear-To-Send) controlling packets, which virtually sense the impending transmission channel prior to the actual transmission of data. We choose 14 bytes (112 bits), the length of a polling packet in Wireless 1394, as the sizes of RTS and CTS packets. Like other Wireless 1394 MAC asynchronous packets, both RTS and CTS have 7-byte MAC header and 4-byte CRC. The field of Packet Type can be used to differentiate RTS and CTS packets. We employ two reserved identifies as the values of packet type field, “001000” for the RTS packet and “001001” for the CTS packet respectively.

The transmission process following the proposed scheme is exhibited in Figure 4.2. The polled leaf station 1 first sends a RTS packet to the destination, leaf station 3. Station 3 will send a CTS packet back to station 1 if the channel between them can be used. Once station 1 obtains the CTS packet from the receiving station (station 3), it becomes aware that the quality of the forward channel between them is acceptable. Then, it begins to transfer its data packet. If station 1 fails to receive the CTS packet from station 3 (e.g. because the path is shadowed), no further data transmission is necessary.

This way, RTS and CTS act as a soft way to inform the transmitter of the channel's current condition. Please note that in our proposed mechanism, the RTS packet acts as acknowledgement to the polling of the hub station as well; thus, separate acknowledging packet is not needed.

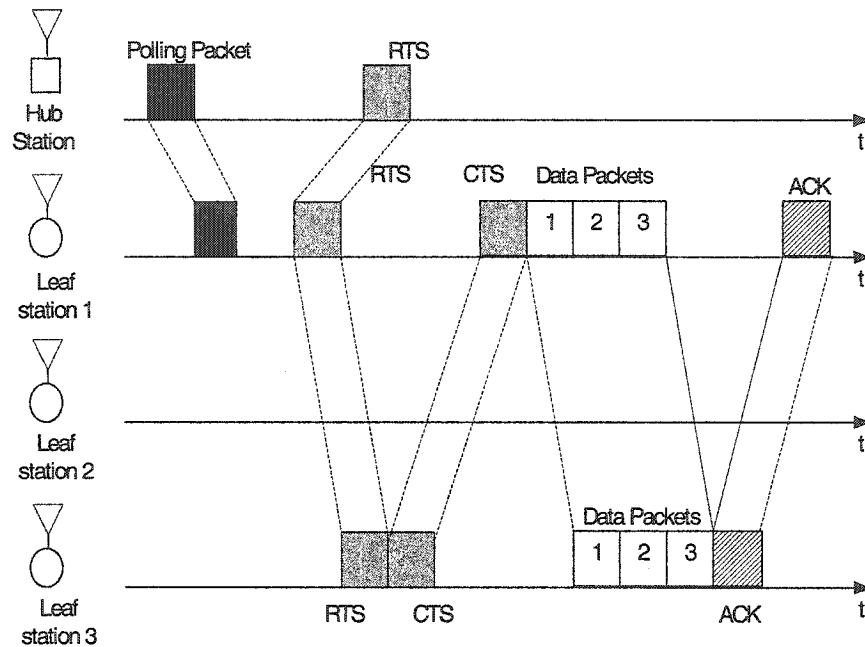


Figure 4.2 Proposed Wireless 1394 Asynchronous Transmission

The benefit of our proposed strategy can be seen in Figure 4.3. The network conditions in Figure 4.3 are the same as those in Figure 4.1. That is, a subnet is composed of one hub station, leaf stations 1 and 2. The hub station is able to pass its message to leaf station 1, whereas leaf station 1 is not able to do so, because the path from leaf station 1 to the hub station is shadowed. Hence, the hub station loses its connection with leaf station 1. Since station 1 has been granted the transmission right by obtaining the polling packet from the hub station, it sends a RTS signal including the numbers of packets it wishes to transmit to target station 2. If the channels between station 1 and station 2 are good, RTS will be received by station 2. It will then send a CTS containing the same information as in RTS (the numbers of packets to be transferred), which will be captured by both, leaf station 1 and hub station. Although the hub station is not able to

receive any information from the source station side, chances are that it can receive the CTS signal from the destination side and extract the information of numbers of packets to be transmitted. This will allow the hub station to estimate the completion time of the current transmission and proceed with the generation of the next polling packet at an appropriate time. Therefore, with the help of CTS, the hub station will only poll leaf station 2 when it finishes its on going communication, avoiding the scenario indicated in in Figure 4.1 (where it polls leaf station 2 or another station before completion of its data reception that leads to packet collision).

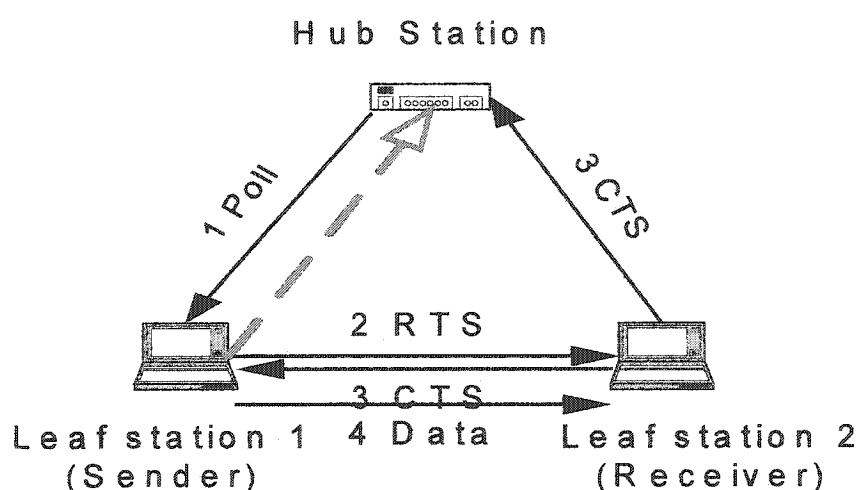


Figure 4.3 Packet Collision Avoidance in Poor Quality Sender-Hub Station Channel

The proposed mechanism also brings another advantage. It requires less time to detect the unavailability of the channel between the polled sender and receiver. As shown in Figure 4.4, employing the proposed mechanism, the sender will become aware of the unavailability of the wireless medium by not receiving the CTS signal (112 bits) after sending a RTS (112 bits) in only $67.9\mu\text{s}$ ($2 \times 112 \times 2 \text{ bits} / 6.6 \text{ Mbps}$), (omitting the propagation delay and processing time at the stations). In the conventional protocol where RTS/CTS is not used, the sender will require more time to figure out the unavailability of the channel due to lack of reception of the ACK packet, because even when transmitting the smallest size data packet (35 bytes [41]), it takes $84.8\mu\text{s}$ ($35 \times 8 \times 2 \text{ bits} / 6.6 \text{ Mbps}$) to be fully received by the destination station. This wastes resources and

degrades the network's performance. The capability of RTS/CTS in terms of "sensing" the unavailability of the channel faster shaves resources, since it allows their reallocation to another station faster.

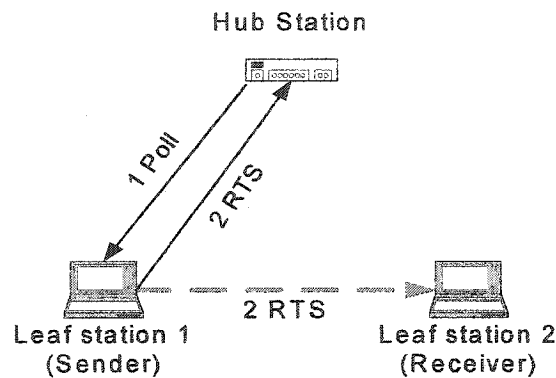


Figure 4.4 Scenario of Poor Quality Sender-Receiver Channel

Figure 4.5 presents the scenario where there is lack of communications between hub station and receiving station due to the poor quality of the channel. In this case, both, the original asynchronous transmission approach and the proposed RTS/CTS approach are able to successfully support packet transfer between transmitting and receiving stations. Should the channel conditions do not change and leaf station 2 is to be polled next, there will be a problem with the conventional scheme. The original asynchronous transmission mode will generate packet collision and packet loss. The RTS/CTS approach will avoid the problem.

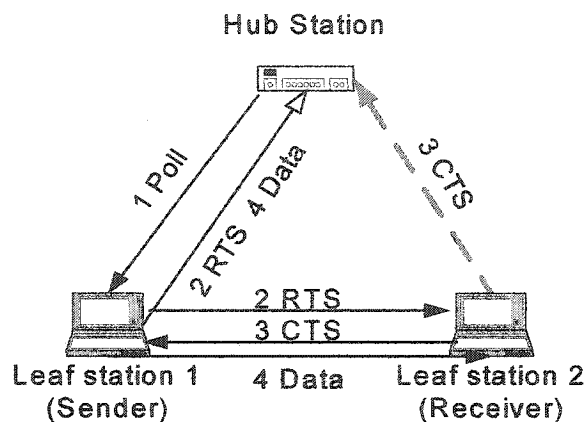


Figure 4.5 Scenario of Poor Quality Receiver-Hub Station Channel

4.1.3 Summary of the proposed mechanism

When employing Wireless 1394 in the home environment, some attention should be paid to the characteristics of the wireless environment, since it could have significant negative effect on system's performance. The behaviour of wireless environment could result in packet collisions (not been expected in the protocol), packet loss and even network congestion. All these are serious contributors for performance degradation. To counteract these problems, the strategy of applying virtual sensing and polling in Wireless 1394 asynchronous transmission has been proposed. As will be seen in Chapter 5, considerable improvements can be achieved through this approach.

4.2 DHSS (Dynamic Hub Station Selection) Protocol in Wireless 1394

Wireless 1394 has serious advantages over other wireless home networking technologies (e.g. IEEE 802.11, Bluetooth, HomeRF, etc.) on account of the fact that Wireless 1394 not only has broadband communication capability, but the ability to provide quality of service support already incorporated into the standard. A crucial element in the architecture of the system, very essential to provision of these enhanced

capabilities, is the use of a central controller, the hub station, which regulates the allocation of network resource and manages all the leaf stations' communication. Thus, presence and proper functioning of the hub station is very essential. User mobility and the channel conditions of the wireless environment could prevent hub station from being always available to service the network. In order to provide the system with an always function hub station, we came up with the DHSS (Dynamic Hub Station Selection) protocol using certain criteria. Detail of the DHSS algorithm will be provided in the following section [6].

4.2.1 Necessity and Motivation

Hub station plays a leading role in the Wireless 1394 system. As shown in Figure 2.4 of Chapter 2, the hub station resides in the core of the Wireless 1394 system. It works as a "commander" in the Wireless 1394 subnet in a sense that it governs all the stations in the system. Particularly, it takes charge of bandwidth allocation within the network. It assigns bandwidth to stations in isochronous transfer mode before allocating that in asynchronous transfer mode, guaranteeing just-in-time delivery of time-critical traffic. Moreover, the hub station administers media access control among stations by distributing transmission rights through a polling packet to a leaf station. The Station ID of the leaf station that is granted the transmission permission is defined in the polling packet. Only the leaf station polled by the hub station can start to transmit. Additionally, the hub station performs real-time monitoring of all the communications in the subnet and sends cycle time information to maintain the Wireless 1394 frame structure. The leaf stations are always in a passive state. They can take action and communicate with other stations only after the right has been passed to them by the hub station (the resource and time defined by the hub station). According to a relatively new proposal, the Hub station performs data traffic relaying as well, when the communication between any leaf station pair fails, which reveals the fact that the Wireless 1394 system has a significant need for flexibility in terms of the hub station's functionalities.

There is no doubt the performance of the Wireless 1394 network highly depends on the proper functionality and availability of the hub station [11]. A Wireless 1394 system lacking an operable hub station is completely paralysed. If there is no active and functional hub station in the Wireless 1394 network, this network is called an unmanaged network, where no communications can be performed among the stations [41]. When implementing this prominent technology in the wireless home environment, some unforeseeable problems, such as the failure of the unit, the loss of connectivity between the unit itself and the other leaf stations because of network topology change or mobility, will bring the Wireless 1394 network to a complete halt. Therefore, procedures need to be defined in order to resolve this issue. A possible way is to equip the system with a backup (standby) hub station and pass the hub station's responsibilities over to the standby hub station, as well as initiate processes to maintain the network communication, should the problems mentioned earlier occur. Since the existing Wireless 1394 protocol does not provide the criteria of selecting hub station candidates and the procedure of how to reorganize the network [41], we propose a method, which we have named DHSS (Dynamic Hub Station Selection) protocol.

4.2.2 DHSS Algorithm

We start by giving a brief review of two of the most important packets of Wireless 1394, the FSP (Frame Start Packet) and SSP (Station Synchronization Packet). Then, we extend these primary packets to accommodate richer information, which is needed in the DHSS protocol we propose. FSP and SSP are located in the management area of a Wireless 1394 frame structure [9,10,13,15], which is shown in Figure 2.9 of Chapter 2. Only the hub station can transmit FSP in order to provide network information, such as network ID, station information and slot allocation information, to the other stations in the network, distributing global information (from the network perspective) locally. Each station in the network transmits its corresponding SSP (a packet keeps a station's status and its request) to the other stations and receives SSPs from the other stations as well, distributing local information (from an individual station point of view) globally. Acting as go-betweens, constant exchange of FSP and SSP

makes the effective communication between the hub station and leaf stations in the Wireless 1394 network possible.

The detail description of FSP and SSP has been given in Chapter 2. The packet structure of FSP is presented in Figures 2.10 to 2.14 and the packet content of SSP is depicted in Figure 2.15. In short, the hub station transmits FSP at intervals of 4ms (the Wireless 1394 frame length), indicating the beginning of a Wireless 1394 frame transmission [41]. Using FSP, the hub station also gives to the leaf stations in the network opportunities to report their individual status and express different requests (e.g. transmission request, sleep mode request, active mode request, etc.) via their SSPs, performed in a certain order. This is accomplished by organizing the leaf stations into different groups, so that stations in different groups transmit their SSPs in different frames and stations in the same group transmit their SSPs at different timing. Specifically, the 2-bit field of “Number of SSP per Frame” in FSP specifies the number of SSP that is allowed in each frame, the maximum value being 4 ($2^2 = 4$). The 4-bit field of “SSP Cycle” in FSP informs how many frames are required in total, in order to complete SSPs transmission by all stations (every station transmits one SSP). Hence, if a Wireless 1394 subnet has 16 stations (the maximum number of stations including the hub station in a Wireless 1394 subnet [9]), implying that 16 SSPs need to be sent, and the value of the “Number of SSP per Frame” field is $(11)_2$ (meaning 4 SSPs will be transmitted in one frame), the value of “SSP Cycle” field will be 4, meaning that 4 frames ($4 \text{ frames} * 4\text{ms/ frame} = 16\text{ms}$) are required to complete a cycle of SSPs transmission by all stations. The field of “SSP Phase Counter” in FSP is used to count the frame up to the value of “SSP Cycle” and distinguish different frames. This way, each station will only transmit their corresponding SSP at different timing, which is regulated in FSP by the hub station. The reason for the hub station to make such effort to manage the station’s SSPs transmission is that SSP is a very useful packet that it stores the station’s “personal” data and its communication concerns. Leaf stations use SSPs to transmit their status and /or express their requests to the hub station.

In particular, SSP contains the fields of SSP type, Sleep Mode Request, Polling Priority, RSSI (Receiver Signal Strength Indicator) values and MAC Packet Destination Station Bitmap, etc. The use of these fields have been explained in Section 2.2.3.3, Wireless 1394 Frame Structure, of Chapter 2. Among them, we present how Polling Priority field is used as an example. Suppose a leaf station wishes to transmit either asynchronous packets or control packets (referring to the packets used for network management). Following the FSP packet transmission (occurring every 4ms), each leaf station can send its SSP to after reception of FSP, at the time the hub station has assigned for transmission of its SSP. The leaf station will inform the hub station of its transmission request by setting proper values ("0001" for asynchronous packets transmission request or "0101" for control packet transmission request) in the field of Priority Type of SSP. Then, by issuing a polling packet to this station, the hub station will grant transmission right to the leaf station. Now, the leaf station can start to transmit its control packets or asynchronous packets. (This is called priority control polling. Another polling option defined in Wireless 1394 is the normal polling, where the hub station will poll each leaf station in turn, regardless if it has requested service or not.). The process occurring through this message flow is shown in Figure 4.6.

Since every station receives SSP from the other stations, it is able to measure the reception quality (the Rx automatic gain) of its signal, indicated by the RSSI values in SSP, and further report these results to the hub station. Therefore, the hub station will know the rough status of connections among stations. However, we believe that signal strength is not the only factor to be taken into consideration.

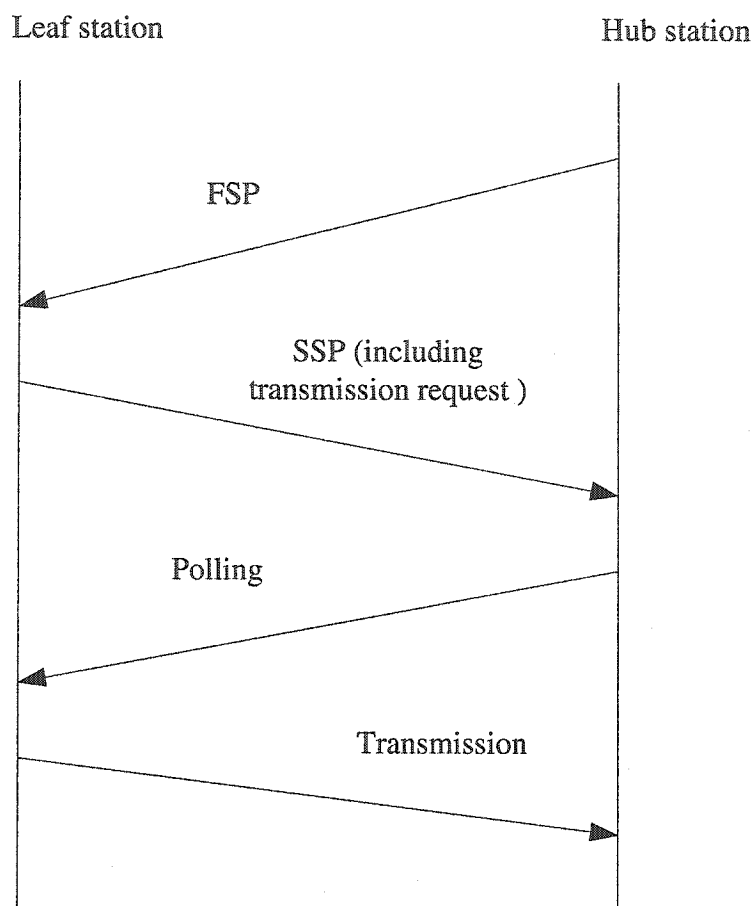


Figure 4.6 Message Flow of FSP and SSP Exchange Example

Based on the features of SSP already defined in the Wireless 1394 protocol, we make use of the “Reserved Field” in this primary packet, in order to include additional information, reflecting the network conditions more accurately. This information will become the cost parameters, used in the cost function that determines in the DHSS protocol the selection of hub station. As depicted in Figure 4.7, we use the “Reserved” field in the first octet of the original SSP (packet format shown in Figure 2.17 of Chapter 2) to be the “E (Extended)” flag in the new version of SSP. When E=1, it refers to an extended version of SSP. When E=0, it means that this is the original SSP.

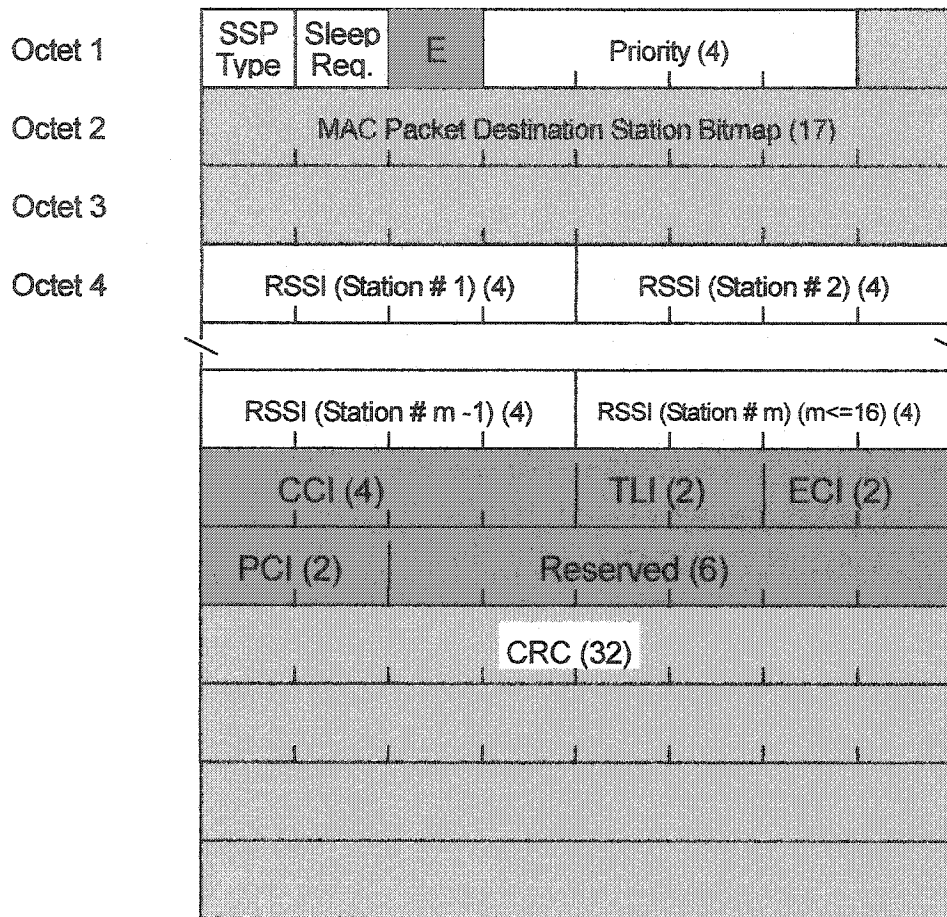


Figure 4.7 Extended SSP Structure and Content

In the extended version of SSP (the value of “E” is 1), we define four new fields, CCI (Communication Capability Indicator), TLI (Traffic Load Indicator), ECI (Energy Concern Indicator) and PCI (Processing Capability Indicator) respectively. Their contents are indicated in Table 4.1. How they will be used will be discussed later, when we introduce the cost function we came up with. As defined in Wireless 1394, every station will transmit SSP and every station will receive SSP from the other stations. Together with the RSSI values, the information of CCI, TLI, ECI and PCI of all stations (reported through SSPs) will be maintained in the hub station.

Table 4.1 Cost Parameters in Cost Function of DHSS Protocol

	Cost Parameters	Length (bit)	Allowable Value	Comment
1.	CCI (Communication Capacity Indicator)	4	0-15	Specify station's capability to be heard by other stations in a subnet.
2.	TLI (Traffic Load Indicator)	2	0-3	00: no-very low (below 25% of capacity) 01: very low-low (25%-50% of capacity) 10: low-high (50%-75% of capacity) 11: high-very high (above 75% of capacity)
3.	ECI (Energy Concern Indicator)	2	0-3	00: low 01: medium 10: high 11: not in use
4.	PCI (Processing Capability Indicator)	2	0-3	00: low 01: medium 10: high 11: not in use

According to the principle of Wireless 1394, a hub station, is always needed to take charge of the network. Therefore, at the very beginning of network initialization, when a device has been turned on and it cannot detect any Wireless 1394 activity around it, it should be given the choice of declaring and advertising itself as a hub station. The decision of doing so should be based on the nature of the device and the applications it plans to run. It will not make much sense to declare a Wireless 1394 hub station responsibility if it is only a PDA looking for a printer to print e-mail. However, the assignment of the hub station is not fixed and will be updated once the system detects the original hub station is not able to function well for a relatively long period of time. Assuming the station decided to declare itself as a hub station, being station S_0 in this subnet, it will move to an open frequency channel and start to send a FSP, announcing an

established Wireless 1394 subnet. Then it will be waiting for the other units to join the subnet. The other units will be marked from S_1 to S_i ($i \leq 15$). New SSPs can be used to declare presence.

Because all stations in Wireless 1394 will transmit their SSPs in a cycle of 4 frames (16 ms), as defined in the FSP transmitted by the hub station we mentioned above, stations will know the specific timing for them to send their SSPs to express their concerns of control packets (refer to the packets used for network management) transmission. Here, we use the reserved packet types in Wireless 1394 [41] to develop seven new control packets, demonstrating different actions taken by the stations to fulfill the task of dynamic hub station selection. These new packets are listed in Table 4.2. Their packet formats and structures will be presented later in this section, referring from Figure 4.9 to Figure 4.15. Their definitions are in accordance with the asynchronous packet structure for the MAC layer defined in Wireless 1394 [41]. The similarities of these control packets are that they all have 7-byte MAC header, where the information such as the packets' source station ID and destination station ID are stored and use 4-byte CRC for parity checking. The difference among them is the content of the payload, where different control packet types distinguish the different tasks they are supposed to be performed.

Table 4.2 Lists of New Control Packets in DHSS Protocol

	Code	Packet Type	Comment
1.	100000 ₂	GNN (Get Nearest Neighbour)	Get station information request
2.	100001 ₂	ENR (Early Neighbour Reply)	Get station information response
3.	100010 ₂	SWU (Station Weight Update)	Inform station of updated weight
4.	100011 ₂	SWUR (Station Weight Update Response)	Obtain others updated weight
5.	100100 ₂	HSV (Hub Station Vote)	Send Station's hub candidates
6.	100101 ₂	HSVR (Hub Station Vote Response)	Get others' hub station candidates
7.	100110 ₂	HSC (Hub Selection Confirmation)	Confirm selection completeness

The complete process of hub station selection is demonstrated in Figure 4.8.

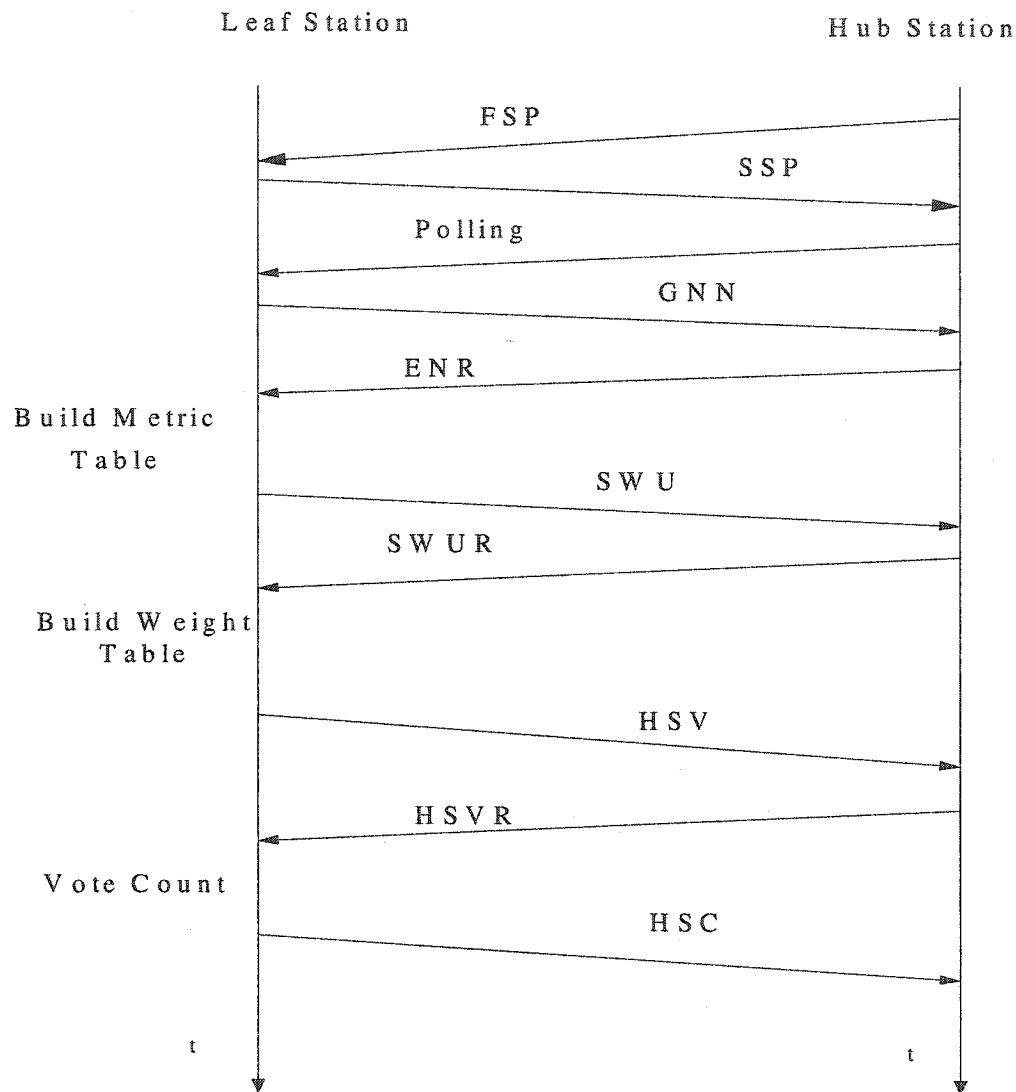


Figure 4.8 DHSS Main Procedure

First of all, leaf station (suppose S_1) transmitted its SSP (the extended version of SSP) to hub station (S_0) to imply its control packet transmission request at the moment defined in FSP by the hub station. After receiving a polling packet address to it, S_1 is able to send the control packet, GNN, to ask for the other stations' detail information.

Then, the hub station will return stations “personal” data, placed in the ENR message, as response to the GNN. In fact, ENR contains stations information such as CCI, TLI, ECI and PCI. These data will be used to calculate each station’s metric M_i . In DHSS, we develop a cost function to select the station with the lowest cost as hub station. The factors to reflect the stations’ capacities of becoming a hub station are interpreted as the cost parameters in a cost function. A possible cost function example is the following:

$$M_i = \text{cost coefficient (1)} * \text{cost parameter (1)} + \text{cost coefficient (2)} * \text{cost parameter (2)} \\ + \dots + \text{cost coefficient (n)} * \text{cost parameter (n)} \quad (1)$$

In (1), we choose $n = 4$. Since one of the main features of the hub station is that it is able to communicate with all the other stations and hear all the activities through the network, CCI, station’s communication capability indicator, should be considered first. Due to the fact that the bigger the value of CCI, the more capacity it possesses to be heard by the others, thus the lower the cost the station should pay to be a hub station, we choose cost parameter (1) $= 1/\text{CCI}$ (the reciprocal of CCI). We specify cost parameter (2) $= \text{TLI}$ (Traffic Load Indicator) as the bigger the value of TLI, the higher load the station has, the higher the cost the station need to pay to be a hub station. Next, we have cost parameter (3) $= 1/\text{ECI}$ (the reciprocal of ECI, Energy Concern Indicator). The reason for this is that the lower the value of ECI, the higher the cost this station has to pay if it becomes hub station. Finally, we have cost parameter (4) $= 1/\text{PCI}$ (the reciprocal of PCI, Processing Capability Indicator), since the higher the value of PCI (more powerful station), the lower the cost the station should pay to become a hub station. For the definitions of cost coefficient, generally speaking, in all the case, the cost coefficients should be associated with the importance of their corresponding cost parameters.

Therefore, once upon obtaining those cost parameters contained in ENR, stations will be able to build their metric tables based on the calculation of the cost function defined above. In each metric calculation, records of different metrics corresponding to different paths from itself to the other existing stations are kept. The lower the metric value is, the lower the cost for this path will be. For each station, the sum of all the

metric values is called this station's weight. In other words, station's weight calculation formula can be specified as $W_i = \sum_{j=1}^{n-1} M_{ij}$, where n is the total number of stations. Upon finishing the weight calculation, stations send SWU (Station Weight Update) W_i to the hub station, and will obtain W_i for the other $n - 1$ stations from the hub station in the message of SWUR (Station Weight Update Response). This way, all the stations can establish their own weight tables, where they store the weight values of the different stations. The purpose of constructing the weight table is that every station should be able to select the stations with the lowest and the second lowest weight value as its candidate hub station, called DH (Designate Hub) and NDH (Next Designate Hub). When all stations' weight tables have been built, the stations would select their DH and NDH. Then, stations compare their own weight value with the weight values for the other stations and select the one with the smallest weight as the DH, the one with the second smallest weight as the NDH, maintaining consistence of weight table and metric table. Consequently, stations send out HSV (Hub Station Vote) to hub station indicating the stations selected as DH and NDH and will obtain the other stations' vote of hub station in the message of HSVR (Hub Station Vote Response). When the vote collecting and counting are complete, stations receiving majority and the second majority votes will become the DH and NDH respectively. If two stations get the same votes from the other stations, a tiebreaker (MAC address) can be used to finalize the selection, i.e. station with bigger MAC address will be DH while station with smaller MAC address becomes the NDH. Finally, HSC (Hub Selection Confirmation) with DH and NDH identifications will be sent to demonstrate the successful hub station selection. Hence, up to this point, the network will be equipped with backup hub stations whose lowest cost reflected the suitability and qualification of them acting as the potential coordinators in the network when the system finds out the necessity to do so.

Change of hub station should be based on some kind of network conditions. Short-term effects should not be resulting in change of hub station as this will end up allowing frequent change and eventually it will have counterproductive effect. By losing connectivity once, we should not have the system initiate change of hub station

assignment. Many of the channel and interference related problems are expected to be of short time effect and provide a random-like behaviour. Many of these impairments should not be initiating change of hub. To avoid this, we regard that change of hub station is triggered by long-term effects (e.g. failure of the unit, loss of connectivity due to changes in the topology of the network or possibly due to mobility, etc.). To measure the duration, we can place a counter and define certain amount of time or certain SSP transmission periods. In particular, we define this period as 10 second [41], the interval of $625 * 16$ ms (a cycle time of SSP transmission). After that, if the problem remains, a change of hub station will be implemented and follow the procedure as elaborated above.

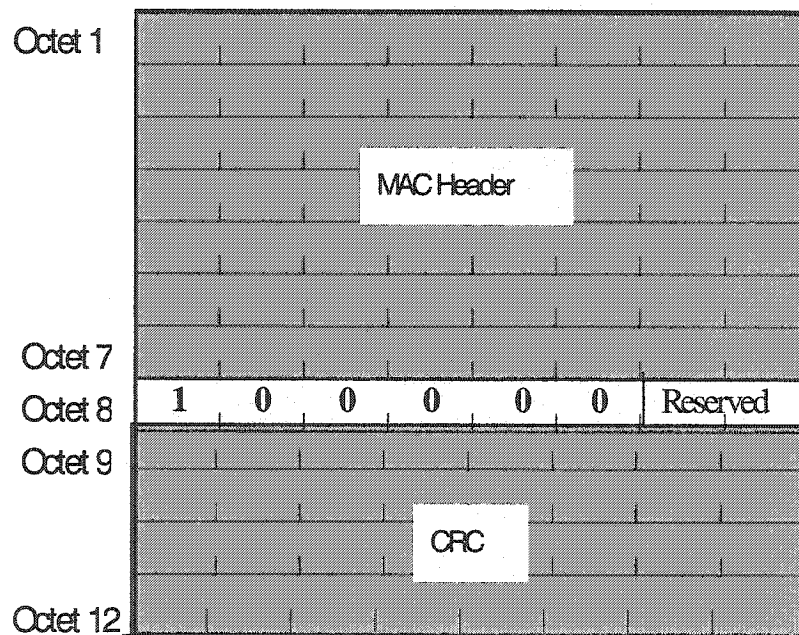


Figure 4.9 Packet Format and Content of GNN

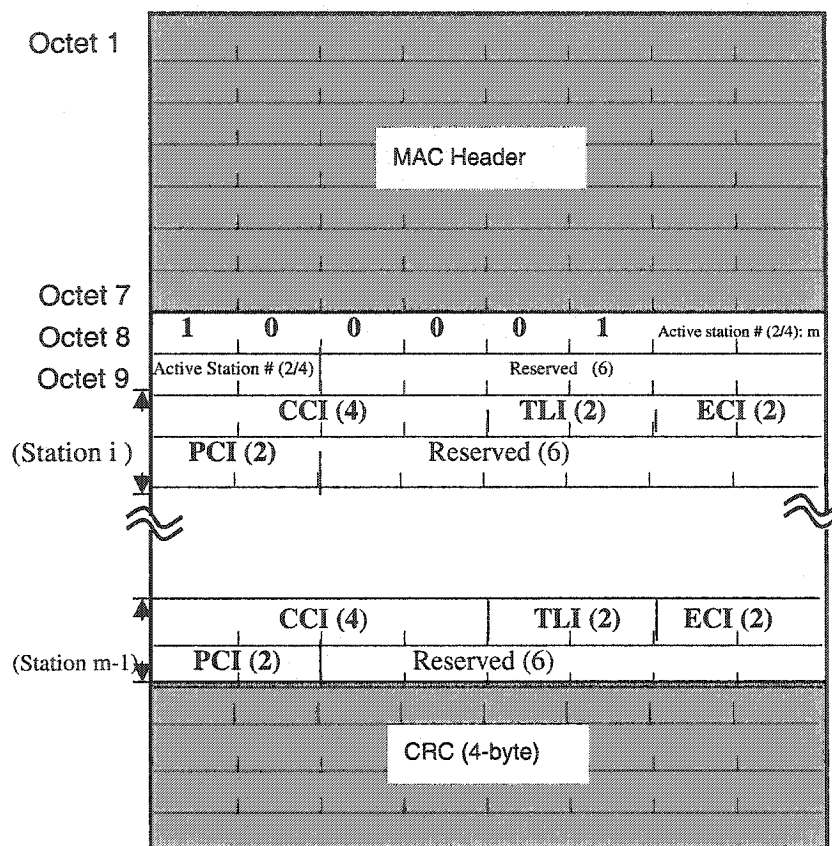


Figure 4.10 Packet Format and Content of ENR

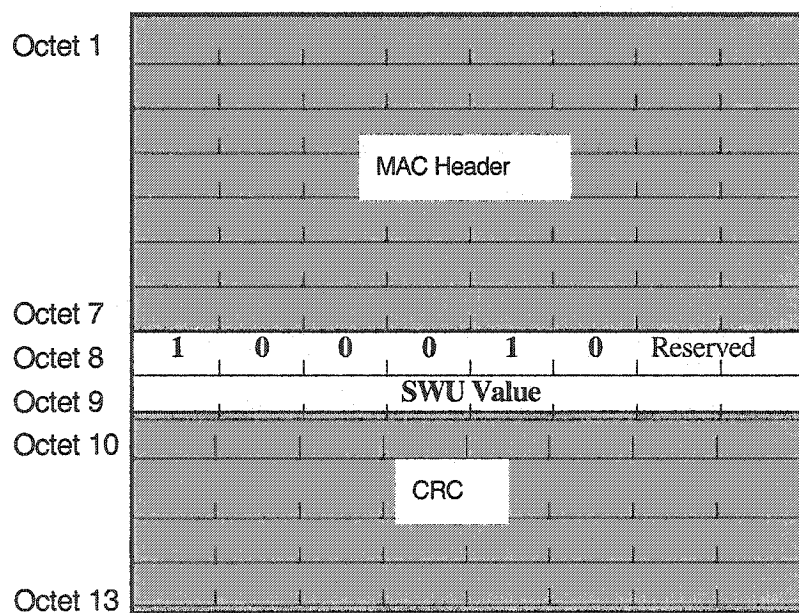


Figure 4.11 Packet Format and Content of SWU

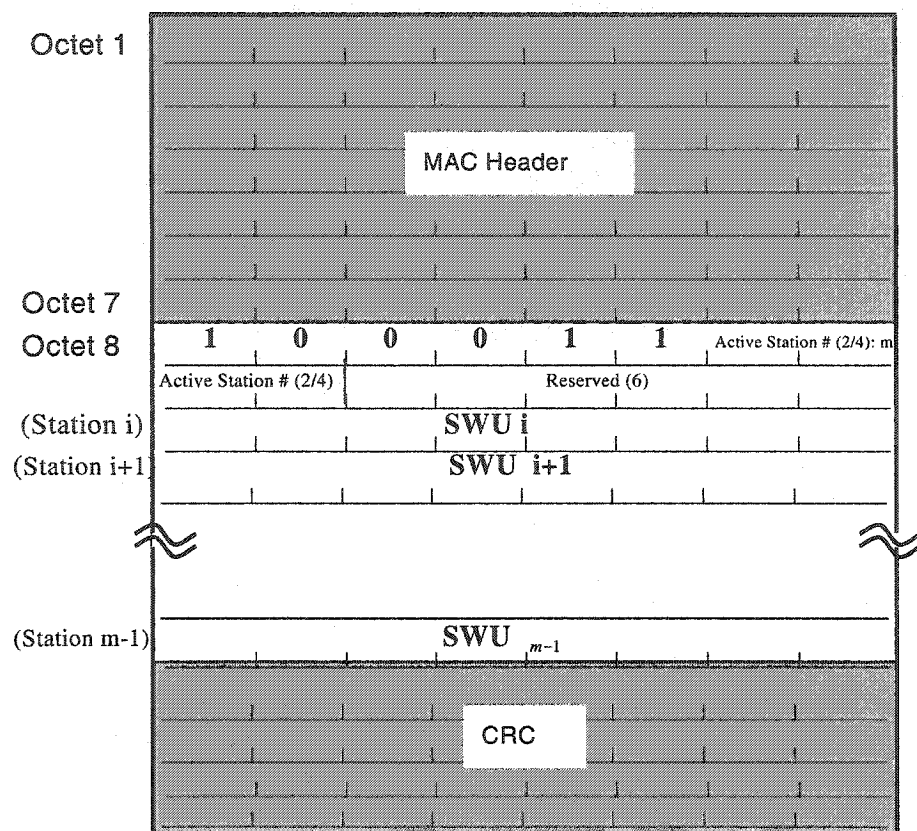


Figure 4.12 Packet Format and Content of SWUR

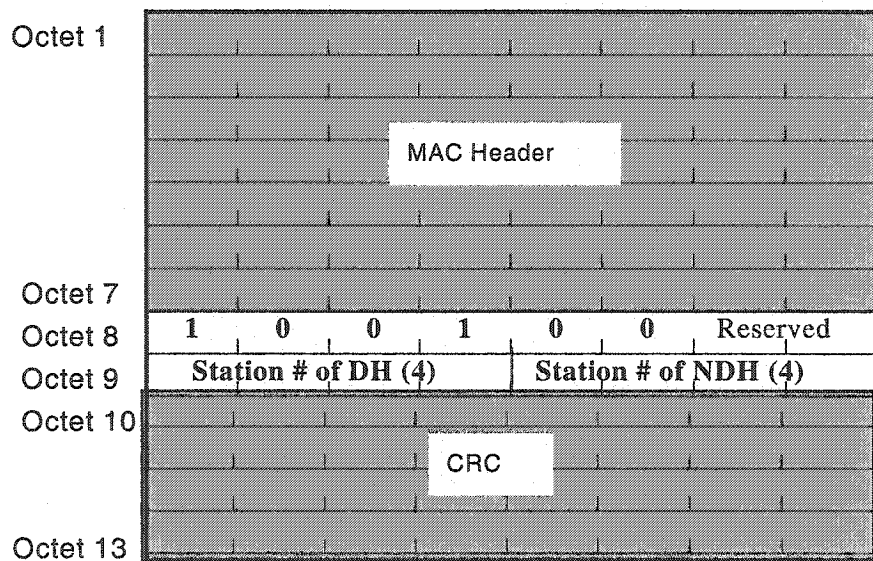


Figure 4.13 Packet Format and Content of HSV

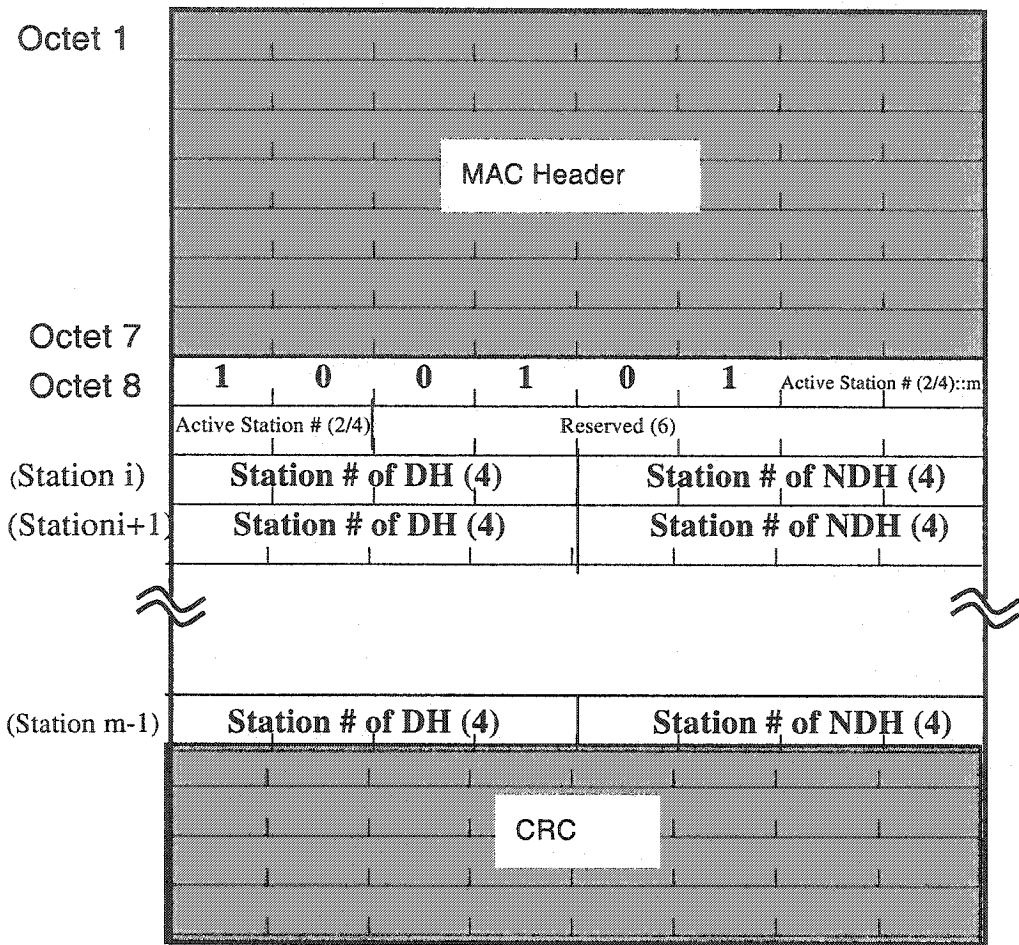


Figure 4.14 Packet Format and Content of HSVR

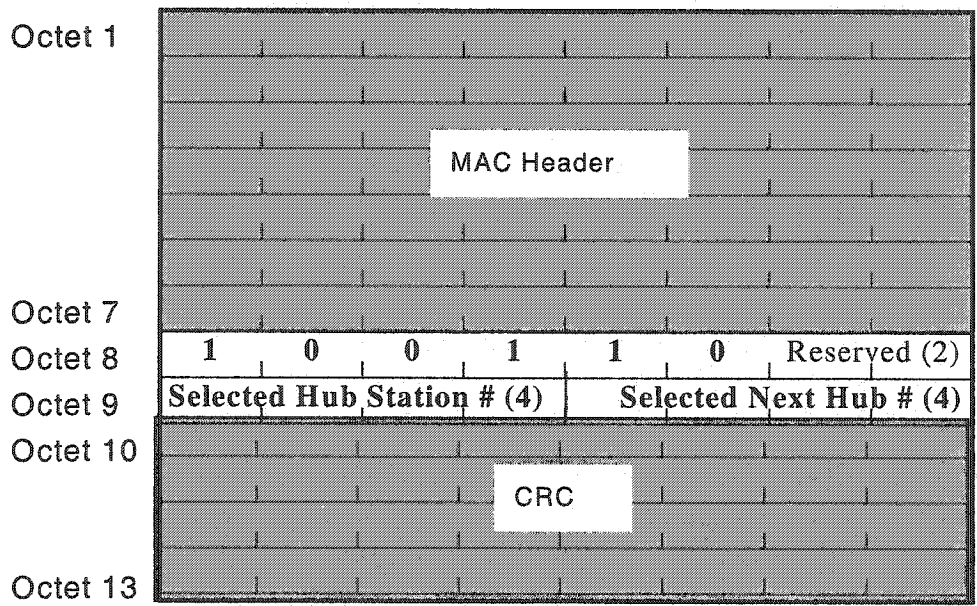


Figure 4.15 Packet Format and Content of HSC

4.2.3 Summary of the Proposed DHSS Algorithm

Hub station possesses supreme standing in Wireless 1394 system. It does not exaggerate to say that the overall Wireless 1394 network performance depends on the functionality of the hub station. However, scenarios such as long-term effects (failure of the unit, loss of connectivity due to changes in the topology of the network or possibly due to mobility, etc) might happen when implementing Wireless 1394 in the home environment. To provide a Wireless 1394 system for reliable and effective communication, solutions ought to be found in any one of the cases.

Consequently, we propose the Dynamic Hub Station Selection (DHSS) protocol to meet the need. In DHSS, backup hub stations can be selected based on the cost function we came up with, where the costs of being hub station have been minimized in order to choose the most appropriate (the lowest cost) and the second most appropriate hub station, taking the factors, for instance, station capability to be heard by the other stations, station's traffic loading, station's energy concern and station's processing ability, as the criteria to choose a hub station. The selected hub station candidates are able to take over the responsibilities of the original one should the long term effects mentioned above happen to the original hub station. Hence, with the lead of the backup hub stations, the system will be able to reorganize itself and maintain normal operation, diminishing the negative effects brought by the "random-like" error prone behaviour to a level as low as possible.

The DHSS protocol makes use of SSP (Station Synchronization Packet) which has already been defined in Wireless 1394 to either report the stations' status regularly or express the transmission concerns they might have. Furthermore, we extend the content of SSP to include more information. Using this information through a cost minimization process, an adaptive mechanism for the selection of the hub station and a standby second station is defined, thus improving considerably the ability of the network to withstand failures due to problematic functionality of the hub station. The performance results of DHSS protocol will be provided in Chapter 5.

4.3 Optimizing Traffic Relay in Wireless 1394

As has been mentioned the quality of the wireless link in the home environment is time and location dependent. Objects inside a home may block or reflect the transmitted signals, causing shadowing and multipath fading, which could impair the transfer of information process. Increasing the transmitting power is not the solution since this could generate interference problems and drain the batteries of portable devices faster as well as does not address the problems generated by signal spreading. Other solutions have to be found.

As regulated in the Wireless 1394 [9,41] protocol, when a link between a sending station and destination station cannot be established, relay control should be implemented. One existing method is to adopt ad-hoc node relaying [12] where relay control is triggered when the received signal strength is below a certain level. A station with relatively strong power may be chosen to relay data. Because we consider that it is difficult and not accurate enough to determine the quality of a connection in the network by only relying on the received signal power, we propose in this work a mechanism, which is able to provide improved relay control by using lowest cost principles for the selection of the relay path and relay station(s) [7].

4.3.1 Background and Motivation

In principle, once the leaf station becomes polled by the hub station, it can perform direct communication with any leaf station in the subnet. However, this assumes that transmitting and receiving stations are able to connect through good quality links. However, as mentioned earlier, this assumption cannot be made for wireless operation in the home environment. In this context, the functionality of relay control has been pointed out in [9], where an intermediate station, which both, sending and receiving stations can contact is used to bypass the traffic from the source station to the destination station.

A traffic relay solution known as ad-hoc node relaying has been proposed to countermeasure the effects of shadowing and is described in [12]. The basic idea of ad-hoc node relaying is to utilize the received signal strength as an indicator to trigger the relay process and to distinguish the channel quality of the current network. In Wireless 1394, every station should transmit a SSP (Station Synchronization Packet) every 16ms. As displayed in Fig.2.17 of Chapter 2 where the field of RSSI (Received Signal Strength Indicator) is our main focus, each station can become aware of the status of the other stations by obtaining their corresponding RSSI values. That is, when a receiving station receives a SSP transmitted by a sending station, it can assess the communication quality by measuring the corresponding sending station's RSSI value in the SSP. If the value is below an acceptable level, the link will not be of good quality. Based on the RSSI value, the station will become aware whether the path is of adequate quality. For the relation between various RSSI values and actual received signal levels, please refer to [41].

An example of how to carry out the ad-hoc node relaying can be explained in Fig. 4.16. Polled source station, station1 has packets to transmit to destination station, station4. As station4 checks the value of RSSI (Station#1) in the SSP, it might find out that the received power from station1 is below an acceptable level, indicating that the path from station1 to itself is of poor quality. It doesn't matter whether station1 will come to the same decision as station4 does by obtaining the value of RSSI (Station#4) because the two directions (from station 1 to station 4 and from station 4 to station 1) might have different status, although the original Wireless 1394 protocol implies two directions are of the similar status [41]. (A weak assumption that can not hold when considering the diversity of devices; station 1 could be power limited and limited in the complexity of built-in electronics, such as a PDA with low batteries, whereas station 4 could be a printer, connected to the electric network, thus having abundance of power and space to accommodate complex electronics). Thus, relay must be performed when a link cannot be established from a transmitting station to a receiving station. To accomplish this, source station, station 1, will express its relay request and indicate its desired MAC packet destination station in its SSP to the hub station at a particular moment determined by the FSP transmitted from the hub station (SSPs for all the stations will be sent in a

cycle of 16ms). After the hub station receives this SSP, a polling packet where information such as a combination of recommended relay station ID (either station2 or station3), modulation scheme and coding rate made by the hub station is contained will be addressed to the station. Then, the source station will deliver its packets to the recommended relay station first, and let it further serve as a “bridge” to pass the traffic to the destination station (station 4).

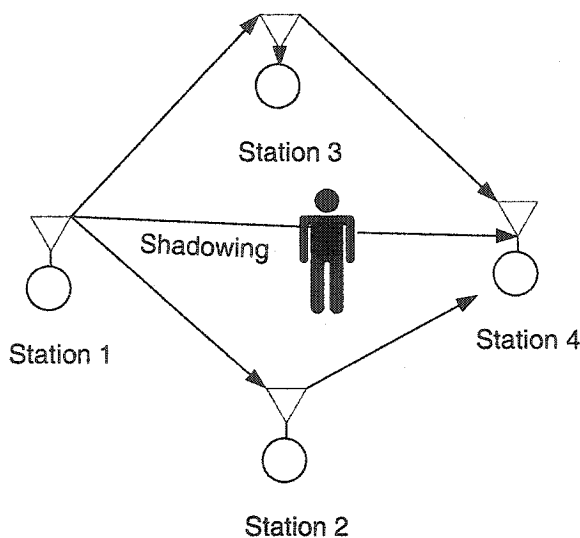


Figure 4.16 Ad-hoc Node Relaying

From the above example, we observe that the method of ad hoc node relaying solely depends on the power of the received signal. It does not provide the ability to select the best relay station and the best relay path when several candidate stations and alternative paths are available. However, the routing decision should be based on more information rather than only the power of received signal. Such parameters could be the present loading of the station considered to become relay station etc. The choices of the relay station and the corresponding path should be made according to some optimization process, which takes other parameters into consideration in order to utilize the system's resource more effectively. An example is when station1 in Fig. 4.16 is a home server or a printer server, which has large amount of data to process and transmit. Station's functionality to select the lowest cost relay path and relay station among the available

choices (e.g. via station2 or station3) will have a significant impact on Wireless 1394 network performance.

4.3.2 Proposed Optimizing Traffic Relay Protocol

Our proposed relay control optimization scheme is based on the Dynamic Hub Station Selection (DHSS) protocol we developed for the Wireless 1394 network, where the extended version of SSP illustrated in Figure 4.7 and the cost function involving the cost parameters summarized in Table 4.1 are employed. A possible cost function example is the following:

$$M_i = \text{cost coefficient (1)} * \text{cost parameter (1)} + \text{cost coefficient (2)} * \text{cost parameter (2)} \\ + \dots + \text{cost coefficient (n)} * \text{cost parameter (n)} \quad (1)$$

The message flow describing the optimization procedure is presented in Figure 4.17. Besides the two new control packets, GNN and ENR we defined in DHSS, which are used here as well, three new control packets, which use the reserved packet types to distinguish themselves, have also been defined for the optimizing relay process. They are listed in Table 4.3. Accordingly, the packet format and content for these three new packets is displayed later in this section from Figures 4.18 to 4.20. They all comply with the structure defined in [41]; 7 bytes MAC header, where source station ID and destination station ID are included, and 4 bytes CRC for parity checking. The sizes of these packets depend on the different packet types and the number of stations in the subnet.

Table 4.3 List of New Control Packets in Optimizing Relay Scheme

	Code	Packet types	Comment
1.	100111 ₂	SCU (Station Cost Update)	Send the cost of the station
2.	101000 ₂	SCUR (Station Cost Update Response)	Get the costs of the other stations
3.	101001 ₂	DRC (Data Relay Confirmation)	Confirm relay station/path selection

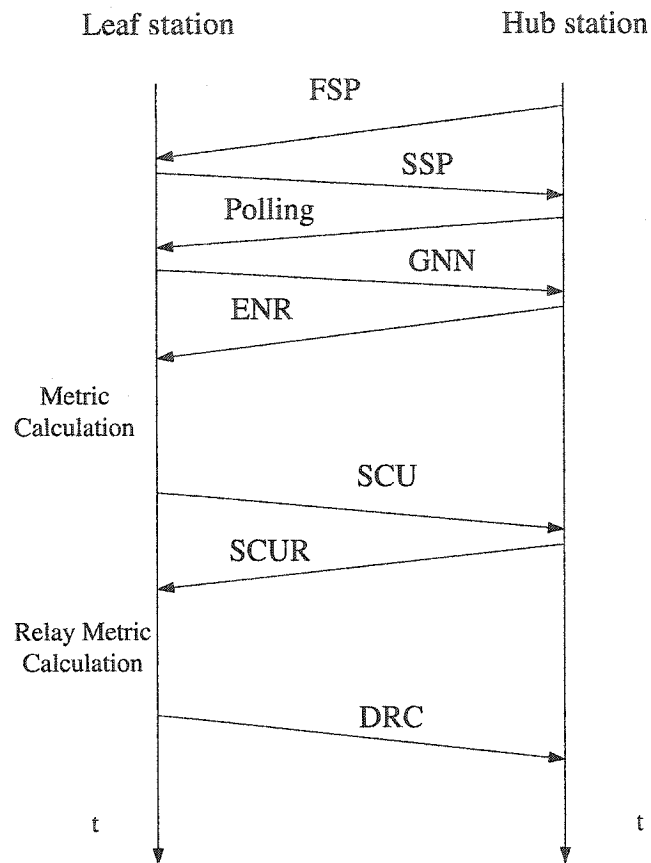


Figure 4.17 Main Procedure of Optimizing Traffic Relay Control in Wireless 1394

The process of optimizing relay control can be summarized as follows. When the polled leaf station has packets to transmit to another leaf station and it finds out the wireless link between them cannot be established (the signal strength is below an acceptable level through checking RSSI), it initiates the process for relay functionality. Thus, through its next SSP, the station will make the hub station aware of its control packet transmission request. Once upon receiving a polling packet from the hub station, this station will be able to send its control packets. The station first sends GNN to ask for the other stations' detailed information. Then, the hub station will return the stations' "personal" data through an ENR message, responding to the GNN. In fact, ENR contains stations information such as CCI, TLI, ECI and PCI. These data will be used to calculate

each station's metric M_i based on the calculation of the cost function we developed and used in DHSS (details can be found seen in Section 4.2.2). In each metric calculation, records of different metrics corresponding to different paths from itself to the other existing stations are kept. The lower the metric value is, the lower the cost for this path will be. After the station finishes its cost calculation, it will transmit a SCU packet containing the cost value to the hub station and expect SCUR from the hub station, obtaining the other stations' cost value. After collecting the stations' cost values, the station will be able to calculate the total cost for different paths from the source station itself via different intermediate stations to finally reach its anticipated destination station. The information is stored in the path selection table. Hence, based on this table, the source station will be capable of selecting the one with the lowest path weigh (cost) as its relay path and that corresponding intermediate station as its relay station. This decision will be sent out in the DRC packet to finalize the optimization process. In short, this selection strategy is superior as it takes more than one parameters into consideration in the process of selecting the relay path.

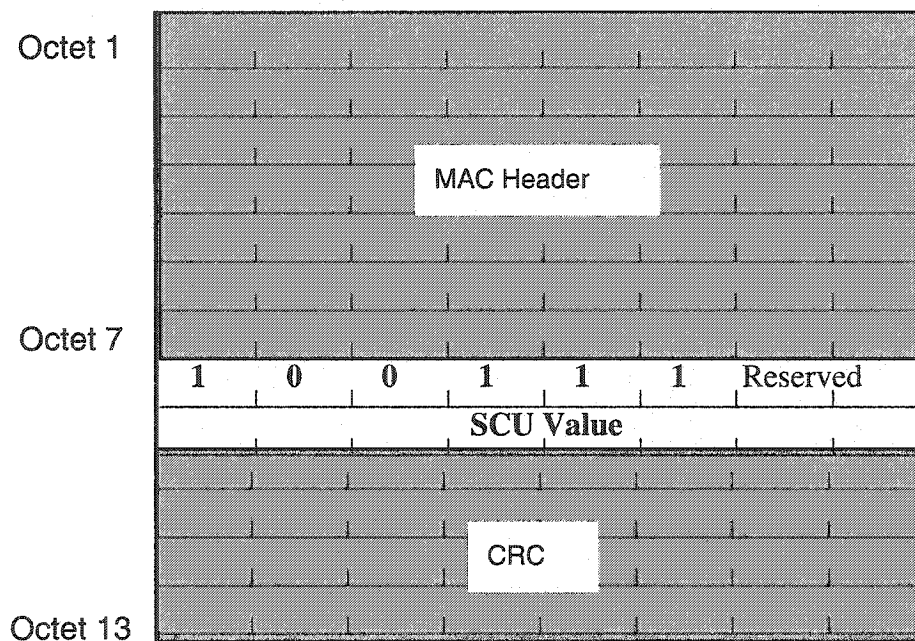


Figure 4.18 Packet Content and Format of SCU

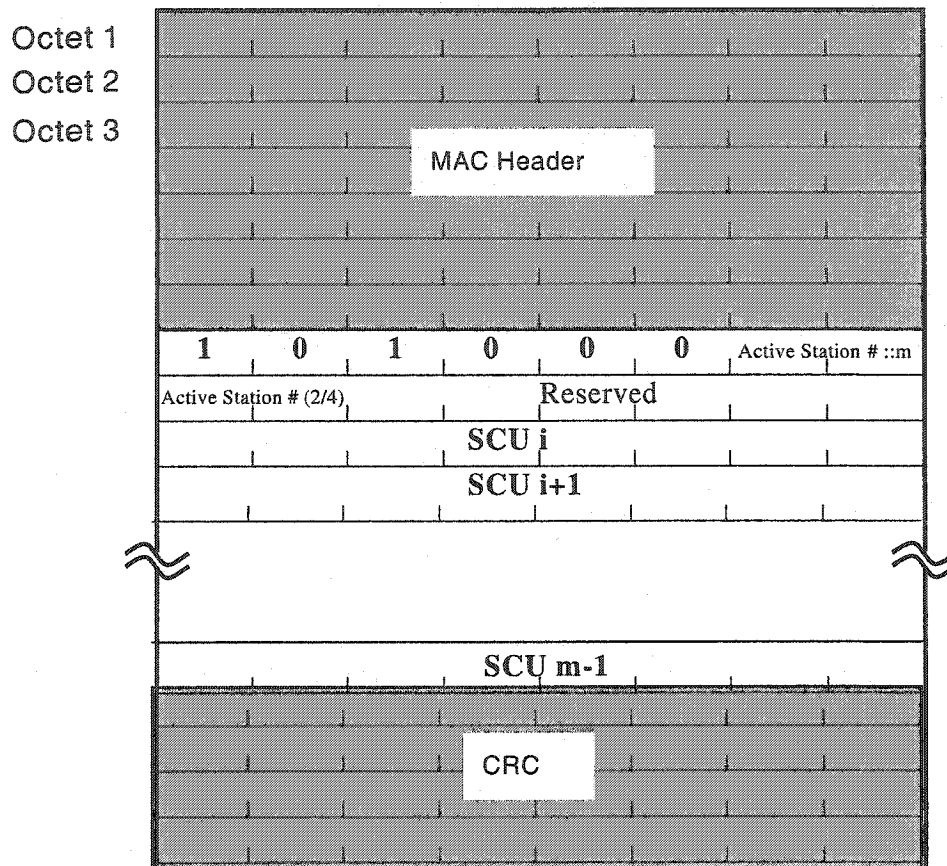


Figure 4.19 Packet Content and Format of SCUR

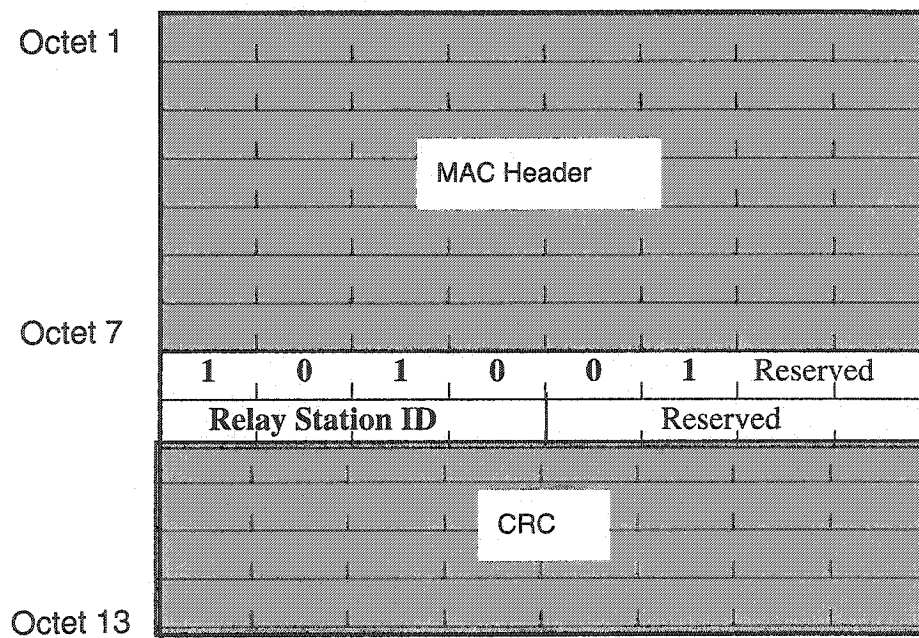


Figure 4.20 Packet Content and Format of DRC

4.3.3 Summary of the Proposed Mechanism

To ensure viable communications in the wireless home networking environment, relay control ought to be performed, to support transfer of information when the direct links between source and destination station are of poor quality, unable to support reliably communication. We propose in this work how such function can be accomplished effectively in a manner that improves the efficiency of the Wireless 1394 network. The performance of the algorithm will be presented in Chapter 5.

4.4 An Improved Traffic Scheduling Algorithm for Wireless 1394

In order to provide an effective traffic scheduling algorithm (the existing protocol is lacking one) and at the same time to keep it not as complicated as those existing algorithms which have been proposed for other wireless networks [54] (in order to comply with the philosophy of simplicity when implementing Wireless 1394), an improved traffic scheduling algorithm, DCRR (Deficit Control Round Robin), has been proposed.

Two approaches, normal polling and priority control polling, have been included in the Wireless 1394 asynchronous transfer mode. In normal polling, the transmission of a polling packet is not triggered by leaf stations' requests. In priority control polling, the polling packet is triggered by the leaf stations' requests. In other words, the polling packet is regarded as the response to leaf stations' transmission request. While some work has been done on the normal polling case and has been reported in the open literature, to the best of our knowledge, it is not the case for the Wireless 1394 priority control polling. It is critical to effectively perform polling list management due to the fact that it influences whether the network resource can be fairly allocated. In this work, we propose a MAC protocol, DCRR (Deficit Control Round Robin), which ensures fairness when used with the priority control polling of the Wireless 1394 [8].

4.4.1 Necessity and Motivation

As mentioned earlier, the original protocol implements a polling method to perform asynchronous packet transmission. Polling control includes polling sequence control by the hub station and the operations at both hub station and leaf stations. First of all, the hub station should know what leaf stations are currently active in the subnet. The hub station will remove from the polling list those leaf stations that are in sleep mode.

In Wireless 1394, every station should transmit a SSP (Station Synchronization Packet), every 16ms. The time for each station's SSP transmission has been first defined in the FSP (Frame Start Packet) transmitted by the hub station. With the help of SSP, every station can report such information as priority, sleeping mode, etc. The information contained in the received SSPs is used by the hub station to build a polling packet, which transmits as priority polling. If the hub station does not receive any transmission request or finishes the priority polling packet transmission, it will start the normal polling packet transmission. This means that the hub station will distribute the polling packet to leaf stations in turn, regardless of if the leaf station wishes to transmit or not.

There is a number of research works reported in the open literature, having as objective the performance analysis and in several cases improvement of the normal polling scheme. Among them, [10] dealt with the case where many leaf stations having the transmission right do not have data to transfer. This scenario leads to longer waiting times for the packets waiting for service, despite the possible low traffic loading of the network. A solution has been proposed in [10], where use of token packets among leaf stations is introduced in order to reduce the waiting time. This way, stations can distribute the transmitting right more effectively without any timeout. Next qualified leaf station will be granted the transmission packet right away when the previous qualified leaf station has nothing to send. There is no need to wait for the polling timeout period to figure out that the current polled leaf station does not have traffic to transmit.

If a leaf station wants to transmit any asynchronous packets or control packets, the leaf station will make the hub station aware by sending out a transmission request, setting a suitable value, as indicated in Table 2.6 of Chapter 2 [41], in the Priority field of the SSP, which is depicted in Figure 2.17 of Chapter 2. This is possible once upon the station has received the FSP transmitted from the hub station, allowing a specific timing for this station to transmit its SSP.

As mentioned earlier, to the best of our knowledge, neither the conventional Wireless 1394 protocol nor the recent researches in this area have explored the priority control polling strategy. When the hub station obtains transmission requests from leaf stations by capturing the “Priority” fields of those corresponding leaf station’s Station Synchronization Packets, the hub station ought to determinate how to transmit the polling packet. However, the conventional Wireless 1394 protocol does not mention how to regulate the polling packet transmission order in this context. Besides that, other polling list management issues, such as the criteria for the hub station to allocate bandwidth to each requested leaf station, the overall packet size allowed to be transmitted, how to differentiate in terms of service and priority level, have not been specified yet. These are critical issues due to the fact that wireless network resources are scarce and expensive. In addition, poor channel conditions could prevent a user from receiving service for a certain period of time. If no measure is taken to compensate this loss of transmission rights at a later time, when the channels are at good condition, the user will be facing unfairness in the resource distribution. A system capable of providing fair and efficient media access has considerable advantage over other solutions. Therefore, it is essential to define a rule for the orderly access of the shared medium. This is the motivation leading to the present work.

4.4.2 Proposed Algorithm

The conventional Wireless 1394 network employs the round robin method in normal polling. The hub station polls all the leaf stations in the subnet in turn.

Implementing the round robin discipline in the control polling scheme is not a good approach due to the fact that round robin will assign equal bandwidth to all the queues despite the fact that several users might require higher bandwidth than others. This will end up building long queues and eventually will result in packet losses. Motivated by the wish to develop a scheme that introduces fairness and makes better resource usage, we developed the DCRR (Deficit Control Round Robin) scheme. It is based on the standard round robin and its slightly modification version, deficit round robin. Most importantly, DCRR enriches the power of those two ancestors by not only inheriting their merits but also adding some new effective control features that improve the level of fairness, users within the network experience.

Some basic definitions in DCRR scheme can be summarized as follows. Any active leaf station can be regarded as a queue. Queuing information can be included in the polling request. Any communication between a leaf station and the hub station can be considered as a connection. Each queue i waiting for resource to be allocated by the hub station is associated with a "Deficit Counter" (DC_i). Let DT (Deficit Threshold) be set to control the maximum size of a packet. We introduce $AcDC$ (Actual Deficit Counter) and $ArDC$ (Accrued Deficit Counter) to control the overall packet size in the queue. Let "Quantum" denote a specific service share/factor, which can be measured in bytes per round (e.g. 500 bytes/rnd). The actual values of $AcDC$, $ArDC$ and DT can be set according to SLA (Service Level Agreement) or even CoS (Class of Service).

Use of the DCRR service discipline involves the following steps (Up to this point, we do not applying service limitation to the user even when the credit is positive. This will be part of our future work.):

- 1) If leaf stations wish to transmit packets, they will send polling request messages to the hub station of the subnet they belong to. The time permitted for this station to transmit such request is determined in the FSP sent by the hub station. DCRR only deals with the priority control polling scheme, which is not explored in Wireless 1394.

2) The hub station takes charge of the polling list management, determined according to the various collected transmission requests sent by the leaf stations in the subnet. Following the rules of DCRR, the hub station regulates how many packets from one queue (leaf station) will be transmitted and in which round. The management parameters, such as DC_i , DT , Quantum, AcDC and ArDC, are set in the scheduler residing at the hub station. The scheduler is assumed to have knowledge of the next packet in the queue, the length of the next packet for instance. This can be accomplished when the station sends its transmission request to the hub station. It will also include the sizes of its next packets.

3) At the first round, DC will be assigned to each queue by the scheduler. At the beginning of each round, the value of DC_i will be increased by a Quantum. The next packet in the queue will be transmitted as long as the DC_i value keeps being non-negative. After completing one packet transmission, the value of DC_i will be decreased to $DC_i - L_i$ (the length of that transmitted packet).

4) When $DC_i < 0$ and $|DC_i| \leq |DT|$, the next packet in the queue i will still be allowed to get the service. If $DC_i < 0$ and $|DC_i| > |DT|$, the next packet in the queue i will have to wait until $|DC_i| \leq |DT|$.

5) Each time $DC_i < 0$ and $|DC_i| > |DT|$, AcDC is triggered and set to a value of $|DC_i| - |DT|$. When the sum of the AcDC value exceeds ArDC, the subsequent packets in this queue will be refused service for a period of time and AcDC and DC_i will be reset to zero.

The merits making DCRR an effective service discipline can be reflected in its two-level network resource controlling capability. In other words, DCRR plays a vital role to fairly distribute resource by implementing the following two levels of control strategies. Through the use of one pair of control factors, DC (Deficit Counter) vs. DT

(Deficit Threshold), DCRR is able to control those leaf stations which have already seized a large fraction of network resource in their previous transmission to stop accepting services for a while and give chances to the other leaf stations to be polled and start transmitting their own traffic. It is the first level of control strategy in DCRR, focusing on one particular flow in one queue. This is accomplished by setting a DT. When the accumulated DC value is larger than the DT, the resource is assigned to service another queue rather than continue servicing the same one. Aiming at making the network fair, the next level of control strategy in DCRR is to monitor the overall packet transmission attempt at all queues with the help of another pair of control parameters, AcDC (Actual Deficit Counter) and ArDC (Accrued Deficit Counter). This is fulfilled by the fact that when one queue or one leaf station attempts to continue transmission of relatively large packets, DCRR uses an accumulated AcDC to keep track of this attempt of the queue; it will take action and refuse to serve those consequent packets in that queue for a period of time when the sum of AcDC is larger than the ArDC, whose value has been defined by the scheduler at the hub station. This penalizes a queue if it was so “selfish” and “greedy”, trying to keep sending a sequence of big packets, which no doubt would delay other stations from receiving service.

4.4.3 Summary of Proposed Algorithm

Generally speaking, the benefits of our proposed DCRR mechanism can be outlined as follows. It is not only able to control the resource allocated to a specific connection, but also to control the overall packet size and consequently shape traffic rate for a traffic flow. Furthermore, the exact value of DT, AcDC and ArDC can be used to differentiate different priority classes of Wireless 1394 services.

As part of our future work, we are planning to apply service limitation to the user even when the credit is positive. No more than MAX_SERV units will be allowed before it is polled and offered service to another station. This will prevent the starvation of other users when dealing with a user who was inactive for a long time and kept collecting credit, as well as will limit the burst this user would generate in the network.

As a novel technology in wireless home networking, many open issues in Wireless 1394 network are worthwhile to be researched. To open the door of probing the priority controlling polling scheme in Wireless 1394 asynchronous transfer mode, DCRR presents a solution to the classical issue of how to fairly distribute network resource in the wireless home networking environment and gives a direction for future work in this area. Performance of the algorithm will be presented in Chapter 5.

5. CHAPTER 5

Performance Analysis of Proposed Techniques

In this chapter, the performance of the protocol extensions and improvements we developed to the original Wireless 1394, which have been described in Chapter 4, will be provided. Moreover, in order to understand the enhancements achieved by those proposed algorithms, we compare their performance to the performance of the conventional Wireless 1394 protocol, where no new mechanisms are applied. We use the same simulation environment that has been depicted in Chapter 3 to carry out the evaluation.

5.1 Performance Analysis of Virtual Sensing and Polling Scheme in Wireless 1394

The objective of this section is to assess the effect of the use of virtual sensing (the pair of RTS/CTS) on the performance of the protocol. Each pair of stations $\{S_i, S_j\}$ is associated with an ON-OFF process. This process indicates whether the pair can hear each other or not. When the system is in the ON state, we are assuming that all packets are delivered correctly. When it is in the OFF (bad) state, we are assuming that packets are received erroneously, with probability P_E (in the simulations, we assume that $P_E = 1$, i.e. no packets can be received correctly during OFF periods). The time the pair stays at the ON stage is exponentially distributed with average value $\overline{\tau}_{i,j}^{ON}$. The time it stays at the OFF state is $\overline{\tau}_{i,j}^{OFF}$.

In all cases in this experiment, the status of the $\{S_i \rightarrow S_j\}$ channel and $\{S_j \rightarrow S_i\}$ channel is identical. It means that when $\{S_i \rightarrow S_j\}$ channel is ON, $\{S_j \rightarrow S_i\}$ channel is ON as well; when $\{S_i \rightarrow S_j\}$ channel is OFF, $\{S_j \rightarrow S_i\}$ channel is OFF as well. All pairs of $\{S_i, S_j\}$ have the same $\overline{\tau}_{i,j}^{ON}$ and $\overline{\tau}_{i,j}^{OFF}$. At the beginning of the simulation, we start with half stations at good state, half at bad state. However, we leave every pair to change state as the time progresses. We use buffer size of 100 packets. We have chosen values in the ON-OFF process that in average, a packet has 0.1 probability to be lost. We run the simulations for different $\overline{\tau}_{i,j}^{ON}$ (from 0.2msec to 20000msec) and $\overline{\tau}_{i,j}^{OFF}$ (from 0.02msec to 2000msec), however, in all cases, we maintain the ratio $\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON}$ equal to 0.1.

The performance of the packet delivery ratio versus traffic load with $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) as parameter when RTS/CTS is shown in Figure 5.1. It demonstrates that the packet delivery ratio will increase when the values of the $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) become higher. As was explained in Chapter 3, this is because longer ON-OFF periods tend to provide a lower packet loss ratio. When the values of the $\overline{\tau}_{i,j}^{ON}$ ($\overline{\tau}_{i,j}^{OFF}$) are large enough (as is the case where $\overline{\tau}_{i,j}^{ON} = 20000$ msec and $\overline{\tau}_{i,j}^{OFF} = 2000$ msec), the packet delivery ratio is the highest.

From Figure 5.1, we also observe that when the traffic load becomes higher, especially when the traffic volume reaches or surpasses 60% of the capacity, the packet

delivery ratio will drop dramatically. This can be explained as follows. When the traffic load increases, the chances to experience network congestion increase as well (the buffer size is fixed to 100 packets in these experiments).

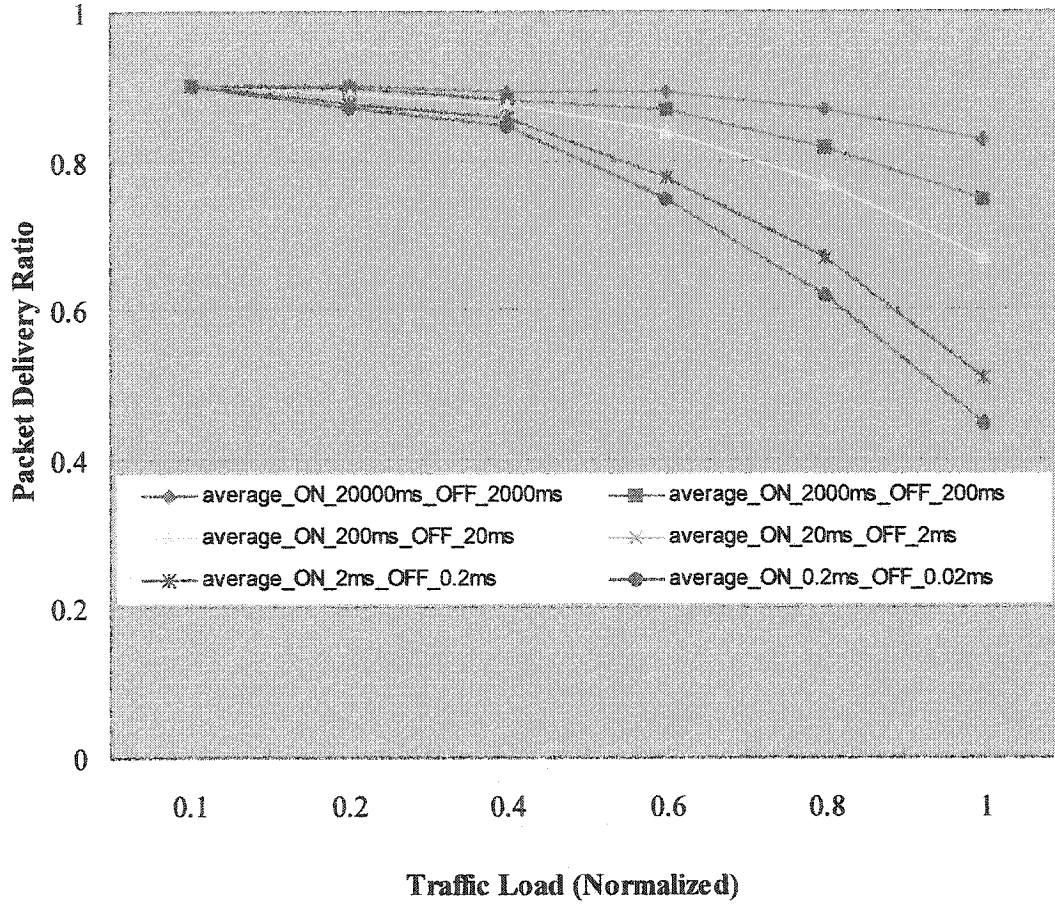


Figure 5.1 Packet Delivery Ratio vs. Traffic Load (with RTS/CTS, $\overline{\tau}_{i,j}^{ON}$

($\overline{\tau}_{i,j}^{OFF}$) as parameter)

In Figure 5.2, we compare the packet delivery ratio performance where the RTS/CTS scheme is used and not used with the $\overline{\tau}_{i,j}^{ON}$ equal to 20000 msec and

$\overline{\tau}_{i,j}^{OFF}$ equal to 2000 msec (the ratio of $\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON} = 0.1$). We display the performance under perfect channel conditions to be used as reference. Figure 5.2 indicates that the packet delivery ratio of with_RTS_CTS scheme is higher than that of the no_RTS_CTS one. Improvements are higher at higher traffic loads. The with_RTS_CTS scheme is able to deal with the channels' impaired condition better than the no_RTS_CTS. As indicated, among other problems, the no_RTS_CTS could experience collisions due to lack of communications between the pair stations and the hub station. (we refer the reader to Section 4.1, Chapter 4).

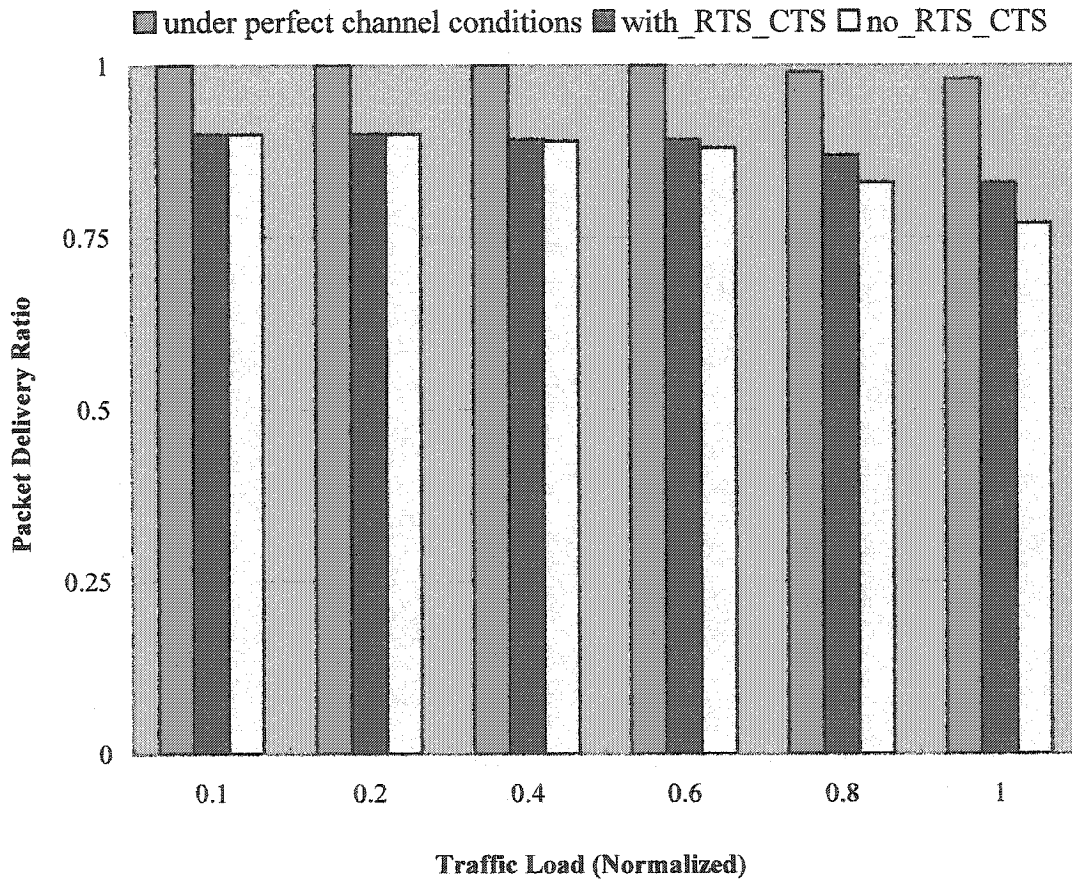


Figure 5.2 Comparison of Packet Delivery Ratio vs. Traffic Load (among perfect channel

conditions, having RTS/CTS and no RTS/CTS both with $\overline{\tau}_{i,j}^{ON} = 20000$ msec and

$$\overline{\tau}_{i,j}^{OFF} = 2000 \text{ msec})$$

Moreover, we choose different ON-OFF periods to compare the performance of packet delivery ratio versus traffic load in the with_RTS_CTS scheme and no_RTS_CTS.

We use $\overline{\tau}_{i,j}^{ON}$ equal to 200 msec and $\overline{\tau}_{i,j}^{OFF}$ equal to 20 msec in Figure 5.3 and

$\overline{\tau}_{i,j}^{ON}$ equal to 0.2 msec and $\overline{\tau}_{i,j}^{OFF}$ equal to 0.02 msec in Figure 5.4. Both figures

prove that the with_RTS_CTS mechanism is able to improve the packet delivery ratio as compared to the no_RTS_CTS one at different ON-OFF periods.

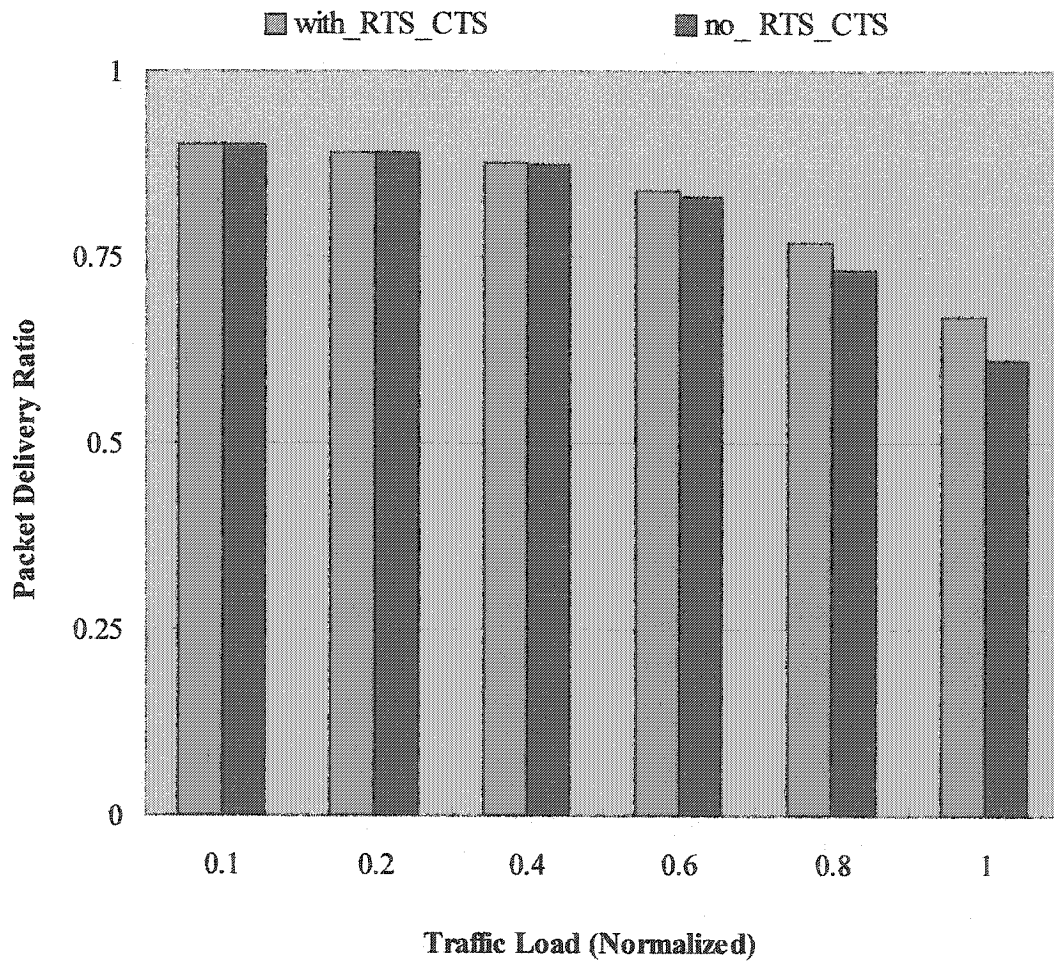


Figure 5.3 Comparison of Packet Delivery Ratio vs. Traffic Load (with RTS/CTS and no

RTS/CTS, $\overline{\tau}_{i,j}^{ON} = 200$ msec and $\overline{\tau}_{i,j}^{OFF} = 20$ msec)

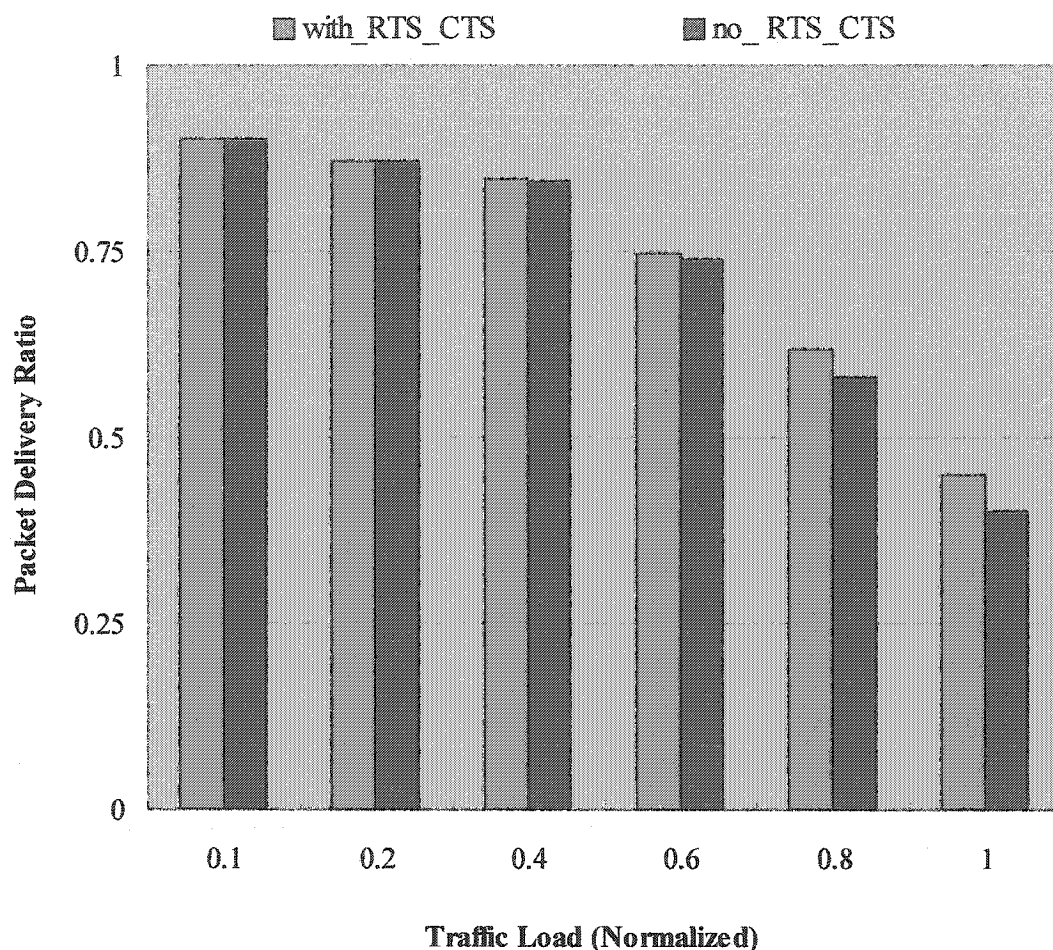


Figure 5.4 Comparison of Packet Delivery Ratio vs. Traffic Load (with RTS/CTS and no

RTS/CTS, $\overline{\tau}_{i,j}^{ON} = 0.2$ msec and $\overline{\tau}_{i,j}^{OFF} = 0.02$ msec)

It becomes evident from the above figures that the benefit coming from the use of the no_RTS_CTS scheme increases as the “speed” average values of the ON-OFF processes become shorted. Please note that the above results were obtained by using a relatively large buffer size (100 packets). Should a shorted buffer was to be used, the improvements in terms of packet delivery ratio offered by the with_RTS_CTS scheme over the no_RTS_CTS would have increased further.

The performance of the average packet delay versus traffic load when the RTS/CTS mechanism is employed with $\overline{\tau}_{i,j}^{ON}(\overline{\tau}_{i,j}^{OFF})$ as parameter is shown in Figure 5.5. It indicates that the faster the channel fluctuations are, the longer the delays become. As explained in Chapter 3, this can be attributed to the fact that under faster channel condition fluctuations there are more random losses of link layer packets. Loss of one of these packets forces the receiver to wait for its retransmission, thus holding the remaining correctly receiving link layer packets, delaying the delivery of the packet to the network layer. It is also evident that the increase of the traffic volume affects the delays.

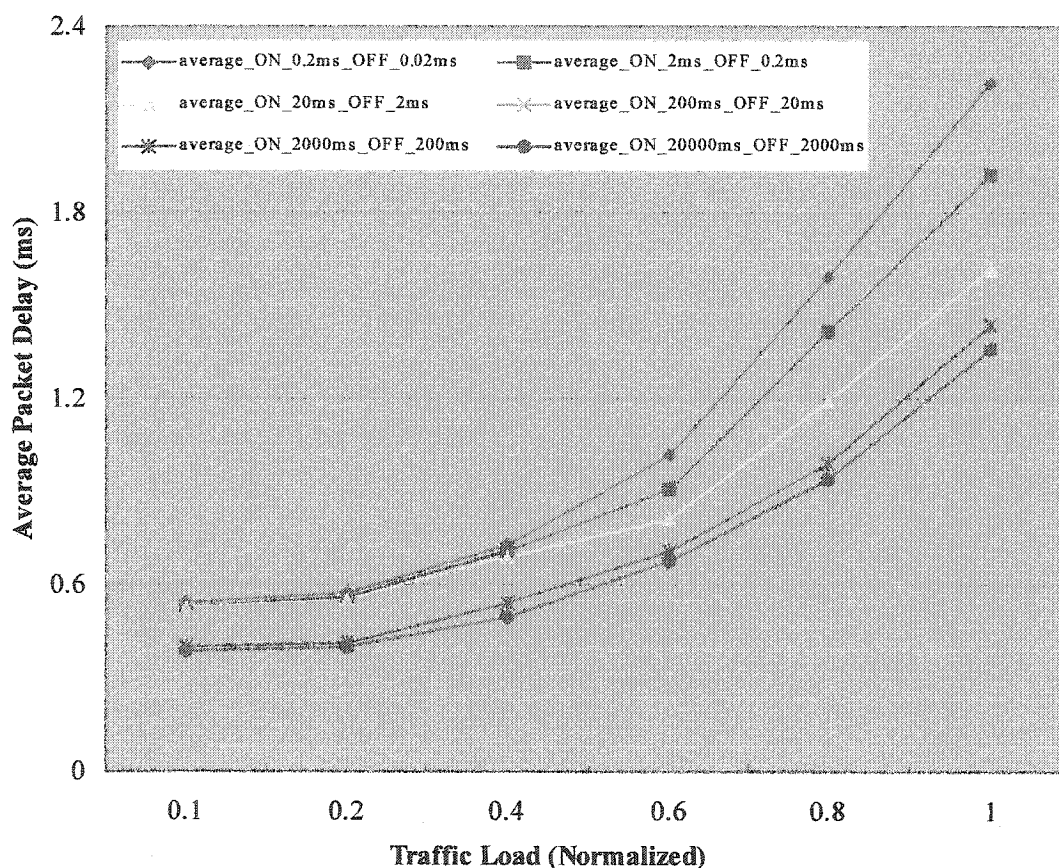


Figure 5.5 Average Packet Delay vs. Traffic Load (with RTS/CTS, $\overline{\tau}_{i,j}^{ON}(\overline{\tau}_{i,j}^{OFF})$ as parameter)

The comparison of the performance of average packet delay with respect to the traffic load when the RTS/CTS scheme is used and not used, where $\overline{\tau}_{i,j}^{ON}$ equals to 20000 msec and $\overline{\tau}_{i,j}^{OFF}$ equals to 2000 ms, is provided in Figure 5.6. It points out the fact that the conventional protocol experiences longer data packet delays than the one implementing RTS/CTS. This is normal since RTS/CTS is able to avoid packet collisions, which, when occurring, increase the delivery time of data packets to the destination. In addition, the capability of RTS/CTS' s sensing the unavailability of the channel faster and be able to allocate the resource to another station allows information to "move" faster through the network.

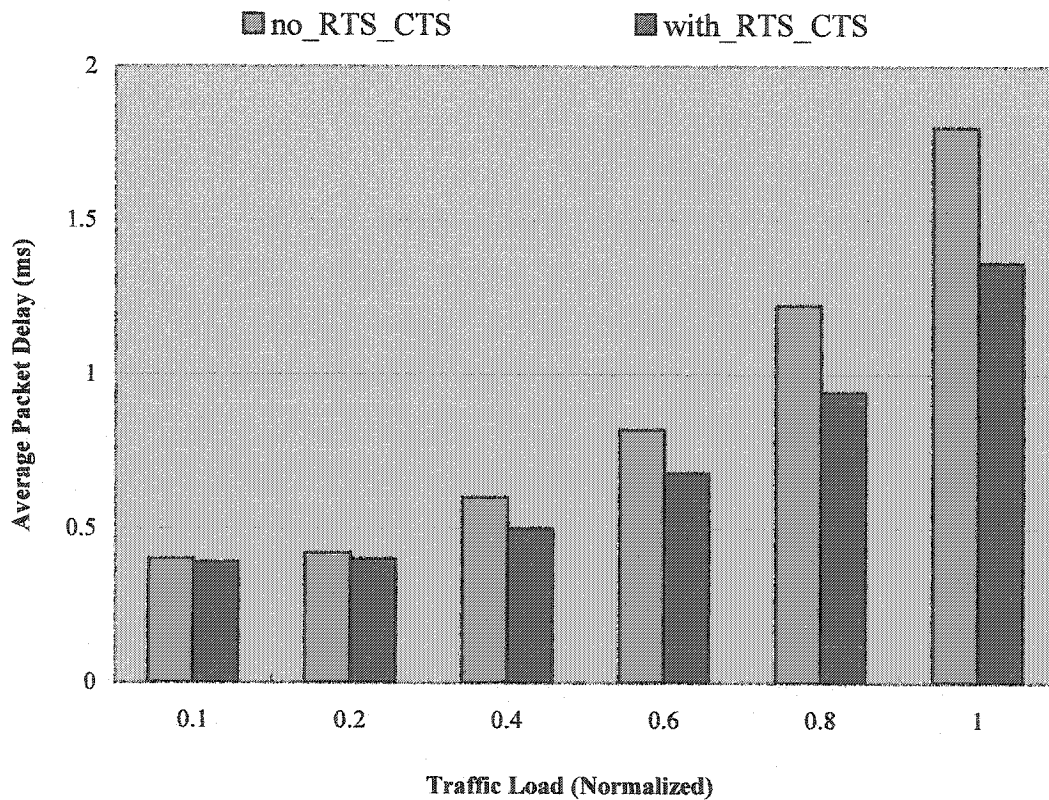


Figure 5.6 Comparison of Average Packet Delay vs. Traffic Load (with RTS/CTS and no

RTS/CTS, $\overline{\tau}_{i,j}^{ON} = 20000$ msec and $\overline{\tau}_{i,j}^{OFF} = 2000$ msec)

The following set of simulations will assess the effect of different ratio values of $(\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON})$. We keep using 100 packets buffer size. We assume that the status of the $\{S_i \rightarrow S_j\}$ channel and $\{S_j \rightarrow S_i\}$ channel are identical. $\overline{\tau}_{i,j}^{ON} = 200$ msec, $\overline{\tau}_{i,j}^{OFF} = \alpha * \overline{\tau}_{i,j}^{ON}$ msec, where different values of α (e.g. 0.0001, 0.001, 0.01, 0.1 and 1) have been investigated.

The performance of the packet delivery ratio versus traffic load with α as parameter is illustrated in Figure 5.7. It is evident that the lower the value of the probability of loss ratio $(\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON})$ is, the higher the packet delivery ratio becomes. This is expected, since the time the channels remain in poor condition decreases.

It is also evident from Figure 5.7 that for a certain value of α , when the traffic load is increasing, especially to a high level (reaching or surpassing 60% of capacity), the packet delivery ratio is on a downward trend. This is due to the fact that the higher the traffic volume is, the bigger the chances of the network become congested are (the buffer size maintains at 100 packets in the set of simulation). Therefore, the packet loss rate will be higher.

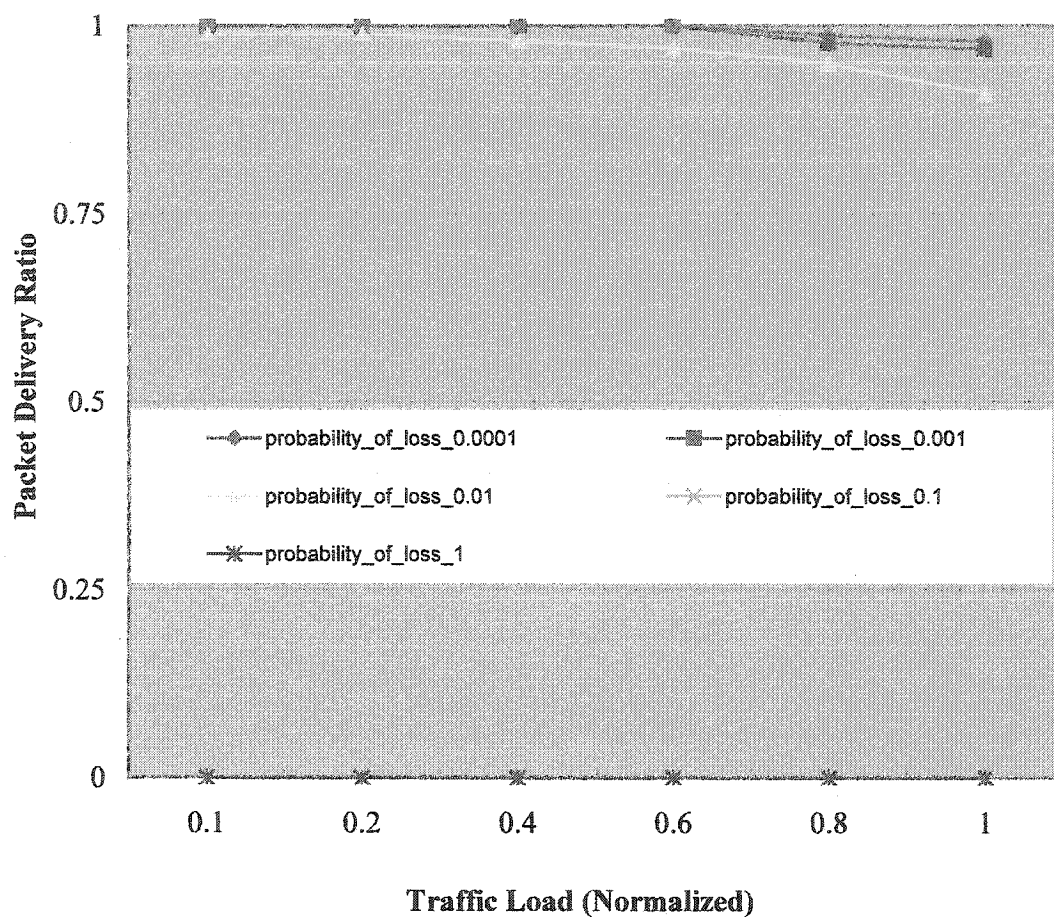


Figure 5.7 Packet Delivery Ratio vs. Traffic Load (with RTS/CTS, α as parameter)

The performance of packet delivery ratio with respect to traffic volume when RTS/CTS is used and not used with α as parameter (we choose α equal to 0.01 as example) is shown in Figure 5.8. The performance under perfect channel conditions is used as reference. It is evident that use of RTS/CTS provides improvement.

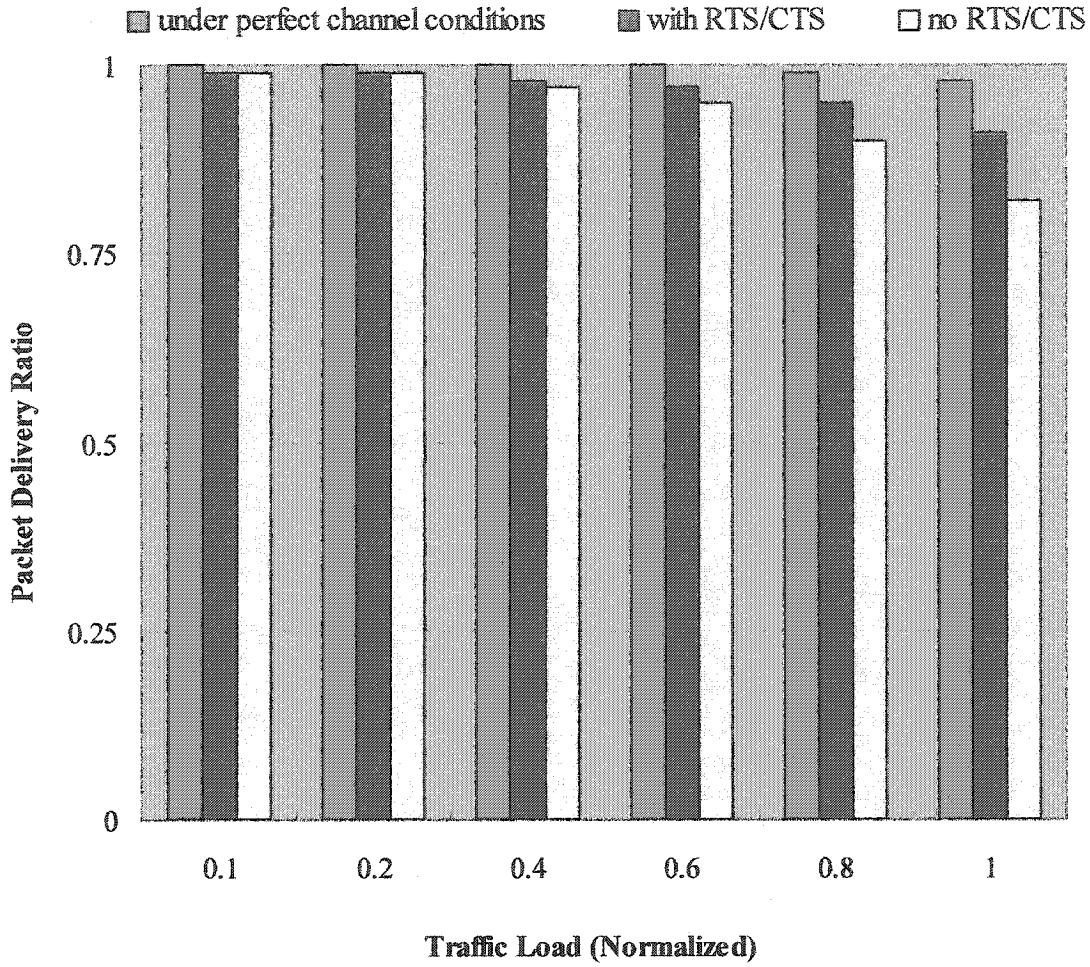


Figure 5.8 Comparison of Packet Delivery Ratio vs. Traffic Load (with RTS/CTS and no

$$\text{RTS/CTS, } \overline{\tau}_{i,j}^{ON} = 200 \text{ msec, } \alpha = 0.01)$$

The performance of the average packet delay versus traffic volume when RTS/CTS is employed with α as parameter is pictured in Figure 5.9. It conveys the fact that the higher the value of α is, the higher the average packet delay becomes. This is associated with the fact that longer fading periods produce more losses and retransmissions of link layer packets, thus delaying the time a network layer packet can be reassembled and passed to the network layer at the destination side. Moreover, when the traffic load increases, the average packet delivery time increases accordingly.

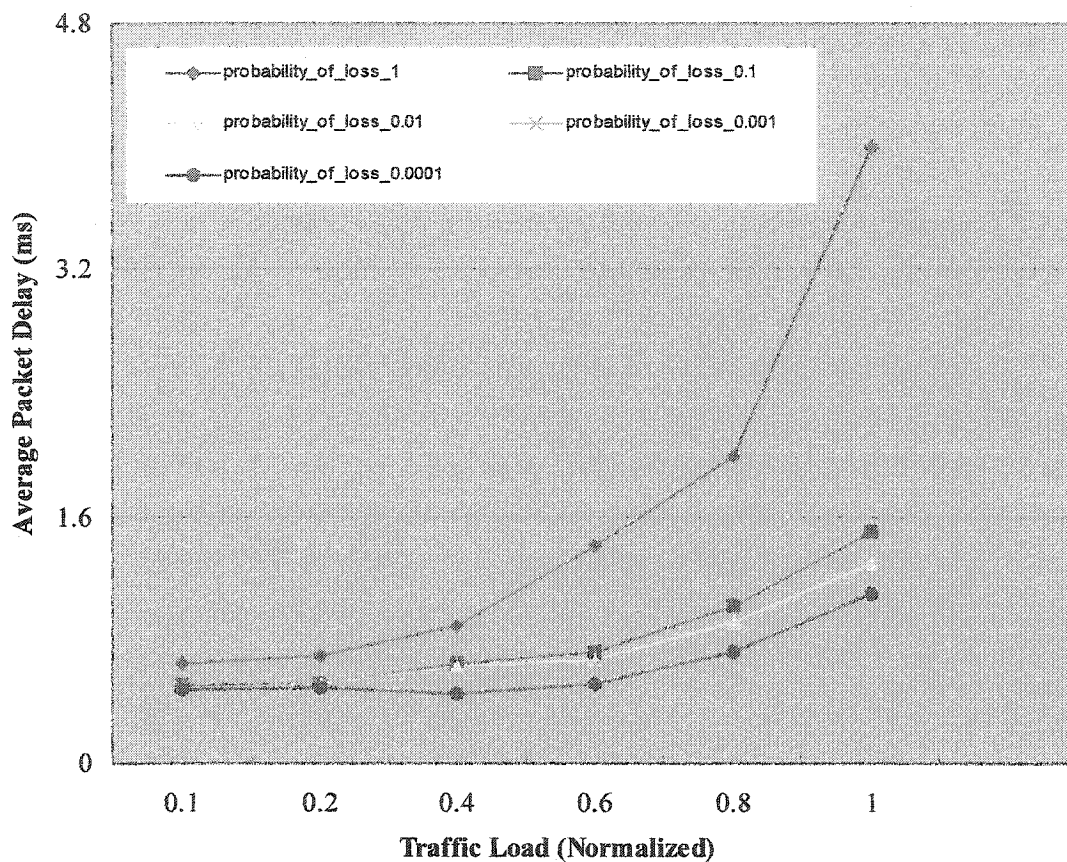


Figure 5.9 Average Packet Delay vs. Traffic Load (with RTS/CTS, α as parameters)

The comparison of the performance of the average packet delay versus traffic load when RTS/CTS is used and not used is provided in Figure 5.10. It proves that RTS/CTS can reduce the packet delivery time.

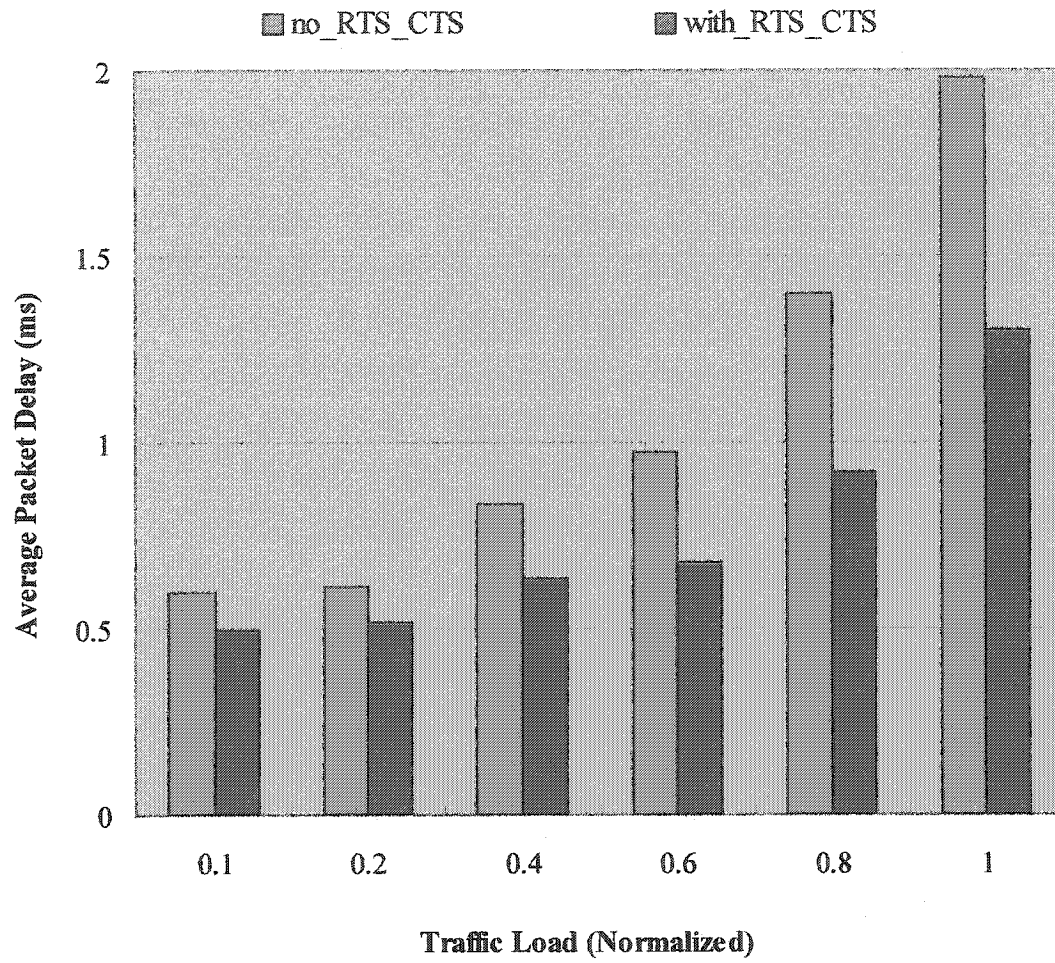


Figure 5.10 Comparison of Average Packet Delay vs. Traffic Load (with RTS/CTS and

no RTS/CTS, $\overline{\tau}_{i,j}^{ON} = 200$ msec, $\alpha = 0.01$)

5.2 Evaluation of the DHSS (Dynamic Hub Station Selection) Protocol and Traffic Relay Technique in Wireless 1394

The objective of the following evaluation is to compare the techniques, DHSS (Dynamic Hub Station Selection) and optimizing traffic relay, which we have proposed, to the conventional Wireless 1394. Performance comparison between the original Wireless 1394 network, where hub station is chosen from the Wireless 1394 capable devices without any criteria [9], and the one implementing DHSS where the lowest cost station is selected as a hub station by following the DHSS criteria, will be provided. Detail of the DHSS has been given in Section 4.2 of Chapter 4. Additionally, hub station might take charge of data relaying if needed when the communication between any pair of leaf stations fail. As a matter of fact, the relay control optimization scheme is based on the DHSS. For the information of traffic relay technique, please refer to Section 4.3 of Chapter 4.

As it was assumed earlier, each pair of stations $\{S_i, S_j\}$ is associated with an ON-OFF process. In the following cases of the experiment, the status of the $\{S_i \rightarrow S_j\}$ and $\{S_j \rightarrow S_i\}$ channel is identical. All pairs of $\{S_i, S_j\}$ has $\overline{\tau_{i,j}^{ON}}$ and $\overline{\tau_{i,j}^{OFF}}$ identical. At the beginning of the simulation, we start with half stations at the good state, half at bad state. However, we leave every pair to change state in a random manner as the time progresses. We use buffer size of 100 packets. We have chosen values in the ON-OFF process that in average produce packet losses with 0.1 probability. We run the simulations for different $\overline{\tau_{i,j}^{ON}}$ (from 0.2msec to 20000msec) and $\overline{\tau_{i,j}^{OFF}}$ (from 0.02msec to 2000msec), however, in all cases, we maintain the ratio $\overline{\tau_{i,j}^{OFF}} / \overline{\tau_{i,j}^{ON}}$ equal to 0.1.

The performance of the packet delivery ratio versus traffic load with $\overline{\tau_{i,j}^{ON}}$ ($\overline{\tau_{i,j}^{OFF}}$) as parameter, when DHSS is used, is shown in Figure 5.11. It demonstrates that the packet delivery ratio will increase when the values of the $\overline{\tau_{i,j}^{ON}}$ ($\overline{\tau_{i,j}^{OFF}}$) becomes higher. As it has been already explained, this is because longer ON-OFF periods tend to provide a lower packet loss ratio. When the values of the $\overline{\tau_{i,j}^{ON}}$ ($\overline{\tau_{i,j}^{OFF}}$) are large enough (as is the case where $\overline{\tau_{i,j}^{ON}} = 20000$ msec and $\overline{\tau_{i,j}^{OFF}} = 2000$ msec), the packet delivery ratio is the highest.

From Figure 5.11, we also observe that when the traffic load becomes higher, especially when the traffic volume reaches or surpasses 60% of the capacity, the packet delivery ratio will drop dramatically. This is because when the traffic load increases, the chances to experience network congestion increase as well (the buffer size is fixed to 100 packets in these experiments).

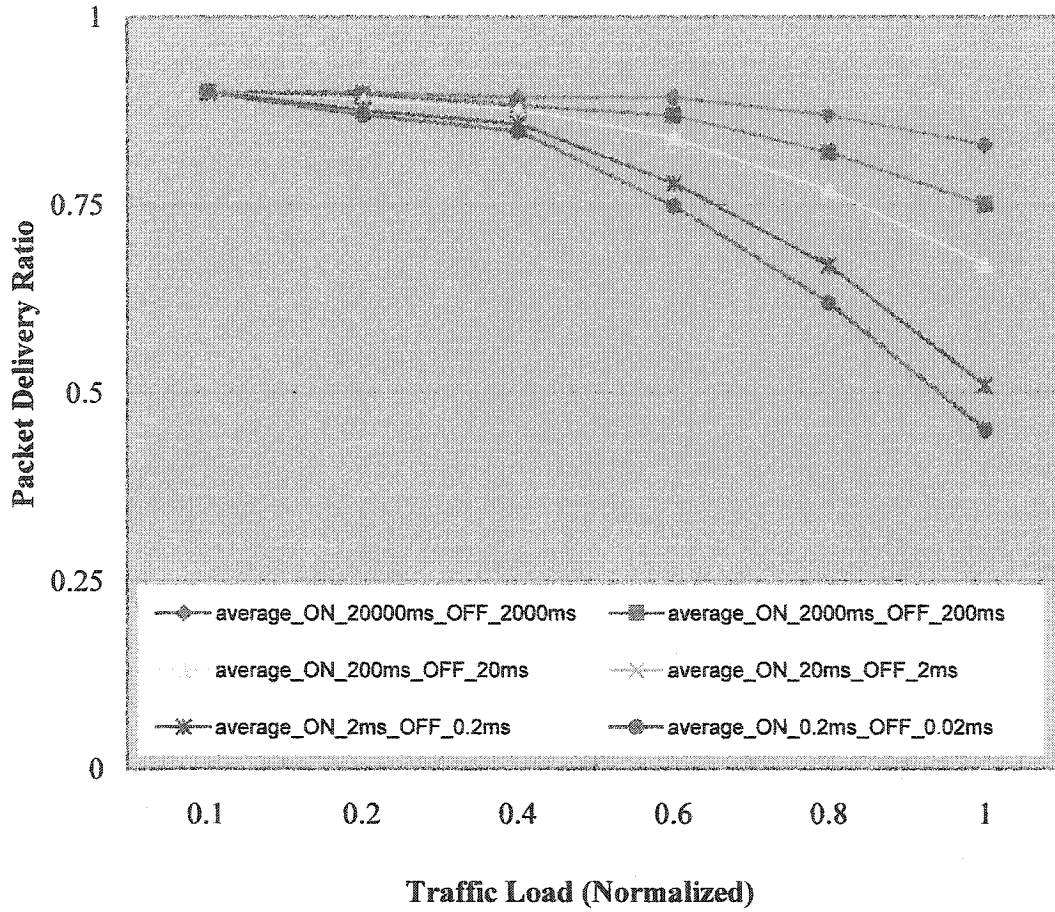


Figure 5.11 Packet Delivery Ratio vs. Traffic Load (with DHSS (Relay), $\overline{\tau}_{i,j}^{ON}$

($\overline{\tau}_{i,j}^{OFF}$) as parameter)

In Figure 5.12, we compare the packet delivery ratio performance when the DHSS scheme is used and not used with the $\overline{\tau}_{i,j}^{ON}$ equal to 20000 msec and $\overline{\tau}_{i,j}^{OFF}$ equal to 2000 msec (the ratio of $\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON} = 0.1$). We employ the performance under perfect channel conditions as a reference. Figure 5.12 reflects that the packet delivery ratio of with_DHSS scheme is higher than that of the no_DHSS one. Improvements are higher at higher traffic loads. The reason is that should any failure happen in the

shadowing prone home environment, with_DHSS scheme always retains working functionality, avoiding problems such as packet collision or congestion, thus having a higher successful packet delivery rate.

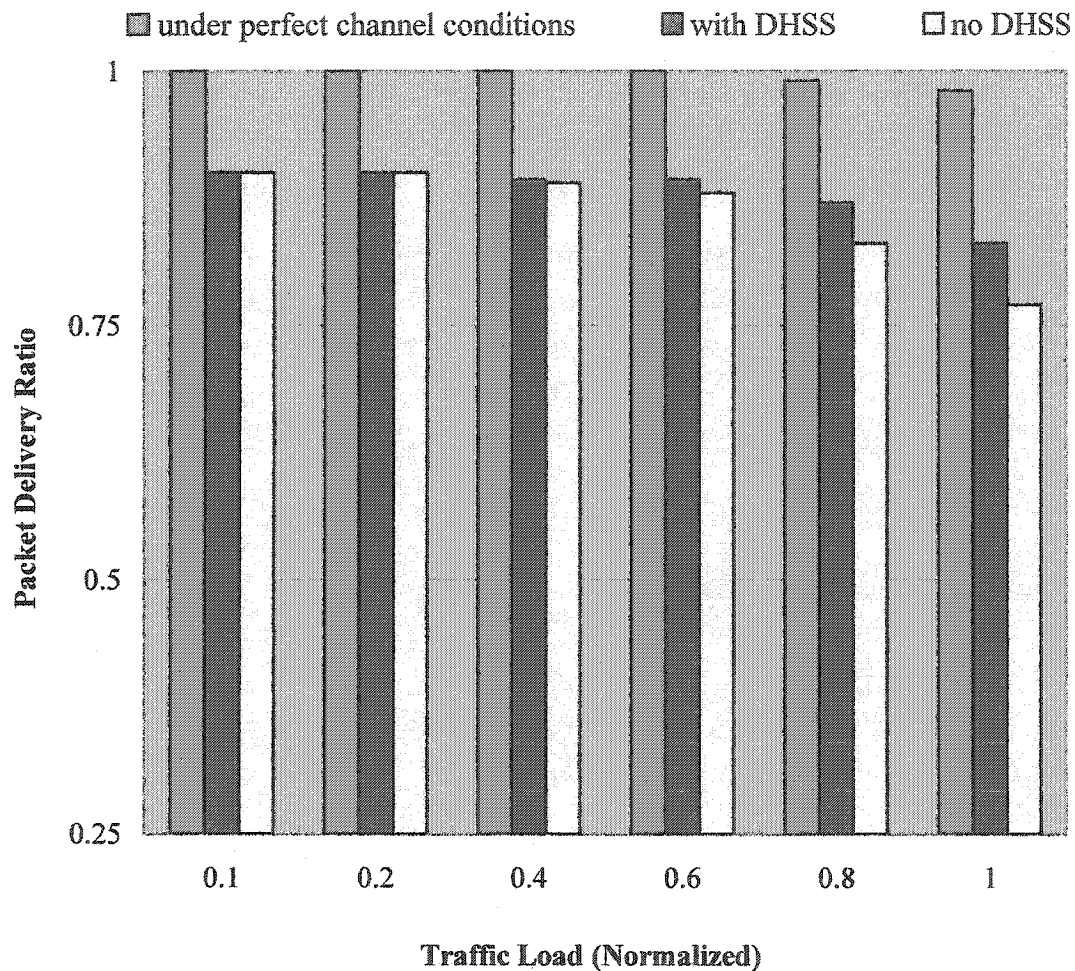


Figure 5.12 Comparison of Packet Delivery Ratio vs. Traffic Load (among perfect channel conditions, having DHSS (Relay) and no DHSS with $\overline{\tau}_{i,j}^{ON} = 20000$ msec and $\overline{\tau}_{i,j}^{OFF} = 2000$ msec)

The performance of the average packet delay versus traffic volume when the DHSS mechanism is employed, with $\overline{\tau}_{i,j}^{ON}(\overline{\tau}_{i,j}^{OFF})$ as parameter, is shown in Figure 5.13. It indicates that the faster the channel fluctuations are, the longer the delays become. As explained before, this can be attributed to the fact that under faster channel fluctuations there are more random losses of link layer packets. Loss of one of these packets forces the receiver to wait for its retransmission, thus holding the remaining correctly receiving link layer packets, delaying the delivery of the packet to the network layer. It is also apparent that the increase of traffic volume affects the delays.

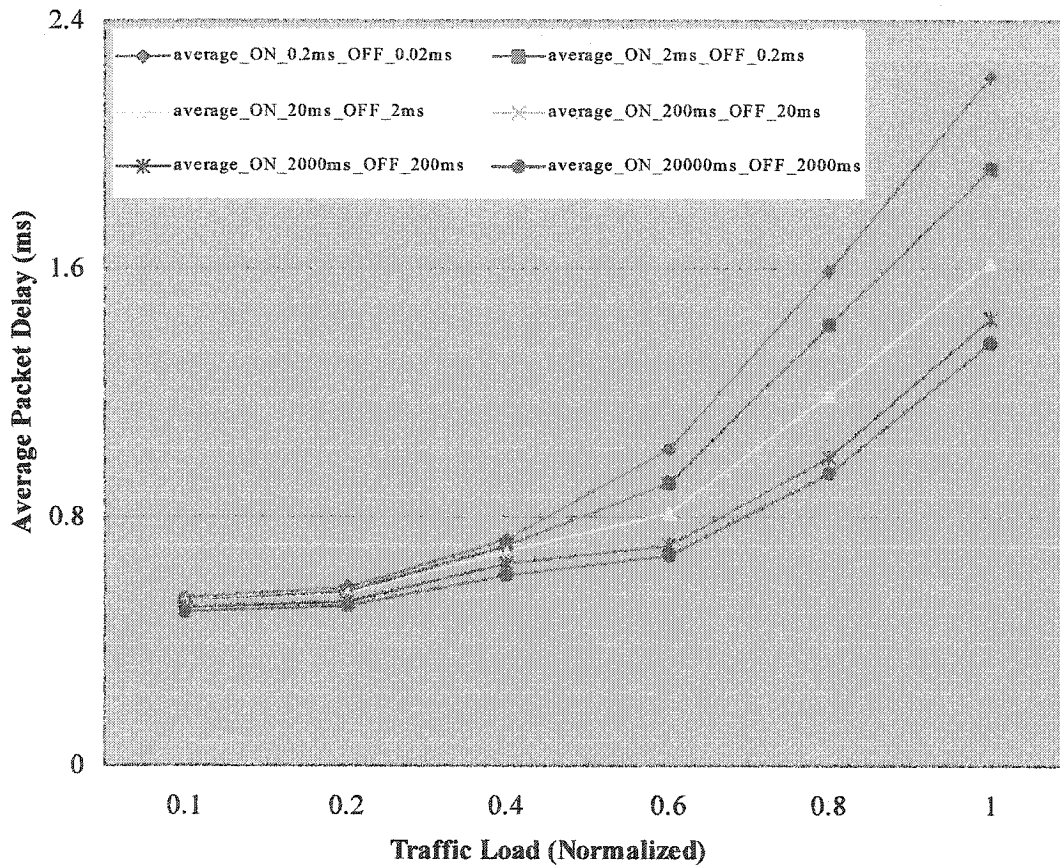


Figure 5.13 Average Packet Delay vs. Traffic Load (with DHSS

(Relay), $\overline{\tau}_{i,j}^{ON}(\overline{\tau}_{i,j}^{OFF})$ as parameter)

The comparison of the performance of average packet delay with respect to the traffic load when DHSS scheme is used and not used, where $\overline{\tau}_{i,j}^{ON}$ equals to 20000 msec and $\overline{\tau}_{i,j}^{OFF}$ equals to 2000 ms, is provided in Figure 5.14. It points out the fact that the conventional protocol experiences longer data packet delays than the one implementing DHSS. This is normal since should any failure happen, DHSS network is able to maintain working functionality, avoiding packet collisions and network congestion, which, when occurring, increase the delivery time of data packets to the destination.

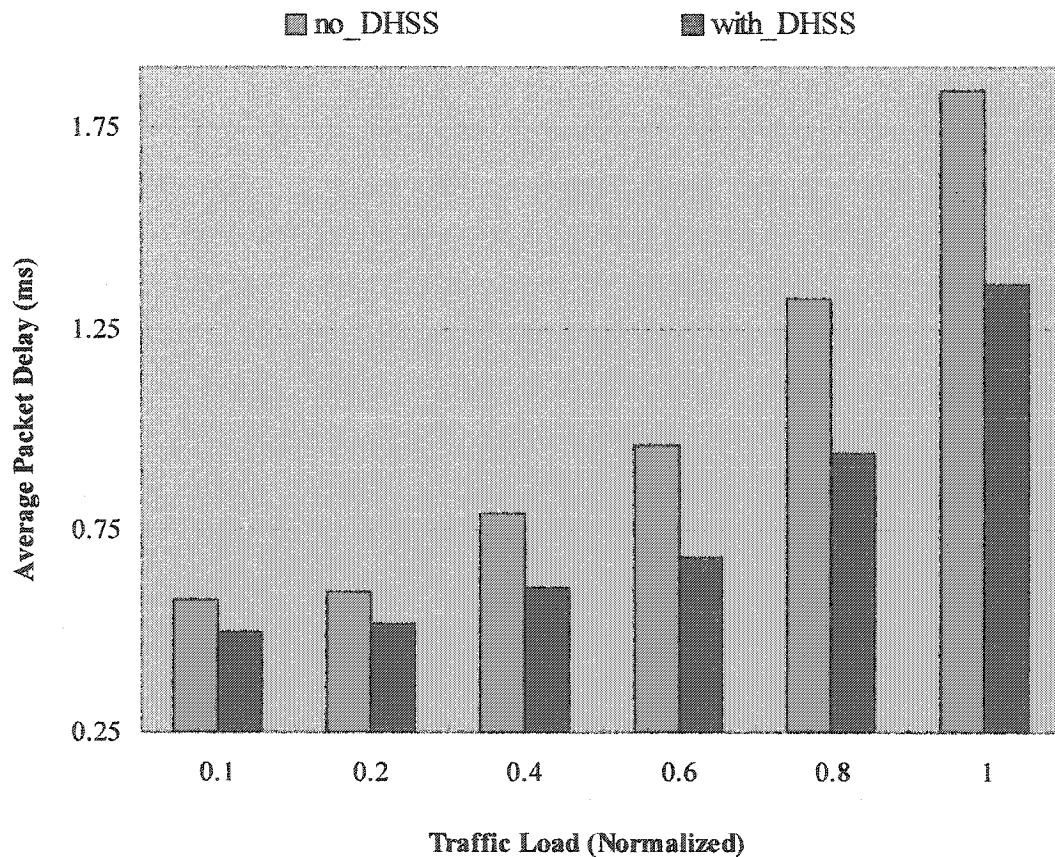


Figure 5.14 Comparison of Average Packet Delay vs. Traffic Load (with DHSS (Relay),

no DHSS, $\overline{\tau}_{i,j}^{ON} = 20000$ msec and $\overline{\tau}_{i,j}^{OFF} = 2000$ msec)

In short, Figure 5.12 and Figure 5.14 reveal the fact that the DHSS enabled system outperforms the conventional one because of its higher packet delivery ratio and lower packet delay performance. The reason is as follows. When implementing the prominent Wireless 1394 technology in the home environment, some unforeseeable problems, such as the failure of the unit (hub station), the loss of connectivity between the unit itself and the other leaf stations because of network topology change, mobility, shadowing or fading, will bring the Wireless 1394 network to a complete halt. DHSS is able to resolve these issues. The DHSS mechanism provides the system with a backup hub station, passing the hub station's responsibilities over to the standby hub station, as well as initiates processes to maintain the network communication, should the problems mentioned above occur. DHSS network always retains working functionality, avoiding problems such as packet collision or congestion brought by those unforeseeable problems mentioned. Hence, it has a higher successful packet delivery rate and lower packet delay latency. This is also the case when using hub station to relay traffic. Because the initial selection of hub station has already taken the lowest cost into consideration, when the hub station transmits traffic, the path it uses is of the lowest cost. Therefore, the delay should be low and the path is reliable to deliver more packets. On the opposite side, the No_DHSS system cannot detect the failure and maintains sending traffic, leading the network to higher congestion levels. This will result in longer packet delay and lower packet delivery ratio.

The following set of simulations will assess the effect of different ratio of $(\overline{\tau}_{i,j}^{OFF} / \overline{\tau}_{i,j}^{ON})$. We keep using 100 packets buffer size. We assume that the status of the $\{S_i \rightarrow S_j\}$ channel and $\{S_j \rightarrow S_i\}$ channel are identical. $\overline{\tau}_{i,j}^{ON} = 200$ msec, $\overline{\tau}_{i,j}^{OFF} = \alpha * \overline{\tau}_{i,j}^{ON}$ msec, where different values of α (e.g. 0.0001, 0.001, 0.01, 0.1 and 1) have been investigated.

The performance of the packet delivery ratio versus traffic load with α as parameter is illustrated in Figure 5.15. It is evident that the lower the value of the probability of loss ratio ($\overline{\tau^{OFF}_{i,j}} / \overline{\tau^{ON}_{i,j}}$) is, the higher the packet delivery ratio becomes. This is because when the time the channels remain in poor condition decreases, the system has the opportunity to pass more packets without losses and retransmission related delays, thus, the overall network performance improves.

It is also evident from Figure 5.15 that for a certain value of α , when the traffic load is increases, especially to a high level (reaching or surpassing 60% of capacity), the packet delivery ratio is on a downward trend. This is due to the fact that the higher the traffic volume is, the bigger the chances of the network congestion will be (the buffer size is maintained at 100 packets in the set of simulations).

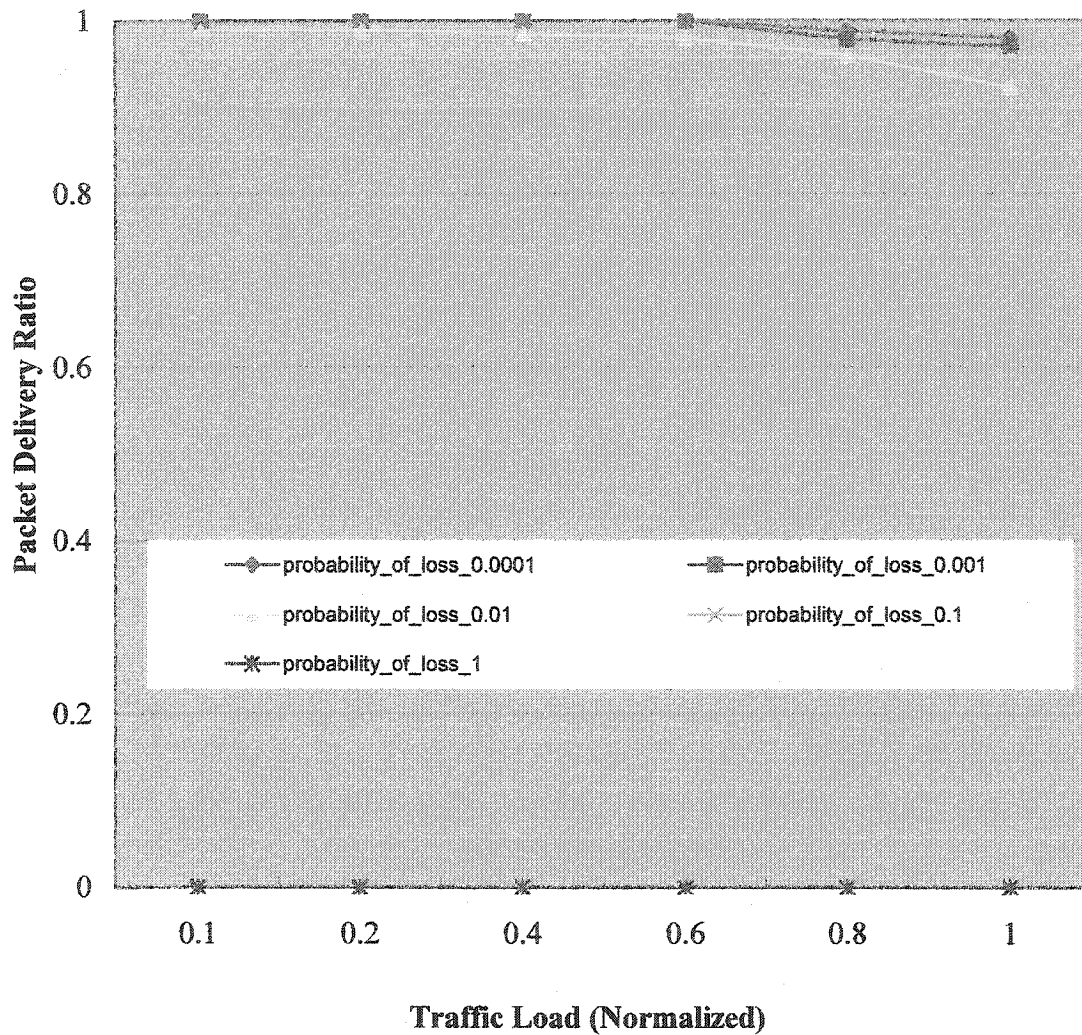


Figure 5.15 Packet Delivery Ratio vs. Traffic Load (with DHSS (Relay), α as parameter)

The comparisons of the performance of packet delivery ratio with respect to traffic volume when DHSS is used and not used with α as parameter (we choose α equal to 0.1 and 0.01 as examples) are provided in Figure 5.16 and Figure 5.17, where the performance under perfect channel conditions is used as a reference. These figures convey the fact that DHSS is able to increase the packet delivery ratio as compared to the conventional one where no DHSS is implemented. This improvement is higher when the

probability of loss ratio α ($\alpha = \overline{\tau_{i,j}^{OFF}} / \overline{\tau_{i,j}^{ON}}$) increases. The reason is that when the network conditions are becoming worse in terms of the higher probability of loss ratio α , system equipped DHSS is capable of confronting the negative effects of shadowing / fading, such as packet collisions and packet loss, as analyzed before, whereas the system without DHSS is vulnerable to tackle these problems, hence, degrading the network performance.

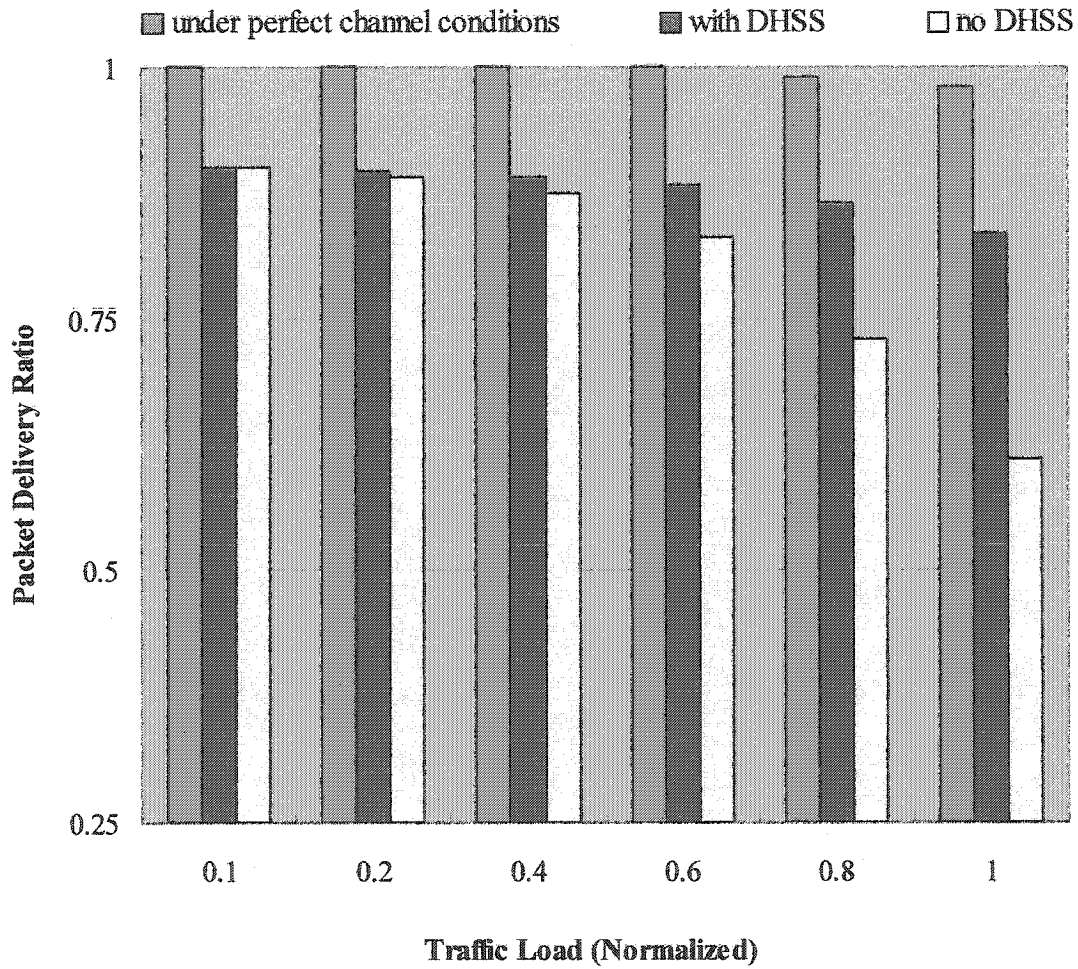


Figure 5.16 Comparison of Packet Delivery Ratio vs. Traffic Load (with DHSS (Relay)

and no DHSS, $\overline{\tau_{i,j}^{ON}} = 200$ msec, $\alpha = 0.1$)

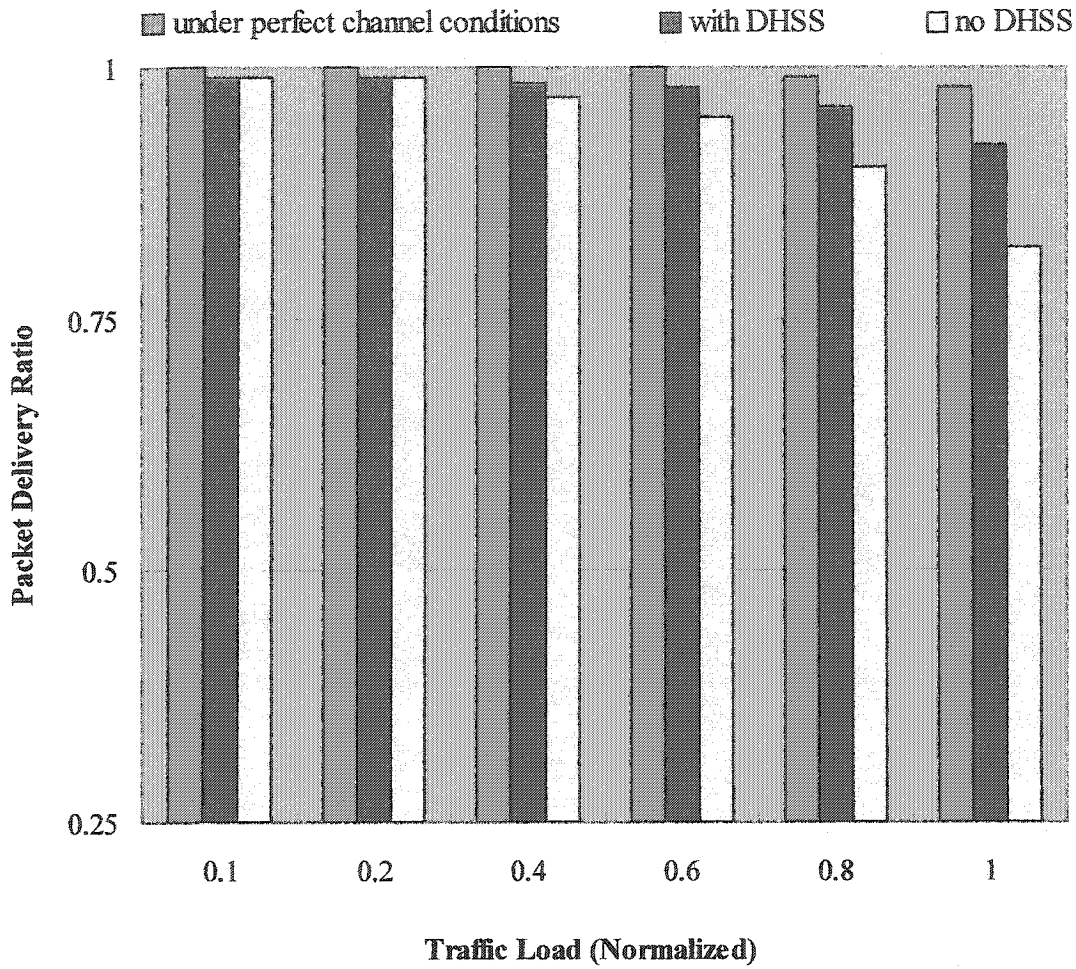


Figure 5.17 Comparison of Packet Delivery Ratio vs. Traffic Load (with DHSS (Relay)

and no DHSS, $\overline{\tau}_{i,j}^{ON} = 200 \text{ msec}$, $\alpha = 0.01$)

The performance of the average packet delay versus traffic volume when the DHSS mechanism is employed with α as parameter is pictured in Figure 5.18. It conveys the fact that the higher the value of α is, the higher the average packet delay becomes. This is associated with the fact that longer fading periods produce more losses and retransmissions of link layer packets, thus delaying the time a network layer packet can be reassembled and passed to the network layer at the destination side. Moreover, when the traffic load increases, the average packet delivery time increases accordingly.

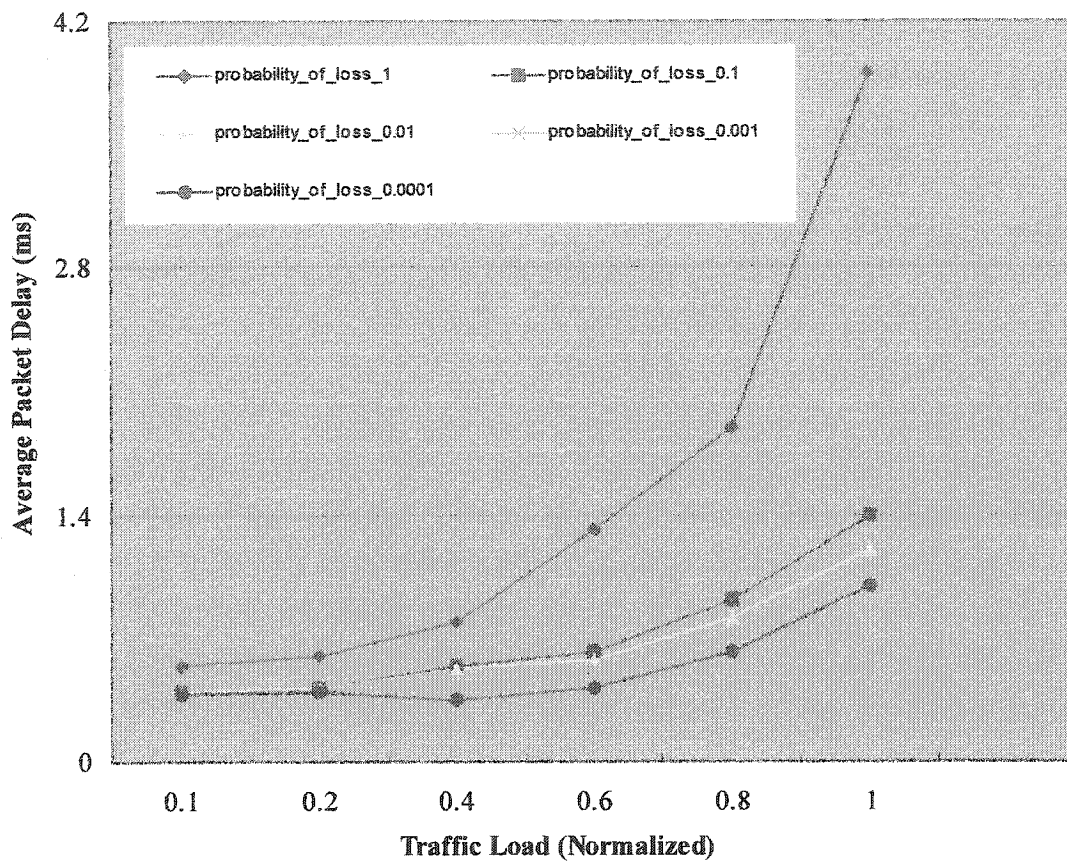


Figure 5.18 Average Packet Delay vs. Traffic Load (with DHSS (Relay), α as parameters)

The comparison of the performance of the average packet delay versus traffic load when DHSS is used and not used is provided in Figure 5.19. It proves that DHSS can reduce the packet delivery time. This is because DHSS is able to avoid packet collisions, which, when occurring, increase the time to deliver data packets to the destination.

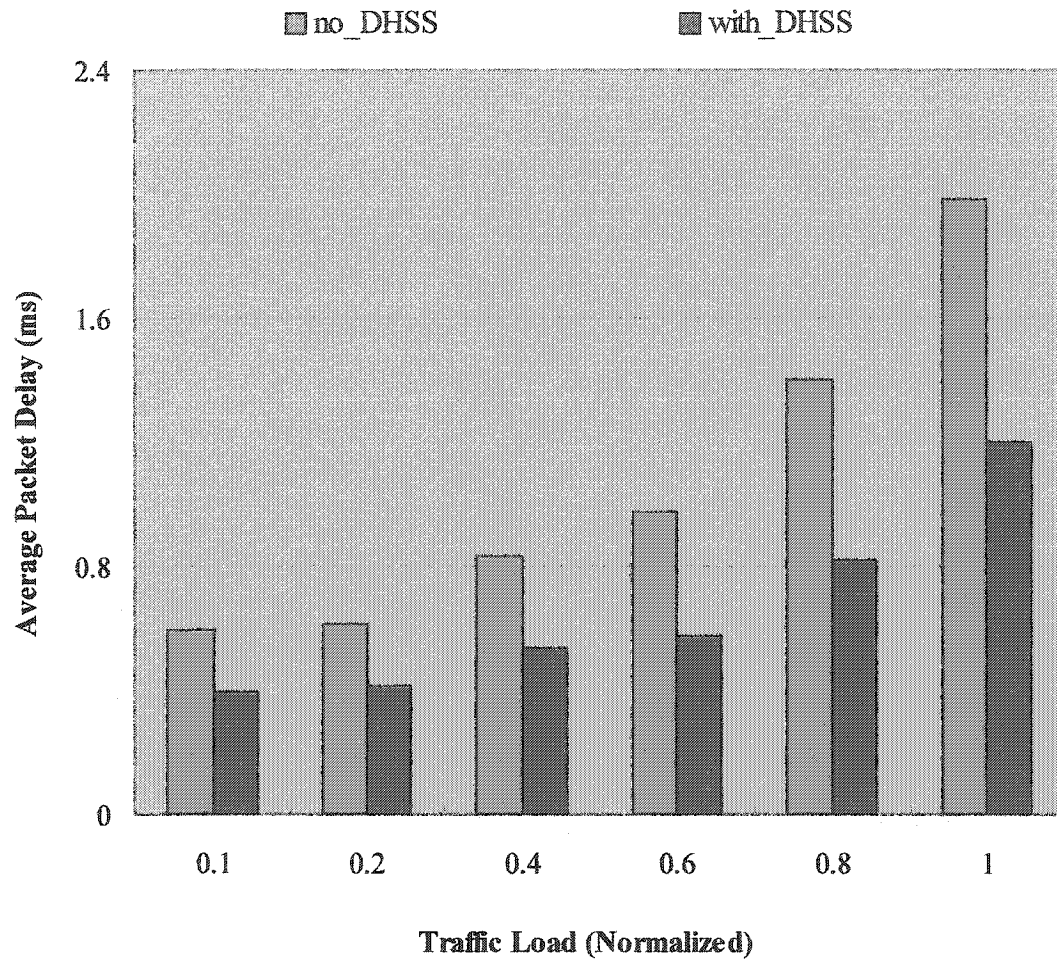


Figure 5.19 Comparison of Average Packet Delay vs. Traffic Load (with DHSS (Relay)

and no DHSS, $\overline{\tau}_{i,j}^{ON} = 200$ msec, $\alpha = 0.01$)

5.3 Evaluation of the DCRR (Deficit Control Round Robin) Algorithm for Wireless 1394

As has been pointed out in Section 4.4 of Chapter 4, in order to provide an effective traffic scheduling algorithm (the existing protocol is lacking one) and at the same time to keep it not as complicated as those existing algorithms which have been proposed for other wireless networks (in order to comply with the philosophy of simplicity when implementing Wireless 1394), an improved traffic scheduling algorithm, DCRR (Deficit Control Round Robin), has been proposed. The objective of this section is to assess the performance of DCRR, as compared to the conventional RR (Round Robin) used in the existing version of Wireless 1394. The main procedures to use the DCRR service discipline have been introduced in Section 4.4 of Chapter 4.

Specific simulation parameters for evaluating DCRR, such as the values of DC, DT, Quantum and ArDC have been set to the values that are indicated in Table 5.1.

Table 5.1 Simulation Values for DCRR

DC (Byte)	DT (Byte)	Quantum (Byte/Round)	ArDC (Byte)
500	500	500	1600

Figures 5. 20 and Figure 5.21 capture the packet delivery ratio and average packet delay features implementing the DCRR and RR disciplines respectively. It is evident that the DCRR approach achieves better performance than that of the RR scheme in terms of packets' higher percentage of successful delivery and lower average delay. The fact that DCRR turns out to be superior to RR is based on the following reasons. Under DCRR, the scheduler uses two pairs of control factors, DC (Deficit Counter) vs. DT (Deficit

Threshold) and AcDC (Actual Deficit Counter) vs. ArDC (Accrued Deficit Counter) to control the packet transmission. For instance, even when the value of DC is negative, as long as $|DC| \leq |DT|$, packets in the queue will still be allowed to transmit. That is, DCRR is able to transmit more packets, resulting in less packet loss ratio when the traffic volumes are increasing from low to high and less time the packets will experience to arrive to the destination. On the contrary, the RR scheduler lacks such resource controlling strategies, making itself inferior to the DCRR.

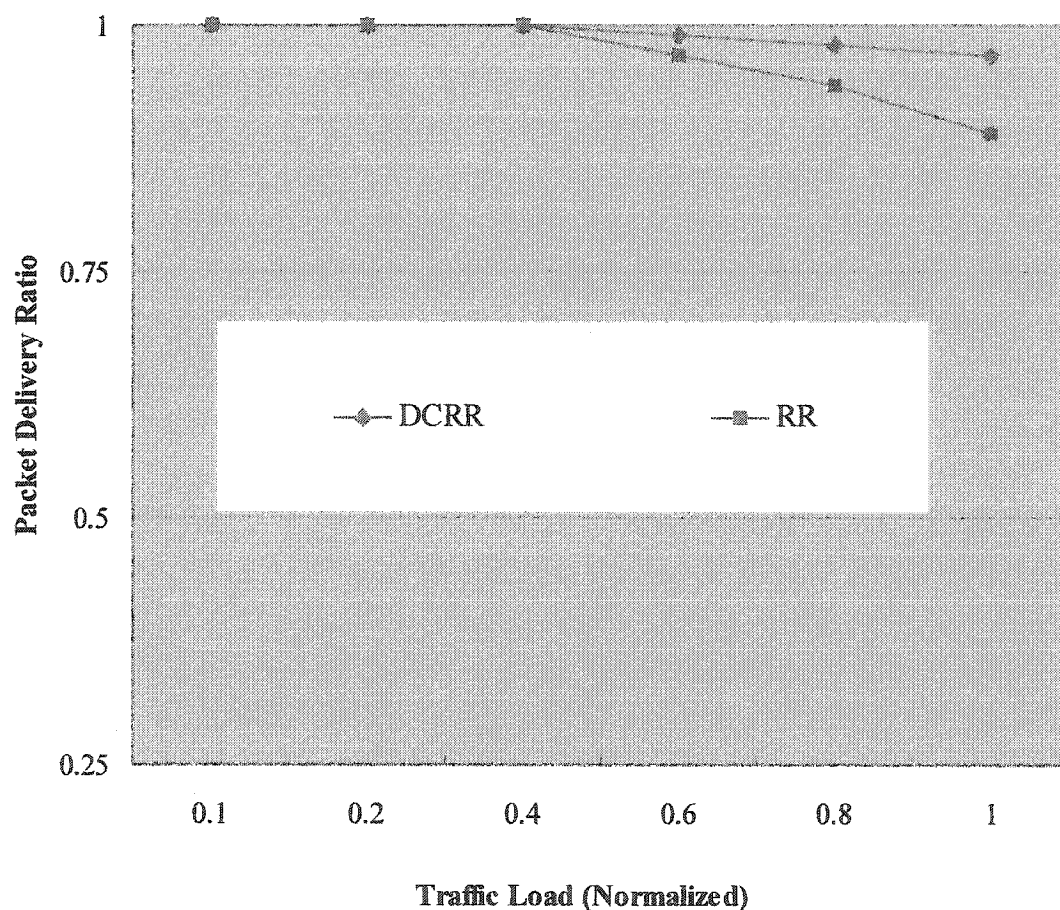


Figure 5.20 Comparison of Packet Delivery Ratio vs. Traffic Load (DCRR vs. RR)

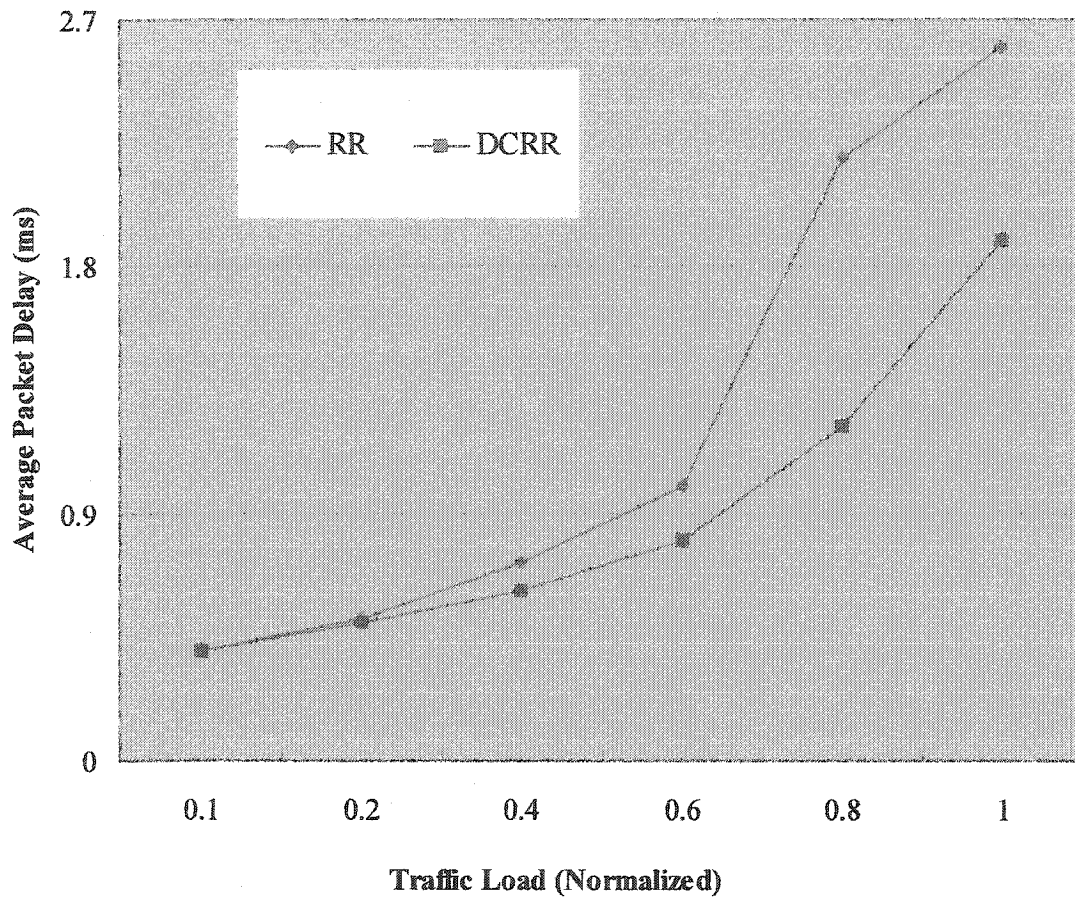


Figure 5.21 Comparison of Average Packet Delay vs. Traffic Load (DCRR vs. RR)

6. CHAPTER 6

Conclusions and Recommendations for Future Work

This thesis concentrates on the issues associated with Wireless 1394 technology, which appears to be the only existing QoS capable broadband wireless home networking solution. Performance of the original Wireless 1394 protocol has been analysed in detail. Deployment challenges when implementing the technology have also been pointed out. To tackle those challenges, research has been carried out. Extensions and improvements of the original Wireless 1394 protocol have been proposed and evaluated.

Wireless channel behaviour is critical in evaluating a wireless system's performance. In order to simulate an accurate wireless home telecommunications environment, we used a more generic and thorough approach. We consider that the channel could be blocked for several reasons (shadowing, fading, mobility, failure, etc.) and it follows an ON-OFF process. ON provides reliable communications, while OFF indicates unreliable communications. When the system is in the ON state, we are assuming that all packets are delivered correctly. When in the bad state, we are assuming that packets are received erroneously, with probability P_E . It has been demonstrated that the Wireless 1394 system acts differently with these channel models and its performance drops compared to the performance attained under ideal channel conditions.

New protocol extensions and improvements to the original Wireless 1394 network have been proposed and evaluated to address these problems. Simulation results prove the superiority of the newly proposed mechanisms. In particular, the combination use of virtual sensing and polling is able to increase the system's robustness to countermeasure the effects of fading and/or shadowing in an error prone wireless home surrounding.

Moreover, because of the critical roles the hub station fills in the system, the Wireless 1394 network always requires a functional hub station. If the long-term effects (e.g. failure of the hub station, loss of connectivity due to the changes in network topology, or the blocked wireless link, etc) which will seriously affect the normal operation of the hub station occur, the dynamic hub station assignment scheme will be triggered to select the most suitable station as a new hub station based on the recent network conditions, thus it can maintain a workable central controller existing in the subnet. Furthermore, the optimizing traffic relay scheme can optimize the system's performance by selecting an optimal (lowest cost) relay path and optimal relay station to pass the traffic when the direct communication between the pair of transmitting leaf station and receiving leaf station fails. Additionally, the deficit control round robin scheme provided a new service discipline in Wireless 1394 network to achieve a better distribution of network resource.

We consider that the strategies we developed and reported in this thesis are the just as the very beginning of fruitful research. Further extensions and future work leading our in-depth research can be carried out in the following directions. In the approach of dynamic hub station selection, when this process is triggered, the cost function to choose the most appropriate hub station and the second appropriate hub station is of linear nature in the current mechanism we proposed. We can expand to non-linear function to let the mechanism react on a progressive consistent change. In the deficit control round robin scheme, improvements can include applying a concept of service limitation to the user even when the credit is positive. This way will not allow more than a maximum service unit before the hub station polls and offers service to another station. Also, this will prevent starvation of other users when dealing with a user who was inactive for a long time and kept collecting credit, as well as will limit the burst this user would generate in the network. New research objectives which have not been studied in the current research, such as the regulation of the process of new station's joining into the network, the interoperation of inter-bus Wireless 1394 system, etc, are of research interest as well. The author of this dissertation intends to pursue these directions during her PhD studies.

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