Design of an IEEE 802.15.4 compliant Slave/Slave Bridge to support Inter-WPAN Communication Using CSMA-CA

by

Ranjith Udayshankar

A dissertation submitted in partial satisfaction of the

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MASTER OF SCIENCE

ABSTRACT

IEEE 802.15.4 is an emerging wireless standard for short range Wireless Personal Area Networks (WPANs) that provides low data rate, low cost, low power consumption and low complexity among battery-operated inexpensive devices. It is considered as an enabling technology for wireless sensor networks. The current IEEE 802.15.4 standard does not propose any mechanism to perform interconnection of IEEE 802.15.4 compliant beacon enabled network clusters. Therefore, I have designed and developed a bridging algorithm in an ordinary device node to enable communication between two or more IEEE 802.15.4 compliant beacon enabled network clusters. The design involves both uplink and downlink transmissions to the coordinator and the bridge respectively. I investigate the interactions among device, coordinator and bridge nodes by varying certain control parameters such as number of devices and packet arrival rate. Furthermore, the performance metrics such as channel access probability, throughput and probability of successful transmission are measured. I analyze network performance of both acknowledged and non-acknowledged packet transfer for array types of network and larger 2-dimensional networks. Moreover, I compare the performance of acknowledged and non-acknowledged packet transfer mode in relatively large networks. Results from my research can provide useful guidelines in the design of large networks regarding cluster size, packet arrival rate and bridge buffer capacity. The proposed work is achieved using simulation study.

keywords: WPAN, LR-WPAN, CSMA-CA

DEDICATION

I dedicate this thesis to my father Dr.P.M.Udayshankar, my mother C.P.Kalaivani Udayshankar and my brother Yeshwanth Udayshankar. You have been my inspiration, my guides and my role-models. Thank you for your unconditional love and support throughout this journey. It would not have been possible without you all.

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Contents

GLOSSARY

1. LR-WPANs: Low Rate-Wireless Personal Area Networks
2. CSMA-CA: Carrier Sense Multiple Access-Collision Avoidance
3. PAN: Personal Area Network
4. POS: Personal Operating Space
5. FFD: Full Function Device
6. RFD: Reduced Function Device
7. OSI: Open System Interconnection
8. CAP: Contention Access Period
9. CFP: Contention Free Period
10. BO: Beacon Order
11. SD: Superframe Duration
12. SO: Superframe Order
13. GTS: Guaranteed Time Slots
14. BE: Backoff Exponent
15. CW: Contention Window
16. CCA: Clear Channel Assessment
17. RTS/CTS: Request To Send / Clear To Send
18. ISO-OSI: International Standard Organization's - Open System Interconnect
19. WPAN: Wireless Personal Area Network

Chapter 1

Terminology

The following are the terms dealt with in this thesis:

- *WPAN* (Wireless Personal Area Network): is a wireless network "in the Personal Operating Space (POS) which is the space around a person or object that typically extends up to 10m in all directions and envelopes the person whether stationary or in motion" [5] [17].

- *LR-WPAN* (Low Rate-Wireless Personal Area Network): is a short range wireless personal area network designed and developed by the IEEE 802.15.4 work group for sensor applications.

- *CSMA-CA* (Carrier Sense Multiple Access-Collision Avoidance): A protocol used by wireless network devices to access the physical medium for data transmission using a back-off procedure to avoid collisions [5].

- *Star Topology* : a network topology that resembles the shape of the star. In this topology, every communication takes place through the central WPAN Coordinator.

- *Superframe* : According to the IEEE 802.15.4 standard [5], physical channel time is divided into superframe structures bounded by network beacons.

- *Saturation Region* : *The region in which no packet is successfully transferred due to excessive collisions in the physical medium.*

- *Bridge Residence Time*: The time taken by the bridge to stay in each WPAN for data exchange with the respective WPAN coordinator.

- *Backoff Period*: A basic time unit defined in the IEEE 802.15.4 wireless standard.

- *Beacon Order* (BO): According to the IEEE 802.15.4 standard, "beacon order is a subfield in the superframe specification field that specifies the transmission interval beacon" [5]. The value of BO determines the length of the superframe. For example, when BO is 0, the length of the superframe is 48 backoff periods.

- *Superframe Order* (SO): According to the IEEE 802.15.4 standard," superframe order is a subfield in the superframe specification field that specifies the length of time during which the superframe is active (receiver enabled), including the beacon frame transmission time" [5]. For example, when the value of SO is 0, the active period in a superframe structure is 48 backoff periods.

- *Slot*: A compound time unit, composed of multiple backoff periods. It is used to grant GTS access in the slotted transmission medium. The value of SO determines the length of a slot, i.e. duration of the slot is equal to $3 \cdot 2^{SO}$ backoff periods. For example, when SO is 0, the length of a slot is 3 backoff periods.(1 backoff period = 20 symbols,1 Symbol = 4 bits)

- *Slotted CSMA-CA*: A channel access protocol used in the beacon enabled mode, where the channel is divided into back-off periods [5].

- *Unslotted CSMA-CA*: A channel access algorithm used in non-beacon enabled networks [5].

- *Backoff Exponent*(BE): " is the number of back-off periods a device shall wait before attempting to access a channel" [5].

- *Piggybacked*: "The technique of temporarily delaying outgoing acknowledgments so that they can be hooked onto the next outgoing data frame is known as piggybacking" [32].

- *NB* : According to the IEEE 802.15.4 standard, "is the number of times the CSMA-CA algorithm is required to back-off while attempting the current transmission" [5].

- *Contention Window* (CW): is the length of the contention window "defining the number of back-off periods that need to be clear of channel activity before the transmission can commence " [5].

- *Clear Channel Assessment* (CCA): According to the IEEE 802.15.4 standard, CCA is a process that occurs after the random back-off period to check the status of the medium in a CSMA-CA algorithm.

- *Soft Channel Reservation Mechanism*: is a channel reservation mechanism that "gives preference to the channel that was used for the last successful transmission", [36] and is employed by the CSMA MAC protocol for channel selection.

- *Channel Fading*: is defined as" the rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance, where large-scale path loss effects may be ignored. Fading is caused by interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times." [27]

- *Request to send/ Clear to send (RTS/CTS)*: is a transmission synchronization technique where, when "a station that has a frame to transmit, sends an RTS frame and the receiving station responds with a CTS frame after SIFS time. The data frame is transmitted after the successful exchange of the RTS and CTS frames. The RTS frame is re-transmitted in case the CTS frame is not received within a predetermined time interval." [37]

- *Channelization*: is a technique used to select the channel with the smallest interference among the set of channels offered by the standard. [27]
- *Modulation*: is defined as "the process of encoding information from a message source in a manner suitable for transmission." [27]

Chapter 2

Introduction

Low Rate-Wireless Personal Area Network standard IEEE 802.15.4 is a new wireless technology for short range applications that replaced the existing cable technology to provide low data rate, low operation cost, low complexity and low power consumption. To enable the above LR-WPAN compliant applications, the IEEE 802 Working Group 15 and the ZigBee alliance, a HomeRF spinoff, define specifications required to operate in the first two layers of the Open System Interconnection (OSI) reference model namely: the Physical Layer (PHY) and the Medium Access Control Layer (MAC) for network communication.

A Low Rate-Wireless Personal Area Network is basically a wireless sensor network used for wireless sensing applications such as environmental, medical, automotive and home network applications including such devices as wireless mouse and joysticks used in computer wireless games [2]. A Wireless sensor network is primarily a collection of battery operated sensor nodes used to perform sensing operations to measure physical parameters such as temperature, heat, vibration, humidity, and moisture content in the atmosphere. These sensor devices can be portable, moving or fixed based on the application. As certain ultra low bandwidth sensing wireless applications require large physical coverage, in my research I have proposed to interconnect independent IEEE 802.15.4 compliant clusters to form a large-network.

2.1 Research Summary

In this work, I propose a Slave/Slave bridging algorithm to perform inter-connection of IEEE 802.15.4 compliant WPAN clusters to cover larger physical spaces. Furthermore, I investigate the interactions among remote bridges, local bridges and local nodes under acknowledged and non-acknowledged packet transfers. The work is tested using simulation and the performance of the solution is evaluated.

2.2 Motivation

The goal of IEEE 802.15.4 is to provide a wireless standard for short range wireless personal area network applications, replacing the existing cable technology. Such network applications generate a large amount of traffic over a single medium of communication possibly resulting in packet loss. To overcome the existing low network efficiency, an idea is being proposed where a single network cluster is divided further into clusters that communicate over different communication media reducing the number of packet arrival over a single communication medium. Moreover, the range of the network physical space is further increased with satisfactory network performance.

Property	*Range*
Raw data rate	2-250 kb/s
Battery life	Application-dependent. Applications are optimized for long battery life
Latency	10-50 ms; or larger than 1 s
Nodes per network	Up to 65,534 (exact number to be determined)
Topology	Star and mesh
Complexity	Lower than current standards
Types of traffic	Asynchronous data-centric; option to support synchronous communication
Desired frequency band	Unlicensed and international band
Temperature	Industrial temperature range -40°to +85°C
Range	Typical 10 cm to 10 m or up to 100 m with trade-offs

Table 2.1: Characteristics of LR-WPAN according to [17]

2.3 Basic Description of the IEEE 802.15.4 Standard

IEEE 802.15.4 [1] is a wireless standard specifically designed for short range WPANs that provides low data rate, low cost, low power consumption and low complexity among battery-operated inexpensive devices. It is considered as an enabling technology for wireless sensor networks. Table 2.1 illustrates some of the characteristics of LR-WPAN.

Each WPAN consists of one central WPAN coordinator and many active slave devices. The IEEE 802.15.4 standard proposes two types of devices to be used in building an LR-WPAN network, Full Function Devices (FFDs) and Reduced Function Devices (RFDs). The central WPAN coordinator is a FFD and requires more resources to be functional. On the other hand, slave devices are RFDs and require less resources.

Based on the requirements of its applications, the IEEE 802.15.4 standard proposes two types of topologies for networks, the star topology and the peer-to-peer topology. In a star topology, slave devices can talk only to the central WPAN coordinator for communication. In the case of peer-to-peer topology, device-to-device communication is possible without using the central WPAN coordinator. In my research, to attain longer network life-time, a star-based topology is used, where the central WPAN coordinator is assumed to be powered by mains and plays a major role in relaying packets to the destination devices without any network life-time degradation. On the other hand, in a peer-to-peer topology, battery operated device nodes that relay packets may exhaust their battery power and will stop relaying packets after their death.

The standard allows three types of packet transmission rates. They are 20 kb/s, 40 kb/s and 250 kb/s in the frequency bands 868 MHz, 915 MHz and 2450 MHz respectively.

The IEEE 802.15.4 standard proposes two modes in which a LR-WPAN application can function, they are the Beacon enabled and Non-Beacon enabled modes. In my work, I consider only the beacon enabled mode for the network to function as the standard proposes more features in the case of beacon enabled mode.

In beacon enabled mode, channel time is divided into superframe structures by the respective central WPAN coordinator. Beacon transmission initiates the start of each superframe structure with active and (optional) inactive portions. The active portion of the superframe structure is further divided into a Contention Access Period (CAP) and a Contention Free Period (CFP). All communication takes place during the active portion of the superframe structure. The Beacon Interval (BI) is the time interval between two successive beacon transmissions and SD (superframe duration) is equivalent to the active portion of the superframe structure.

Each superframe structure is divided into 16 equally sized slots of 3*16 backoff periods. This 48 backoff period constitutes the shortest period in the active part of the superframe structure (*aBaseSuperframeDuration*).

The channel has a raw data rate of 250kbps (i.e *aUnitBackoffPeriod* of 10 bytes). The parameters Superframe Order (SO) and Beacon Order (BO) affect the overall length of the superframe using the following formula:

Superframe Duration (SD) = *aBaseSuperframeDuration* * 2^{SO}symbols

Beacon Interval (BI) = *aBaseSuperframeDuration* * 2^{BO} symbols

Where, *aBaseSuperframeDuration* = *aBaseSlotDuration* * *aNumSuperFrameSlots*

Figure 2.1 illustrates the structure of a superframe used in beacon enabled mode and Figure 2.4 illustrates the processing performed by the CSMA-CA algorithm.

The inactive period is determined as I = *aBaseSuperFrameDuration* * (2^{BO} -2^{SO}). During

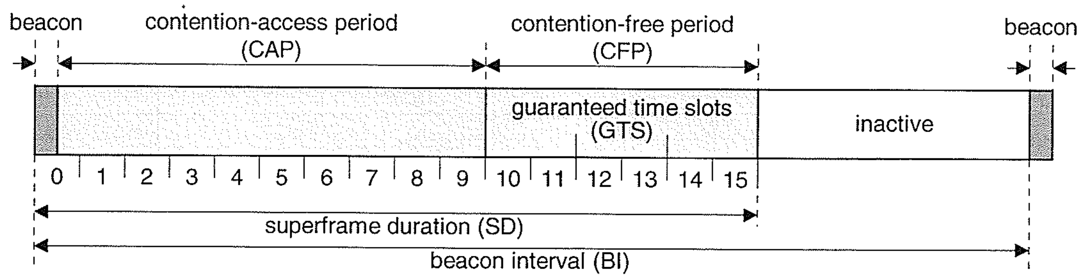


Figure 2.1: Superframe Structure [5]

this period, the device can enter into a sleeping mode if no communication is required.

There are two types of channel access mechanisms proposed by the existing IEEE 802.15.4 standard. They are slotted CSMA-CA and un-slotted CSMA-CA. In a slotted CSMA-CA channel access mechanism, channel time is divided into back-off slots. Every packet in the slotted CSMA-CA mechanism has to be aligned with the beacon signal for transmission.

In non-beacon enabled mode, no beacon is transmitted and data communication is performed using an un-slotted CSMA-CA mechanism. Each device node uses polling to send data to the central WPAN coordinator. The main drawback of this scheme is that, if the coordinator wants to send data to a device node, it has to wait for that device node to poll [7].

Two types of data communication exist in an IEEE 802.15.4 compliant network; uplink and downlink transmission. The uplink transmission includes the data flow from the device node to the central WPAN coordinator and the data request packets from the bridge to the central WPAN coordinator if there is any pending data for the respective bridge device. The downlink transmission includes the acknowledgment packet from the central coordinator for successfully received packets and the transmission of pending data from the central coordinator in reply to data requests from the bridge.

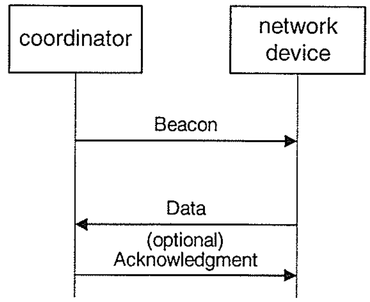


Figure 2.2: Uplink Transmission

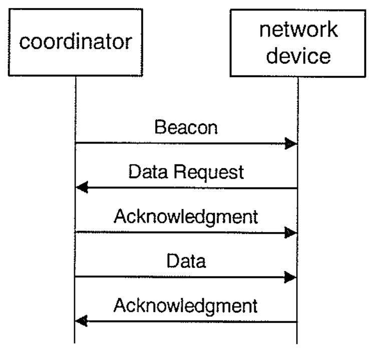


Figure 2.3: Downlink Transmission

2.4 The Slotted CSMA-CA Algorithm

The Slotted CSMA-CA algorithm is a channel access mechanism, where each data transmission is aligned with the boundary of a back-off period. Following are the activities performed during slotted CSMA-CA processing, namely backoff activity, Clear Channel Assessment(CCA), transmission of packets and (optional) receipt of acknowledgment. The following are the steps performed [1].

1. Every packet generated in a device has to locate the boundary of the back-off period before the actual transmission.

2. After locating the boundary of the back-off period, the device has to wait for a random

period before doing CCA. The random period depends on the value of BE (the back-off exponent). According to the IEEE 802.15.4 standard, the device can have up to 5 backoff transmission attempts with window sizes of 8, 16, 32, 32 and 32. The device has to wait for 2 CCAs to clear off the activities present in the channel before transmitting.

3. After the first CCA operation, if the medium is busy, the number of times (retry count) the CSMA-CA algorithm is used for channel access is incremented. The maximum retry count is 4 before giving a failure report.

4. After the second CCA, if the medium is idle, the device checks whether the remaining back-off period in the current Superframe is enough to perform 2 CCAs, to transmit data and to receive acknowledgment. If there is enough time, the device will start transmitting the packet. If the time is not enough for the above operation, the device waits until the start of the next Superframe for further transmission.

5. If the medium is busy, the device will start repeating the CCA operation by re-initializing the value of CCA to 2.

2.5 Overview of My Thesis

The rest of this thesis is organized as follows. In chapter 3 I review the literature related to IEEE 802.15.4 technology. In chapter 4, I present my proposed solution to address the problem of limited spatial extent faced by the existing standard. In chapter 5, I evaluate the performance of the proposed approach using simulation. In chapter 6, I validate my proposed simulated solution by comparing with the analytical model. In chapter 7, I present the simulator design. Finally, chapter 8 concludes my thesis.

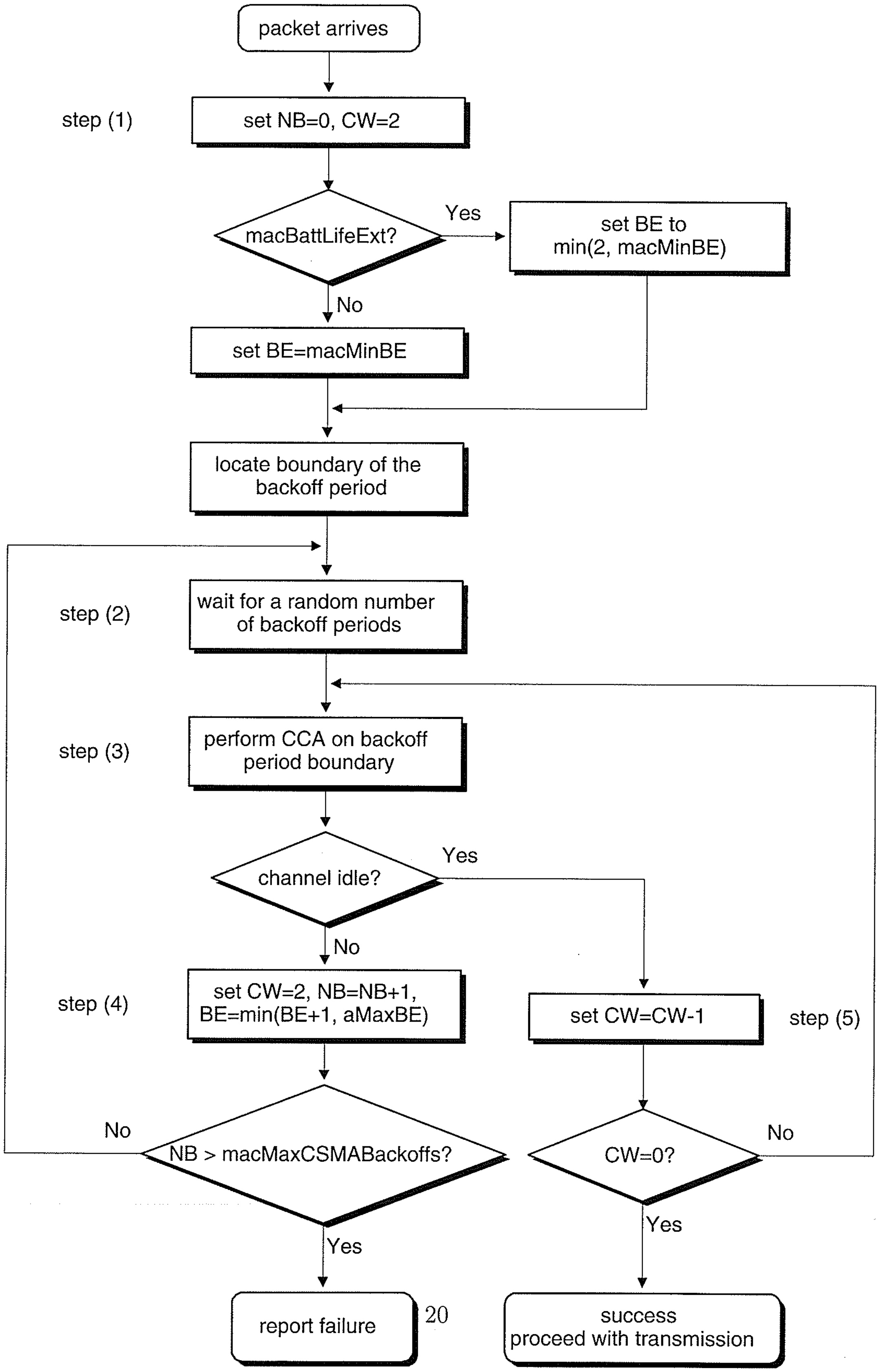


Figure 2.4: Slotted CSMA-CA [5]

Chapter 3

Literature Review

In recent years, Wireless Personal Area Networks (WPANs) have seen tremendous growth for short range wireless sensor applications in fields such as medical sensors, home sensors, industrial, vehicular and agricultural sensors, etc. Akyildiz [1] discuss the various concepts related to wireless sensor networks such as transmission media, communication, power consumption, etc as required by the wide range of sensor applications. Various factors such as flexibility and cost that affect the overall deployment of a sensor network are also discussed. In addition, the authors have also presented some of the current sensor research projects that work towards the advancement of the wireless sensor network technology. To address requirements such as limited throughput, low operation cost and limited power consumption for emerging WPANs, motivated researchers designed new wireless standards, which were not addressed in any of the wireless standards at that time. Three IEEE wireless standards have been built to enable short range wireless communications under WPANs. These include IEEE 802.15.1, IEEE 802.15.3 and IEEE 802.15.4 which were designed [17] for medium data rate, high data rate and low data rate applications, respectively. Zheng et al [13] presented some of the diverse applications that benefit from IEEE 802.15.4 technology to show its capability in the existing wireless world.

IEEE 802.15.4 WPAN [5] is a standard for low rate wireless personal area networks that supports small, cheap, energy-efficient devices operating on battery power which require little infrastructure to operate [5] [17]. IEEE 802.15.4 operates on the first two layers of the ISO-OSI model. This standard was designed by two research groups namely IEEE 802 Working group 15 and ZigBee (a HomeRF spinoff group). In comparison, ZigBee [8] is a standard for mesh networks built on top of the IEEE 802.15.4 WPAN standard to support low power, short range applications. ZigBee covers all the seven layers of the ISO-OSI model including the network, transport, session, presentation and application layers. In my work, I have designed and developed a bridge to increase the communication range by interconnecting two or more different IEEE 802.15.4 compliant WPANs that operate on the first two layers of the ZigBee standard. The standard completely defines the specifications of the MAC layer and PHY layer required for LR-WPANs.

Since IEEE 802.15.4 is a new developing standard, there is only limited literature that has been published. In 2001, the first paper was published by Gutierrez et al [17] who discussed system requirements and technical issues required for deploying IEEE 802.15.4 compliant wireless network applications. This paper addressed an issue faced by peer-to-peer network topology compliant wireless applications, which deploy extended networks in which control and synchronization of information traveling through multiple links is difficult. This leads to high power consumption.

In my work, I simulated extended networks using star topology, where it is easy to control and synchronize information, as the communication will always be directed towards the central WPAN coordinator which is assumed to be powered by AC lines.

During its initial development, Callaway et al [9] presented a draft of the IEEE 802.15.4 standard and further discussed in-home networking applications enabled by the standard. In their paper, the MAC layer and the PHY layer properties needed for deployment were discussed. Gutierrez et al [8] subsequently, reviewed the technical components of the IEEE

802.15.4 standard draft and further focused on the design and its implementation requirements.

In 2004, the first performance evaluation was done on IEEE 802.15.4 technology using the NS-2 [34] simulation system by Lu et al [15]. In this simulation, an IEEE 802.15.4 compliant star network was formed in beacon-enabled mode with channel access performed using CSMA-CA. Throughput, latency and delivery ratio for the above network were assessed.

Lee [16] conducted a real-time experiment to measure the performance of IEEE 802.15.4 by investigating parameters such as delivery ratio, throughput and received signal strength indication (RSSI). In this experiment, the network was arranged in a star shaped fashion with the coordinator in the center and all the other slave devices generating traffic towards the center.

Zheng et al [12] has done a comprehensive study on the performance of IEEE 802.15.4 using NS-2. In this work, experiments were conducted to study features like CSMA-CA channel access technique, Guaranteed Time Slot (GTS), beacon transmission and network formation. However, incorporating GTS in IEEE 802.15.4 compliant applications can be an expensive approach as most of the GTS slots allocated in the experiment are wasted. In addition, the performance of IEEE 802.11 technology was compared to the IEEE 802.15.4 standard.

Since LR-WPAN is an enabling technology, new applications have started being developed up using this technology. The medical field is one of the areas where LR-WPAN plays a vital role. Golmie et al [3] evaluated the performance of the IEEE 802.15.4 standard for wireless applications in the medical field. In this work, they have developed an interoperable and universal interface for medical equipments and concludes that IEEE 802.15.4 compliant devices from two different WPANs never causes interference when communicating in the same channel. Timmons and Scanlon [33] analyzed the performance of IEEE 802.15.4 for medical sensor body area applications. In this work, there objective is to have a long life-time of the battery without any replacement and concludes that network with non-beacon enabled devices provides only a limited solution to the body area network. They implemented a star

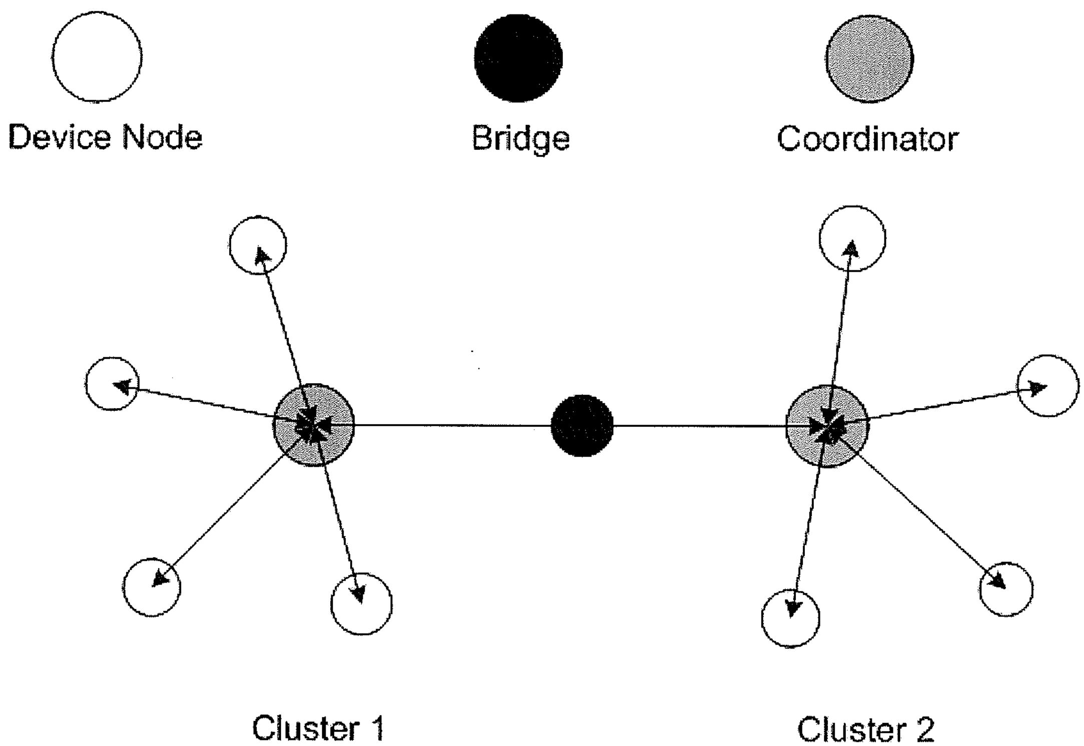


Figure 3.1: (a) Star Cluster Network

topology, where the coordinator stays outside the body connected to an external main for power supply. The coordinator controls and synchronizes the network.

In 2004, Mišić [30] designed an analytical model to analyze the performance of the IEEE 802.15.4 standard where performance parameters such as queue length distribution and access probability were measured. Some of the outcomes of the design include maximized access probability, minimized packet service time and a lower boundary blocking probability under favorable conditions.

Mišić et al [31] investigated the performance of an IEEE 802.15.4 compliant cluster in a beacon enabled mode. The simulations included both uplink and downlink packets. In this paper, authors considered both saturation and non-saturation regions during performance evaluation. The authors further identified a vulnerability in the IEEE 802.15.4 MAC definition that degrades its network performance. The paper concludes by comparing an analytical model with the simulation results for performance metrics such as throughput and access probability of a single cluster.

In addition, Park et al [29] proposed an analytical model for the IEEE 802.15.4 standard in a slotted enabled mode and validated the results using the NS-2 simulator. In addition, energy consumption and throughput were measured at saturation point.

Since power saving is one of the key objectives in LR-WPANs, a new power-saving algorithm called Beacon Order Adaptation Algorithm (BOAA) was developed by Neugebauer et al [26], where energy was saved by sacrificing delay in the network. This algorithm is suitable only for wireless applications, where packet delay is not an issue. Bougard et al [2] studied the performance of IEEE 802.15.4 in a dense wireless network and further proposed another power-saving algorithm to reduce the overall energy consumption of an IEEE 802.15.4 compliant wireless network in a wireless micro-sensor application.

In IEEE 802.15.4, power-saving techniques are used to limit energy consumption by devices. This can be achieved by putting them into sleep mode. Unfortunately, this may result in increased sleeping delay [14] in a high contention environment. To solve this issue, Kim et al [14] proposed a priority based algorithm to guarantee packet delivery on time in a more contention period by relaxing the sleep delay.

In another paper, the results show that increased power consumption is due to contention and acknowledgement overhead in the network. Bougard [2] proposed an "energy aware radio activation policy" that optimized MAC and PHY level protocols to achieve reduced power consumption. This eventually improved the lifetime of the self-powered IEEE 802.15.4

compliant wireless network.

Mišić et al [19] designed two algorithms for duty cycle management to achieve very high reliability with minimum utilization in an IEEE 802.15.4 compliant network. In these algorithms, the end nodes manage their sleeping time based on their cluster information. In one of the algorithms [19], "the sleep period is a geometrically distributed random variable with a given mean value"; on the other, "the sleep period is inversely proportional to the most recent duration of the packet service time".

Howitt et al [11] designed a new extended model for the existing energy-aware radio activation policy [2] designed by Bougard et al in a Low Rate WPAN, where the energy cost between operational states was taken into consideration. A comparative study was done to analyze the improvement made in this model to achieve better lifetime of the network.

Pang [25] proposed a new backoff scheme for IEEE 802.15.4 called memorized dynamic backoff. This dynamic backoff scheme showed better performance at higher loads. In their work, the size of the contention window dynamically changed based on the traffic load.

Yoo et al [4] have proposed a real-time message scheduling algorithm to enable GTS efficiently for scheduling real time messages during the optional superframe structure. Their proposed algorithm was evaluated using simulation. Further, GTS with the algorithm was deployed in a "prototype platform" [4] equipped with a transceiver for evaluation. In their simulation, schedulability of the real time messages was analyzed.

Recently, Kim et al [14] proposed two techniques to avoid additional delay caused by the periodic sleeping of the nodes and guaranteed delivery of packets in a high contention medium. The techniques were priority toning and frame tailoring. In the case of priority toning, high profile packets are given priority over other regular packets. Here, the nodes that generate high priority packets are allocated a part of the active period for transmission. In this technique, the contention is reduced by separating the transmission of high priority packets from the regular ones. On the other hand, frame tailoring avoids collision of data packets from their acknowledgment packets by allowing only one CCA for transmission. In this technique, the CCA overhead is reduced to half. Since, the data packet length determines the length of the acknowledgment frame, the length of the data packet has to be adjusted to keep the acknowledgment frame length to a minimum to enable priority data transmission in a high contention medium.

Mišić et al [10] proposed remedial measures to address the fact that IEEE 802.15.4 compliant networks are prone to security threats at the MAC layer. Some of the threats include spoofing, corruption of packets, and transmitting packets to the wrong destination. The authors have measured performance metrics such as success probability and mean packet delay at nodes to show the impact of security attacks and vulnerability at the MAC layer. Some of the proposed counter measures are a sequential freshness service, intrusion detection techniques and extending encryption even to packet headers to make it more difficult to breach.

In a recent project, a Master-Slave bridge has been built by, June Fung a Master's student from the department of computer science, for the IEEE 802.15.4 standard to achieve inter-cluster communication. In this algorithm, the central PAN coordinator of the source cluster acts as a bridge between the source and the sink cluster. By design, there is only one Master-Slave bridge in the cluster which might affect the performance of routing decisions. Also, Master-Slave bridge function integrated with the coordinator presents a single point of failure in the cluster. To date, no Slave/Slave bridge has been designed for 802.15.4 networks.

In the following sub-section, I review some of the earlier papers related to bridges built for wireless network extension. Since IEEE 802.15.4 is a fairly new standard, there was no published literature on bridges for network extension. Therefore, I present some of the published papers related to bridges, designed and built for Bluetooth technology, which is more or less similar.

3.1 Bridge Scheduling Policies

In this section, I present previous work related to bridging mechanisms for Bluetooth technology and contemporary IEEE 802.15.4 compliant bridging algorithms.

Recently, Misic et al have published a number of papers demonstrating the impact of bridging policies in Bluetooth scatternets:

1. Mišić [20] [23] analyzed the performance of Slave/Slave bridges for Bluetooth technology. In their work, they considered two scheduling policies namely, exhaustive and limited service scheduling policies. In the case of exhaustive scheduling policy, the device tries to send all the packets in its buffer before going to sleep and whereas in the case of limited scheduling policy the device tries to send a fixed number of packets before going to sleep. Further, they derived the probability distribution of end-to-end delay and access delay for both local and non-local packets.

2. Mišić [23] proposed an algorithm in a scatternet using a Master/Slave bridge to achieve minimum end-to-end delays for inter-piconet communication. In addition, they analyzed the effect of various parameters such as number of devices and packet arrival rate in the scatternet, on end-to-end delays.

3. Mišić et al [24] proposed two algorithms to achieve minimum end-to-end delays for packets in a scatternet with a Slave/Slave bridge in a Bluetooth network. In one of the algorithms, the resident time of the bridge was fixed and in the other, the resident time of the bridge changed based on the intensity of the non-local traffic. They conclusively proved that an adaptive algorithm with dynamic bridge residence time performed better than one with fixed bridge residence time.

Zhao et al [35] proposed a relayed wireless access network based on IEEE 802.11 to support real-time traffic in an extended network. The main feature of their work is that it supports multi-frequency relaying using a single radio and handles non-real time traffic. Moreover, they used a packet-scheduling algorithm for variable and constant bit rate traffic to support real-time traffic. In their work, relay stations use only minimal resources even when the load of the traffic was high to serve traffic bound between mobile stations and the relay station.

Recently, Mišić et al [7] proposed a bridging algorithm to achieve inter-cluster communication in an IEEE 802.15.4 compliant network. In this work, the central coordinator of the source cluster acts as a bridge by switching between the source and the destination cluster to perform inter-cluster communication. Communication is carried out using a slotted CSMA-CA channel access mechanism. Further, authors have investigated their bridging algorithm using theoretical analysis. The analysis shows that with low packet arrival rate and packet size, clusters can operate without any performance degradation.

Finally, Mišić et al [6] investigated and compared two channel access mechanisms, CSMA-CA and GTS for inter-cluster communication in an IEEE 802.15.4 compliant network. In both cases, the performance is better when the residence time of the bridge in the destination cluster is short.

Chapter 4

Solution Methodology

To address the limited physical area covered by IEEE 802.15.4 compliant clusters, it is necessary to interconnect IEEE 802.15.4 clusters to build large networks required for some sensing applications and this must be done while providing satisfactory network performance. Currently, the IEEE 802.15.4 standard does not address inter-cluster communication. In the standard, each cluster can exist with a large number of devices with in a short transmitter range which leads to network performance degradation. The focus of my research is to allow multiple 802.15.4 networks to be inter-connected via slave/slave bridging.

4.1 Inter-Cluster Communication

In my approach, all independent clusters are interconnected to form a large network by means of a bridge. The purpose of the bridge is to relay packets from one cluster to the adjacent neighboring clusters. I will use one of the ordinary devices (slave) to act as a bridge, with necessary functional changes. So, all adjacent IEEE 802.15.4 clusters are interconnected in a Slave/Slave fashion. Thus the bridge is referred to as slave/slave bridge. There are two transmissions constitute bridging operation, namely uplink and downlink transmissions.

4.2 Bridging Algorithm

Consider two independent clusters operated in a beacon enabled CSMA-CA mode, interconnected by means of a slave/slave bridge as shown in Figure 3.1. The scenario considers one of the clusters as the source and the other as the sink cluster. In this network, all the traffic originated in the source cluster has to be relayed to the adjacent sink cluster using the intermediate slave/slave bridge. This traffic is also known as non-local packets. To perform the above operation, the bridge has to move back and forth between the two clusters on a time-division basis. In the source cluster, all the local devices transmit packets to the central source coordinator using CSMA-CA. The local packets received by the coordinator are further transmitted to the bridge using downlink transmission by the coordinator [21] [22].

To receive data packets from the coordinator, the coordinator has to first advertise the received packets in the beacon transmission. It can advertise a maximum of 7 devices in a beacon frame. We assume that the coordinator advertises in a round-robin scheme if the number of pending data packets exceeds 7. In my scheme, the coordinator advertises only the bridge MAC address for the pending downlink data. Upon receiving the advertisement, the concerned slave/slave bridge transmits a data request packet for the pending data packet in the downlink buffer at the coordinator. Every uplink data request packet is acknowledged by the coordinator. Following the acknowledgment, the bridge waits for a period of *aMaxFrameResponseTime* (1220 symbols) to receive the downlink data packet. If the downlink packet is not received successfully, the bridge will not acknowledge it. In that case, the coordinator has to repeat packet advertisement, and the request packet has to be re-sent, acknowledged and followed by repeated downlink transmission. Finally, all successful downlink packets are acknowledged by the slave/slave bridge.

Downlink packet transmission is achieved using slotted CSMA-CA. According to the standard, the downlink can be performed without CSMA-CA if the transmission is able to start between *aTurnaroundTime* (12 symbols) and *aUnitBackoffPeriod* + *aTurnaroundTime* and has enough time for packet inter-frame spacing and acknowledgment. This transmission without CSMA-CA leads to network performance degradation causing increased packet collision. In my scheme, I assume every transmission is done using CSMA-CA. All transmissions take place during the active portion of the superframe structure (48 backoff periods). If there are any further downlink packets pending at the coordinator, the bridge sends a new data request packet prior to the downlink transmission. Figure 2.3 illustrates the downlink transmission cycle as discussed in Section 2.

In my scheme, I assume that the slave/slave bridge stays in each cluster for a period of one superframe and the clusters will have the same fixed beacon interval BI. The clusters operate in different frequency channels and hence have insignificant interference. Each channel has a raw data rate of 250kbps i.e *aUnitBackoffPeriod* of 10 bytes, *aBaseSlotDuration* of 30 bytes. To be a part of the cluster, the bridge should first listen to the beacon transmission from the concerned coordinator. The time taken by the bridge to receive beacon frames from the respective clusters is known as the synchronization time. The bridge stays in each cluster for a period of one superframe and this is known as the bridge residence time. The bridge moves back and forth on a time-division basis as shown in Figure 4.1 and Figure 4.2. The bridge starts its stay with the source cluster. After the source bridge residence time, the bridge moves to its adjacent sink cluster to deliver all its packets to the sink coordinator. When the bridge's buffer transmits all its packets successfully within the allocated remote bridge residence time, the bridge moves back to its source cluster for further collection. If the bridge was unable to send all its packets within the bridge residence time, it freezes the current back-off counter and resumes sending in the next bridge residence time in the sink cluster. In the sink cluster, the bridge competes with other local uplink data transfers for successful transmission.

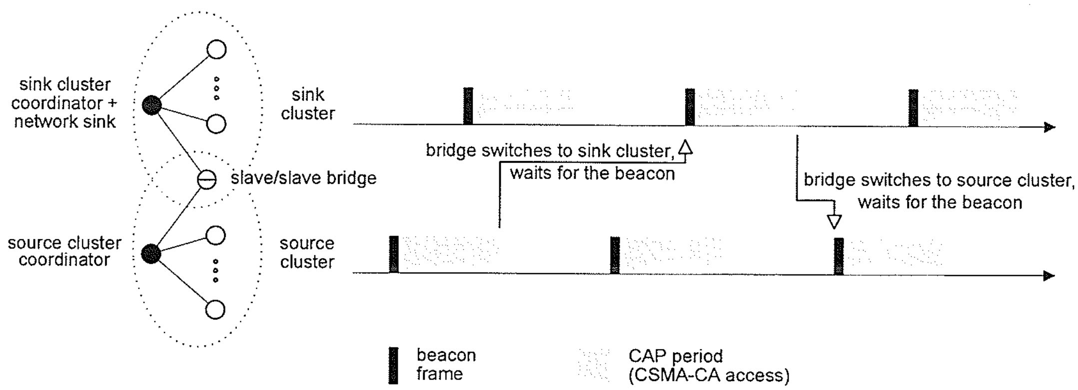


Figure 4.1: Bridge Switching [28]

In the above figure, there are three states in which the source and the sink coordinator can be in. The first state is the beacon transmitting state, at which the coordinator transmits beacon frames to advertise pending data and to synchronize all slave devices under one central coordinator. The second state is the listening state where the coordinator listens to the uplink data packets from the regular slave nodes and data request packets from the bridge. Finally, the coordinator can be in the packet transmitting state at which the coordinator transmits downlink data packets to the bridge after receiving the necessary data request packets.

Similarly, the following are the states the bridge and the regular devices can be in for the source and the sink cluster. In the source cluster, the regular devices and the bridge device can be in the packet transmitting state and request packet transmitting state. The bridge device can also be in the uplink request synchronization state and waiting state for the downlink data. In addition, regular slave devices can be in the idle state during which no uplink and downlink transmissions takes place. In the case of sink cluster, both the bridge and the regular slave devices can be in the packet transmitting state. Figure 4.3 illustrates the interactions between the slave/slave bridge, slave nodes and the coordinator in the source and the sink clusters.

In my work, I considered both acknowledged and non-acknowledged transmissions. In the

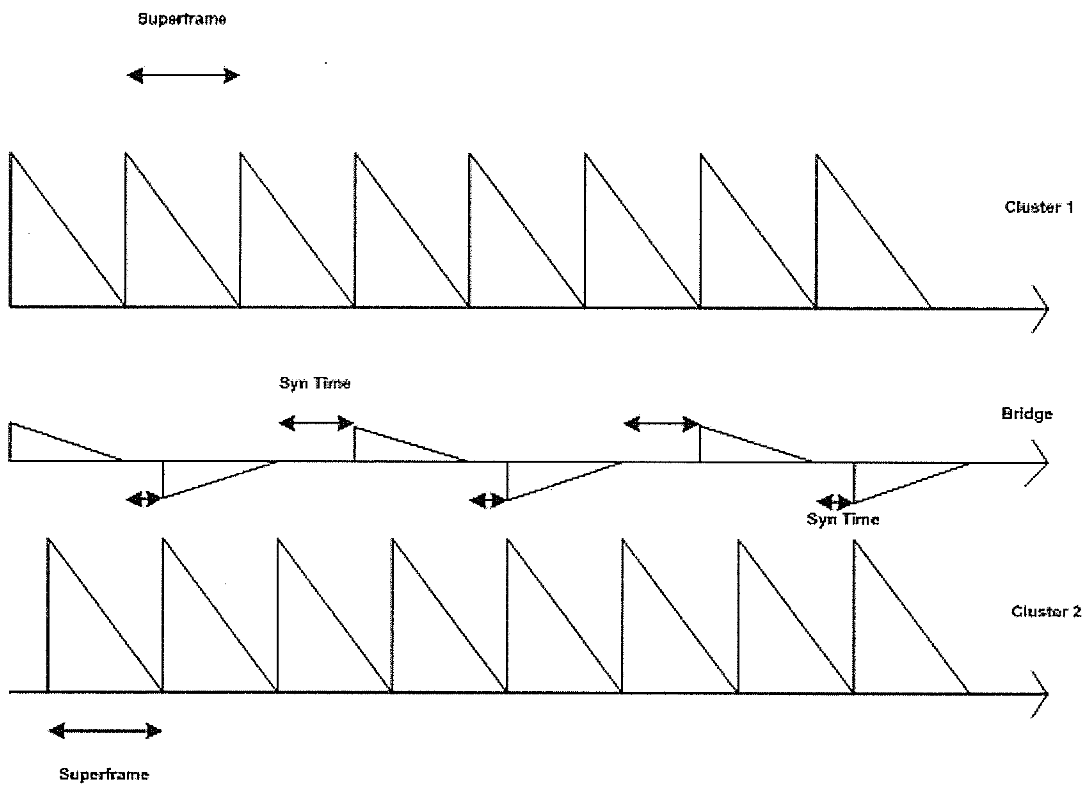


Figure 4.2: Timing of the SS bridge's presence in source and sink cluster [22]

case of acknowledged transfer, all transmissions must receive acknowledgement. This eventually increases the load on the network. There are conditions during which the destination device may fail to acknowledge a transmitted packet. They are as follows:

1. The destination device fails to acknowledge a transmitted packet when it fails to enter a full buffer.

2. The destination device fails to acknowledge a transmitted packet that is involved in a collision or is discarded due to noise at the transmission medium.

3. The destination device fails to acknowledge a transmitted packet if it is not received within the standard, prescribed time.

In such cases, the source device repeats its packet transmission until it gets acknowledged by the destination device.

No transmission gets acknowledged by the destination device. This significantly reduces the load of the traffic in the network. However, the data request packet from the bridge to the coordinator is worth getting acknowledged before the downlink operation. Therefore, no data packet is acknowledged and retransmitted when it is involved in a collision, is blocked or discarded during transmission.

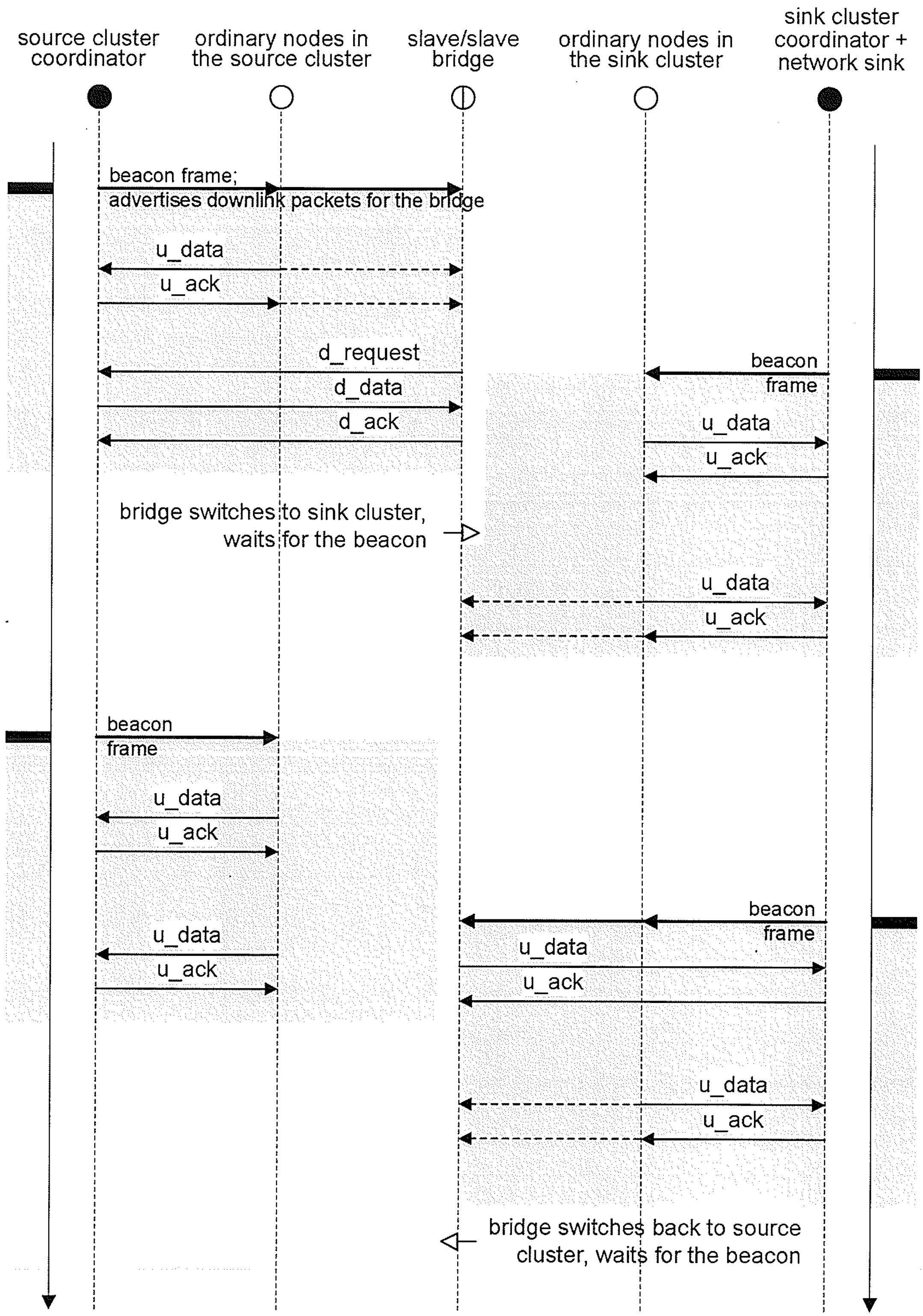


Figure 4.3: Bridging Algorithm [28]

Chapter 5

Performance Evaluation

In this section, I assess my strategy for two network designs. In the first case, I consider an array of three independent clusters 5.1 interconnected by means of a slave/slave bridge and in the second case I consider a 2-dimensional network with six clusters 5.8. Following are the performance metrics measured in my simulation design: probability that the medium is idle in the first CCA (alfa), probability that the medium is idle in the second CCA (beta), successful transmission (gama) and throughput (Th).

5.1 Assumptions

The following are the assumptions made in my performance evaluation:

1. The slave device is already selected through inter-device communication [1][2] to act as a bridge between the source and sink WPAN.

2. Only slave devices are allowed to generate packets, while the bridge and the master device are allowed to relay traffic towards the destination.

3. Slave devices generate packets that follow a negative exponential distribution with a given packet arrival rate (lambda).

4. There are an equal number of slave devices in the source, middle and the sink cluster of an array type of network.

5. According to the standard, the concept of piggybacking [3] is used to send data packets from the coordinator to the device after receiving a data request along with the acknowledgment. In this case, no CSMA-CA is used to access the channel. In some cases, data packets from the coordinator will be sent using CSMA-CA, when there is in sufficient time in the CAP for the transmission or not enough time for the inter-frame spacing and acknowledgment. In my research, I consider only CSMA-CA for all downlink transmissions from the coordinator.

5.2 Small Network Test

Figure 5.1 illustrates an array type of network setup where the source and the sink clusters are interconnected by means of a middle cluster using bridges in a slave/slave fashion. Every packet generated in the source and the middle cluster has to reach the sink cluster. The packet in the source cluster takes exactly 5 hops to reach the sink coordinator. The hops include both the uplink and the downlink transmissions.

All transmissions take place using slotted CSMA-CA. The example network was built using a simulator called Artifex developed and designed by RSoft Design, Inc. The clusters in the network operate in the ISM band using three different channels. They have a raw data rate of 250 kbps (i.e aBaseSlotDuration of 30 bytes and aUnitBackoff Period of 10 bytes). Each cluster contains an equal number of devices varying between 5 and 30. The arrival rate

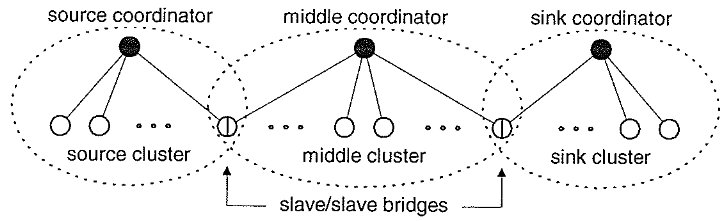


Figure 5.1: Network under evaluation

of packets in each slave device ranges between 80 packets/min and 280 packets/min. The size of the data packet and the data request packet are 3 and 2 backoff periods respectively. The buffer size of the slave device and the bridge are 3 and 6 packets respectively.

The size of the superframe in all three clusters is determined by the value of SO and BO. In this scenario, the values of SO and BO are 0 and 1, respectively, and hence aNumSuperframeSlots is 16 and aBaseSuperframeDuration is 480 bytes. In addition, macMinBE and aMaxBE, denoting the minimum and maximum backoff exponent, have values of 3 and 5.

The bridge resides in each cluster (source and foreign) for the same superframe period (48 backoffs). As discussed earlier, the bridge relays packets from the source to the sink cluster through the intermediate cluster. Two bridges exist in this network scenario. Bridge 1 relays packets from the source to the middle cluster and bridge 2 relays packets from the middle to the sink cluster. A bridge will become a part of a particular cluster only when it is able to sense the beacon signal transmitted by the respective cluster. Each bridge uses performs CSMA-CA to access the channel for transmission, like other regular slave devices. Further every successful transmission is acknowledged by the respective destination device.

Performance metrics including the probability of success for the first CCA, the probability of success for the second CCA, the probability of successful transmission and throughput are measured. To get a clear picture about the device and the bridge's behavior, I have examined the channel activity for data and data request packets separately.

Figures 5.2 and 5.3 illustrate the channel activity and throughput for the devices in the source cluster. The difference in behavior shown by data and data request packets in the source cluster is due to the following reasons:

1. Data request packets will have their first backoff count immediately following the beacon frame with the size of the window being 8. Data packets will have their first backoff count anywhere during the active part of the superframe structure.

2. Data request packets escape most of the collisions if the value of backoff is 0 or 1.

3. There is a possibility of data request packets colliding with data packets that were unable to complete their transmission in their previous superframe structure. Because, certain transmissions will be postponed to the next superframe structure when the current superframe structure is unable to allocate time for the current transmission.

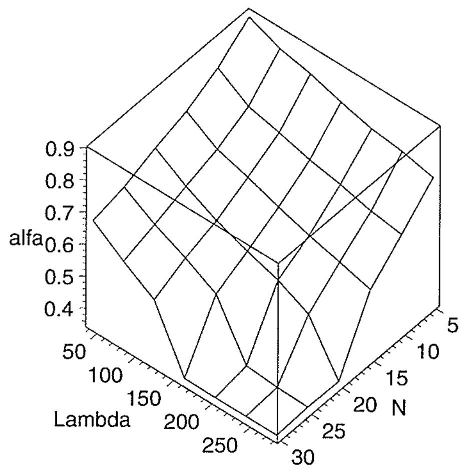
Downlink transmission occurs immediately after the uplink data request packet and, in the best possible case, takes place somewhere between the 25^{th} and 30^{th} backoff periods in the superframe structure. If not successfully transmitted in the allocated 61 backoff periods, the downlink process has to be restarted again from advertising the downlink pending data by the beacon frame.

Although every successful uplink data packet transmission is followed by a data request packet, the throughput of the data request packets falls behind the throughput of the uplink data packet for the following two reasons:

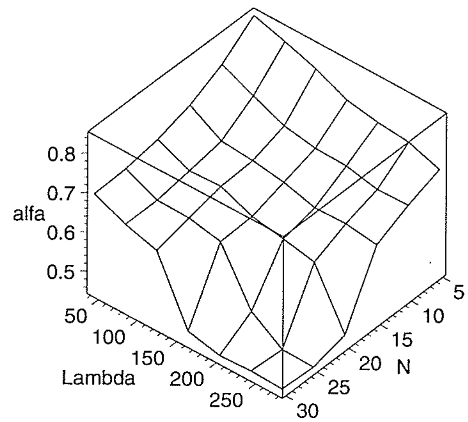
1. When the bridge buffer is full, the bridge stops sending data request packets to the coordinator for the remaining pending data packets.

2. In the middle cluster, due to the repeated retransmission of the data request packets from bridge 2, bridge 1 is unable to perform efficiently under high traffic load. Whereas, the uplink data packets in the source cluster will be completely unaffected by the high load condition in the source cluster.

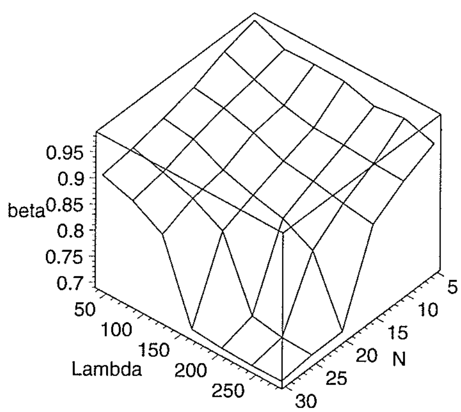
In the case of the middle cluster, I present the behavior of channel activity separately for the case of data packets from bridge 1, data request packets from bridge 2 and the local



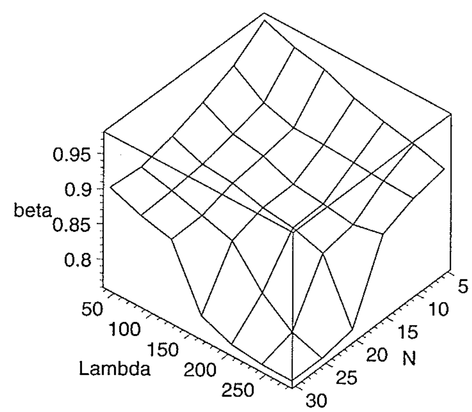
(a) First CCA for device node



(b) First CCA of Request Packets

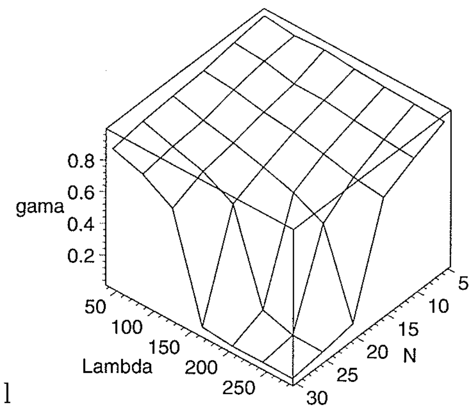


(c) Second CCA for device node

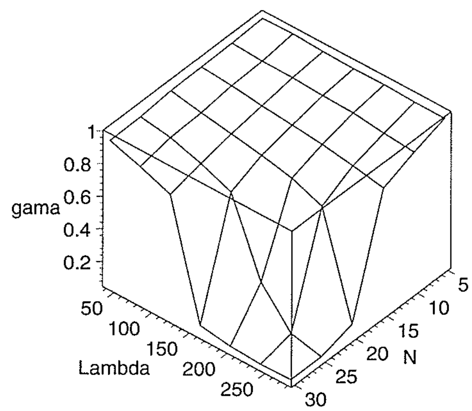


(d) Second CCA of Request Packets

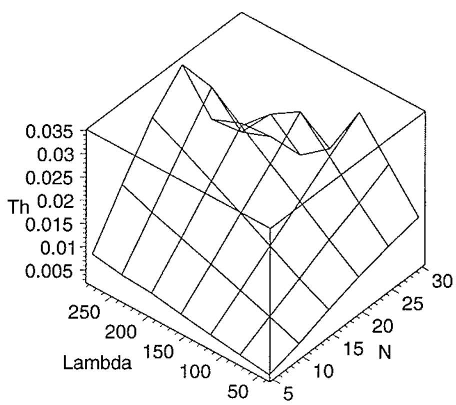
Figure 5.2: Probability of success of first and second CCA in the source cluster.



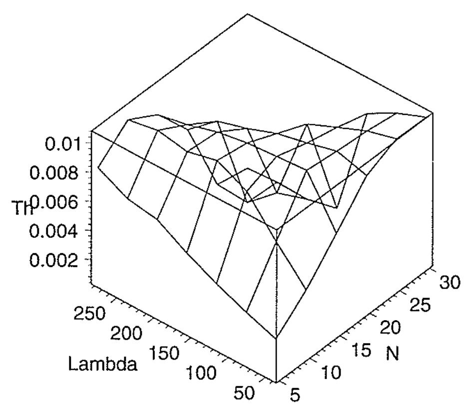
(a) Successful Transmission for source nodes



(b) Successful Transmission of Request Packets

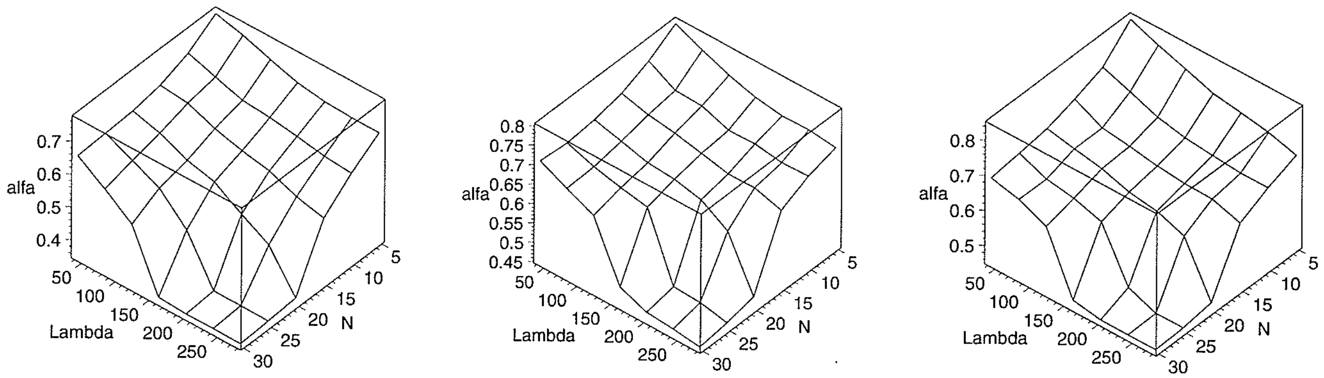


(c)Throughput for source nodes

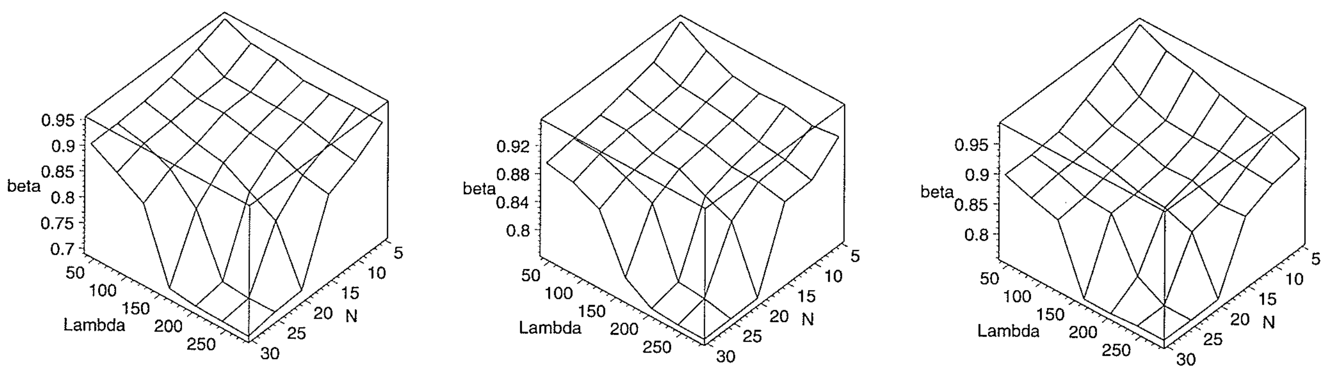


(d)Throughput of Request Packets

Figure 5.3: Probability of successful transmission and throughput in the source cluster

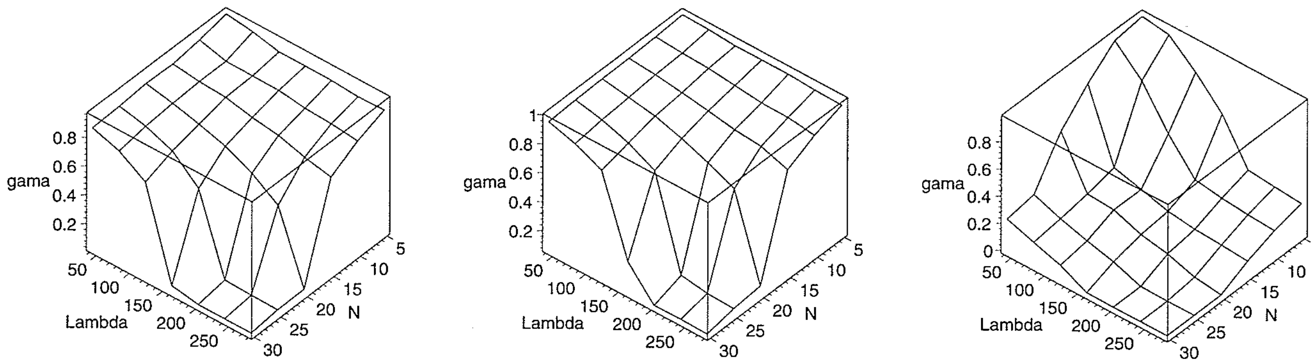


(a) First CCA for Device node (b) First CCA of Request packets (c) First CCA of Downlink packet

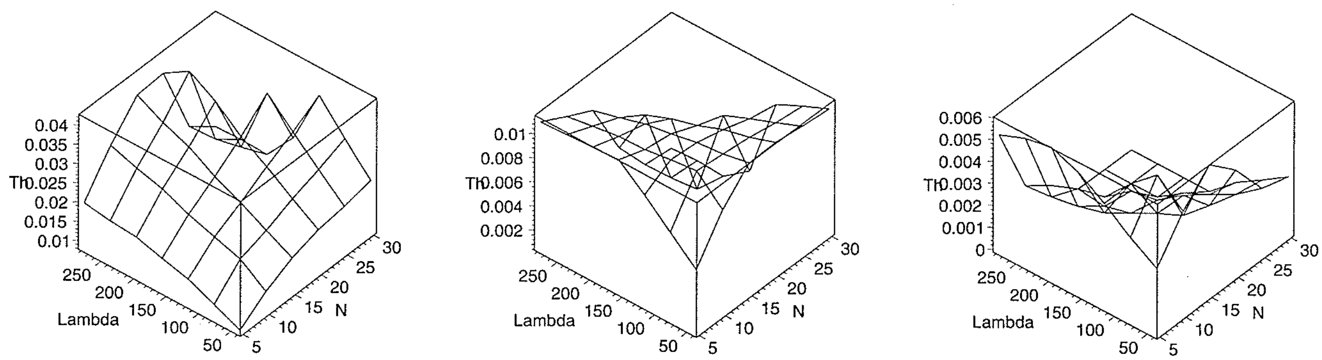


d) Sec CCA for Device node (e) Sec CCA of Request packets (f) Sec CCA of Downlink packet

Figure 5.4: Probability of success of first and second CCA in the middle cluster

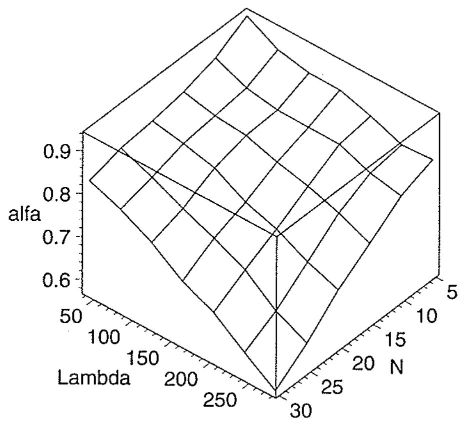


(a) Succ.Trans for Device node (b) Succ.Trans of Request packet (c) Succ.Trans of Downlink packet

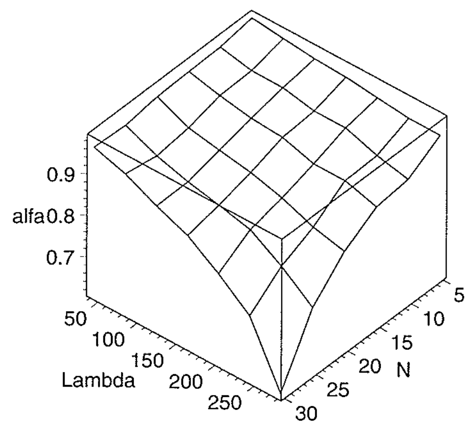


(d) Thru for Device node (e) Thru of Request packets (f) Thru of Downlink pack

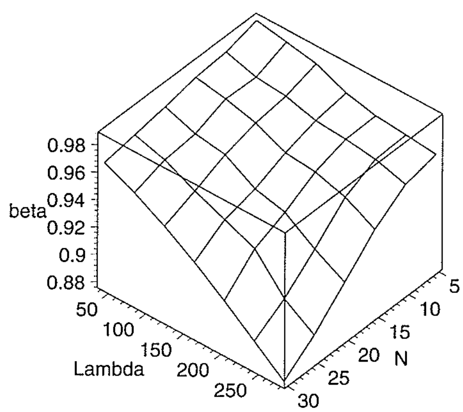
Figure 5.5: Probability of successful transmission (Succ.Trans) and Throughput (Thru) in middle cluster



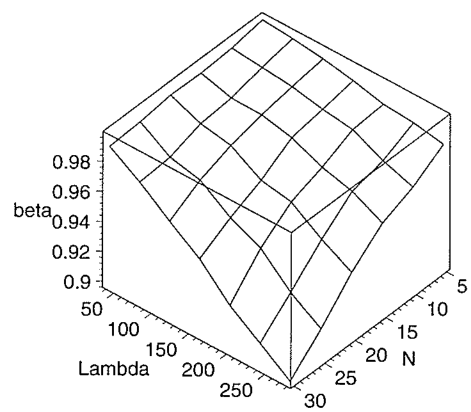
(a) First CCA for source node



(b) First CCA of Downlink Transmission

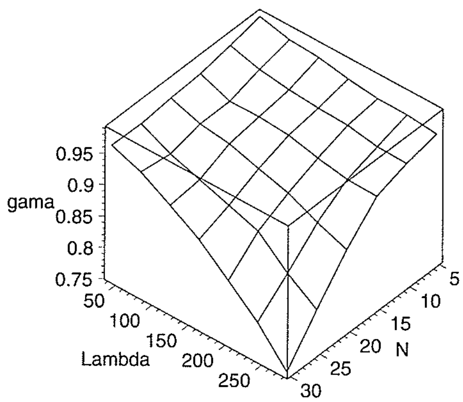


(c) Sec.CCA for source node

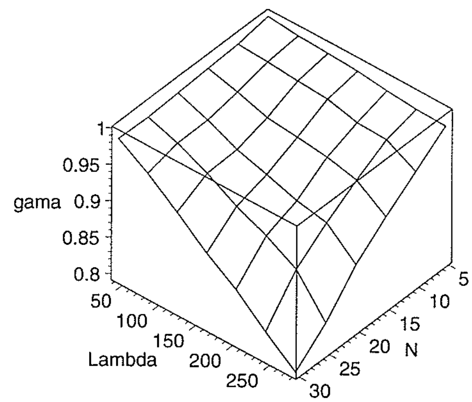


(d)Sec.CCA of Downlink Transmission

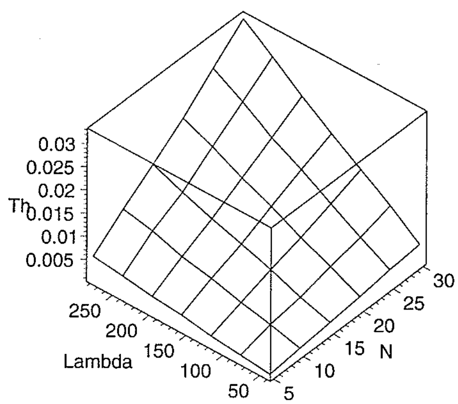
Figure 5.6: Probability that first and second CCA is successful in the sink cluster



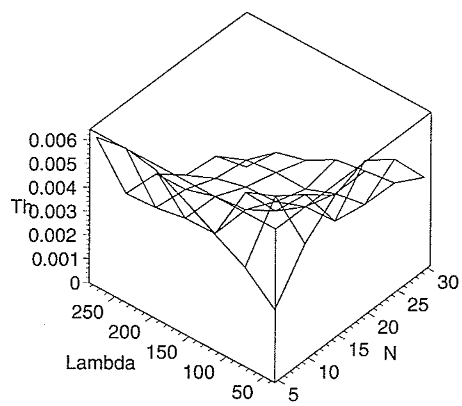
(a) Successful Transmission for source nodes



(b) Successful Transmission of Bridge Packets



(c) Throughput for source nodes



(d) Throughput of Bridge Packets

Figure 5.7: Probability of successful transmission and throughput in the sink cluster

uplink data packets as shown in Figure 5.4 and Figure 5.5. Among the three clusters, the middle cluster has the most congested medium. This is due to the presence of both local and non-local traffic. The throughput in the source and the middle cluster shows almost the same behavioral pattern. However, the middle cluster reaches deep saturation with high load condition and more devices.

The throughput of the data request packets by bridge 2 is twice the throughput of data request packets transmitted by bridge 1 in the source cluster under low load condition. As the load increases, bridge 2 shows a decrease in throughput as more packets get dropped due to a full buffer. As a result, the throughput of the local uplink packet in the sink cluster was not affected, as shown in Figure 5.6 and Figure 5.7.

5.3 Large Network Test

In this case, I consider a triangular network with 6 clusters interconnected by means of slave-slave bridges as shown in Figure 5.8. The 6 clusters include 3 source clusters, 2 middle clusters and 1 sink cluster at the vertex. In this network, I consider two cases, with acknowledgment and without acknowledgment of data transfers.

5.3.1 Case 1: Acknowledged Transfers

This example network will have the same control parameters and assumptions as the previous "array" structured network. However, the bridge buffer size and the packet arrival rate are different than in the previous experiment. In this experiment, the bridge buffer size is 20 packets and the packet arrival rate is varied between 40 packets/min and 280 packets/min. Figure 5.9 and Figure 5.10 illustrate the behavior of the medium and the throughput of each different packet class in the source cluster. The source clusters 1 and 3 show similar behavior to the source cluster from the previous "array" network. The middle source cluster

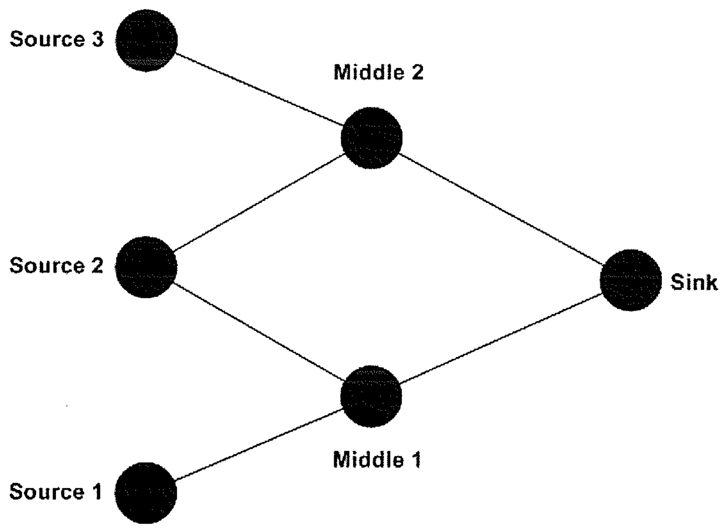


Figure 5.8: Network under evaluation [28]

2 in Figure 5.8 consists of two slave/slave bridges. The purpose of the two bridges is to divide the total outgoing traffic from cluster 2 to the two different middle clusters (Middle 1 and Middle 2). This achieves load balancing between the two available packet routes to the sink cluster. Unlike source cluster 1 and cluster 3, the middle source cluster was loaded with more data request traffic generated by the two slave-slave bridges. Hence, the middle cluster reaches saturation earlier than source clusters 1 and 3. In all three source clusters, the throughput of downlink data packets shows better results and does not contribute to the congestion identified after the beacon frame. Therefore, throughput steadily increases for the case of data packets until the medium is congested with too many packets. Eventually, there was a sharp drop in throughput under high load conditions.

In the case of the middle clusters, non-local data packets from two bridges compete with one another in the initial part of the superframe structure after the beacon. Thus too many packets collide under high load conditions. Under medium load, the local uplink packets from the slave devices get suppressed by the non-local packets from two bridges as is shown in Figures 5.11 through 5.15.

In the case of the sink clusters, the local packets do not get affected by the non-local packets from the two bridges under high load condition as is shown in Figures 5.16 and 5.17. This is due to the following two reasons:

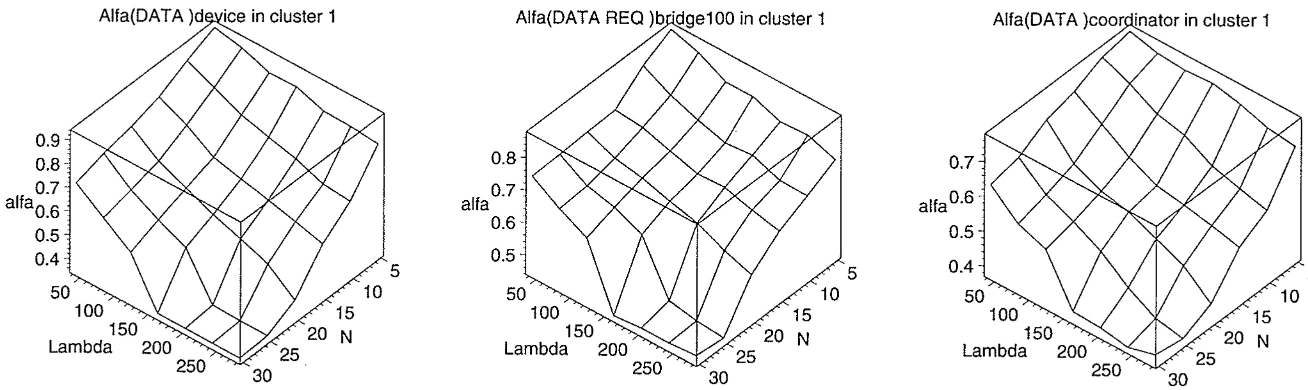
1. There are no data request packets and downlink transmission in the sink cluster.

2. The bridges bring only a small number of non-local packets into the sink cluster as more packets collide in the source and the middle clusters.

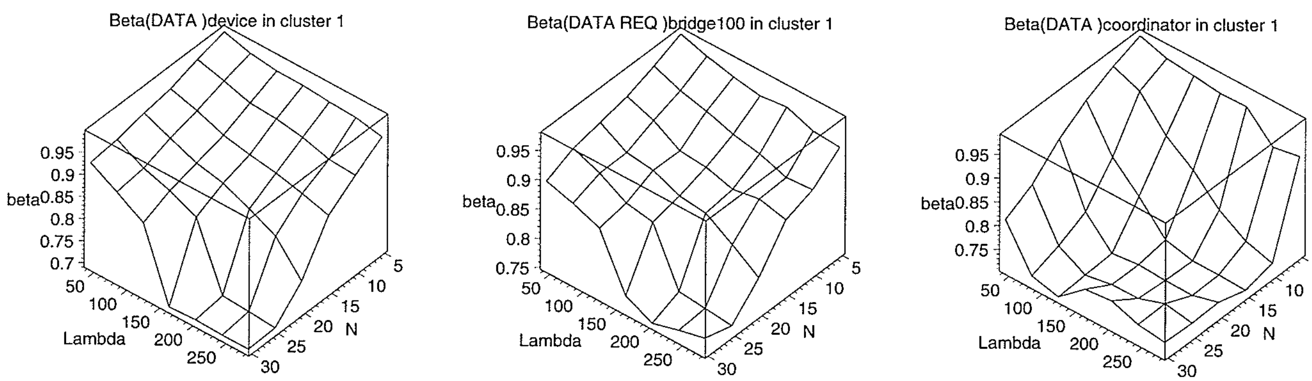
Thus, the slave/slave bridging scheme shows poor performance under high load conditions. Therefore, I conclude that a bridge with GTS might performs better in relaying packets than my slave-slave bridge.

The middle cluster 'middle 1', gets data from source cluster 1 and half of the data from the source cluster 2 via its bridges. Remote bridges from source clusters behave as ordinary nodes and attempt uplink transmissions. A middle cluster also collects its local data. Remote and local data are transferred to the outgoing bridge towards the sink cluster. Therefore there is contention among uplink transmissions from N ordinary nodes, two remote bridges (from source clusters 1 and 2 in the example), request packets issued by the outgoing bridge and downlink transmissions from the coordinator towards the outgoing bridge. Transmission medium view for all these participants in the transmissions is shown in Figures 5.11, 5.12, 5.13, 5.14 and 5.15. Comparing the figures, we observe that local traffic in the middle clusters is totally suppressed by the activities from the bridges. This can be alleviated by using non-acknowledged transfer or by using GTS slots for remote bridge access.

In the sink cluster there is contention among two remote bridges coming from midle clusters 1 and 2 and N ordinary nodes. To illustrate this effect, we present the transmission medium view for local nodes in the sink cluster (Figure 5.16) and for the remote bridge coming from the middle cluster 1 (Figure 5.17). Throughput of the local packets in the sink cluster is not affected because:

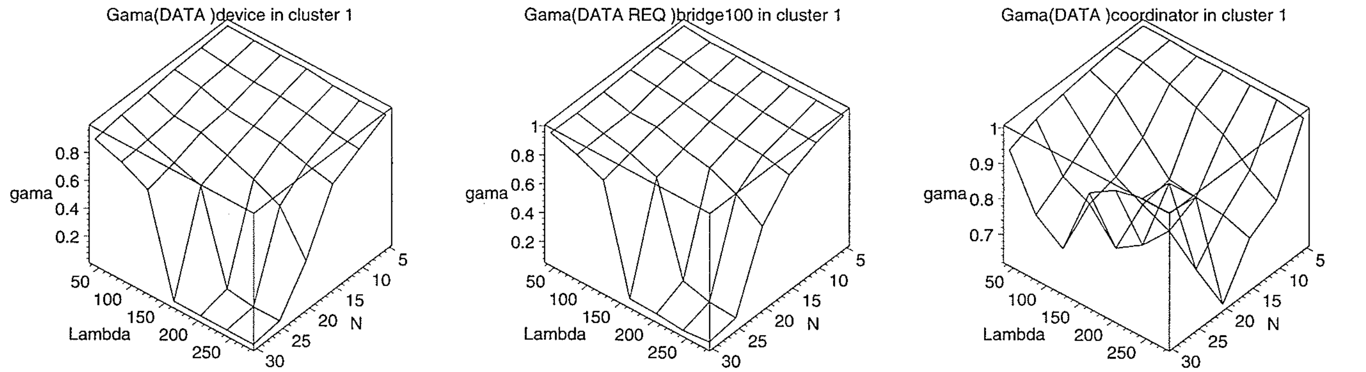


(a) First CCA for Device node (b) First CCA of Request packets (c) First CCA of Downlink packet

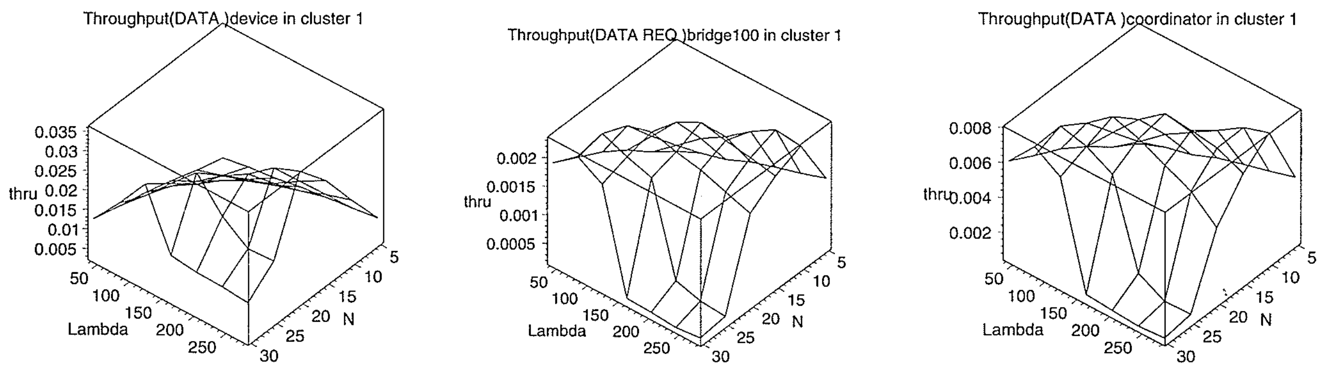


(c) Sec CCA for Device node (d) Sec CCA of Request packets (e) Sec CCA of Downlink packet

Figure 5.9: Probability of success of first and second CCA in the source cluster

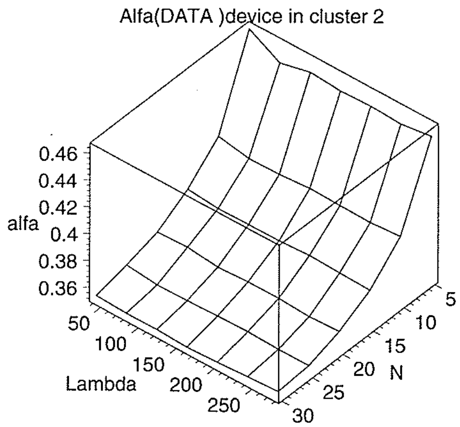


(a) Succ.Trans for Device node (b) Succ.Trans of Request packet (c) Succ.Trans of Downlink packet

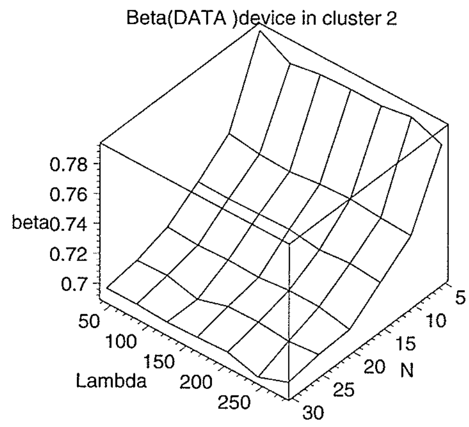


(c) Thru for Device node (d) Thru of Request packet (e) Thru of Downlink packet

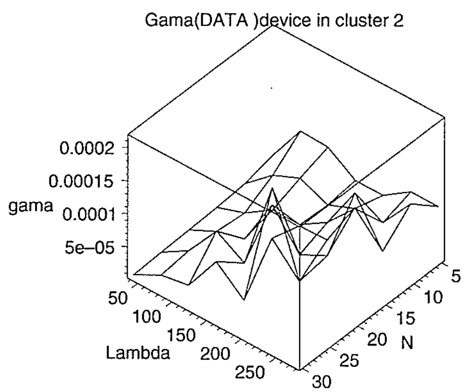
Figure 5.10: Transmission success probabilities (Succ.Trans) and Throughput (Thru) in the source cluster



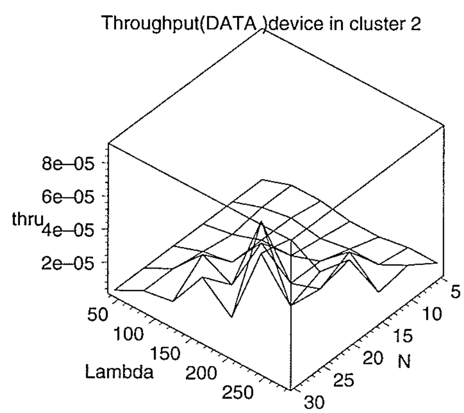
(a) First CCA for device node



(b) Second CCA for device node

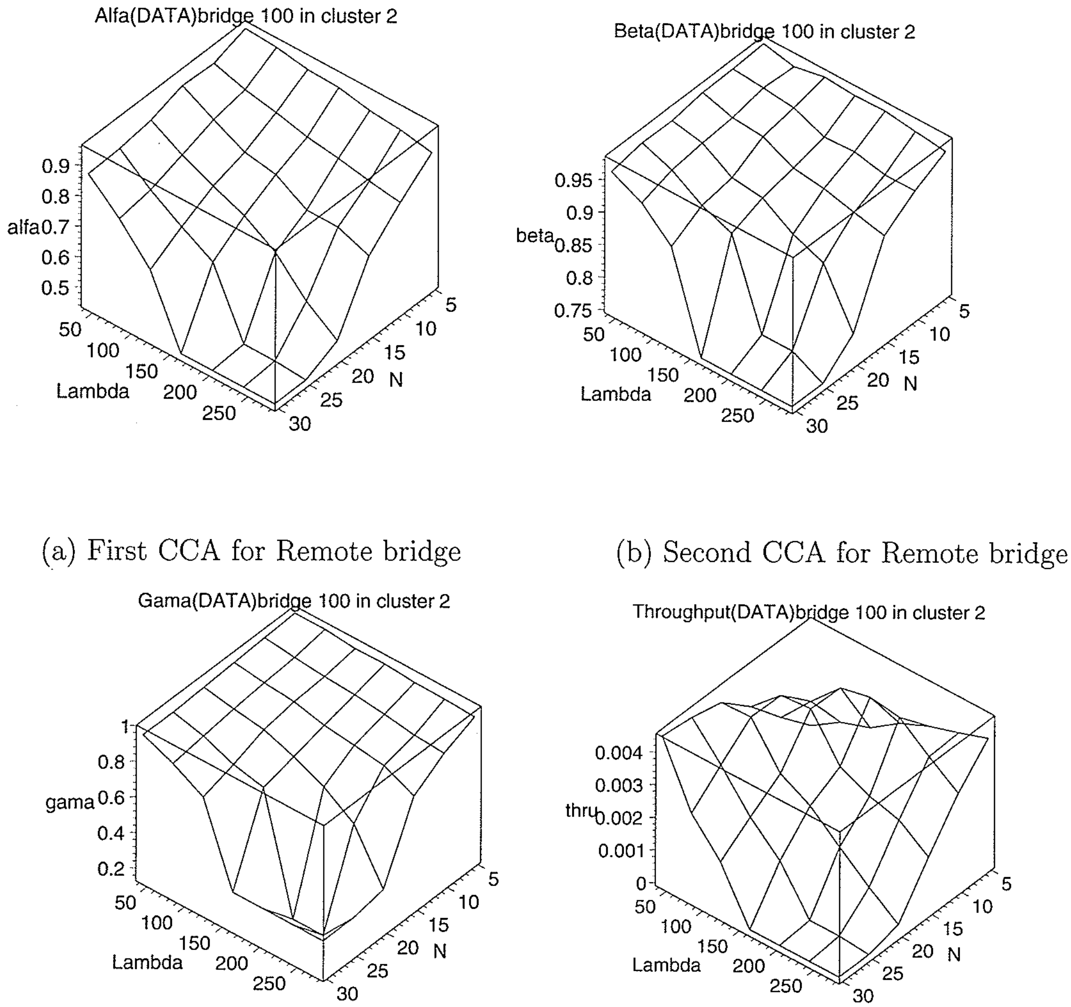


(c) Succ.Trans for device node



(d) Throughput for device node

Figure 5.11: Medium view for device node in the middle cluster



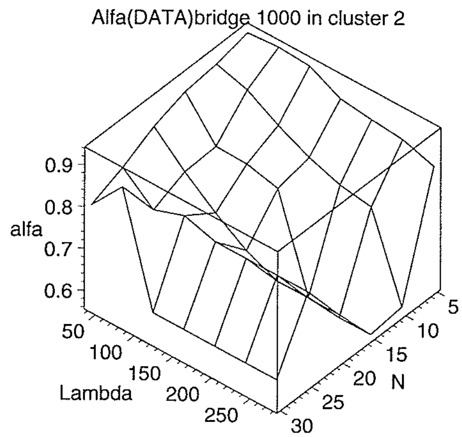
(a) First CCA for Remote bridge

(b) Second CCA for Remote bridge

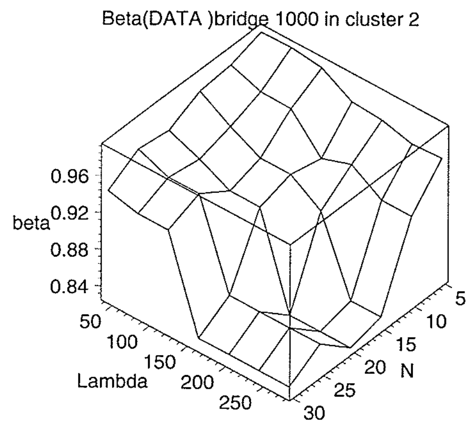
(c) Succ.Trans for Remote bridge

(d) Throughput for Remote bridge

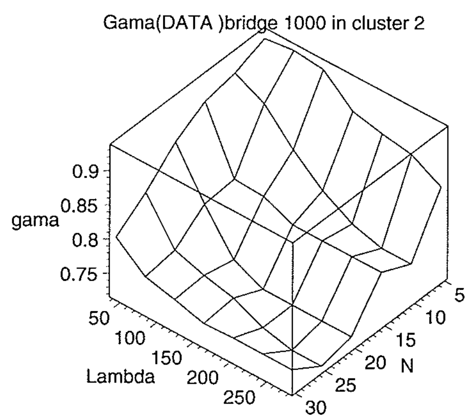
Figure 5.12: Medium view for remote bridge coming from source cluster 1



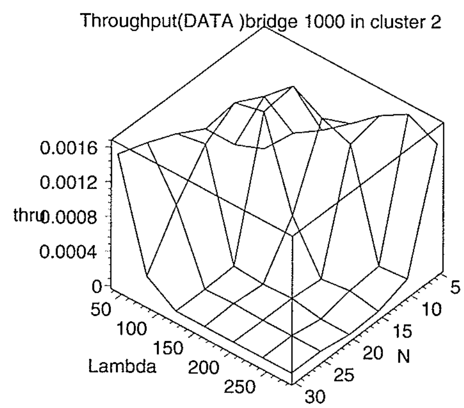
(a) First CCA for Remote bridge



(b) Second CCA for Remote bridge

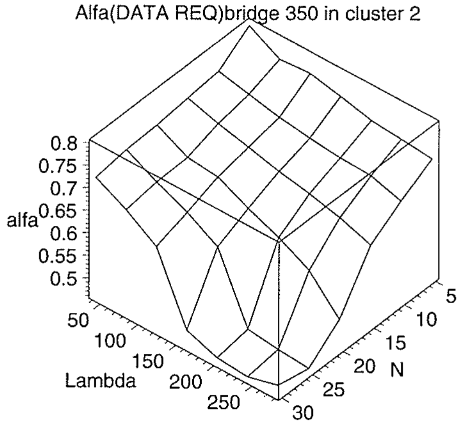


(c) Succ.Trans for Remote bridge

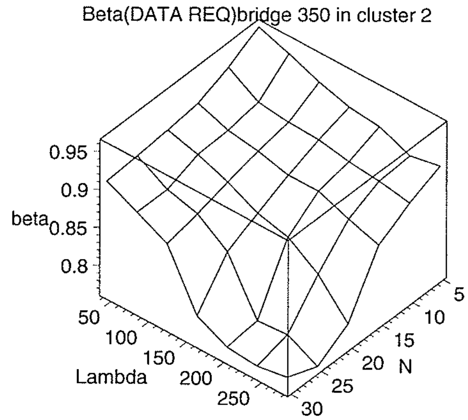


(d) Throughput for Remote bridge

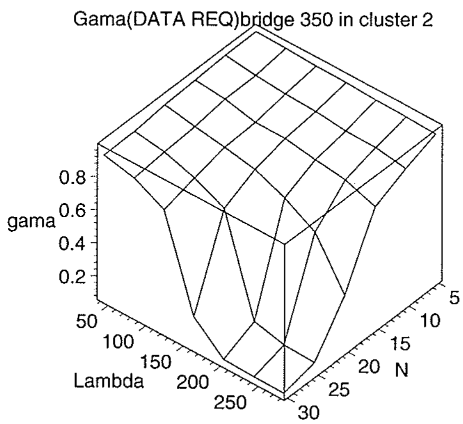
Figure 5.13: Medium view for remote bridge coming from source cluster 3



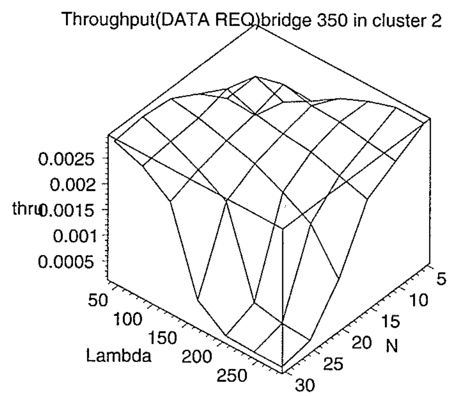
(a) First CCA of Request packet



(b) Second CCA of Request Packet

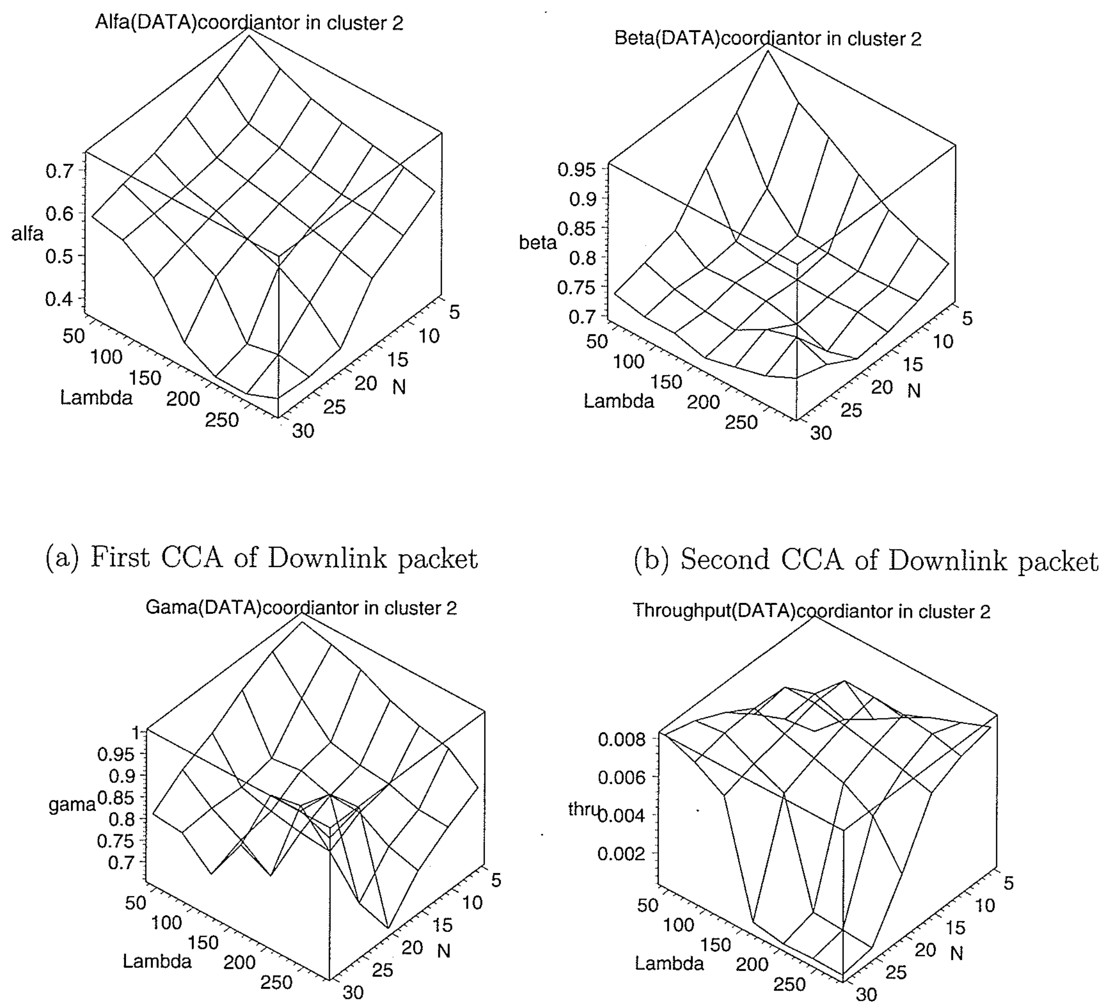


(c) Succ.Trans of Request packet



(d) Throughput of Request Packet

Figure 5.14: Medium view (in the middle cluster) for uplink request packets issued by the outgoing bridge towards the sink cluster



(a) First CCA of Downlink packet

(b) Second CCA of Downlink packet

(c)Succ.Trans of Downlink packet

(d) Throughput of Downlink packet

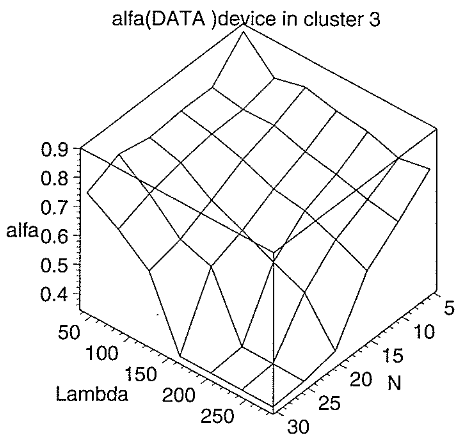
Figure 5.15: Medium view for coordinator in the middle cluster which loads the outgoing bridge towards the sink cluster

1. There are no request and downlink packets.

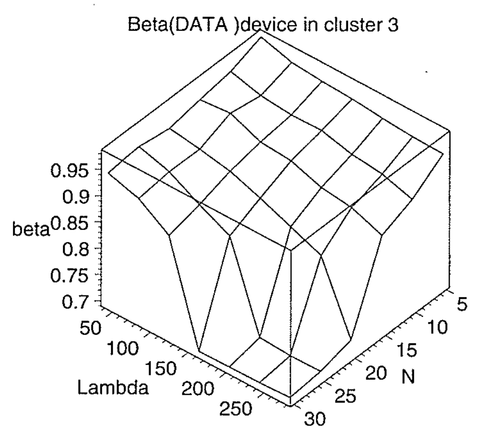
2. Remote bridges bring less data under higher data rates due to contention in the source and middle clusters.

5.3.2 Case 2: Non-Acknowledged Transfer

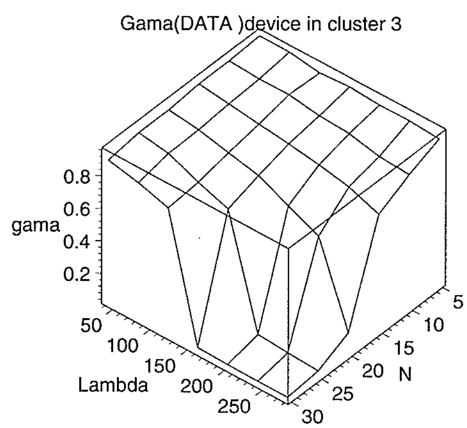
In the case of non-acknowledged transfers, successful transmissions are not acknowledged by the destination device except for data request packets from the bridge to the coordinator, which are worth acknowledging. This experiment used a similar type of triangular network except for the bridge buffer which was changed to a size of 10 and the packet arrival rate which was varied between 50 packets/min and 300 packets/min. The throughput of various packet classes shows better results compared to the throughput measured during transmission with acknowledgment as more packets gets transmitted within a unit time. The load of the traffic in each cluster is significantly reduced. However, the behavioral pattern does not change much, for example, the throughput increases with increase in packet arrival rate and number of devices in each cluster, as shown in Figures 5.18through 5.23. From my simulation study, I have shown that the slave/slave bridge gives better performance in the case of non-acknowledgment under moderate and high load conditions than with acknowledgment. Networks without acknowledgment are suitable for wireless sensor applications where the reliability of the network is not critical.



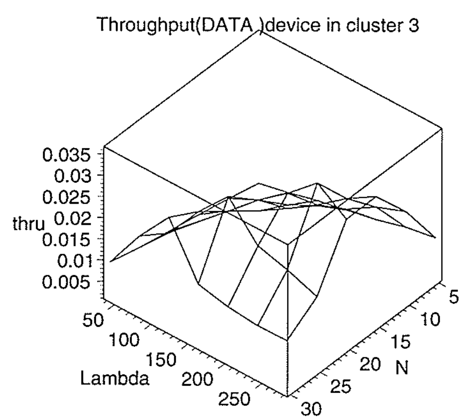
(a) First CCA for Device node



(b) Second CCA for Device node

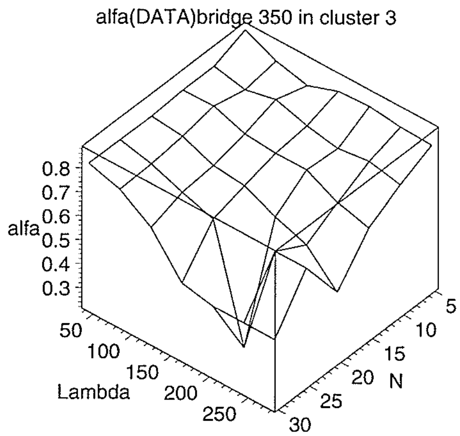


(c) Succ.Trans for Device node

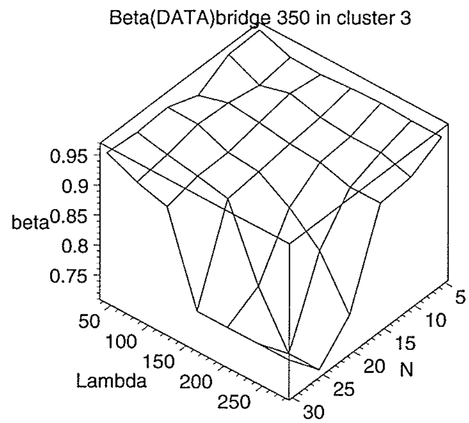


(d) Throughput for Device node

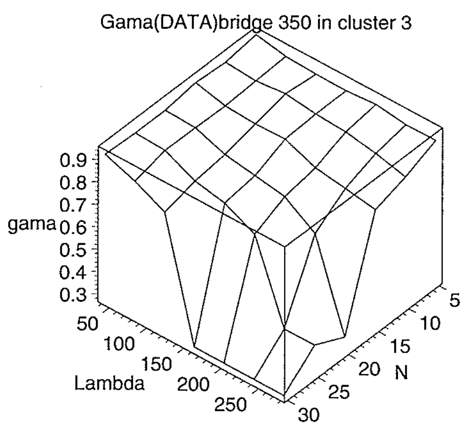
Figure 5.16: Medium view for device node in sink cluster



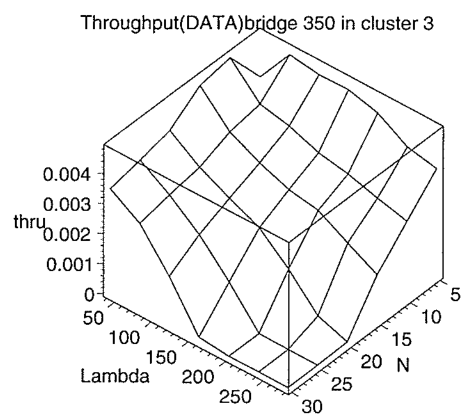
(a) First CCA for Remote bridge



(b) Second CCA for Remote bridge

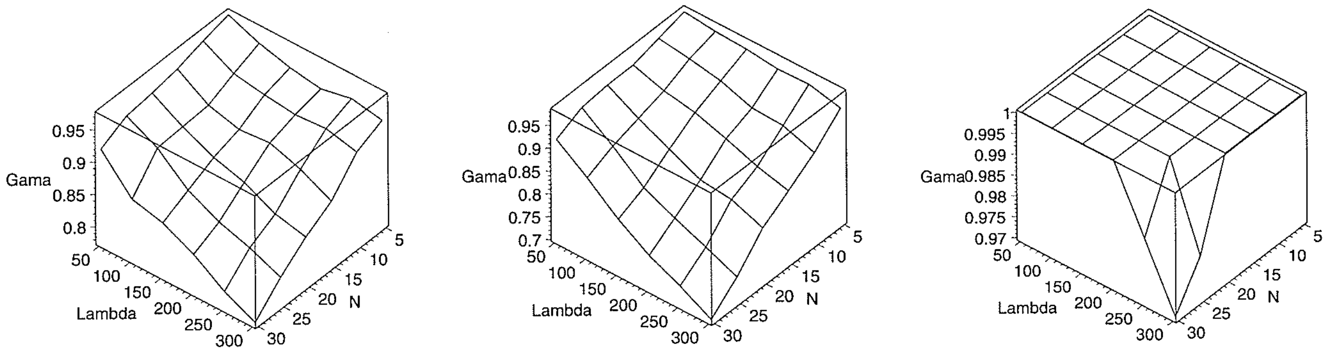


(c) Succ.Trans for Remote bridge



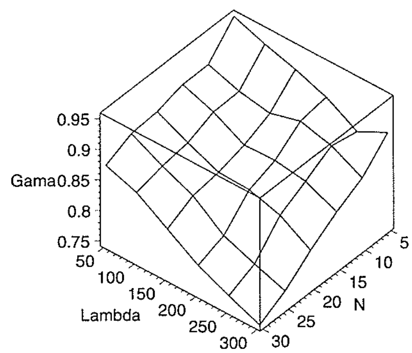
(d) Throughput for Remote bridge

Figure 5.17: Medium view for remote bridge coming from middle cluster 1 in sink cluster

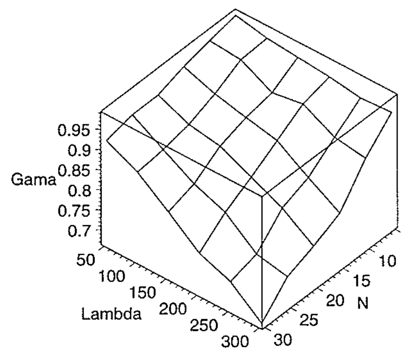


(a) Succ.Trans for Device node (b) Succ.Trans of Request packet (c) Succ.Trans of Downlink packet

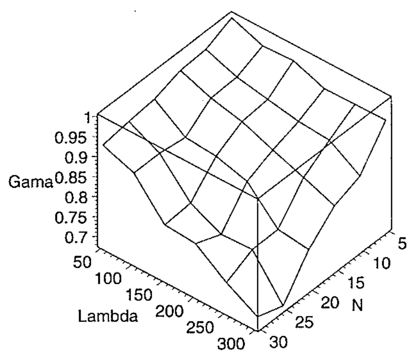
Figure 5.18: Transmission success probabilities in the source cluster



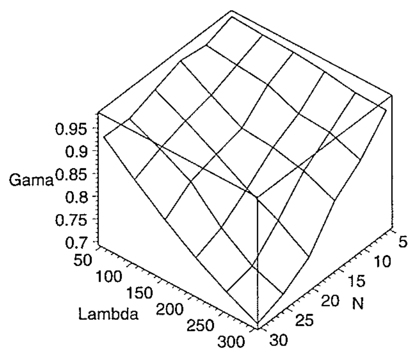
(a) Succ.Trans for Device node



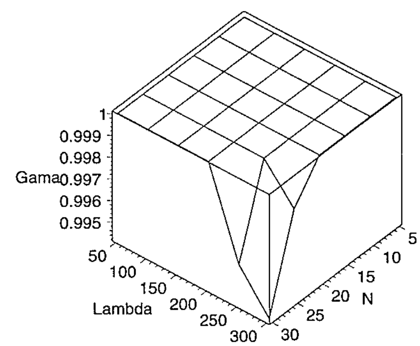
(b) Succ.Trans of Src 1 packet



(c) Succ.Trans of Src 3 packets

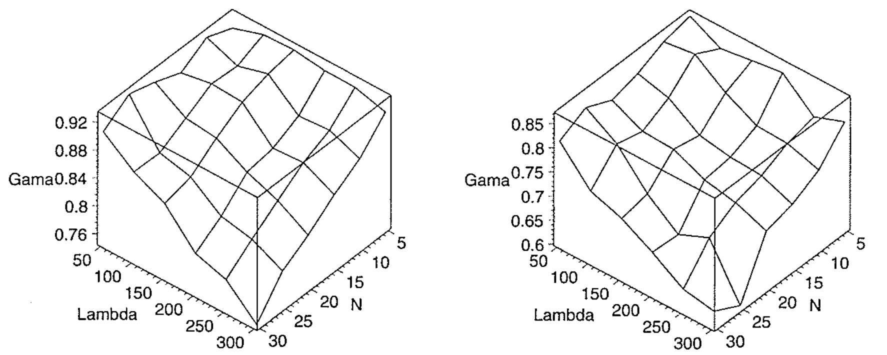


(d) Succ.Trans of Request packet



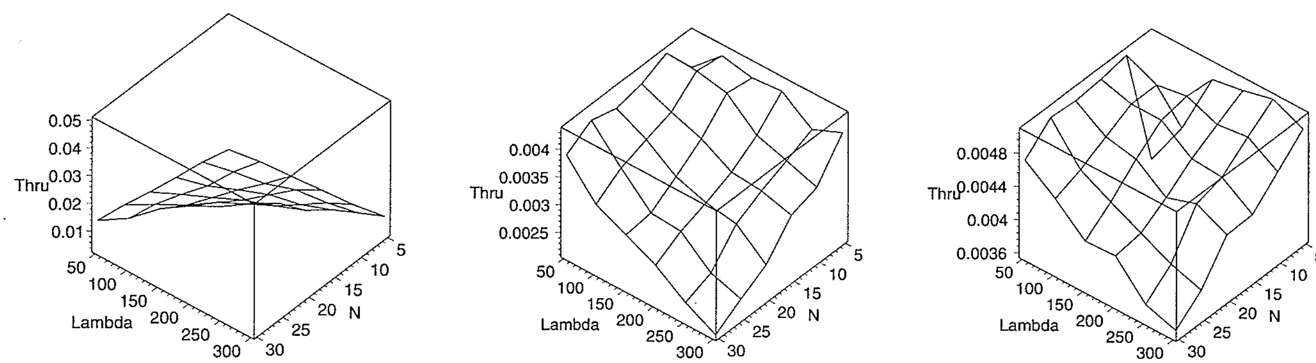
(e) Succ.Trans of Downlink packet

Figure 5.19: Transmission success probabilities in middle cluster



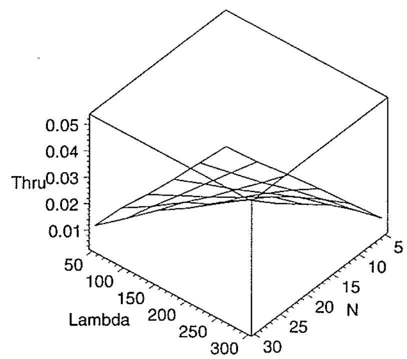
(a) Succ.Trans for Device node (b) Succ.Trans of Mid 2 packet

Figure 5.20: Transmission success probabilities in sink cluster

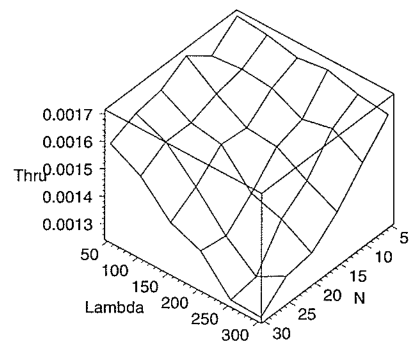


(c) Thrughput for Device node (d) Throughput of Request packet (e) Throughput of Downlink

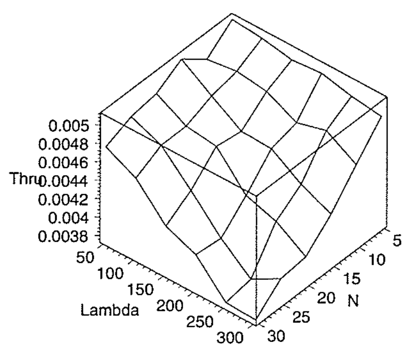
Figure 5.21: Throughputs in source cluster



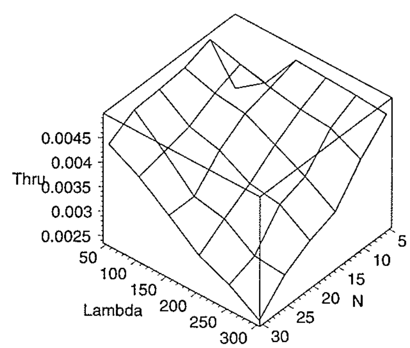
(a) Throughput for Device node



(b) Throughput of Request packet

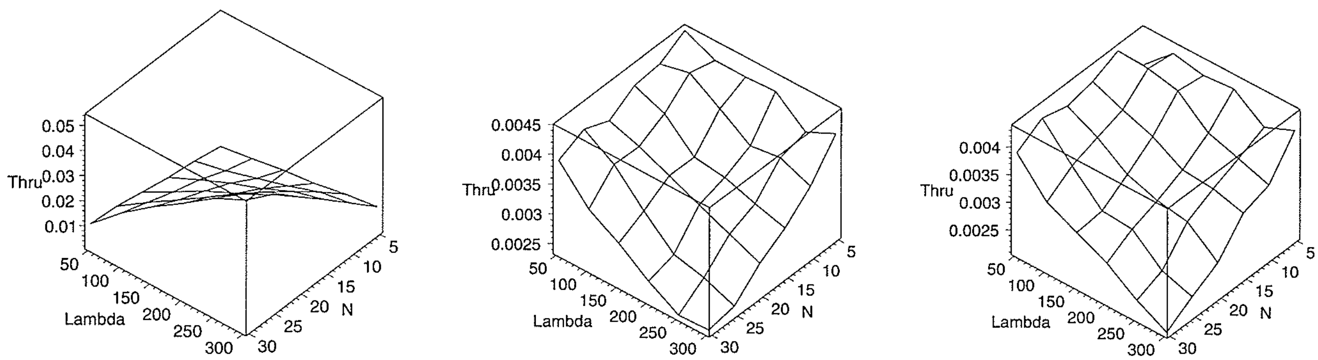


(c) Throughput of Downlink packet



(d) Throughput of Src 1 packet

Figure 5.22: Throughputs in middle cluster:



(a) Throughput for Device node (b) Throughput of Mid 1 packet (c) Throughput of Mid 2 packet

Figure 5.23: Throughputs in the sink cluster

Chapter 6

Validation of Simulation Results

Validation of simulation results was carried out in the final phase of my implementation. Since IEEE 802.15.4 is an enabling technology, we cannot provide exact input parameters unless we come to know the real purpose of an application and its necessary inputs.

Since reaching a steady state condition precludes the generation of results, the initial warm-up simulation results were not be included as part of the regular simulation runs. This warm-up period removal diminishes the effect of the initial conditions on the final result. This was ascertained by using a moving average method to determine transient interval. In each experimental replication with different seeds for random variables, simulation runs were done "until the mean response narrowed to a desired width"[27][25]. Figure 6 presents the transient interval removal of the simulation in the case of downlink transmission.

By varying the window size, a steady state was attained around 37,000 backoffs in the simulation runs. Throughput of the downlink traffic was measured using the above method in the case of the source cluster to remove the warmup period from the final results.

According to the analytical results [18] designed by Mišić for slave-slave bridging, results

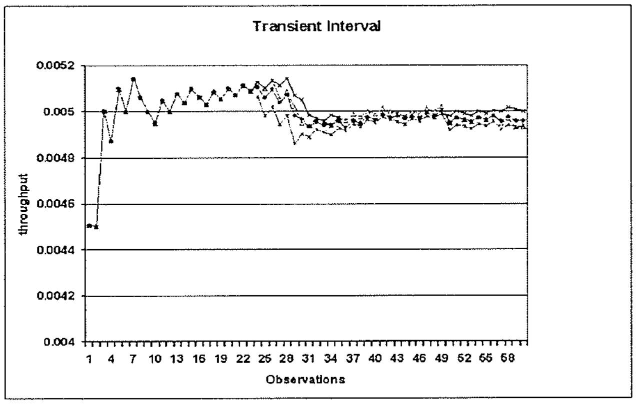


Figure 6.1: (a) Transient Interval for Downlink transmissions

shows similar behavioral pattern with changes in the number of devices and the packet arrival rate. Figures 6.4 and 6.5 illustrate the throughput pattern of downlink traffic in the source cluster derived analytically and by simulation studies. In the case of analytical results, BER $= 10^{-4}$ is incorporated unlike the simulation results.

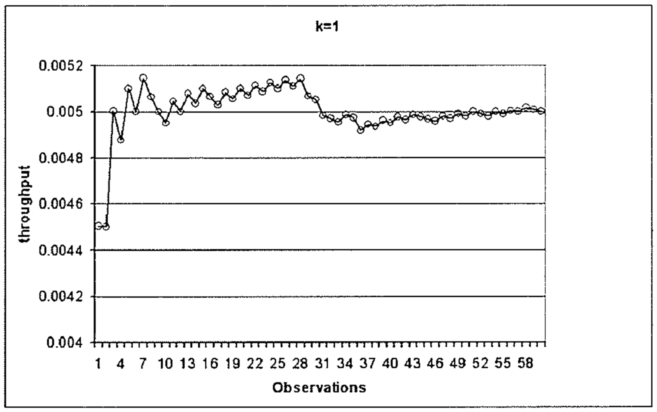


Figure 6.2: (a) Transient Interval for Downlink transmissions with window size 1

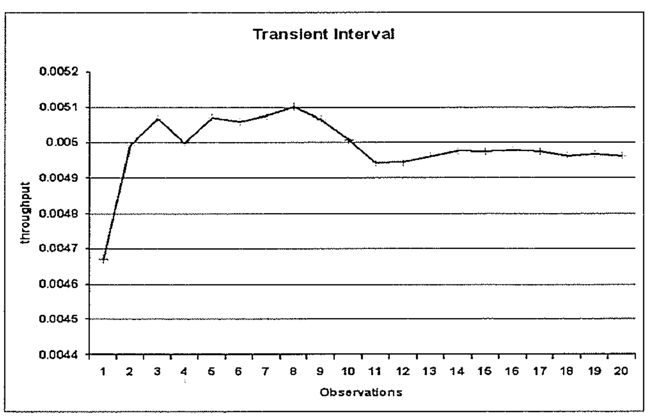
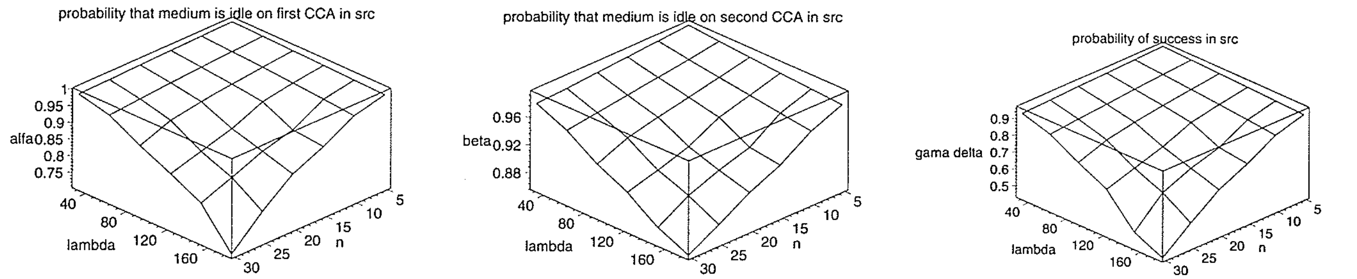
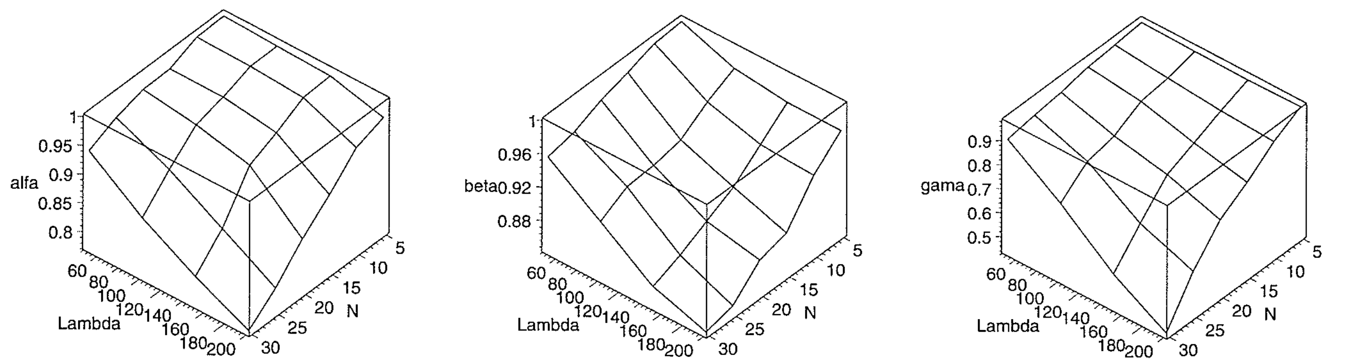


Figure 6.3: (a)Transient Interval for Downlink transmissions with window size 3

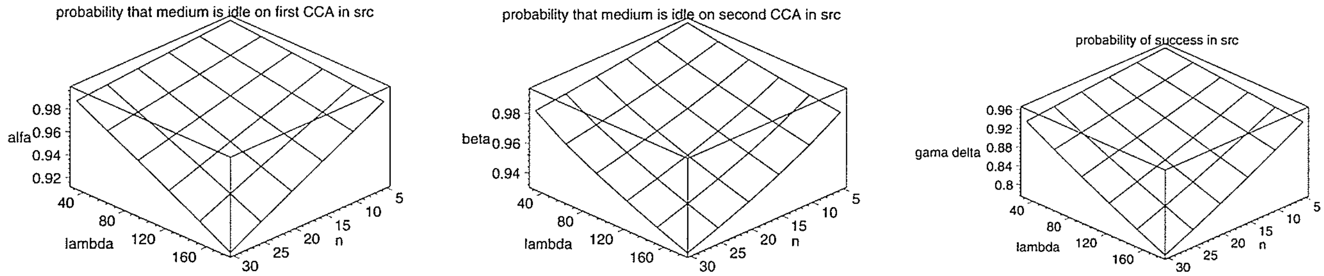


(a) First CCA for Device node (b) Second CCA of Device node (c) Succ.Trans for Device node

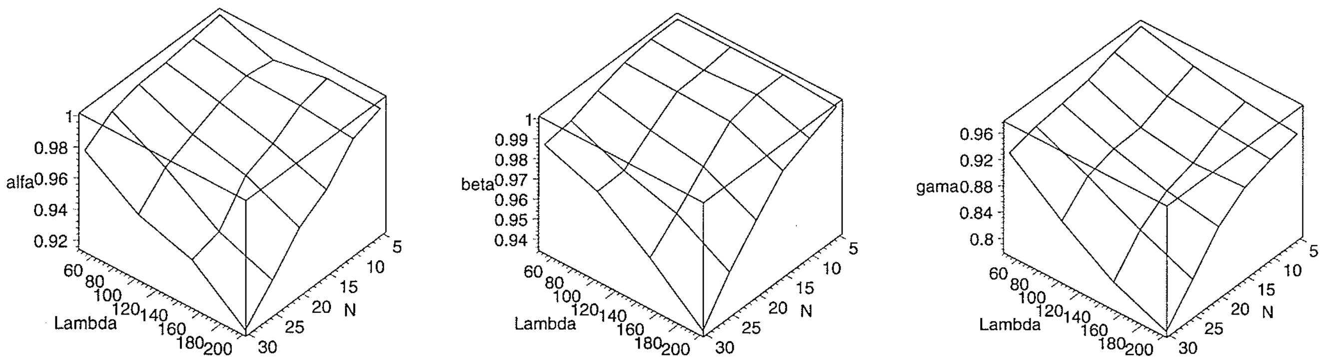


(a) First CCA for Device node (b) Second CCA of Device node (c) Succ.Trans for Device node

Figure 6.4: Probability of success of first and second CCA in source cluster (With Acknowledgment) Row 1. Analytical Results 2. Simulation Results



(a) First CCA for Device node (b) Second CCA of Device node (c) Succ.Trans for Device node



(a) First CCA for Device node (b) Second CCA of Device node (c) Succ.Trans for Device node

Figure 6.5: Probability of success of first and second CCA in source cluster(Non-Acknowledgment) Row 1. Analytical Results 2. Simulation Results

Chapter 7

Simulation Design

The simulation study was done using the Artifex simulator. Artifex is an object-based Petri-net [29] simulator. Artifex was used to model discrete event system types. I used C programming language inside the simulator to specify the proposed bridging algorithm. There are three different symbols used to identify the states of the design. They are the Place, the Transition and the Links. Places are used to identify events, states and conditions and are represented by a circle in the simulator. Transitions identify activities and transition periods and are represented by a rectangle. This is where developers write code to process. Finally, links represent the relationship between places and transitions connected by an oriented line. In my network design, there are four entities used to represent the various components in the simulated network. They are the central WPAN coordinator, the medium, the device and the bridge. Each WPAN cluster consists of these entities. Figure 7.1 represents the experimental IEEE 802.15.4 compliant triangular cluster interconnected by means of slave/slave bridges in the Artifex simulator. Apart from entities, the simulator also has a built in data structure called CMN unit. Only through this data structure, entities

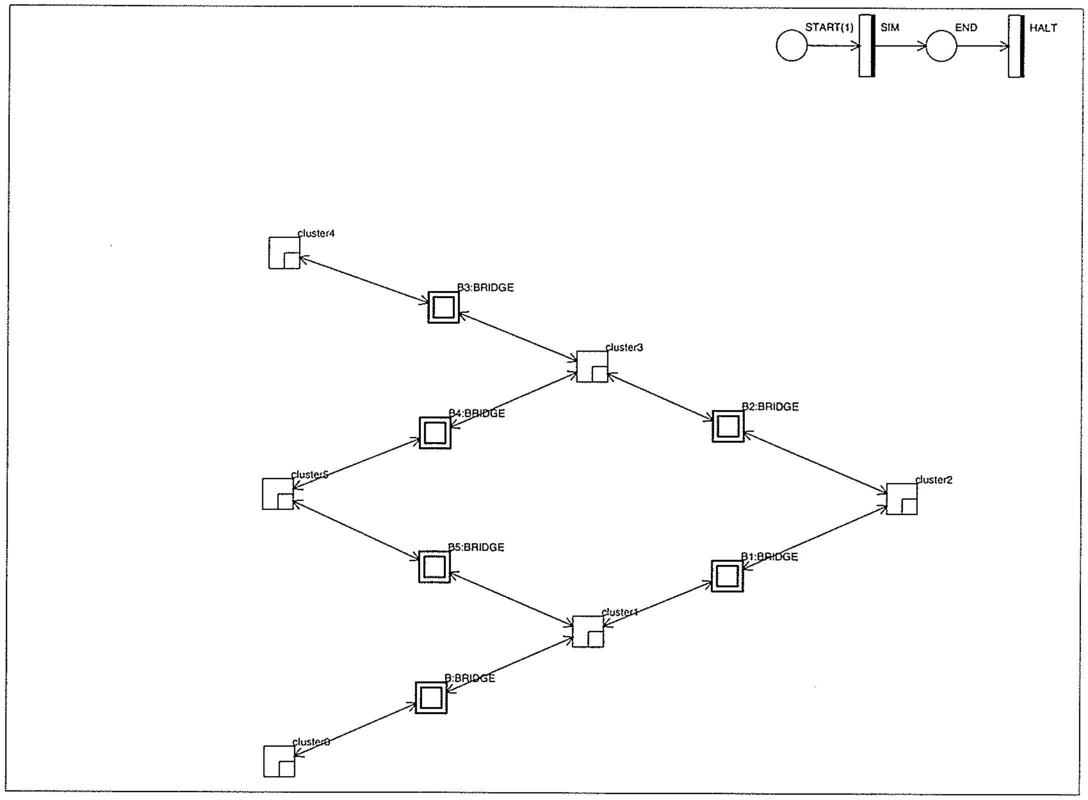


Figure 7.1: (a) 2-Dimensional Network in Artifex Simulator

exchange information between them. For example, packet_id , dest_id, packet_size, etc. are some of the parameters exchanged between entities during packet transmission. Similarly, backoff information such as backoff_boundary, medium status, etc. are exchanged during backoff transmission. Finally, events are the activities performed by entities on a discrete time basis with necessary changes to state variables and attributes. Some of the attributes include current_backoff, CW, NB, BE, device_id, backoff_in_one_sf etc and state variables include medium status, count etc. All the measurements are done using a MEASUREMENT output place. Figure 7.2 illustrates the bridge entity in the above 6-cluster network.

7.1 Bridge Device

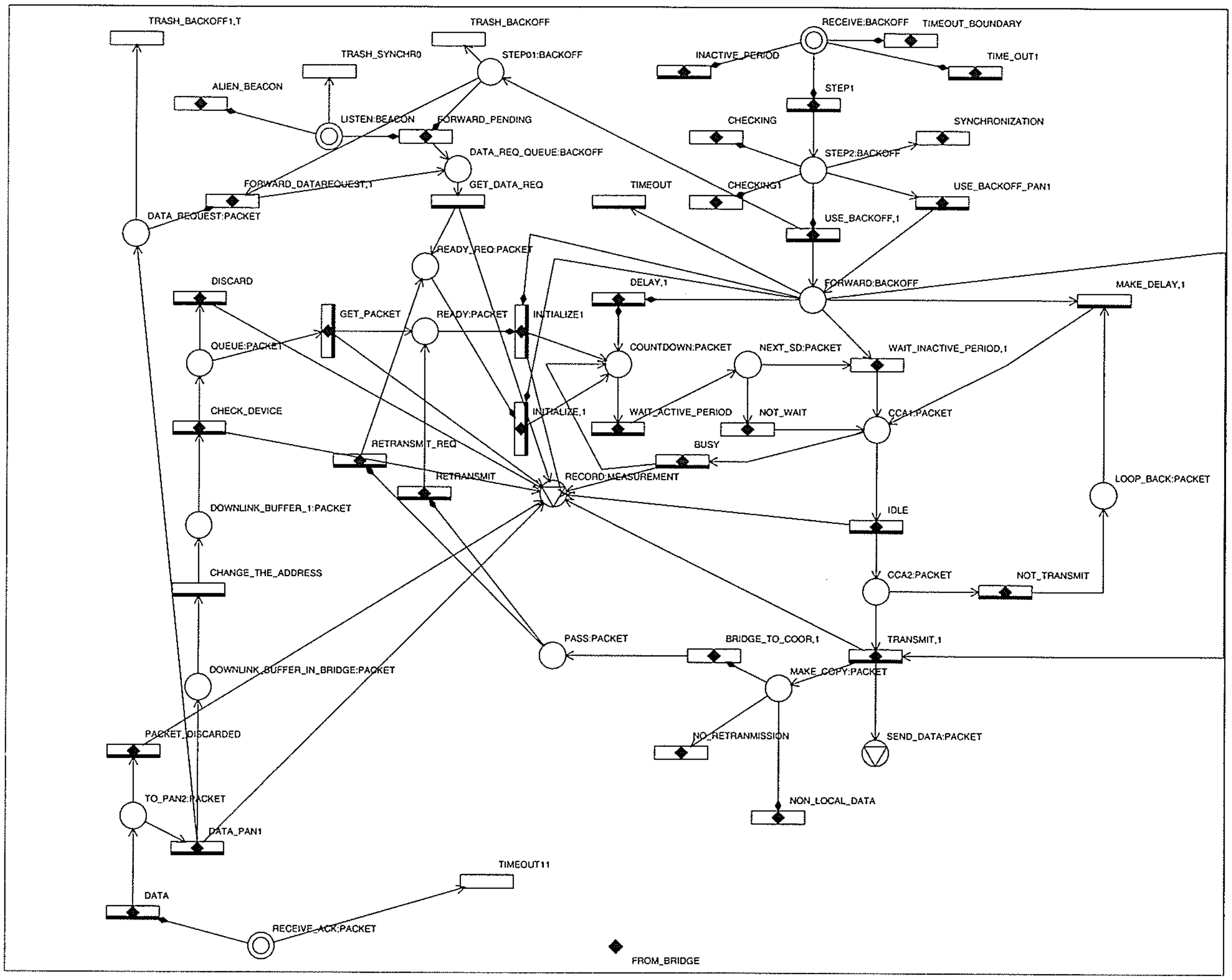


Figure 7.2: Bridge entity in Artifex Simulator

The following are the events performed by the slave/slave bridge entity between two clusters.

1. In the process of arrival, the bridge generates a data request packet when it senses any pending data in the central coordinator, advertised by the beacon.

2. Before sending data request packets for the additional pending data, the bridge's buffer is checked for fullness.

3. If the buffer is full, there will be no further data request packets sent.

4. While sending a data request packet, the bridge uses CSMA-CA to transmit the data.

5. If the data request packet is not successfully received by the central coordinator, the bridge device attempts retransmission.

6. After successful data request transmission, the device waits and acknowledges the successful transmission of the downlink pending data.

7. The bridge transmits received data packets from the source cluster to the coordinator in the destination(sink) cluster.

Chapter 8

Conclusions and Future Work

My work has evaluated the performance of 2-dimensional IEEE 802.15.4 compliant clusters interconnected using Slave/Slave bridge. The above topology mimics all the complexities such as multiple remote bridges, local bridges, multi-hop communication with the sink cluster and contention between device nodes, the bridge and the coordinator in each cluster faced by a real-time multi-cluster network. In this research, I have considered both acknowledged and non-acknowledged transfers in the network. My results show that the network performs satisfactorily in the case of acknowledged transfers at a packet arrival rate of up to 90 packets/minute and a cluster size of up to 15 nodes. On the other hand, non-acknowledged packet transfer shows better results compared to the acknowledged transfer under moderate packet arrival rates.

In this network, the local packets in the middle cluster get suppressed by the non-local packets traversed across the network. As a future work, to remove this suppression faced by the local packets, GTS slots can be incorporated in the superframe structure for remote bridge access. Moreover, to avoid expensive GTS technique for inexpensive applications, the middle cluster can be further divided into small clusters to avoid excessive traffic from other neighboring clusters. Finally, the existing simulation design can be extended to a large network design with heterogenous type of devices.

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