Delft University of Technology

Wireless and Mobile Communication (WMC) Group
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology

Performance and Fairness Enhancement in ZigBee Networks

Assignment: Master Thesis
Instructors: Dr. Venkatesha Prasad Ranga Rao
Huaizhou Shi
Supervisor: Prof.dr.ir. Ignas Niemegeers
Student: Ke Dong(4038533)

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Abstract

ZigBee is a robust wireless communication standard which is based on IEEE 802.15.4. It can be implemented in various applications, for example, health care networks, smart home networks and plenty of sensor networks. However, the performance of ZigBee is also critically limited by low packet delivery ratio and unfairness on network accessing amongst nodes in ZigBee networks with large amount of nodes (more than 100 or so in our simulations). Therefore, how to fairly and efficiently access the network and deliver packets is one of the crucial issues in ZigBee networks.

However, there are many different network parameters and different parameters would influence the performance and fairness in different manors. Hence, we have measured the influence of performance by different values of various network parameters in ZigBee networks, such as network depth, retransmission time, size of the network and traffic etc. The simulation results show that the packet delivery ratio and fairness amongst nodes are influenced much more significantly by the amount of end nodes, size of packets and retransmission time. Very low delivery radio (lower than 10%) and severe unfairness have been found in scenarios with large amount of end nodes, big packet size and limited retransmission time. Therefore, we propose three mechanisms to enhance the performance and fairness of ZigBee networks, which are the packet aggregation mechanism to improve the packet delivery ratio, intra-cluster and inter-cluster fairness mechanism to guarantee the fairness amongst nodes in ZigBee networks.

The packet aggregation mechanism is introduced in ZigBee networks to aggregate packets with the metrics of both certain time units and certain packet numbers, the results of which show that the delivery ratio of the network has been improved significantly in light traffic networks. However, the unfairness still can be seen in networks. Therefore, intra-cluster and inter-cluster fairness mechanisms are proposed to enhance the fairness both in and among different clusters in a ZigBee network. With intra-cluster fairness mechanism, routers buffer the packets from an end node when the number of received packets from this end node is much more than the average level in this cluster. Our intra-cluster fairness mechanism can bring in much

fairer delivery ratio amongst nodes in a cluster, which is shown by the simulation results. However, intra-cluster fairness mechanism only guarantees the node fairness inside a cluster, and unfairness can still be found amongst different clusters. Therefore, inter-cluster fairness mechanism is designed to achieve the fairness amongst all the end nodes in the whole network. The simulations results show that it could balance the delivery ratio amongst all end nodes in the network as we have expected.

Contents

Chapter 1

Introduction

In the past decades, wireless communications have promoted the development of protocol standardizing. ZigBee protocol has been proposed in order to meet the needs of long lifetime, low cost and low data rate in short range sensing network which is known as Wireless Sensor Network (WSN) based on the IEEE 802.15.4-2003.

1.1 ZigBee Networks

ZigBee-compliant products operate in unlicensed bands: 2.4 GHz (global), 902 to 928 MHz (Americas), and 868 MHz (Europe). The raw data rates is 250 Kbit/s at 2.4 GHz band (16 channels), 40 Kbit/s at 915 MHz band (10 channels), and 20 Kbit/s at 868 MHz band (1 channel). The transmission range is from 10 to 75 meters, depending on the transmit power. Besides, the maximum output power of the radios is generally 0dbm (1 mW) [1].

Since ZigBee uses master-slave configuration, it can be formed as star, mesh and cluster-tree topology with at least one coordinator existing in the network. In the simple star topology, ZigBee network can have up to 254 end nodes around the coordinator. Several star topologies can be contained in a clusters tree topology. More than 65000 nodes can be supported in a large ZigBee network when the several clusters are controlled by the upper coordinator.

ZigBee coordinator can decide the superframe order and beacon order for the end nodes. In order to reduce the overlapping, beacon order should be much larger than the superframe order. Thus, each device can communicate with the coordinator or router so that they are non-overlapping in time. Especially in the Peer-to-Peer (mesh) topology, devices are allowed to sleep to save the power. In star or cluster-tree topology, end nodes can only communicate to the coordinator or routers in activate mode and can go to sleep mode most of the time when there is no traffic.

IEEE 802.15.4 is a low-rate Wireless Personal Area Networks (WPAN) standard with high level of simplicity and stability. However, 2.4GHz band, is also used by the other wireless standards. The coexistence of the devices has become an important issue that they can operate without interference on each other. Especially with IEEE802.11 stations, IEEE802.15.4 stations may be extremely critical if the same carrier frequencies are selected. This scenario will lead to a timeout of Physical Layer (PHY). The impact of other systems (Bluetooth or microwave ovens) on IEEE802.15.4 results in an enlarged packet error rate, however, the level of below 10 % is not critical [2]. It shows that the ZigBee interference has more effect on the IEEE 802.11g uplink than the downlink. Furthermore, the results illustrate how IEEE 802.11g is greatly more affected by Bluetooth than ZigBee and how IEEE 802.11g affects the performance of ZigBee when the spectrum of the chosen channels of operation co-inside [3].

IEEE802.11 standard uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) medium access mechanism which supports the three topologies. The media access is contention based; however, using the optional superframe structure, time slots can be allocated by the coordinator to devices with time critical data. ZigBee coordinator can provide connection to the other networks. [4].

In ZigBee networks, one of the most common scenarios for transmission is that all devices send packets to a sink. The overhead may have to be the critical issue on performance analysis. Interference and collision could obviously decrease the packet delivery ratio and throughput of the global network. On this issue, tree topology is always used to lower down the end-to-end delay and discard the duplicated packets which could be generated in the same environment. Instead of transmitting the packets directly to the sink, packets may be transferred to the router first and then the router integrates the received packets and sends to the sink. Thus, the overall packet delivery ratio can be improved with less overhead at the sink. The sink should be capable to handle large amounts of data than the ordinary end nodes.

Regarding to the simulation part, OPNET [5] and NS-2 [6] are the most useful tools to simulate the protocols. Due to the fact that NS-2 was originally developed for IP networks and then extended for IEEE 802.11 wireless networks, OPNET can simulate the ZigBee protocol more accurately without unnecessary overheads. Simulation should be implemented to test how topology, the amount of end nodes, access mechanism, traffic size and transmit power influence the performance of the ZigBee network.

Similar as ZigBee, Bluetooth provides short range connections and operates on 2.4 GHz band. In contrast to ZigBee, Bluetooth works with higher data rate up to 1Mbpse which is much higher than 250Kbps in ZigBee. However, Bluetooth can only have up to 8 nodes in a subnet cluster while ZigBee support a large number of end nodes and can have up to 255 nodes in star topology. Bluetooth could use scatternets to extend the network with several piconets. Bluetooth has many different modes and states depending on the requirements of latency and power, such as sniff, park, hold, active, etc [7]. Only active or sleep modes are used by ZigBee. When the end node is powered shut down, ZigBee can activate from sleep mode in 15 msec or less while it costs three seconds for Bluetooth devices to wake up. The sleep mode considerably reduces the average power consumption and extends the battery life. Individual device should have a battery life of at least two years to pass ZigBee certification [8]. Bluetooth use three-slot mechanism and it's more efficient for larger packet size. While slotted CSMA/CA mechanism is optional for ZigBee and it's more efficient for transmissions with small packet size. Zigbee makes use of low data rate and uses lower power consumption. Bluetooth, on the other hand, works with higher power. Zigbee is usually used for monitoring and control while Bluetooth is all about connectivity between PDA's, laptops and other such devices. [9].

1.2 Related works

Based on the standard IEEE 820.15.4, ZigBee is a reliable standard for plenty of applications with low data rate and low cost. ZigBee is an ideal standard for sensing, tracking and monitoring because it is built on power-saving. Since mesh topology can be used in ZigBee network, a large amount of nodes are supported because of multi-hop routing capabilities. In the real wireless environment, the traffic from all the end nodes may be transferred to a certain sink. Therefore, collision may happen, which may dramatically influence the performance of the network. The data from the end nodes may be crucial for the system to locate and make a quick response, thus the data could be dropped during the transmission and cause less delay. Collision at the router and interference within the communication range will surely decrease the packet delivery ratio in the network. In particular, lots of cheap devices using ZigBee technology are being deployed for sensitive applications, such as hospital monitors and lamp controllers in smart home networks, which may require high throughput and packet delivery ratio especially with large amount of end nodes [10]. However, there are many factors would influence the performance of ZigBee networks, such as types of the network topology, size of the networks, amounts of the traffic, mobility, retransmission threshold, and so on. Some works can be found in literature on the ZigBee network performance, which are summarized below.

(a) Impact of the network topology

In simulating ZigBee networkss, three topologies are commonly used: star, mesh and cluster-tree. In the star topology, the end nodes only have one hop to the coordinator which handles routing and decision-making. In the mesh topology, end nodes are Full Function Devices (FFD) which can communicate to with each other instead of only communicating with the coordinator. The mesh and cluster-tree normally use Ad hoc On Demand Distance Vector (AODV) routing protocol which is suitable for large scale networks. Global Medium Access Control (MAC) throughput is the total data traffic in bits/sec successfully received and forwarded to the higher layer by the 802.15.4 MAC in all the nodes of the WSN. Packet delivery ratio is the ratio between successfully received packets and the total transmitted packets. Simulations of the three topologies in [11] illustrate when the amount of end nodes increases the MAC throughput increases. This behavior agrees in general with the results presented in [12]. However when the amount of end nodes increases above a certain level in mesh and tree topologies, more collisions will take place as the MAC layer cannot handle the increased the amount of end nodes. The packet delivery ratio decreases sharply if the amount of end nodes increases above a certain level due to access collisions. There is a slight difference on packet delivery ratio between mesh and cluster-tree topologies with the same amount of end nodes, this is because the mesh topology supports multipath routes which can cause a minor increase in the packet delivery ratio. In the star topology the packet delivery ratio increases until it reaches a maximum value with more nodes than the mesh and cluster-tree topologies, and then drops rapidly for larger amount of end node. This difference in packet delivery ratio between star topology and the other two topologies is not related to the ETE delay. This difference appears in node numbers between 80 and 100. This is due to excessive demand from all the nodes within their MAC layers which will cause the MAC packet delivery ratio to increase momentary then after 100 nodes, due to excessive collisions, the packet delivery ratio drops rapidly.

(b) The impact of network sizes

Due to large number of collisions, packet delivery ratio is heavily influenced by the traffic load. Therefore, retransmission would be needed while the network transmission rate reduces. After the collision, the packet should be delayed for a certain period because of the backoff mechanism. The node could wait for a very long time that cannot send the data. Besides, the packet delivery ratio could increase as the packet size rises while it decreases dramatically after achieving a certain level of packet size. Therefore, it is possible to determine the optimal packet size to maximize the packet delivery ratio.

(c) Impact of Mobility

Since ZigBee networkss could use mesh topology using AODV routing protocol which provides self-organizing functionality to moving devices. The characters of movement such as speed, direction and path can significantly affect the operation and the performance of the WSN. Mobility models are designed to describe the movement pattern of the nodes, and how their locations, velocity and acceleration change over time. Fixed networks have limitations on collecting and disseminating data. The work [13] is on evaluating the network performance, specifically the interdependence between end-to-end congestion and local contention based on the IEEE 802.15.4 protocol for LR WPAN for different scenarios involving mobility. IEEE 802.15.4 allows the nodes to turn to sleep mode for a certain period by changing the SO and BO parameters of the superframe. In the simulation, a many-to-one communication model is used. The results show that slow mobility of the sink g high generates packet delivery ratio without increasing the collisions among neighboring nodes in the half-active operation. The results in the full-active operation prove that the movement of the coordinator among randomly deployed stationary nodes yields best results for the packet delivery ratio. The mobility can be utilized to increase the performance of the sensor network. Regarding to the packet delivery ratio, the work [14] indicates that keeping the sink static gives the best performance. The type of the trajectory along with the node density and the traffic are also major factors that decide the system performance. Choosing a random topology is among the means possible to prevent exceptionally low throughput. Having the routers placed within range for effective meshing gives sharper curves which are closer but even in this case, it is better to keep the sink static at a location from where each route has an access to the sink possible with minimum hops. In circumstances sink movement is necessary, clever selection of the trajectory is essential for best packet delivery ratio and throughput.

(d) Impact of the SuperframeOrder on the Guaranteed Time Slot (GTS)

In most simulation models for IEEE 820.15.4 protocols, they are incomplete and in particular GTS mechanism is disabled. To evaluate the impact of the GTS mechanism, an accurate OPNET simulation model is proposed in [15]. In the experiment, a star topology is used with a coordinator and an end node within its radio range. The model is assumed that there are no inactive periods in each superframe. The result shows that data throughput is related to time effectively used for data transmission inside the GTS. The wasted bandwidth is generated from Inter-Frame Spacing periods or waiting for an empty buffer. For low SuperFrameOrder values (SO), throughput grows since the buffer does not become empty during the duration of GTS. On the other hand, the throughput for high SO values falls, since the buffer becomes empty before the end of the GTS. For a large GTS, a significant amount of bandwidth is wasted when waiting for the incoming frame payload from the application layer. Throughput for high SO increases with the arrival data rate. Throughput performance for high SO values is identical and independent on the size of the frame payload. The result also shows that increases with the buffer capacity. The highest utilization of the GTS is achieved for SO between 2 to 5. For the lowest SO values, the throughput depends neither on the arrival data rate nor on the buffer capacity, since the number of incoming frames during a superframe is low but still sufficient for saturating the GTS. For the higher SO values, the throughput does not depend on the buffer capacity and the throughput values grow with the arrival data rate. This occurs since the buffer becomes empty at the beginning of a large GTS and then, the generated frames are directly forwarded to the network with the rate equal to the arrival data rate. For applications with low data arrival rates and low buffer capacities, the maximum utilization of the allocated GTS is achieved for low superframe orders (3-4). However, the superframe order equal to 2 is the most suitable value for providing real-time guarantees in time-sensitive WSNs, since it grants the minimum delay bound for the GTS frames. High superframe orders are not suitable for ensuring efficient usage of the GTS neither in terms of data throughput nor delay.

(e) Impact of beacon enabled slotted CSMA/CA

MAC layer is based on beacon enabled and beacon disabled mode. In beacons disabled mode, unslotted CSMA/CA is used. In the beacon enabled mode, the superframe is divided into 16 slots and bounded by the beacons which are used to synchronize the attached devices. The superframe contains two periods: active and inactive period. In the inactive period, the coordinator could get to the sleep mode.

The active period is divided into Contention Access Period (CAP) and Contention Free Period (CFP). Devices should compete with the other devices using slotted CSMA/CA in the CAP. The macBeaconOrder and macSuperFrameOrder determines the length of the superframe. The Number of Backoffs (NB) is the number of times the CSMA/CA is required to backoff when attempting the transmission. Contention window (CW) length defines NB periods before the start of the transmission. Backoff Exponent (BE) is the parameter that determines how many backoff periods a device should wait before attempting the channel. Since a lot of packets are lost due to collisions, [16] shows that a lower BE is not optimal. With BE=2, more packets are sent but less packet delivery ratio is achieved with more power consumption in the collision transmissions. It can be seen that when a delay of 100 slots or 32ms is introduced, the probability to start a transmission attempt is reduced significantly. However, if the number of packet transmissions is smaller, a higher packet delivery ratio is achieved for large amount of end nodes in the unsaturated traffic case compared to the saturated case. Thus, for a saturated network, it is best to choose a larger exponent delay backoff to achieve a better packet delivery ratio. The (aggregated) throughput of the nodes will decrease due to the large back off interval. In low density networks, the probability of a collision will be significantly lower. Therefore it would be interesting to lower the *macMinBE* in such scenarios [7]. In practice, only uplink and downlink transmission is possible per CAP, which significantly reduces the available throughput. In addition, a collision probability is high due to the shorter backoff time. The goodput is modeled with the requested packet delivery ratio and throughput. In the study [17], it indicates that a goodput of about 200 bits per superframe can be achieved with 90 % transmission success rate. As SO varies from 0 to 2, the maximum throughputs are 302, 545 and 897 bits per beacon interval. These are obtained with throughput percentages between 33% - 55%. With higher requested throughput, the increased contention reduces throughput rapidly. A longer CAP length reduces contention and improves the throughput.

(f) Impact of packet size

PHY operates at the 2.4 GHz frequency band and with 250kbps data rate. And the maximum size of a MAC frame is 127 bytes with 25 bytes MAC header. As can be seen, the increase in packet size results in a decrease of access probability and an increase in probability that the medium is idle. Let PHY throughput denote the throughput which comprises the time fraction that the channel is used on transmission of Presentation protocol data unit (PPDU). In [18], a real model of IEEE 802.15.4 in beaconless mode based on Micaz has been presented. The PHY throughput gives us an insight of the channel usage. The channel usage for shortest PPDU (20 bytes) is as low as 9.14%. While the usage becomes larger as the PPDU length grows. For the Application layer throughput, it includes the effect of headers over different payload lengths. AP throughput grows slower than the PHY throughput due to the impact of the overhead on the application channel usage.

(g) Impact of number of hops

In the work [19], throughput is defined as packet delivery ratio which is the amount of the data units (PDU) correctly arrived to the sink, divided by the length of the interval of the experiments. The packet delivery ratio in a multi-hop path decreases quickly in the experiment. In particular the result shows that increasing the number of hops the packet delivery ratio degrades faster for larger sized payloads. This higher degradation is due to higher probability of collisions for large packets during CSMA, if there are several nodes of the WPAN in the same transmission area. In particular, the injecting nodes join in the same network and exchange data with the coordinator (ZC) sending a certain amount of traffic to the sink. It shows that the degradation of the packet delivery ratio when two hops divide the streaming sender from the receiver and only one injecting node was connected to the router. The presence of an intermediate relay drastically reduces the network packet delivery ratio with respect to a one hop scenario, due to the fact that the shared radio medium is occupied, for a single data packet transmission, for a longer time. Thus, MAC protocol should be designed for networks with multi-hop communications.

(h) Impact of the amount of channels

To achieve higher network utilization it is necessary to maximize the amount of end nodes which can transmit concurrently. Therefore exploiting spatial reuse becomes essential. The negative effect of contention and interference on multi-hop data packet delivery ratio can be reduced by using multiple radio channels; several communication protocols use multiple radio frequencies to achieve higher multi-hop packet delivery ratio [20], [21]. With larger number of radio channels than the number of transmitting nodes, each unicast transmission can be performed on a dedicated radio channel.

(i) Impact of packet copying

Since the ZigBee PHY has its own limitation of data rate, it is not possible to send more data than the maximum bit rate. According to the character of the practical hardware, the microcontroller firstly copies the packet data into the transmit buffer over the serial peripheral interface (SPI) bus. The work [22] shows that packet copying between the radio transceiver and the microcontroller is the bottleneck in multi-hop 802.15.4 transport. By moving packet copying off the critical path, conditional immediate transmission which is a proposed packet forwarding abstraction nearly doubles the multi-hop 802.15.4 throughput. It shows that the throughput is affected by packet copying and the impact of the Clear Channel Assessment (CCA) is low in single hop network. However, the impact is even higher in the multi-hop network.

(j) Impact of packet buffers

There are several methods for future ZigBee hardware designs for achieving maximum packet delivery ratio. One of these is to create additional packet buffering capabilities at the radio transceiver [23]. The microcontroller could deallocate the packet buffer as soon as a copy is transferred to the radio. By increasing the buffer size, it can hold more packets during the transmission. It can schedule more packets simultaneously, reducing the probability that the radio will have idle time.

(k) Impact of the other WLANs (Wireless Local Area Networks)

Since ZigBee networkss can operate on 2.4GHz frequency which is also used by WLAN and WPAN standards. There must be interference among the wireless protocols and throughput of IEEE 802.11g, Bluetooth, and ZigBee devices should be evaluated when co-existing within a particular environment. In [3], it shows that the packet delivery ratio drops from 100% to 90% with the interference of IEEE 820.11 g. correspondingly. The packet delivery ratio drops 11% with the interference of Bluetooth. However, when the distance between two ZigBee devices is much smaller than the distance between the two different standards devices, no interference effect was reported neither on the performance of the IEEE 802.11g client nor on the packet delivery ratio of the ZigBee devices.

1.3 Summary

Even though there are some works on ZigBee networks, we still do not know which are the most important ones influencing the network performance. With large amounts of nodes in ZigBee networks, fair resource sharing is very important too, but fairness issues have not been studied in ZigBee. Hence, in this thesis, firstly we analyze the network performance and fairness with different values of different parameters, then three mechanism, the packet aggregation mechanism, intra-cluster and inter-cluster fairness mechanisms are proposed and simulated. The simulation results show that our mechanisms can improve the network performance and fairness significantly.

This thesis is organized as follows. In Chapter 2, the performance of ZigBee networks with different topologies (star, mesh and cluster-tree topologies) are simulated and analyzed with various network parameters. In Chapter 3, we propose a packet aggregation mechanism for ZigBee networks with cluste-tree topology. Packet delivery ratio and delay are analyzed with comparison of normal cluster and mesh topology. In Chapter 4, three fairness models are described, and fairness in ZigBee networks is evaluated and analyzed with different values of network parameters. In Chapter 5 and Chapter 6, intra-cluster and inter-cluster fairness mechanisms are proposed and examined. Finally, in Chapter 8, we conclude the whole thesis and demonstrate our future works.

Chapter 2

Performance analysis in ZigBee networks

Some research can be found in literature on performance analysis of IEEE 802.15.4. However, the performance of ZigBee networks with different topologies has not been considered systematically yet and it is also not clear which network parameters influence the network performance the most. Therefore, all star, mesh and cluster-tree topologies are simulated and analyzed in this thesis with different values of network parameters. Since packet delivery ratio and delay are very important performance metrics in WSNs, they are adopted as the main performance metrics in this chapter. Different network parameters, such as depth, retransmissions, size of the network and traffic etc., are employed too. The results show that the network size, traffic size, and retransmission thresholds are the most significant factor to influence the network performance.

2.1 Simulation scenarios

The star, mesh, and cluster-tree topologies are simulated and analyzed with different network parameters, such as the size of network, amounts of nodes, threshold of retransmission time, and so on. ZigBee coordinator is placed in the center of the network and acts as a sink. The end nodes send traffic directly to the coordinator in star topology or indirectly through ZigBee routers in the cluster-tree topology which are shown in Figure 2-1 and Figure 2-2. Traffic is transferred through multi-hop path in mesh topology which is shown in Figure 2-3.

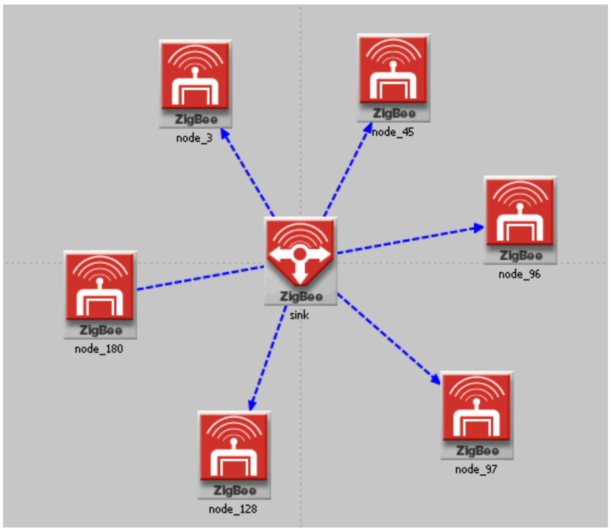

Figure 2-1 An example of a star topology ZigBee network.

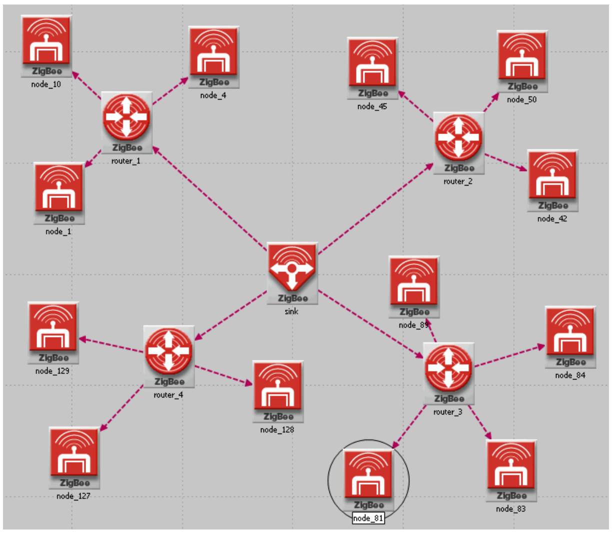

Figure 2-2 An example of a cluster-tree topology ZigBee network.

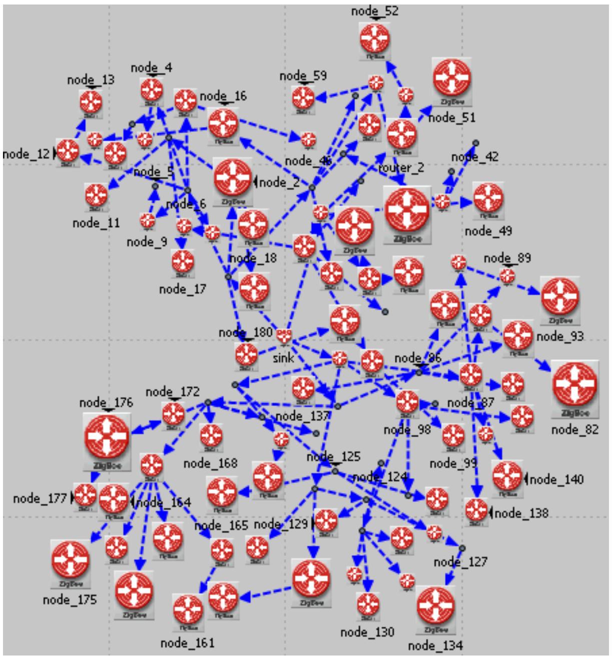

Figure 2-3 An example of mesh topology ZigBee network.

Packet delivery ratio is adopted as one of the main performance metric in our simulations, which can be calculated as the ratio between number of data packets that are received by the sink and the number of data packets that are sent by the end node.

$$PDR = \frac{P_r}{P_s} \tag{2.1}$$

For a certain node i, if it generates P_i^s packets and only P_i^rpackets are successfully received by the sink. We define the node packet delivery ratio as:

$$PDR_i = \frac{P_i^r}{P_i^s} \tag{2.2}$$

Average packet delivery ratio is used for all the end nodes when analyzing the performance of ZigBee networks. The ratio is between total number of data packets that are received by the sink and the total number of data packets that are sent by all the end nodes.

$$PDR_{average} = \frac{P_i^{total}}{P_i^{total}} \tag{2.3}$$

The values of other network parameters are listed in Table I.

Table I Values of the network paramters.

Network Layer Parameters	
Beacon Order	0
Superframe Order	0
Maximum Children	200
Maximum Routers	15
Maximum Depth	6
MAC Layer Parameters	
ACK Wait Duration(sec)	0.05
Retransmission time s	5
Minimum BE	3
Maximum NB	4
Channel Sensing Duration	
PHY Parameters	
Data rate (kbps)	250
Transmission band (GHz)	2.4
Transmission power (W)	0.05 (Coordinator)
	0.015 (Router)
	0.005(End node)
Application Traffic	
Destination	Coordinator
Packet Interarrival Time(sec)	Exponential (1.0)
Packet Size (bit)	Constant (800)

2.2 Simulation results:

2.2.1 Star and cluster-tree topology

Star topology use one hop path network between coordinator and end nodes. Therefore, star topology can be considered as a special case in cluster-tree topology with one depth.

(a) Packet delivery ratio against the amount of end nodes and depths

In Figure 2-4, it shows packet delivery ratio for different amounts of end nodes and depths for the star topology and cluster topology. In star topology with one hop between coordinator and end nodes, the whole network will not work when there is something wrong with the coordinator. Packet delivery ratio is pretty high for star topology in a small network and decreases proportionally with the increase of the amount of end nodes. Packet delivery ratio stays 100% as the depth of the network increases to 4. However as the amount of end nodes increases, packet delivery ratio drops dramatically (the ratio gets to less than 70% even in the star topology). After the amount of end node gets more than 50, the ratio decreases to less than 60% in the three networks with different types of depths. As the amount of end node grows more than 100, only star topology is reliable with packet delivery ratio more than 50%. The network with 200 end nodes is the worst case in the simulation because of large collisions.

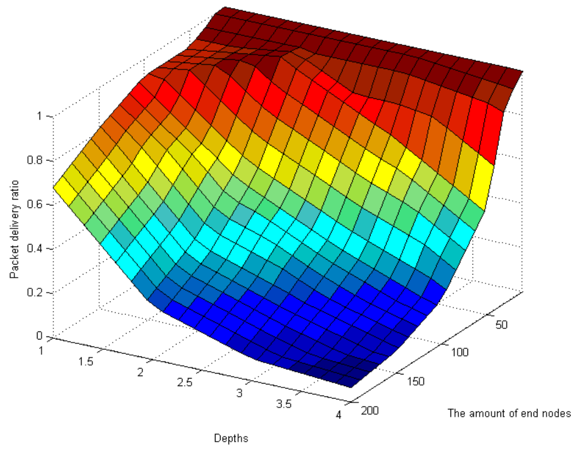

Figure 2-4 Packet delivery ratio against the amount of end nodes and depths

The statistics clearly show that packet delivery ratio has nearly the same performance for networks with different depths. Due to the contributions of collisions in the added routers between coordinator and end nodes, packet delivery ratio decreases to almost 0 if the network contains more than 200 end nodes with more than 3 depths. Packet delivery ratio in cluster-tree topology is higher when the amount of end nodes goes below 50 due to the additional traffic through the routers between the end nodes and coordinator. Because of more collisions caused in the three depths network, the depths and amount of end nodes are important parameters to evaluate the performance of the networks.

(b) Packet delivery ratio against the amount of end nodes and retransmission times

Retransmission is used to make sure that the packets can be retransmitted when the packets are not received by the destination. As retransmissions increase, packet delivery ratio could get to 100%. At the same time it increases the burden in the network, more traffic will be generated with high quantity of retransmissions.

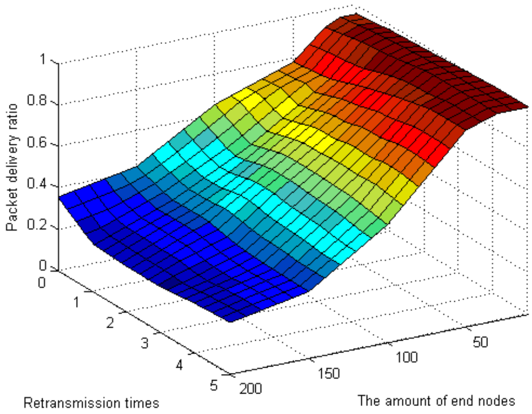

Figure 2-5 Packet delivery ratio against the amount of end nodes and retransmission times

In Figure2-5, it shows packet delivery ratio with 0-5 retransmission times with different amounts of end nodes. As can be seen in a small size network with less than 50 nodes, in this figure, the squares are almost dark red that means the ratio is more than 80% even when the retransmission mechanism is disabled. As the amount of end nodes increases, the ratio continues decreasing linearly. After the amount of end nodes goes up to 150, the squares are almost dark blue which means the ratio is less than 30%. Moreover, in a small size network, retransmission has the positive impact and can make sure that all the packets could be received by the destinations successfully. However, in a large size network, retransmission has the negative impact and cause large collisions which will seriously affect packet delivery ratio. At this moment, no retransmissions could reduce the global traffic and increase packet delivery ratio (in the network with 200 nodes, there are still 35% of the packets are received by the coordinator).

(c) Packet delivery ratio against the amount of end nodes and packet size

Packet size varies when the network is used for different purposes. In this case, different sizes of packets are defined: 10bits, 20bits, 40 bits, 80 bits, 200 bits, 400 bits and 800 bits. Packet delivery ratio is shown in Figure2-6, as functions of the amount of end nodes and packet size. The packet is generated to the value 1packet per second.

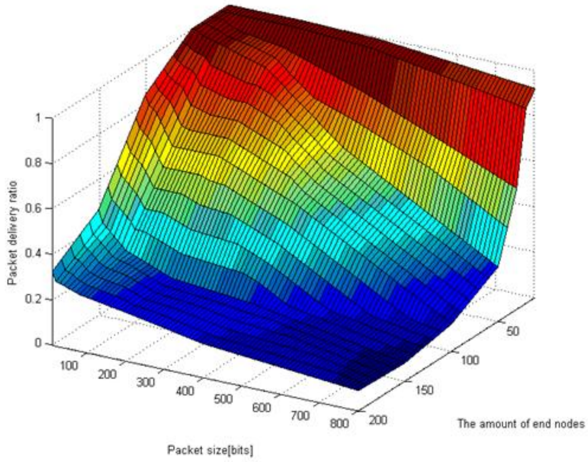

Figure 2-6 Packet delivery ratio against the amount of end nodes and packet size

As can be seen in Figure 2-6, the ratio with less than 30 nodes stays above 90% even if the packet size is 800 bits. As the amount of end node increases to 50, the ratio drops dramatically below 80%. Especially for large packet, the ratio reduces to 40% even in a 50-node network. On the other side, the small size of packet could remain on a relatively high level of 50% when the amount of end nodes goes up to 150 which is considered as a bad result for large size of packet. In a large network with more than 200 nodes, small size of packet (less than 100bits/packet) could obtain an unexpected result with 30% of the packets received. In normal case, packet delivery ratio for 200 nodes only gets the value of 10% approximately. For large packet, the network should deploy less than 50 end nodes and it can ensure that results reach a relatively high level. Otherwise, packet delivery ratio will get less than 40% which is not reliable for practical applications.

(d) Packet delivery ratio against the amount of end nodes and packet interarrival time

The packet interarrival time determines the packet rate which will have a great impact on the performance of the network. In order to capture the effect of the packet interarrival time to packet delivery ratio, the packet are generated and sent to the destinations with different values: 0.01s, 0.05s, 0.1s, 0.5s, 1s, 5s and 10s. In this case, the corresponding packet rate is as: 100, 20, 10, 2, 1, 0.2 and 0.1packet/s and the packet size is fixed to 100 bits/packet.

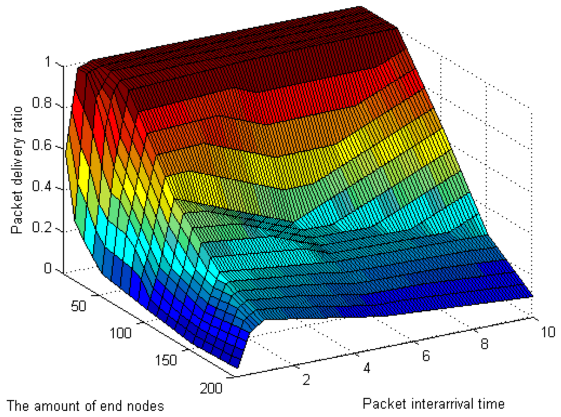

Figure 2-7 Packet delivery ratio against amount of end nodes and packet interarrival time

In Figure2-7, it shows packet delivery ratio against packet interarrival time and the amount of end nodes. In this figure, it obviously shows that almost all the packets can be received successfully when the packet interarrival time is more than 1 second with fewer than 50 nodes in the network. There is one special situation that it reaches the best performance of packet delivery ratio when the packet interarrival time is 1second. Even for 200 nodes, packet delivery ratio is more than 20% while the other results are almost below 10%. It means that 1 sec packet interarrival time can be used in all cases to obtain the best performance. For higher packet rate such as fewer than 0.1second, packet delivery ratio is considerably low even for small size of network. Since this case is using the packet size of 100 bits/packet, it can be expected to tolerate relatively high rate when smaller size of packet is used.

(e) Packet delivery ratio against retransmission times and packet size

The comparisons above have shown several parameters against the amount of end nodes, through there are also connections between retransmission times, packet size and packet interarrival time. 100 end nodes are deployed in the network to establish the simulation for different values of retransmission times and packet size. In the presented simulations, end nodes generate packets for several sizes: 10, 20, 40, 80, 200, 400, 800 bits. In the mean time, retransmission times vary from 0 to 5 with different values of packet sizes.

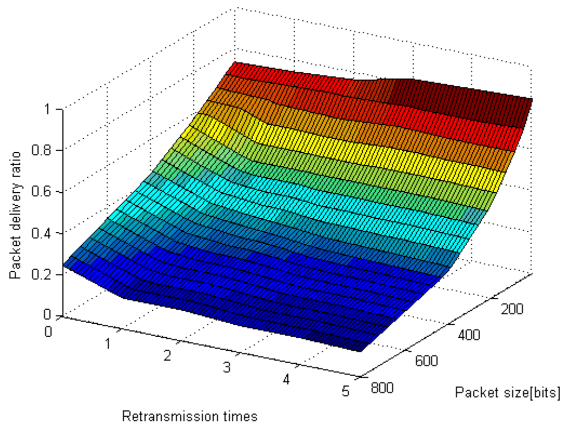

Figure 2-8 Packet delivery ratio against retransmission times and packet size

In Figure2-8, it shows packet delivery ratio as a function of retransmission times and packet size. To identify the impact of retransmission times and packet size the on packet delivery ratio, the packet interarrival time is fixed to 1s. If the packet size is small, more retransmissions are possible to transfer the packets to the destination because the total traffic is not large in the network. Therefore, more packets can get to the coordinator for 5 retransmissions and the result is much better than the other parameters. As the packet size grows, the packet delivery ratio decreases roughly with retransmissions. If the packet size is set to 800 bits large, results illustrate that packet delivery ratio is almost zero with 5 retransmissions and it means there are no packets get to the destination. Due to pretty large traffic in routers, collisions will lead to more packet loses. However, for large packet size, packet delivery ratio increases with small retransmissions and it gets to 25% if there are no retransmissions at all. In this situation, 25% of the large packets are received by the coordinator when the network contains 100 end nodes. This result proves that for large packet size, no retransmissions could minimize the total traffic and improve the performance of the network.

(f) Packet delivery ratio against retransmission times and packet interarrival time

Since packet interarrival time is also relative to packet delivery ratio, it should be simulated for different values of retransmission times. 100 end nodes and packet size of 100 bits are used in this case. The packets are generated and sent to the destinations with different values: 0.01s, 0.05s, 0.1s, 0.5s, 1s, 2s, 5s and 10s and the packet is fixed to 100bits/packet. In Figure 2-9, it indicates that low packet rate ensure higher packet delivery ratio which is close to 1 for 5 or 10 seconds packet interarrival time. A higher packet rate generates more collisions due to large amount of packets in the routers.

The end nodes are unable to send the packets successfully under the high packet rate. There one special curve happens at the rate of 2 packet/sec (0.5 second packet interarrival time) while higher retransmissions leads to a fully success transmission but the lower retransmissions decrease packet delivery ratio. This curve contributes to the former results and will significantly affect the decisions for a packet rate in different environments.

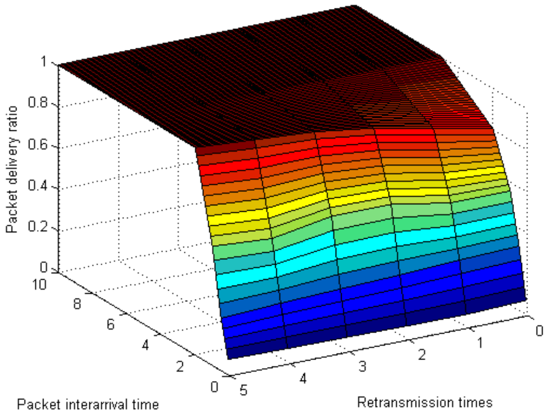

Figure 2-9 Packet delivery ratio against retransmission times and packet interarrival time

2.2.2 Mesh topology

From the performance results in cluster topology, when we change the values of packet size and packet interarrival time, the performance varies significantly in all the scenarios. In the mesh topology, all the devices are ZigBee routers which are FFDs. Each end node can both send and forward the packets to the sink. Therefore, packets could get to the sink through several hops while the number of depths is much larger than in cluster topology or star topology. Routers executive CSMA/CA process if it's not busy to transmit the incoming packets. If the CSMA/CA process is busy, it must wait for a period and buffer the packets in the queue. As a result, it increases the end-to-end delay. Moreover, in mesh topology, all the end nodes around the routers within the transmission range could send packets to this router. It will cause more collisions in this router and will absolutely decrease the performance of the network. For large network with more than 100 end nodes, packet delivery ratio is pretty low regardless of packet size. If the packet interarrival time is much more (packet generating rate is much higer), almost none of the packets are received by the sink.

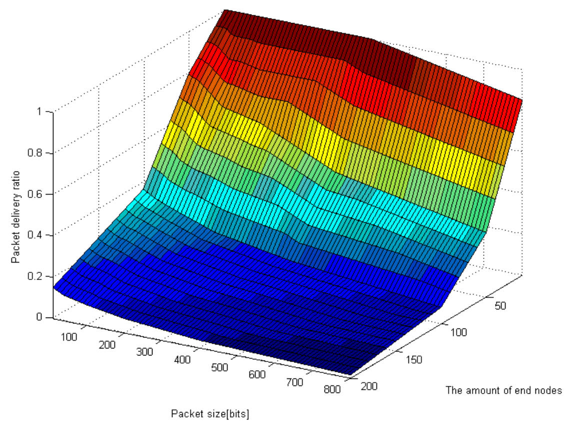

Figure 2-10   Packet delivery ratio against the amount of end nodes and packet size

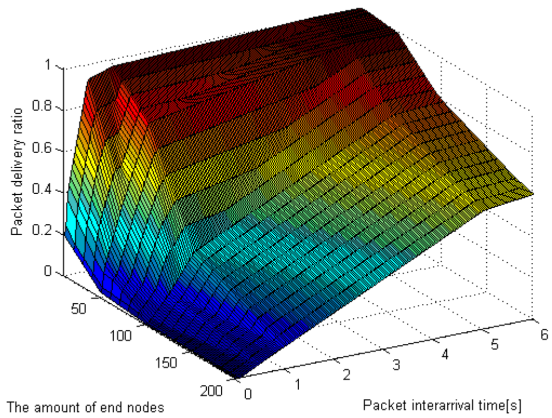

Figure 2-11   Packet delivery ratio against amount of end nodes and packet interarrival time

2.3 Summary

In this chapter, we analyze the simulation results of ZigBee networks with different topologies and different values of network parameters. With the simulation results, we can see that amount of end nodes, packet size and retransmission time threshold influence the packet delivery ratio the most amongst the different parameters. When the amount of end nodes and the packet size increases, the packet delivery ratio drops dramatically. Due to large amount of dropped packets through multi-hop, mesh topology shows the worst performance for packet delivery ratio. Cluster tree topology has higher packet delivery ratio even in a large network with up to 200 end nodes.

Chapter 3

The packet aggregation mechanism in ZigBee networks

With the development of wireless technology, in ZigBee networks there could be hundreds even thousands of end nodes which should have ability of sensing and communicating. In Chapter 2, it is shown that the network performance could be quite poor under certain circumstances, for example in networks with large amount of nodes or large packet size. The low delivery radio is mainly caused by the packet collision during transmission due to our analysis due to the former chapters. Therefore, we propose a packet aggregation mechanism in order to reduce the number of packets in ZigBee networks to decrease collisions and improve the packet delivery ratio. The results with different size of network and traffic have been obtained via simulations, and they show that the networks with our mechanism provide much better performance in light traffic ZigBee networks.

3.1 The packet aggregation mechanism

In the standard ZigBee cluster-tree networks, the routers form clusters and routes packets for end nodes. However, when there is only one sink but with large amount of end nodes, lots of collisions happen, which result in very low packet delivery ratio for each node. With cluster-tree topology, routers can gather all the packets from the members within the cluster and then transmit a super packet to sink instead of transmitting several small packets. In addition, the packets in the same cluster can be duplicated because of the same environment.

Hence, we propose a packet aggregation mechanism which can aggregate a super packet with linear combinations of one packet header and several data frames from cluster members. The overall packet delivery ratio can be improved without too much overhead at the sink by packet aggregation. The packet aggregation mechanism can be designed based the certain number of packets or time duration. For certain number of packets in Figure 3-1, the router stores the packets in buffer and wait until the packets reach a certain number $N_{aggregation}$, then the router aggregates these packets into a superframe and sent it. We define $N_{aggregation}$ which indicates the number of packets in a superframe. The router discards the redundant packet headers and duplicated data frames during packet aggregation. Packet aggregation mechanism can also designed based on time duration which is shown in Figure 3-2. After a certain period, all the received packets in the buffer are aggregated in the router during $T_{duration}$. The procedure of packet aggregation is shown in Figure 3-3.

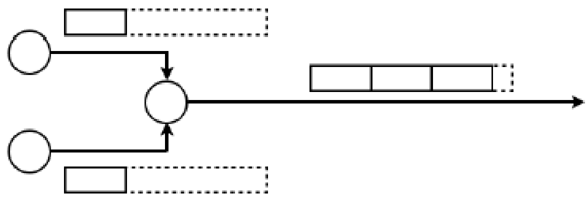

Figure 3-1 Packet aggregation mechanism based on packets amount.

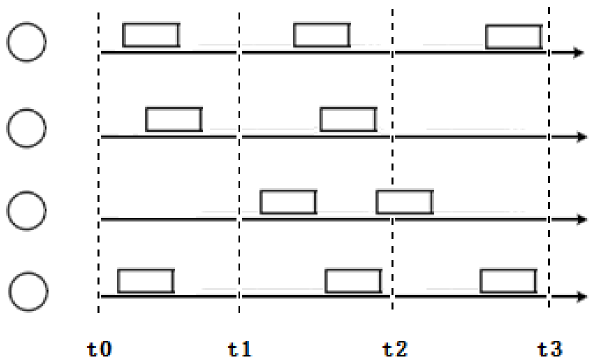

Figure 3-2 Packet aggregation mechanism based on time duration

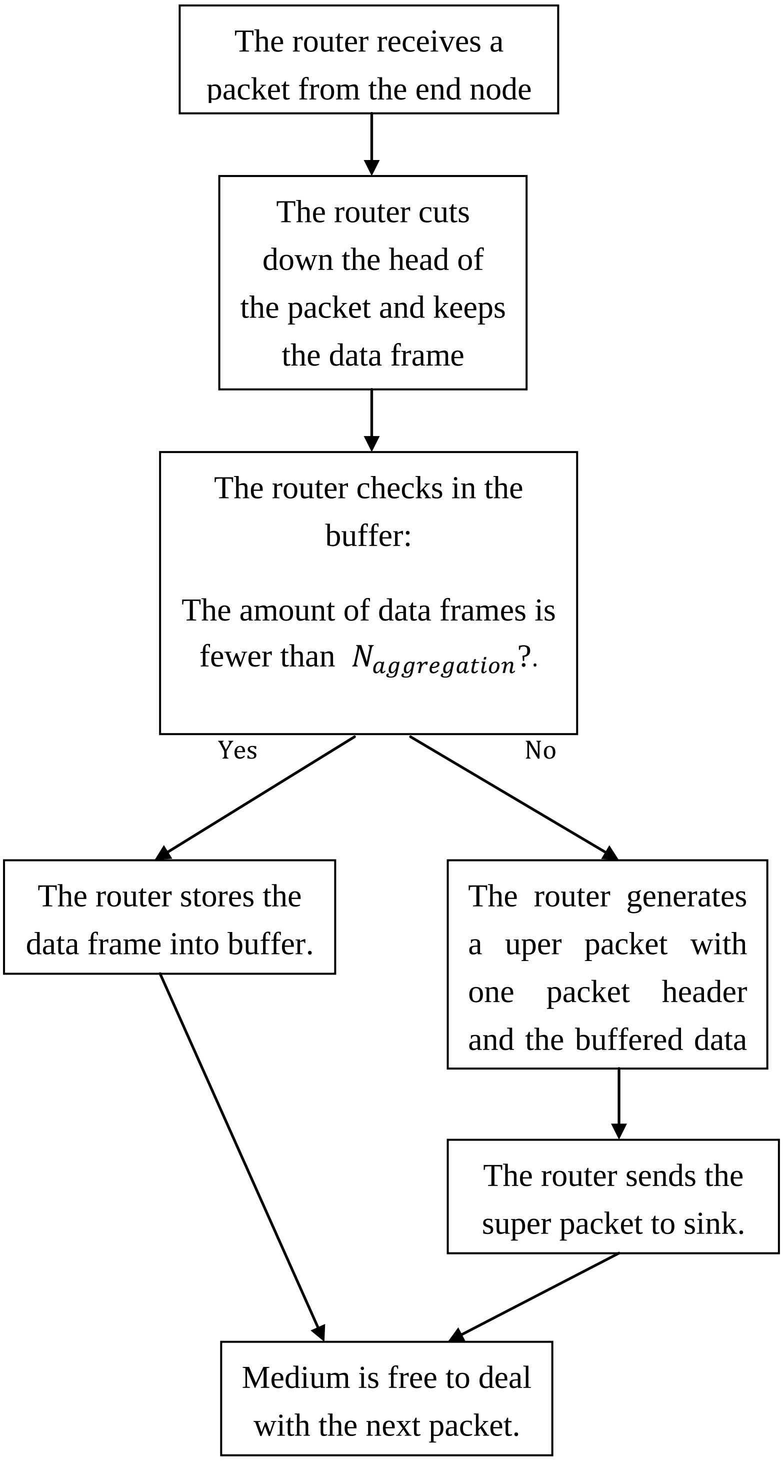

Figure 3-3 Procedure of packet aggregation mechanism

In order to know the best values of $N_{aggregation}$ or $T_{duration}$, we simulated ZigBee networks using the same scenarios as in chapter 2. In Figure 3-4, the result illustrates that the network could achieve the optimal performance when the router aggregates every 3 packets ($N_{aggregation}$).

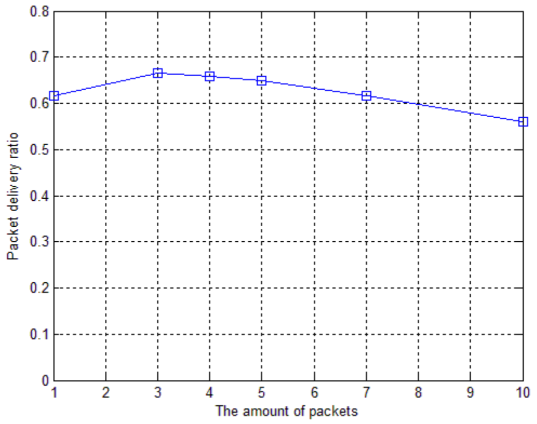

Figure 3-4 $N_{aggregation}$ for packet aggregation at routers

In contrast, when the routers need to aggregate according to time duration, 0.15s is the best choice for 100 nodes with the traffic of one packet per second. This time duration could be obtained through eq(3.1). In Figure 3-5, it shows that when $T_{duration}$ is larger than 0.15s, it will increase the size of the integrated packet which may get to larger than 5kbits and the packet delivery ratio could get much worse even in a small size network.

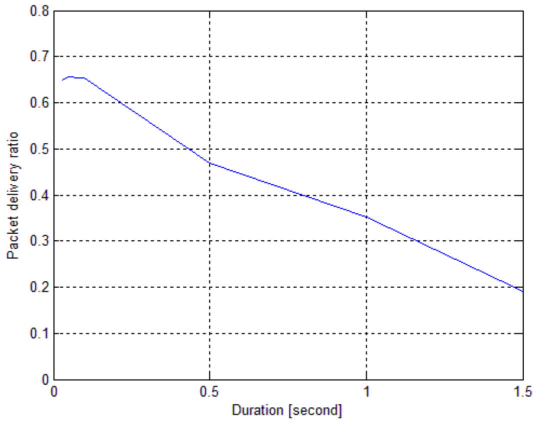

Figure 3-5 $T_{duration}$ for packet aggregation at routers

In our mechanism and the following simulations, $N_{aggregation}$ is set as 3, and $T_{duration}$ is set as 0.15s. Either $N_{aggregation}$ reaches 3 or $T_{duration}$ reaches 0.15s.

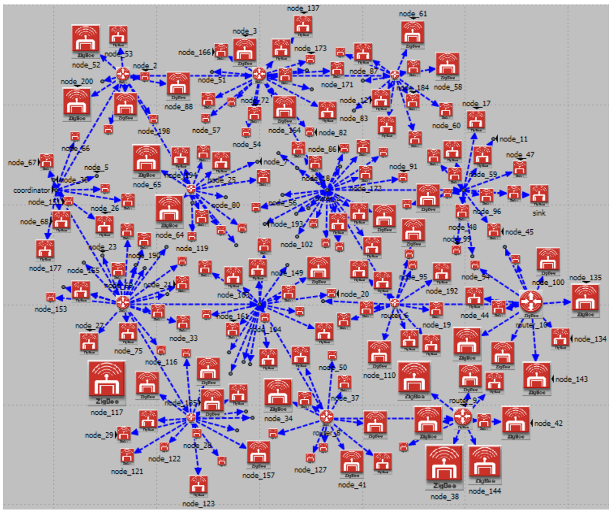

Figure 3-6 Cluster-tree topology

We consider a network with end nodes randomly distributed in a 4000*4000m^2 field which is shown in Figure 3-6 with a cluster-tree topology. The amount of end nodes varies between 10, 20, 50, 100 and 200. The packets size varies between 10, 20, 50, 100, 200, 400 and 800 bits/packet. The packet interarrival time is defined as 0.05, 0.1, 0.5, 1, 5, 10 second.

3.2 Simulation results

(a) Packet delivery ratio against the amount of end nodes and packet size:

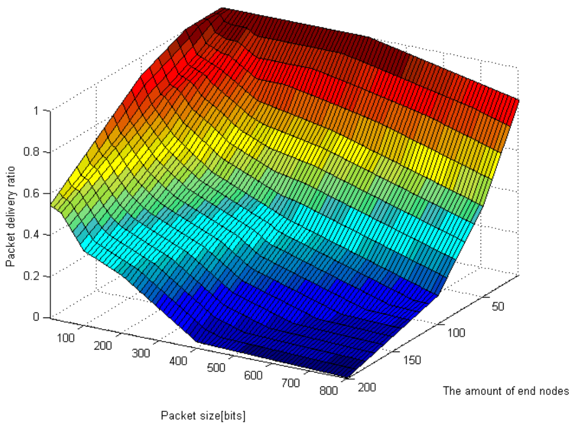

Figure 3-7 Packet delivery ratio against amount of nodes and packet size after packet aggregation

Packet size varies when the network is used for different purposes. In this case, different sizes of packets are defined: 10bits, 20bits, 40 bits, 80 bits, 200 bits, 400 bits, 800 bits. Packet delivery ratio is shown in Figure 3-7, as functions of the amount of nodes and packet size. The packet is generated to the value 1packet per second. In this scenario, every 3 received packets are integrated at routers. The redundant packet headers are dropped and it will reduce the load of the whole network.

Here, three scenarios are compared: mesh topology in Figure 2-10, cluster topology in Figure 2-6 and cluster with packet aggregation in Figure 3-6.

In mesh topology with less than 30 nodes, packet delivery ratio stays above 90% even when the packet is 800 bits. As the amount of end nodes increases to 50, the ratio drops dramatically below 80%. Especially for large size packet, the ratio reduces to 40% even in the 50-node network. On the other side, small size of packet could ensure packet delivery ratio on a relatively high level of 50% when the amount of end nodes gets to 150. For large network with more than 200 end nodes, small size of packet (less than 100bits/packet) could obtain an unexpected result with less than 20% of the packets are received. In this case, packet delivery ratio for 200 nodes only gets the value of 10% approximately. For large packet size, the network should deploy less than 50 end nodes and it can ensure that result reach to a relatively high level. Otherwise, the total packet delivery ratio will get less than 40% which is not reliable for practical applications. Mesh topology has the worst performance among the three scenarios.

In cluster topology, routers are considered as the head of the cluster with several end nodes surrounding it. In this simulation, all the nodes are using power control which will ensure all the cluster members are within the transmission range of their router. The router could forward the packets from end nodes to the sink. In this scenario, only two hops are needed for a successful transmission. The redundant packet headers are dropped and it will reduce the load of the whole network. For cluster topology in Figure 2-6, it increasingly improved the packet delivery ratio when the amount of end nodes is larger than 100. It has a 25% improvement than the mesh topology when 100 nodes are sending a 100 bits packet.

After packet aggregation, packet delivery ratio has been improved when the packet size is small than 200bits. If the packet size increases to 800bits, there are almost no packets arrived at the sink node but in the cluster topology without packet aggregation, packet delivery ratio is about 10% with 100 end nodes. This is because the size of the packets transferred by the router is approximately 2400bits which is much larger than the standard packet size. If the individual packet size is still 800 bits, less end nodes will get a much higher packet delivery ratio than the cluster topology without packet aggregation. The packet delivery ratio could get to more than 50% when 200 nodes are sending a 100 bits packet while it is 40% and 25% higher than the mesh and cluster topology respectively. Above all, packet aggregation significantly improves the performance of the ZigBee network when the packet size is smaller than 200 bits in a large size of network.

(b) Packet delivery ratio against the amount of end nodes and packet interarrival time

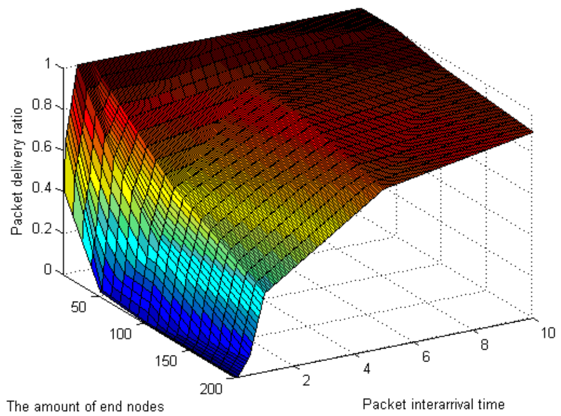

Figure 3-8 Packet delivery ratio against the amount of end nodes and packet interarrival time after packet aggregation

The packet interarrival time determines the packet rate which will have a great impact on the performance of the network. In order to capture the effect of the packet interarrival time to the packet delivery ratio, the packet are generated and sent to the destination with different values: 0.05s, 0.1s, 0.5s, 1s, 5s and 10s. The packet size is fixed to 100 bits/packet. As can be seen in Figure3-8, packet aggregation significantly increases the packet delivery ratio when there is a small size of network or the packet interarrival time is more than 1. But the packet delivery ratio remains on a lower level if there are over 20 packets are generated from the end nodes per second. Large traffic still causes collisions even with packet aggregation.

When comparing with the mesh topology in Figure 2-11 and cluster topology in Figure 2-7, it obviously illustrates that almost all the packets can be received successfully when the packet rate is less than 1 packet/s with less than 50 end nodes in all the three scenarios. There is one special situation that it reaches the best performance of packet delivery ratio when packet interarrival time is 2(0.5 packet/s packet generating rate). Even for 200 nodes, packet delivery ratio is more than 70%

while the other results are below 20%. It means that 0.5 packet/sec can be used in all scenarios to obtain the best performance. For lower packet interarrival time such as more than 0.1s (10packet/s packet generating rate), packet delivery ratio is considerably low even for small size of network. Since this case is using packet size with 100 bits/packet, it can be expected to tolerate relatively high rate when smaller size of packet is used. Although, the packet delivery ratio has 20% and 15% improvement than the mesh and cluster topology when 10 nodes are sending a packet within 0.05 second. For the cluster topology in Figure 2-7, without packet aggregation, packet delivery ratio is lower than 80% when the amount of end nodes is 200. However, packet aggregation mechanism improves the ratio to 90% especially when the end nodes don't need to send the packets frequently.

(a) Delay for the three scenarios:

Since delay is another important statistic to evaluate the performance the ZigBee network, delay is defined in OPNET as the end-to end delay of all the packets received by the 802.15.4 MACs of all WPAN nodes in the network and forwarded to the higher layer. Here, lower and upper bounds for a 95% confidence interval for mean delay are used to indicate the reliability of an estimate. In Figure 3-9, the end-to-end delay shows the results in mesh topology, cluster topology and cluster with aggregation. In the mesh topology, delay is much higher than the other two scenarios because of multi-hop. During the transmission, the packet must invoke the CSMA/CA process to access the media and it causes an excess delay in each router. Several hops will accordingly increase the end-to-end delay in mesh topology. After clustering the end nodes, only 2 hops are needed between end nodes and the sink. As a result, it decreases the chances to execute the CSMA/CA process.

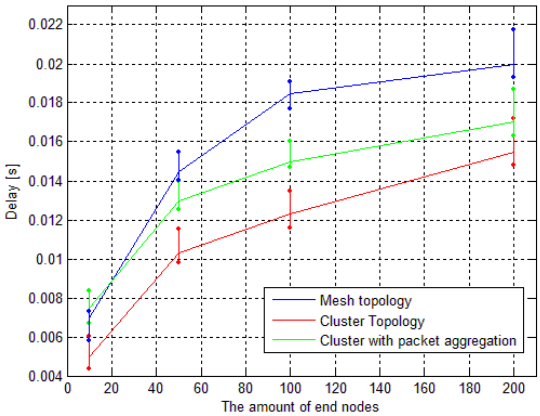

Figure 3-9 the end-to-end delay in mesh topology, cluster topology and cluster with packet aggregation

Here, 100 bits packet is generated every second (0.01 packet interarrival time) from 100 end nodes in all the three scenarios. Cluster topology without packet aggregation has the lowest delay and the packet aggregation mechanism slightly increases delay while it is still much lower than the mesh topology. When using packet aggregation, the packets are stored in the buffer with less than 3 packets. Therefore, the time for buffering the packet will cause the excess delay than the original cluster topology.

3.3 Summary

A packet aggregation mechanism is proposed in this chapter to enhance the packet delivery ratio of ZigBee networks by aggregation packets in a cluster to avoid collisions. Our simulation results show that our packet aggregation mechanism significantly improves the performance of ZigBee networks when the packet size is smaller than 200 bits in a large size network. From packet interarrival time's point of view, the packet aggregation improves the ratio to 80% especially when the end nodes don't need to send the packet frequently. After the comparison of three topologies, mesh topology has the worst performance. Cluster-tree topology could obviously increase the performance of the network. It has a 25% improvement than the mesh topology when 100 nodes are sending a 100 bits packet. In the network with packet aggregation, the packet delivery ratio could get to more than 50% when 200 nodes are sending a 100 bits packet which is 40% and 25% higher than the mesh and cluster topology respectively. During packet aggregation, the packets are stored in the buffer when the incoming packets are less than 3. Therefore, the time for buffering the packet will cause the excess delay than normal cluster topology.

Chapter 4

Fairness analysis in ZigBee Networks

In ZigBee cluster-tree networks, if the load is too heavy for routers, large amounts of packets may be dropped and unfairness may be caused. Hence, it is very important to explore the fairness issues in ZigBee networks. In this chapter, we adopt three different fairness models to simulate and analyze the fairness issues in ZigBee networks. The simulation results show that severe unfairness may happen in ZigBee networks with large amount of nodes or large packet size.

4.1 Fairness models

Quantitative fairness metrics are the fairness metrics that can reveal fairness property by real numbers. In this chapter, two quantitative fairness metrics (Jain's index and entropy metrics) and one qualitative fairness metric (Max difference) are used to evaluate fairness for sent packets, packet delivery ratio and delay.

4.1.1 Jain's Index

Jain's index or the so-called "Fairness index" was first proposed in [31] by Rajendra K. Jain, as the pioneer of fairness research in computer science. Jain's index is defined as,

$$f(\mathrm{X}) = \frac{[\sum_{i=1}^{n} x_i]^2}{n\sum_{i=1}^{n} {x_i}^2} \qquad (4.1)$$

From Eq (2.2) we consider PDR_i as the node packet delivery ratio. In our following fairness analysis, x_i in Eq (4.1) is defined as PDR_i for node i. $Delay_i$ and P_i^s respectively denote the delay and sent packets for node *i*. For Jain's index, the allocation tends to be fairer if the index value is closer to 1. In the following part, it shows Jain's index for sent packets, packet delivery ratio and delay. There is much difference when packet aggregation is used.

4.1.2 Shannon's entropy

Entropy was introduced by Shannon in [32] originally as entropy metric instead of fairness metric.

The Shannon's entropy is defined as

$$H(\mathrm{P}) = \sum_{i=1}^{n}(p_i \log_2 \frac{1}{p_i}) \quad (4.2)$$

Where $p_i = \frac{x_i}{\sum_{i=1}^{n} x_i}$.

We can also use PDR_i as x_i for node i to analyze the fairness of node packet delivery ratio in the network. Based on the character of Shannon's entropy, $H(\mathrm{P})$ is larger when the allocations are fairer.

4.1.3 Max difference

Max difference or bottleneck optimality has been studied widely and implemented in many applications, such as flow control, bandwidth sharing, radio channel accessing [33][34][35].

$$Md = \max(x_i) - \min(x_i) \quad (4.3)$$

According to the definition of max difference, it is smaller when the allocations are fairer.

4.2 Simulation results

4.2.1 Jain's Index

(a) Sent packets

The sent packets P_i^s can be defined as the packets which are successfully received by the router. Not all the packets are equally transmitted by the end nodes and because of collisions in the routers. In Figure 4-1, it illustrates Jain's index for sent packets in terms of packet size and packet interarrival time. In normal cluster topology, only small size of network could reach fairness at about 1. The other situations are much worse than cluster with packet aggregation. After aggregating the packets in routers, only 200-node-network with traffic of 800 bits/second get the worst fairness at 0.8. Because the integrated packet with the traffic of 800 bits/second may exceed 4000 bits which is too large for routers to delivery. Therefore, some of the super packets may be dropped and will dramatically affect fairness of network. In terms of packet interarrival time, Jain's index shows better results for packet aggregation in average especially when the nodes generate less packet per second because more packets will be successfully sent into a supper packet.

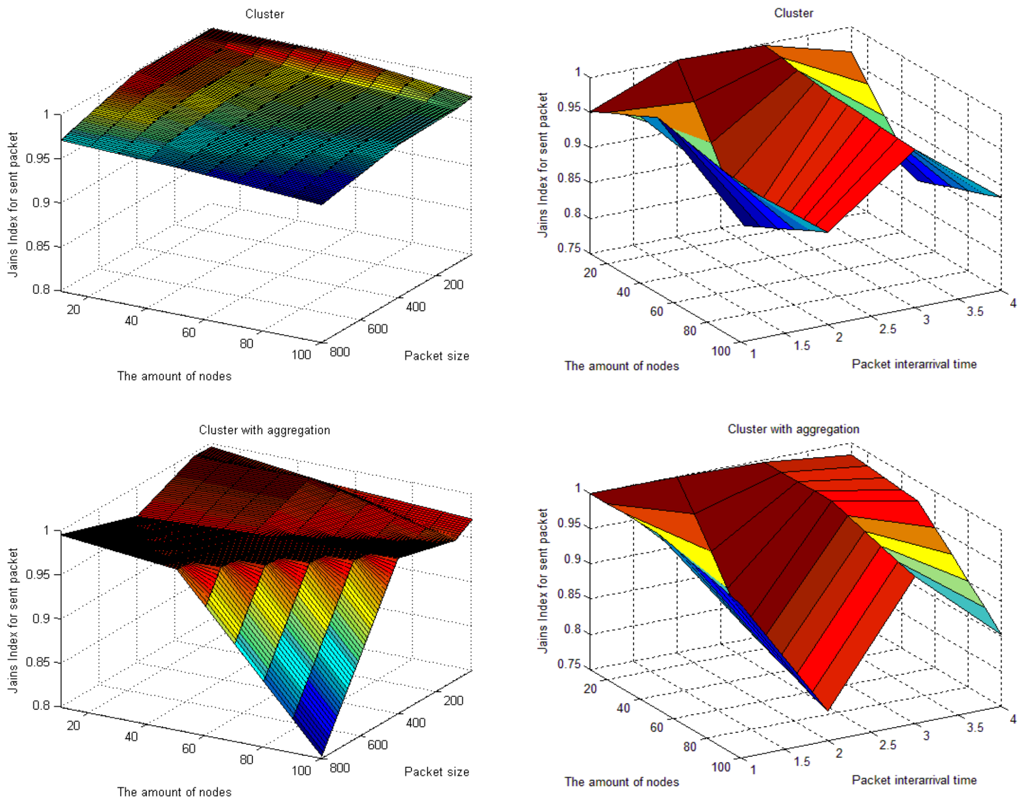

Figure 4-1 Jain's index against packet size and interarrival time for packet sent

(b) Packet delivery ratio

PDR_iin Eq(2.2) is used to analyze the fairness in ZigBee networks. Since unfairness happens in sent packets, we also can't guarantee all the sent packets are successfully received by the sink. In Figure 4-2, it indicates that the fairness is much worse in a larger network with huge traffic size in terms of packet size and packet interarrival time. In addition, packet aggregation mechanism slightly improves the fairness for packet delivery ratio.

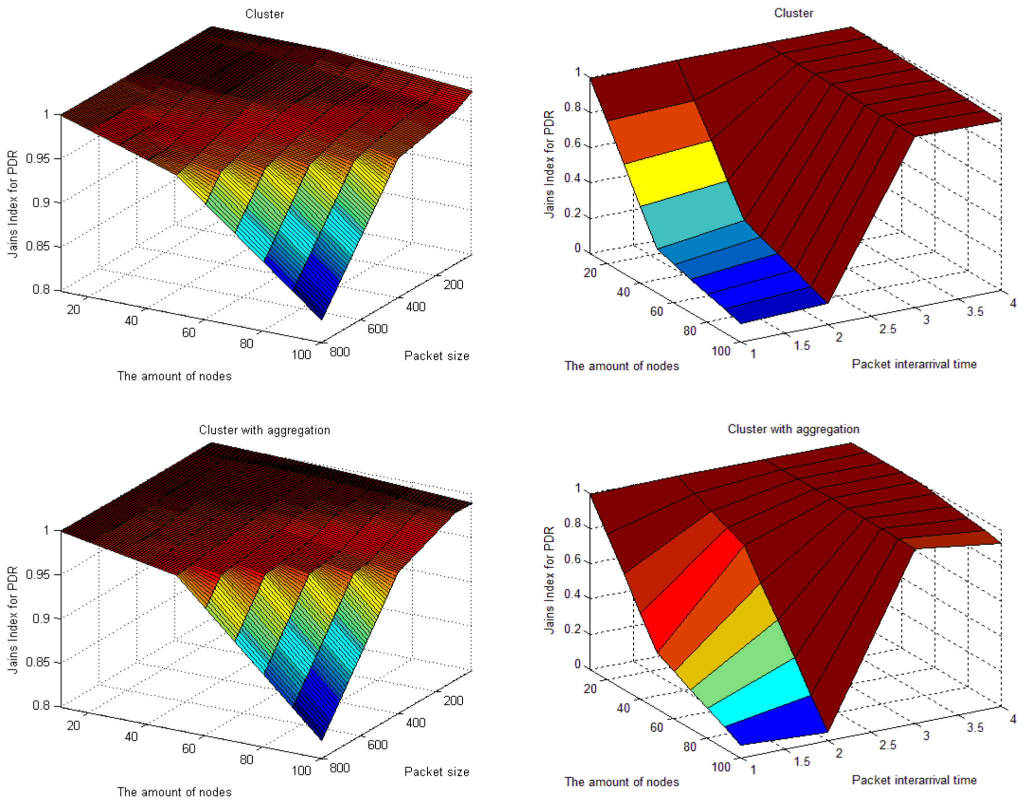

Figure 4-2 Jain's index against packet size and interarrival time for packet delivery ratio

(c) Delay

$Delay_i$ is used for fairness analysis with node delay. $Delay_i$of each node represents total delay between creation and reception of application packets generated by a specific node. End nodes should wait for different backoffs before access the medium and it causes the differences of $Delay_i$among all the nodes. Delay for Jain's index in Figure 4-3 shows a huge difference between normal cluster and aggregation cluster in small networks with varied packet size, because some nodes would have equal delay within a super packet. There's also much increase for delay with varied packet interarrival time in small networks. Although, in large network with up to 200 nodes, fairness gets worse than normal cluster topology because some super packet may cost excess time to transmit. Unfairness happens for delay in a large network with traffic of 800 bits/second.

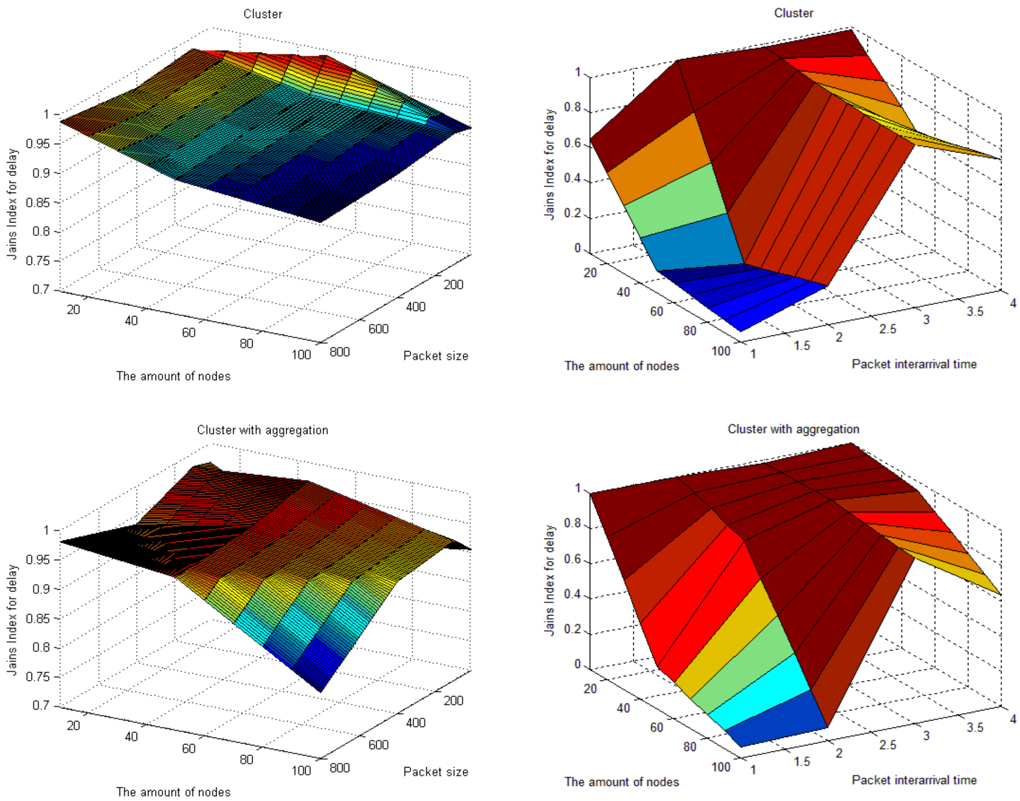

Figure 4-3 Jain's index against packet size and interarrival time for delay

4.2.2 Shannon's entropy

(a) Sent packets

Shannon's entropy for sent packets doesn't show obvious difference between normal cluster and aggregation cluster network in terms of packet size and packet interarrival time.

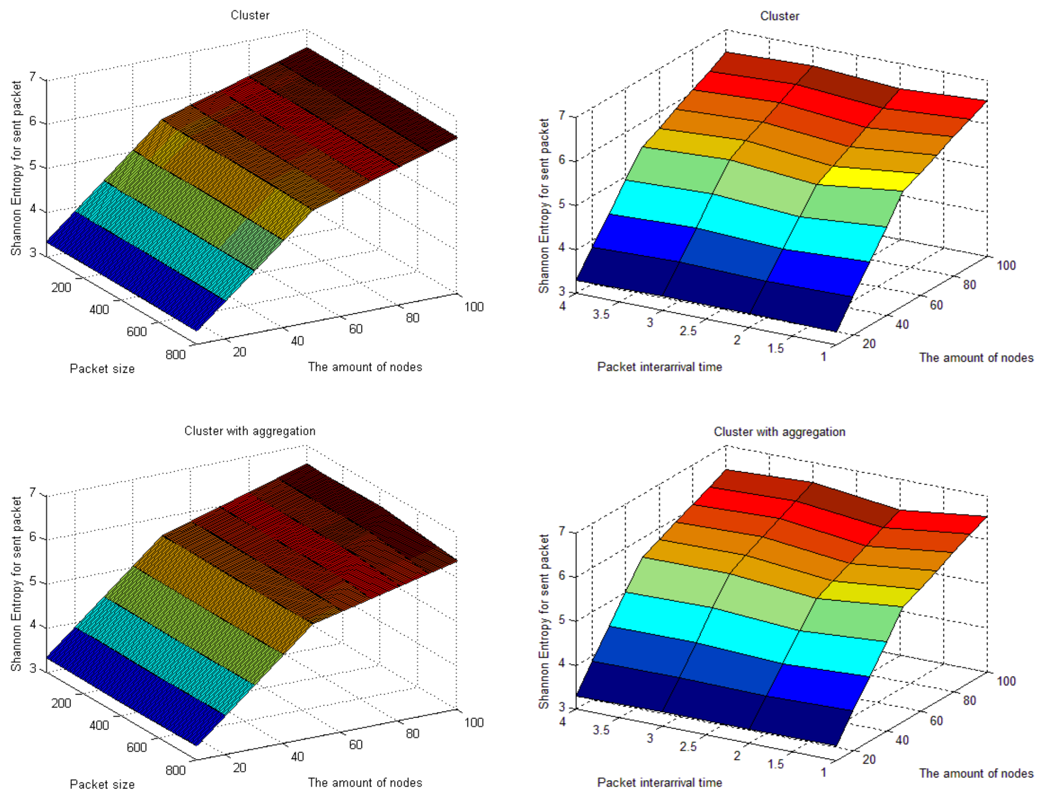

Figure 4-4 Shannon's entropy against packet size and interarrival time for packet sent:

(b) Packet delivery ratio

There's also not much obvious difference between normal cluster and aggregation cluster network in terms of packet size and packet interarrival time for packet delivery ratio in Shannon's entropy.

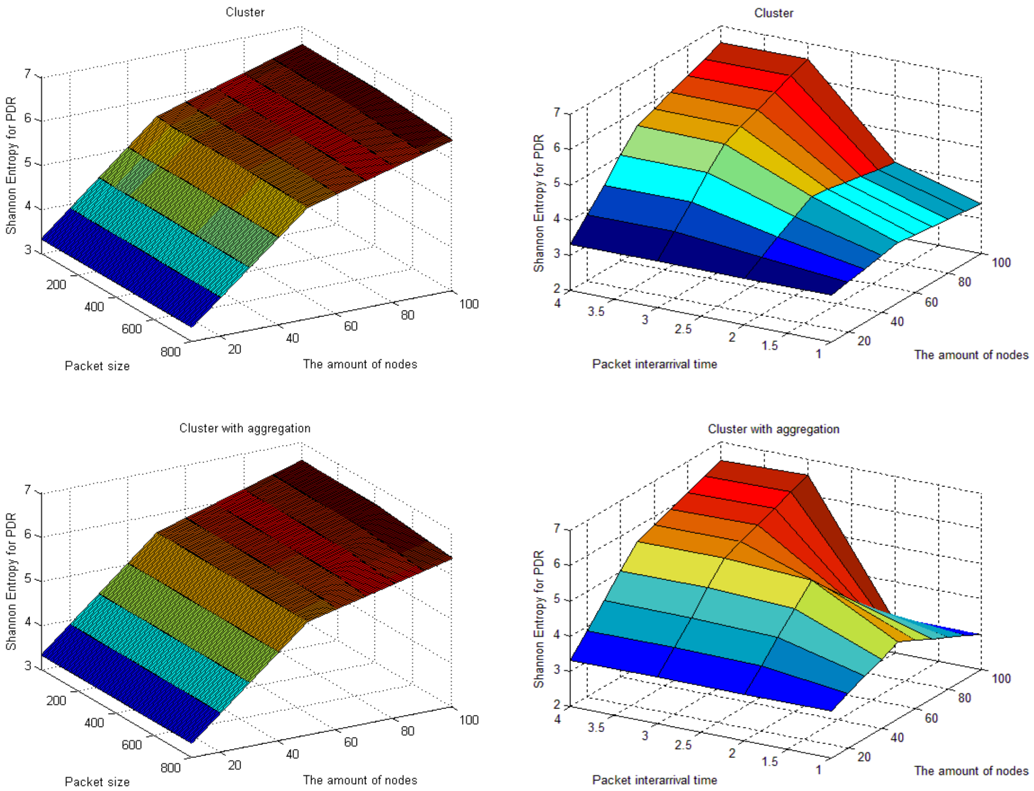

Figure 4-5 Shannon's entropy against packet size and interarrival time for packet delivery ratio:

(c) Delay:

Shanon's entropy for delay in Figure 4-6 illustrates that only large network with huge traffic size could get improvement after packet aggregation is involved in cluster topology.

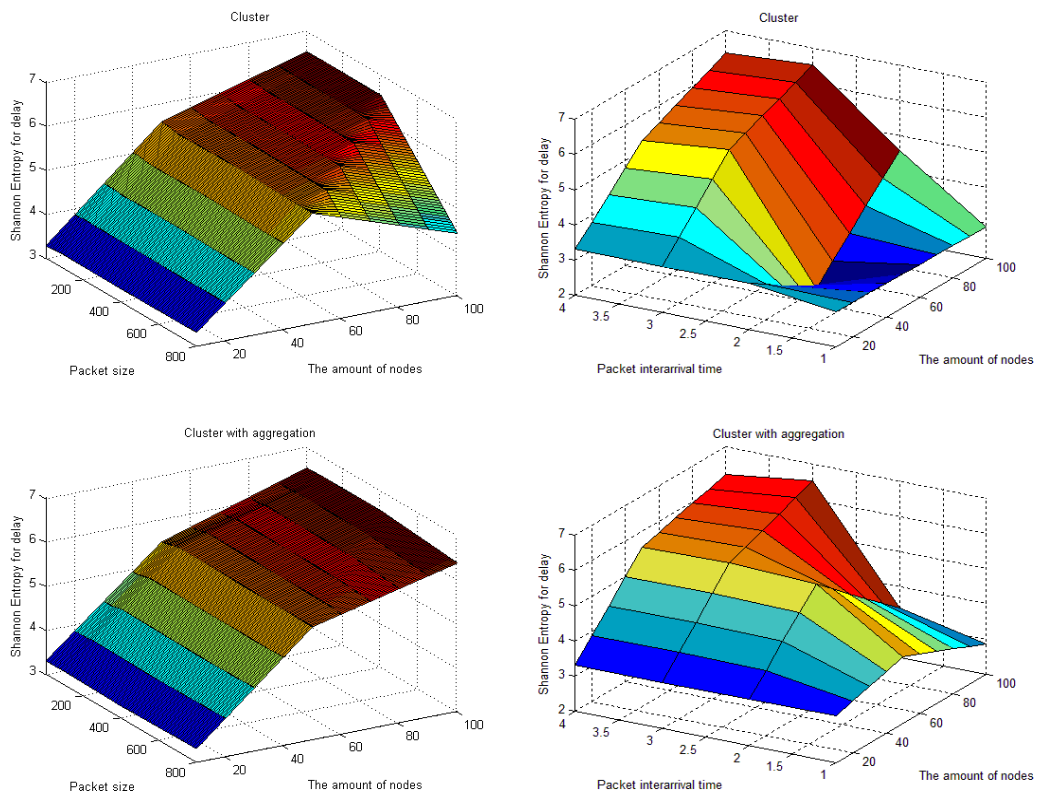

Figure 4-6 Shannon's entropy against packet size and interarrival time for delay:

4.2.3 Max difference

(a) Sent packets:

For Max difference fairness, small value shows better fairness. The result for sent packet in this scenario is the ratio between Max difference value and total transmitted packets. It shows that fairness in cluster with aggregation is worse than normal cluster. The reason for that is because some nodes may send more packets which can be compressed in a super packet without fairness control mechanism.

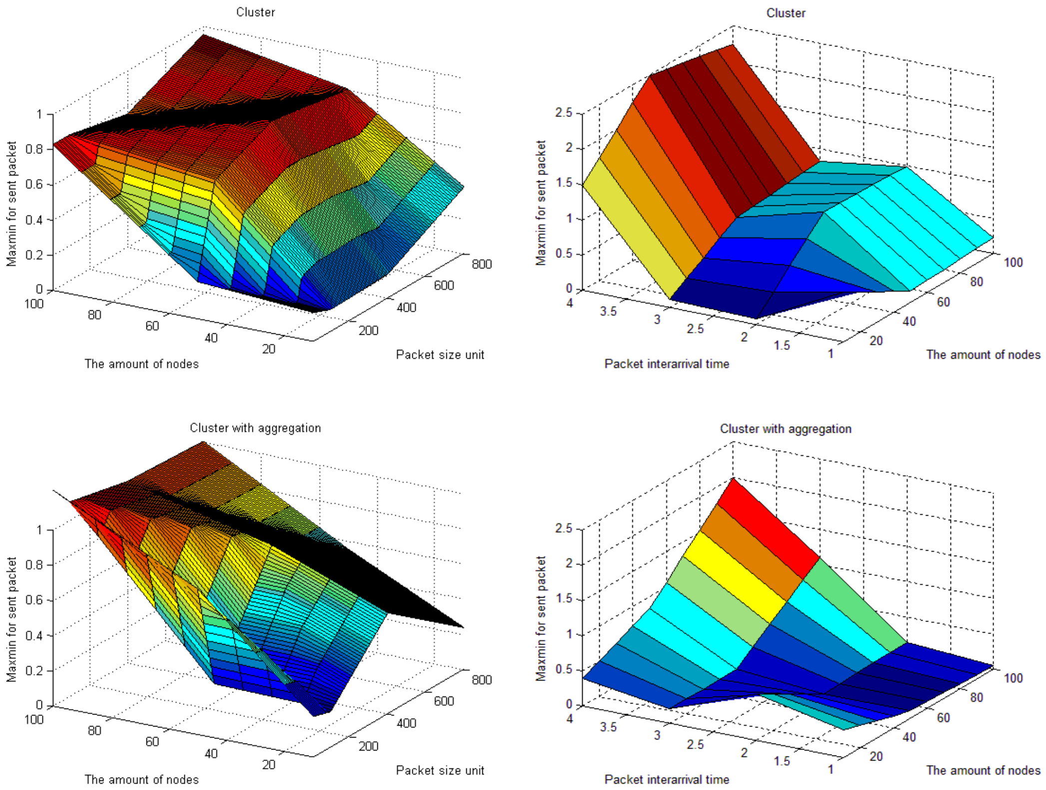

Figure 4-7 Max difference against packet size and interarrival time for packet sent

(b) Packet delivery ratio:

There's a slight difference between normal cluster and aggregation cluster when the network is without too much traffic. The gap between max and min is smaller after packet aggregation for packet delivery ratio. Instead of dropping the packets, packet aggregation may save some packets in a busy router because of fewer collisions. The shape for packet interarrival time is flat except large networks after aggregation and it illustrates much better fairness.

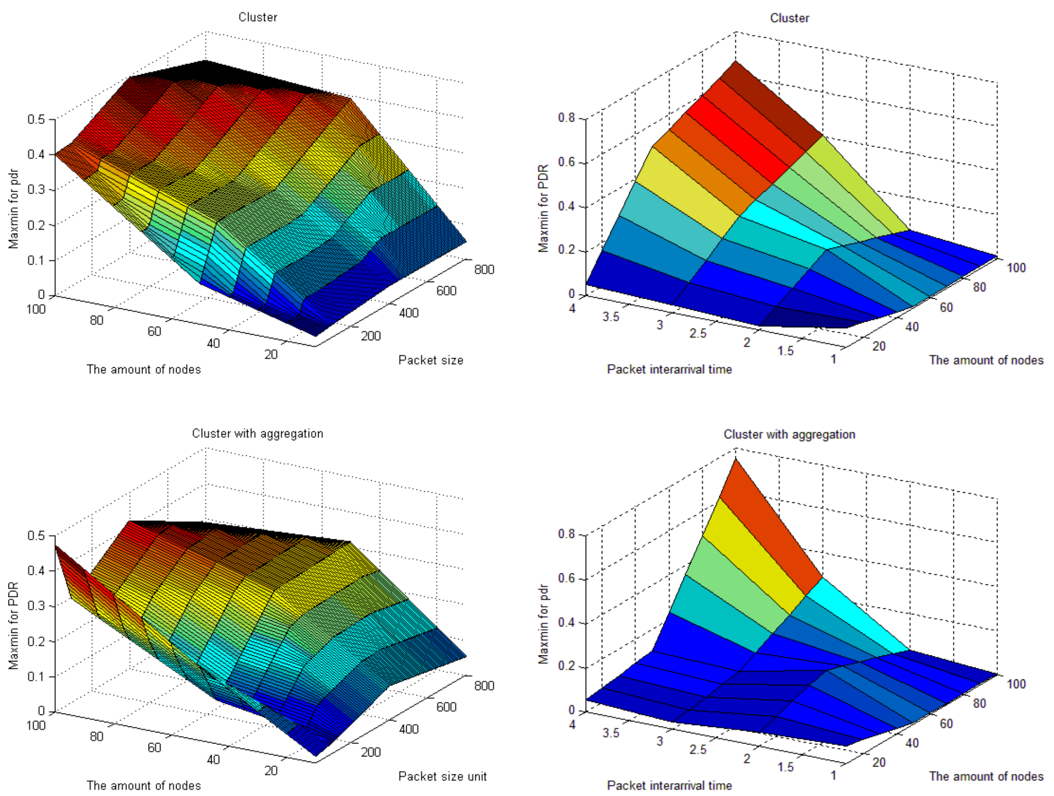

Figure 4-8 Max difference against packet size and interarrival time for packet delivery ratio:

(c) Delay:

The results for delay in Max difference fairness are much better in small networks in terms of packet size and packet interarrival time. The shape for aggregation is much smooth with varied packet size. It shows better fairness in these situations for delay while it means delay for most nodes are controlled within a certain range without a sudden increase.

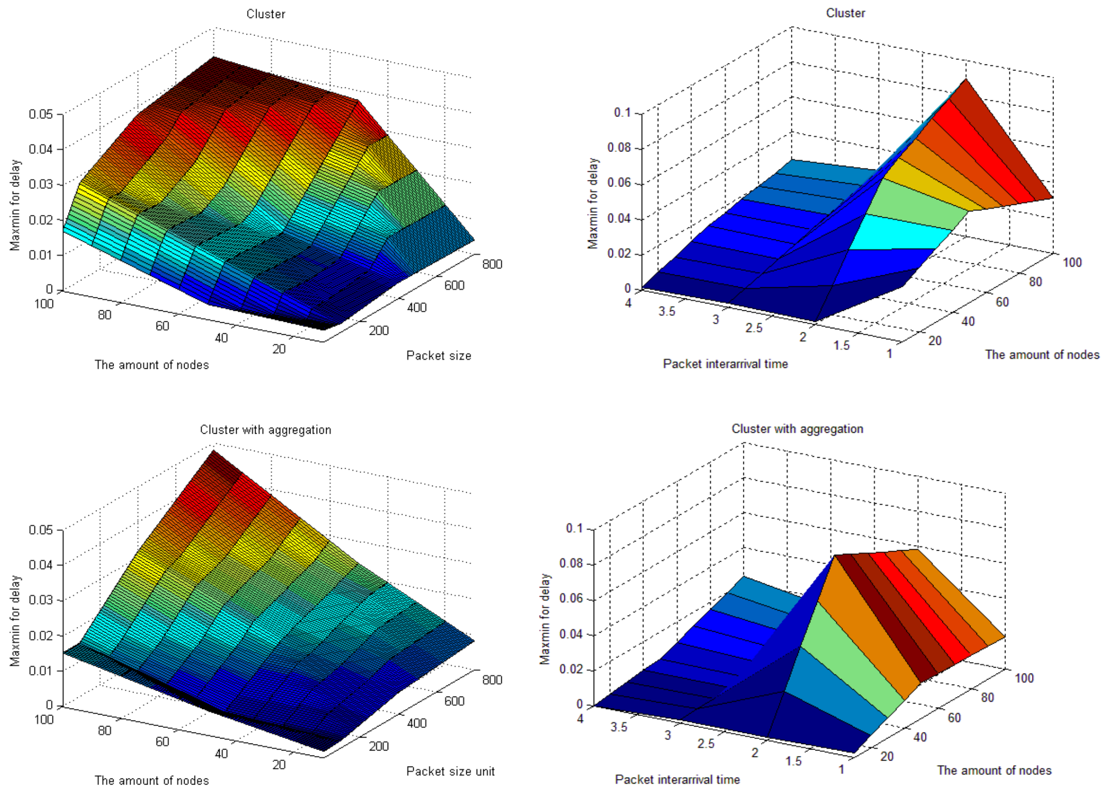

Figure 4-9 Max difference against packet size and interarrival time for delay:

4.3 Summary

To evaluated fairness in ZigBee network, packets are traced to show the packet delivery ratio of each end node. The simulation results show that not all the nodes have the equal chance to transmit the packets and successfully complete the process of transmission. If the network is small with less than 50 nodes, end nodes could achieve better performance of fairness because of fewer collisions. However, if the ZigBee network is with lots of nodes, and the traffic is heavy, then severe unfairness may happen.

Chapter 5

The intra-cluster fairness mechanism

Fairness models are employed to analyze fairness in ZigBee networks in Chapter 4. The results show that severe unfairness happens in plenty of cases. According to the results, firstly, not all the nodes have the equal right to access the network. Secondly, at the sink node, the received packets are not equally generated from nodes. Therefore, how to guarantee each node have the fair chance to send and transmit the packets successfully is an important issue in ZigBee networks. Firstly, we should concern the fairness of nodes in the same cluster which may generate packets with the same information. Further, we should also consider the fairness of routers to balance the capacity of the router and finally achieve fairness of the whole network. Hence, intra-cluster and inter-cluster fairness mechanisms are proposed in this thesis. Intra-cluster fairness is to balance the throughput of all the members inside a certain cluster. Inter-cluster fairness is to balance the throughput of all the routers which are the heads of clusters. Eventually, fairness in the whole network can be achieved. The intra-fairness mechanism is proposed in this chapter and the inter-fairness mechanism is described in Chapter 6.

5.1 The intra-cluster fairness mechanism

As shown in Figure 5-1, we define two types of ZigBee fairness: intra-cluster fairness and inter-cluster fairness. Intra-cluster fairness is a fairness established by end nodes in a single cluster and an inter-cluster fairness is a fairness established by several routers of different clusters. The same cluster members are defined as groups of devices that share the same channel information and use the same bandwidth. Either a ZigBee router or ZigBee coordinator can be a router. ZigBee end nodes are the member of a cluster in cluster-tree topology. For our simulations, we assume a stationary network without mobile nodes in the network. Inter-cluster fairness is the balance between routers.

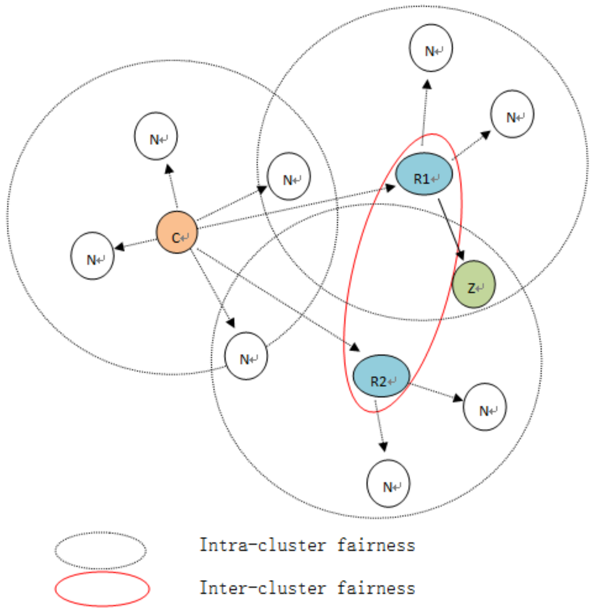

Figure 5-1 Intra-cluster fairness and Inter-cluster fairness

The proposed intra-cluster fairness mechanism is to make the router select the packets in the cluster while different nodes can be chosen to complete the process. When the number of received packets from one end node is more than the average level, router should delay the packets and process the packets from the other nodes. After the average number increases to a level higher than the previous one, the delayed node can deliver the packet again. This mechanism uses ‘average feedback’ to balance the packets from all the members in the same cluster. After comparing the total transferred packets with ‘average feedback’, the router can choose whether the node can access the network and send the packets.

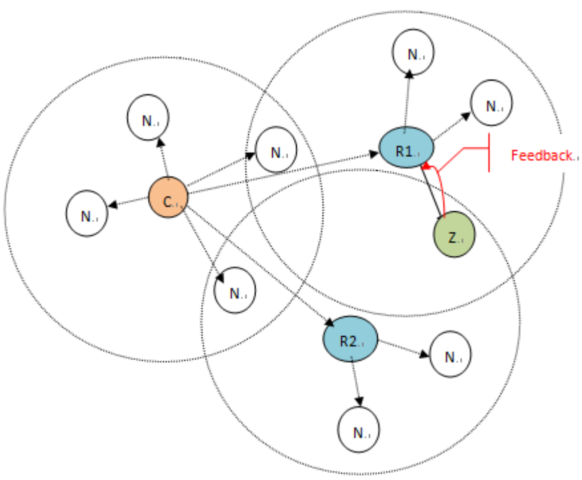

Figure 5-2 Intra fairness mechanism

The procedure is as following:

```
If packet.type = data packet
   For i=1 to number of cluster members
           Router_count= Router_count +Node_count
   Next
   Mean_count= Router_count/ number of cluster members
   If Node_count < Mean_count
     Send retransmission request
     Destroy the packet
   End if
End if
```

5.2 Simulation results

5.2.1 Packet delivery ratio

The packet delivery ratio doesn't show much difference between aggregation and intra-cluster fairness, because almost all the packets are preceded during the transmission. The only difference is the processing time.

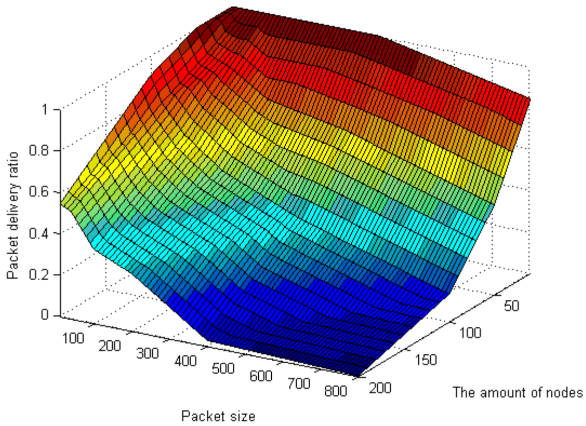

Figure 5-3 Packet delivery ratio for mesh, cluster, aggregation and intra-cluster fairness

5.2.2 Delay

The black line shows delay for the intra-cluster fairness mechanism which has a 0.001s increase than aggregation cluster. The reason is that excess processing time makes the packet wait in the buffer. Only if the feedback average amount exceeds the sent packet, the end node could continue to send the packet while it means the number of packet from one node must be smaller than the feedback average amount.

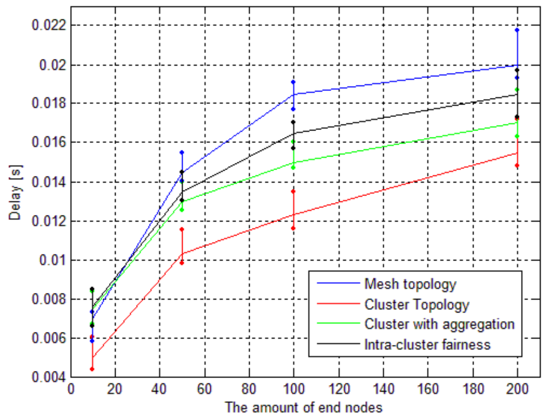

Figure 5-4 Delay for mesh, cluster, aggregation and intra-cluster fairness

Here, lower and upper bounds for a 95% confidence interval for mean delay are used.

5.2.3 Fairness

5.2.3.1 Jain's index

(a) Sent packets:

In Figure 5-5, Jain's index shows a high level of fairness when the network and traffic is small. But a dramatic decrease happens when there are 100 nodes with traffic of 800 bits/second. Unfairness still exists in this situation which should be concerned for further improvement. For packet inter arrival time, large size of network still has fairness issue regardless of the traffic size.

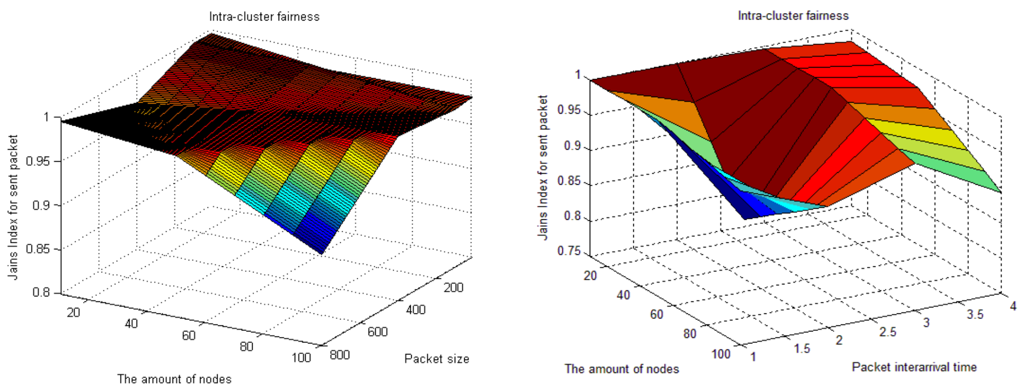

Figure 5-5 Jain's index against packet size and interarrival time for packets sent

(b) Packet delivery ratio:

Figure 5-6 illustrates a much better fairness in packet delivery ratio when the nodes generate fewer packets per second. Small packet size still gets the best fairness result even in the network with over 100 nodes. On the other side, large size of network still has fairness issue when the packet size goes up to 800bits/second.

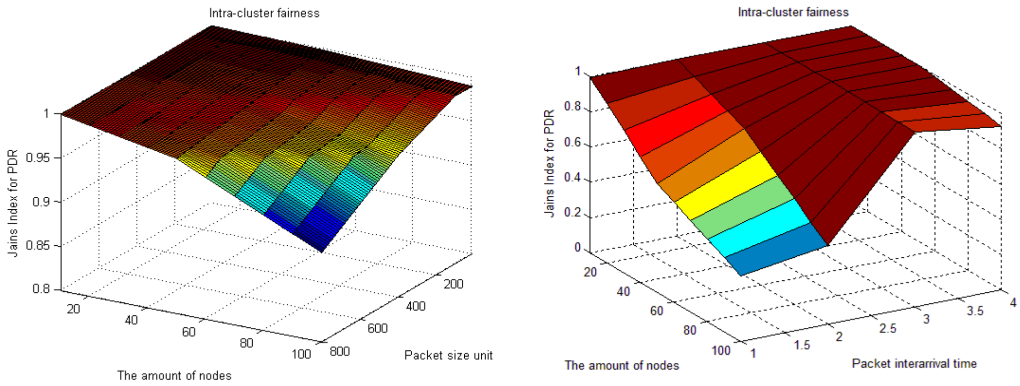

Figure 5-6 Jain's index against packet size and interarrival time for packet delivery ratio

(c) Delay:

From the result of Jain's index for delay, it has a smooth shape around 0.93 except large network with huge traffic size. It means almost all the nodes can get the same packet delivery ratio through intra-cluster fairness mechanism. The effect for large network with huge traffic size is still not obvious.

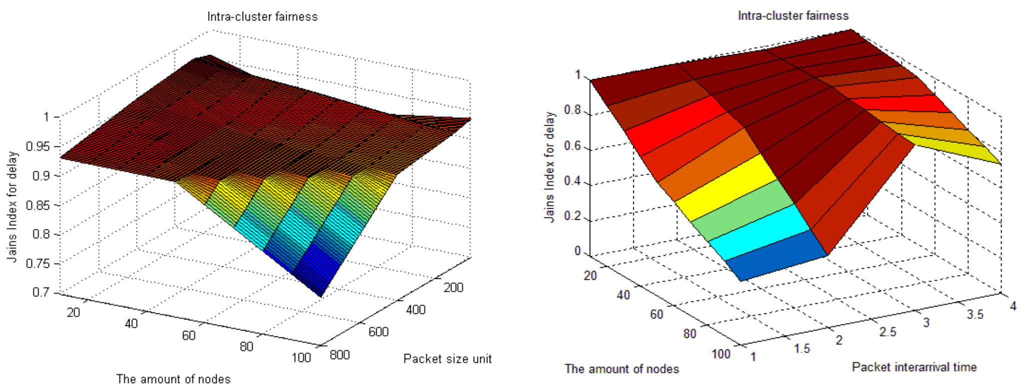

Figure 5-7 Jain's index against packet size and interarrival time for delay

5.2.3.2 Max difference

(a) Sent packet:

The max difference value in our simulations is the max difference value over total sent packets. The results illustrate that even with large traffic size, the max difference fairness happens regardless of network size. And the gap between small networks is small (0.2).

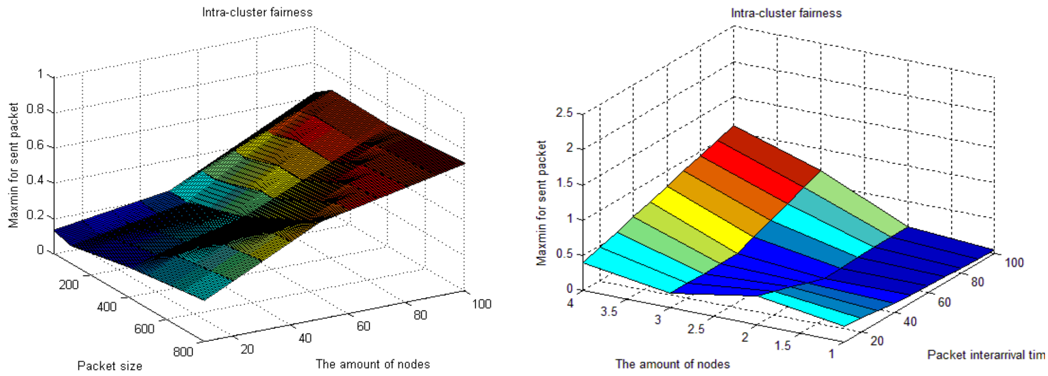

Figure 5-8 Max difference against packet size and interarrival time for packet sent:

(b) Packet delivery ratio:

The reason for small numbers in large network is that there are not many packets arrived at the sink node. Only the successful transmission could contribute to the simulation results. Thus, the large network with large traffic size shows little information for us to evaluate the performance of the network that. We only consider the useful information with normal size of network when there is not enough collected information. The flat shape in packet inter-arrival time result shows a great fairness achievement after packet aggregation.

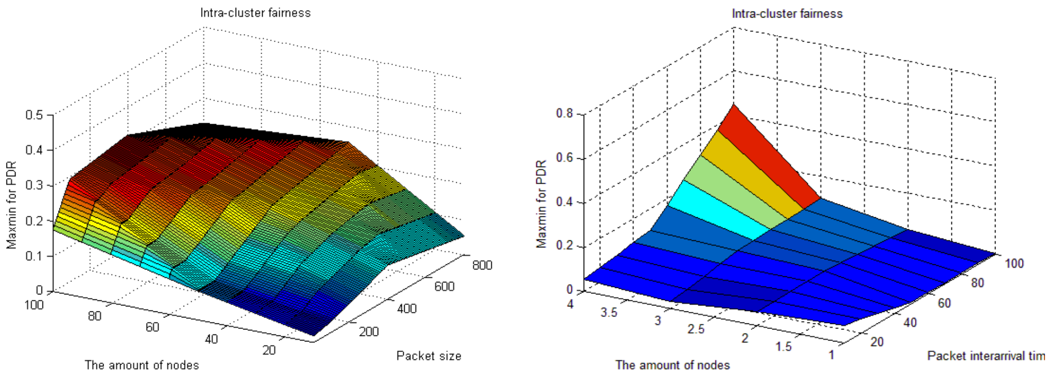

Figure 5-9 Max difference against packet size and interarrival time for packet delivery ratio:

(c) Delay

In Figure 5-10, the results for delay illustrate that unfairness exists in large network while small size network would have much fairy delay. That’s because when the amount of nodes grows up to 100, the packets are postponed to wait in the queue and it would cost excess time to deal with large amount of packets.

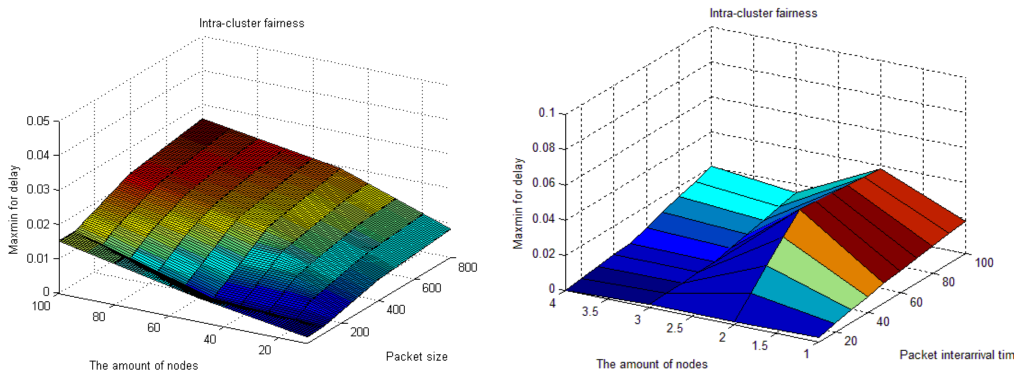

Figure 5-10 Max difference against packet size and interarrival time for delay:

5.3 Summary

From the simulation results for fairness, intra-cluster fairness mechanism has significantly improved the fairness. Especially for large size of packet and large number of end nodes, it has a 9% increase comparing to normal cluster-tree network for fairness in packet delivery ratio. But for delay fairness, it shows a 5% decrease in average in Jain's index fairness model. Because some node needs to wait for a back off time to send the packet until the feedback average amount exceed the number of packets it has already sent. Therefore, these delayed nodes would have an excess delay than average.

However, for the performance of packet delivery ratio, intra-cluster fairness doesn't show an obvious effect. The total delay for the network also got 0.001s increases than packet aggregation cluster network. We can also notice that packet aggregation cluster got approximately 0.001s increases than normal cluster network. Because the router should wait for 3 packet time to aggregate a super packet, almost 2/3 for the packets should be delayed for aggregation.

Figure 5-11 shows that all the members in the same cluster have almost the same ratio around the average level. However, different clusters have different levels of average packet delivery ratio. Therefore, inter-cluster fairness should be introduced to the network to achieve fairness in the whole ZigBee networks. In other words, all the clusters can get approximately the same level of packet delivery ratio no matter how many nodes in a single cluster.

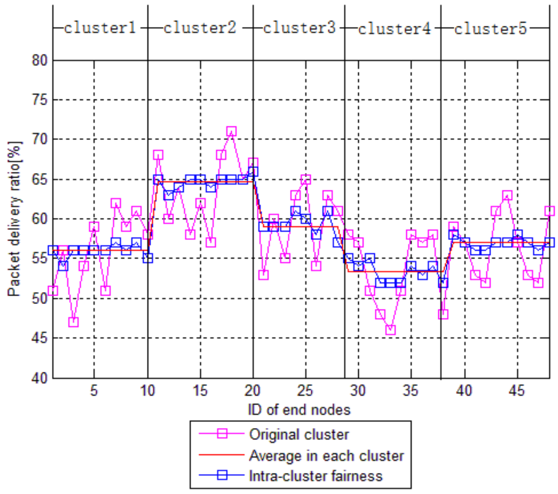

Figure 5-11 Packet delivery ratio from 20 nodes

Chapter 6

The inter-cluster fairness mechanism

With the intra-fairness mechanism, members in the same cluster could get almost the same level of delivery ratios. However, unfairness still exists among different clusters and the result is show in Figure 5-11. Hence, the inter-cluster fairness mechanism is proposed to guarantee the fairness amongst clusters in this chapter. Based on IEEE 802.15.4, ZigBee adopts AODV and tree routing for different topologies. We consider the intra-cluster fairness cluster-tree topology. The scheme for inter-cluster consists of several scenarios according to different traffic size.

6.1 ZigBee routing

The ZigBee specifications define the routing and application layer. ZigBee uses cluster AODV routing and tree routing. AODV routing may generate a lot of control traffic and will wastes resource. Cluster-tree routing is simple and reduces the routing overhead, uses less resource.However it may be inefficient when two nodes have completely different parent nodes. The packets may be transferred through many hops to get to the destination.

6.1.1 In mesh topology

Mesh routing protocol (AODV) is based on routing and route discovery tables with the path cost metrics. AODV routing belongs to reactive routing [36] which finds the route on demand but causes excessive flooding .Reactive routing will increase the latency when finding the route. In ZigBee network, coordinator and routers maintain routing tables. The mesh topology is established in Figure 6-1 with one ZigBee coordinator on the left and one sink on the right. All the devices in mesh topology are FFDs. Therefore, every node could forward the packet to the neighbor node. Most of the 200 end nodes send traffic to the sink indirectly due to the limited communication range of the end node.

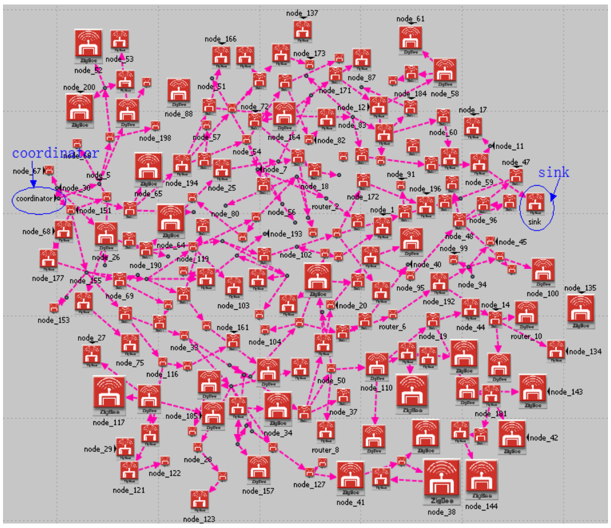

Figure 6-1   Topology of the non-cluster network

6.1.2 In cluster-tree topology

Cluster tree based proactive routing provides fast responses to topology changes in the network. This protocol periodically maintains the lists of destinations and routes. However, it will cause maintenance data overhead when the routers are maintaining routing information for all the destinations. In cluster-tree topology, the coordinator is the root of the network and it has routers as its child nodes. Both coordinator and routers are FFD as the head of each cluster, whereas the end nodes are Reduced Function Devices (RFD). As the child of the routers, the end node is not able to communicate to another end node and covered by the nearest routers. For delivering packets to the sink node, the end nodes must pass the packet to the head of the cluster and then the packet can be continually transferred to the sink node through the tree routes. For this kind of topology, it’s not as reliable as the mesh topology. When a router fails, all the members of the cluster are cut off from connecting to the other nodes in the network.

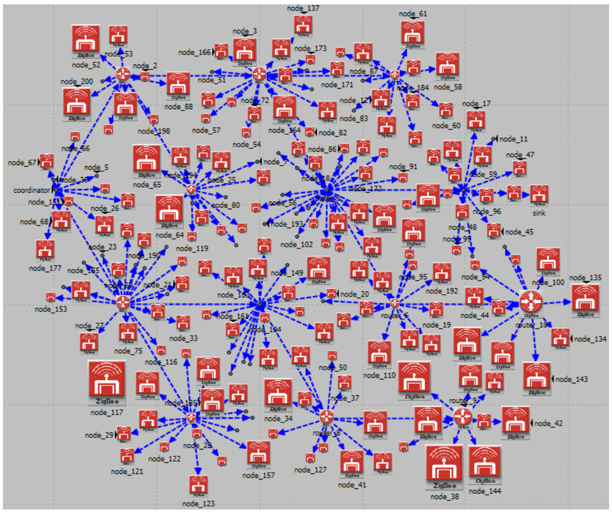

Figure 6-2 Topology of the cluster network

In cluster tree routing, routers forward the packet from the end nodes to the sink node. The next address of the end node is his parent node when end nodes send packets towards the sink. Cluster-tree routing could reduce the routing control packets. Tree routing is simple and use less resources, however it can be inefficient when two devices are in different clusters with a short distance. Packets may be transferred through many hops using tree routing but maybe one hop path could finish the transmission when AODV routing is used. When the cluster router is shut down, all the end nodes within the cluster will not work anymore. To overcome this problem, the on-demand AODV routing could work when the route has problems. If the node wants to send the data packet without routing information, it should firstly initiate a route discovery process to find the shortest path to the sink. On the other side, this process will cause a lot of energy consumption when there are over 100 nodes in the network. The total received traffic is pretty low due to the heavy collisions with large amount of end nodes using AODV routing.

Procedure of cluster-tree routing

Due to the definition of intra-cluster fairness mechanism, it is designed to balance the packet transmission within the cluster. That mechanism can be considered as fairness improvement for the intra-cluster. When the traffic in one cluster is pretty large that the routers can't handle, packet will be dropped and the unfairness will happen among different clusters. This is the issue that the next routing mechanism will be introduced.

The network is divided into several clusters. A cluster consists of several nodes with a router and cluster members(ZigBee end device). According to the rules of ZigBee cluster, only ZigBee coordinator and ZigBee router have the qualification of becoming a router. ZigBee end nodes could be the member of the cluster.

In Figure 6-3, it illustrates the steps for constructing the cluster in standard ZigBee network.

1. The initial cluster is constructed with coordinator as a router. The coordinator then searches the neighbor nodes within its transmission range. Such as coordinator finding node 1,2,3, R1 and R2 in its transmission range.

2. If one router is found in the first step as the member of the cluster, it starts searching for other nodes within its radio range. This router has the ability to become the head of a new cluster. If the router can't find a child node then it will have a higher right to become head when a new node is joining the network within this router's transmission range. For example, R1 found node 5, 6 and 7.

3. The found routers in an exist cluster will proceed the same process as step 2. Once the route is found, the information will be stored in the routing table of FFD (ZigBee coordinator or routers).

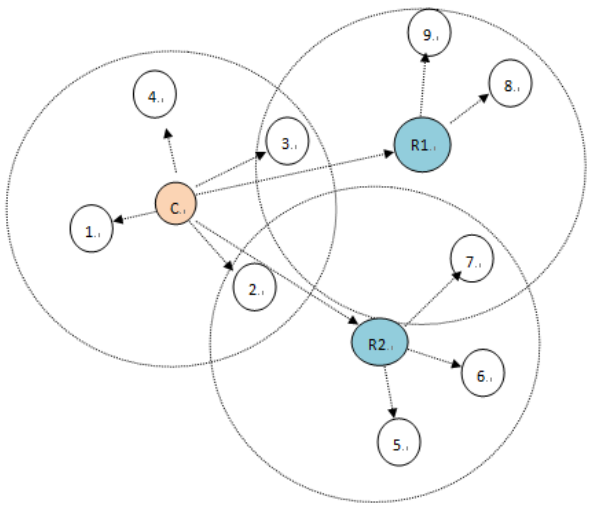

Figure 6-3 cluster-tree routing

As can be seen in Figure 6-3, node7 is in the transmission range of both router 1 and 2. Router 2 is the header of cluster 2. The scenario can be designed as: Router 2 is the next hop in the current routing table but the traffic in cluster 2 is much more than that in cluster 1 which has only 2 end nodes in the cluster. Energy and collision issues would be brought to cluster 2 while router 1 can easy handle all the traffic. Here router 2 may drop the packets from the cluster members and effect the whole packet delivery ratio in the network. To increase the stability and efficiency, the cluster radius and the amount of end nodes should be well controlled. But that is not enough to balance the traffic and increase the fairness of the whole network since not all the nodes send the same traffic all the time. There are several existing clustering protocols to select routers, stable clustering and controlling cluster radius or cluster size. However, for ZigBee cluster routing, this report will introduce a traffic-balance routing method which could make a bounce routing from an end node to different routers.

6.1.3 Router Capacity

Network capacity is usually quoted as packets per second. The assumption is that routing processing is the bottleneck with software routers and switches. Most processes are handled by hardware and it will create less of a bottleneck. This is usually for small IP packets, routed where feasible. Different routers have different performance curves for packet size, processing complexity. For different routers, they have different functionalities and scope, which is called the heterogeneity of devices. The capacity of the router consists of connectivity, mobility, available power and memory. The capacity contains various properties of the routers and addresses the heterogeneity of the devices.

Available resources (R), available memory (A) and available power (E) will be taken into account. The available resources R_i for router i is in Eq.10.1 [38], where the parameter X_1 is the weight factor.

$$R_i = X_1 A_i E_i \tag{6.1}$$

The definition of R addresses the heterogeneity of routers. What’s more, the contribution of this definition is mainly considering energy efficiency in router selection when the node needs to determine which router should be chosen for the a potential router with higher battery power and memory. It’s an energy-efficient solution when the router has higher capacity. The node within the routers transmission range may select this router to transmit the packet.

6.2 Inter-cluster fairness mechanism

To achieve better performance for selecting the router with higher capacity, there are several steps before an isolated node can successfully transmit a packet to the destination: 1. how a node can determine that the current router is busy with scheduling the packets; 2. how this node can find another router within its range; 3. how the potential router can announce the status that it is; 4. how the potential router to process a join request.

Firstly, in the proposed mechanism, when the packet needs to be retransmitted, MAC beacon should be used for end node to detect if the routers are within its transmission range.

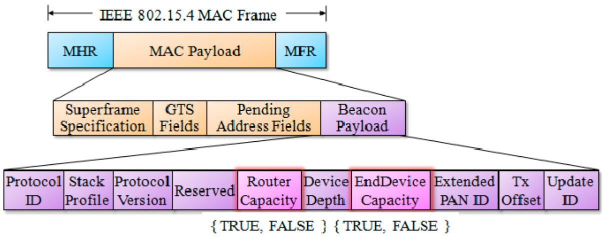

Figure 6-4 Format of ZigBee MAC beacon[37]

Figure 6-4 illustrates the format of MAC beacon payload defined in ZigBee. Router Capacity field has a TRUE/FALSE value that shows whether the beacon broadcasting node has capability to accept a ZigBee end device as its child. Since MAC beacon can be sent periodically in ZigBee network, it will not increase the load of the whole network which will cause the communication overhead. But only the ZigBee coordinator and routers can send the MAC beacons. For the ZigBee end device, a notification should firstly be sent to the routers within the transmission range of the node. This notification is used only when the node need to retransmit a packet instead of sending the notification periodically. Here, a new notification command should be added to the ZigBee command list.

When the router received the notification from its neighbor, it can check its Capacity for deciding that whether it has ability to accept another node. If the router could handle a new node, it sends back the MAC beacon back with true value of Router Capacity. In this mechanism, if the Router Capacity is set to FALSE, the end node will continually transmit the packet to the current router until the other routers are free to accept a new node. If the Router Capacity is set to TRUE, the end node will join a new cluster and build the connection with the potential router for a new packet transmission.

6.2.1 In heavy traffic case

Figure 6-5 shows the procedure of cluster routing mechanism when node Z in cluster2 selects to join cluster1 which has a higher router capacity.

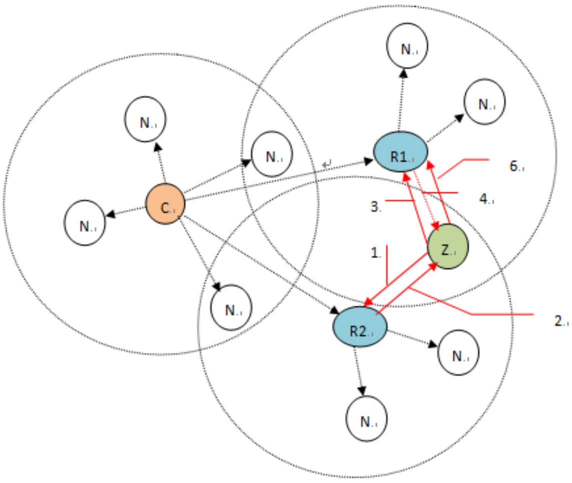

Figure 6-5 procedure of cluster routing mechanism

The procedure is described as in Table II :

Table II Procedure of inter-cluster fairness

1	One node sends packets to the current router
2	The router is busy with transmitting packets and response to the end node with retransmission request.
3	The end node calculates the capacity of the current router. At the same time, it send notification to look for another router with higher capacity in the neighborhood.
4	The other routers send a response MAC beacon with Router Capacity field back to the end node.
5	If the value of Router Capacity is true, the node calculates the capacity of the potential router. The node compares two capacities of the router to select a higher capacity router. After the comparison, the node will determine whether to leave the current cluster and join a new cluster.
6	After the decision of selection, the node may choose to join the new cluster and send packet to the new router.

For the modifications of ZigBee routing protocols in OPNET version 16A, the network layer is not available to edit the routing information. Therefore, only the MAC layer could be used to make changes to achieve the purpose of the proposed mechanism.

6.2.2 In light traffic case

Traffic threshold

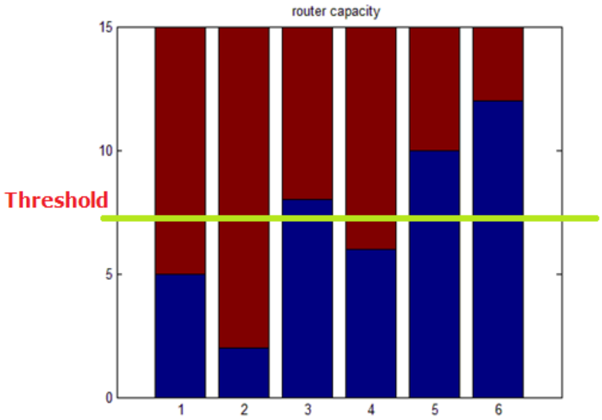

Figure 6-6 Router capacity

If the network contains several end nodes such as 10, the traffic size in the network is not too much to cause collisions in the routers. For example, the capacity of the router is 15 and all the nodes can send packet through routers without waiting in the queue. In this situation, the intra-cluster fairness mechanism cannot work because all the routers can handle the packets in the cluster. Although some routers have heavier traffic, it doesn't exceed the capacity of 15. Therefore, the inter-cluster fairness mechanism can't be used for the whole network's fairness. On the other side, when inter-cluster fairness is not used in the network, extra beacon request will not be generated. There is a balance between packet delivery ratio and fairness. Thus, routers will not deal with extra packet which may cause collisions and the packet delivery ratio could stay on a high level.

Another method should be involved in the small network. A threshold can be defined for the router capacity. If the threshold is 8 for this example, routers will not deal with the packets when there are 8 nodes waiting in the queue. Then the nodes in the cluster will choose to join another cluster to send the packet as the process in the proposed mechanism for inter-cluster fairness.

6.3 Cluster joining procedure

As introduced for intra cluster, intra-fairness mechanism is used among the cluster members which belong to the same router. All the cluster members could almost get the equal chance to send the packets. As a consequence, different clusters could have different result for transmitting packets. For example, members in cluster 1 could send 40 packets per second in average, while members in cluster 2 could send 30 packets per second. Fairness is achieved among the members in the same cluster but unfairness happens between different clusters. Therefore, Inter-cluster fairness should be introduced for the whole network to achieve absolute fairness among all the end nodes.

6.3.1 In heavy traffic case

Inter-cluster fairness is introduced as the cluster routing mechanism. According to the traffic size of the whole network, routers should have different options to deal with the packets.

Process.inter-cluster_fairness for small network is also the same as in the large network with heavy traffic. Here process.inter-cluster_fairness is defined as in Table III:

Table III Procedure of inter-cluster fairness in heavy traffic case

```
If N.device_type =ZigBee_router or N.device_type=ZigBee_coordinator
    If capacity.router is full
       send retransmission request to child
       send original MAC beacon with capacity_router_original to child
    End if
End if
If N.device_type =ZigBee_end_device
      Send notification to routers
End if
If N.device_type =ZigBee_router or N.device_type=ZigBee_coordinator
       Send new MAC beacon with capacity_router_new to child
End if
If N.device_type =ZigBee_end_device
    If capacity_router_new>capacity_router_original
       Address_nexthop= address in new MAC beacon
    End if
    Packet.send
End if
```

6.3.2 In light traffic case

For a small network with less traffic, threshold can be used as the maximum capacity of the router. The procedure is as in Table IV:

Table IV Procedure of inter-cluster fairness in light traffic case

```
Begin
If N.device_type =ZigBee_router or N.device_type=ZigBee_coordinator
   For i=1 to number_router
totle_router_handle= totle_router_handle +router_handle(i)
   next
   mean_router_handle= totle_router_handle/ totle_router_handle
   if router_handle(i) > mean_router_handle
        router_capacity = threshold
go to process.inter-cluster_fairness
end if
end if
```

6.4 Simulation results

6.4.1 Packet delivery ratio

In Figure 6-7, it illustrates that inter-cluster fairness mechanism got a decrease in packet delivery ratio comparing to intra-cluster fairness. That’s because the excess transmission of beacons and notifications happens when a node could find the router busy and then the node would like to join another cluster.

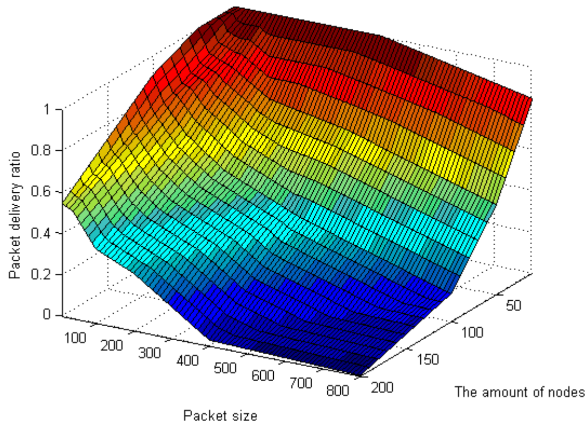

Figure 6-7 Packet delivery ratio against packet size from normal cluster, aggregation, intra-cluster and inter-cluster fairness

6.4.2 Delay

The cyan line shows that inter-cluster fairness has a slight increase than the intra-cluster fairness. Due to the processing time for waiting and joining a new cluster, the packet could be delayed. However the result is still much better than the mesh topology because there is a worse situation with many collisions when all the end nodes are ZigBee routers. All the routers could transfer the packets and significantly increase the load of the network and it will postpone almost all the packet in mesh topology. Here, lower and upper bounds for a 95% confidence interval for mean delay are used.

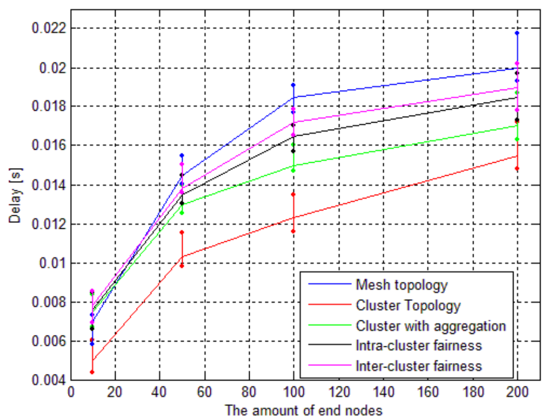

Figure 6-8 Delay for normal cluster, aggregation, intra-cluster and inter-cluster fairness

6.4.3 Fairness

(a) Jain's index for packet delivery ratio:

With the comparison of normal cluster, cluster with aggregation, intra-cluster and inter-cluster fairness, in Figure 6-9, it shows a great improvement in each step for packet delivery ratio. The lowest Jain's index for inter-cluster fairness is 0.96 which is the best for fairness. It means almost all the end nodes can get the same level of packet delivery ratio regardless of network size or packet size. Because inter-cluster fairness combines the advantages of packet aggregation and intra-cluster fairness, all the packets from the each node can be balanced within and outside the cluster. There's also a trade-off between packet delivery ratio and fairness, because there needs more management for packets. Therefore, decreased packet delivery ratio happens in some nodes which would transfer more packets in another cluster with less traffic. However, small network with less traffic has great improvement for both packet delivery ratio and Jain's index fairness.

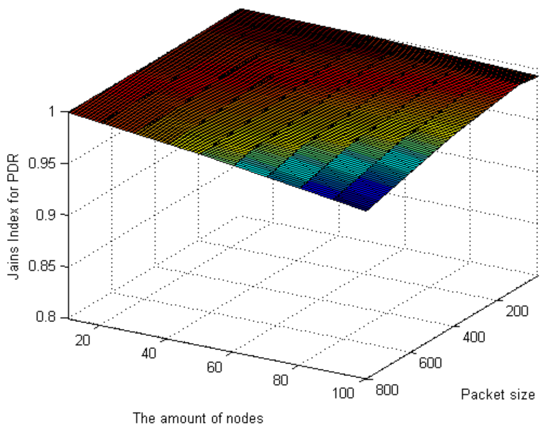

Figure 6-9 Jain's index against packet size for packet delivery ratio

(b) Jain's index for delay:

In Figure 6-10, it shows that the shape of delay gets much smoother to about 0.95 which means most nodes could get the same delay in a small network with less traffic. But for large network with more than 100 nodes, unfairness happens and some nodes may be delayed for an extremely long time to process.

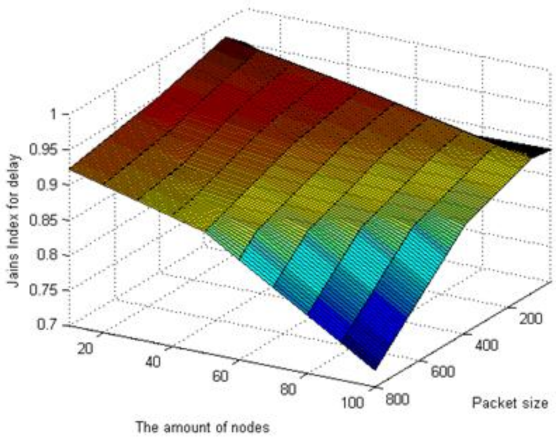

Figure 6-10 Jain's index against packet size for delay

6.5 Summary

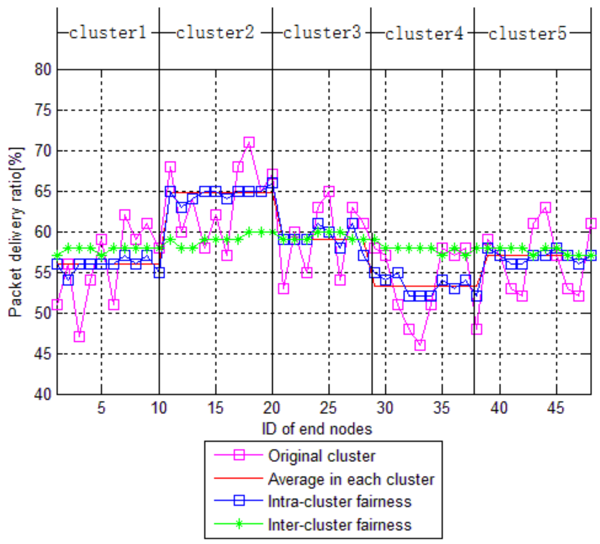

Figure 6-11 Packet delivery ratio from 50 nodes

Figure 6-11 shows that almost all the nodes can reach around 58% of the packet delivery ratio with small fluctuations amongst 50 end nodes. It is obvious that the fairness is enhanced significantly with intra-cluster and inter-cluster fairness mechanisms. However, the average packet delivery ratio got a slight decrease as the trade-off for fairness. Besides cluster 2 in the figure with nodes from 10 to 20, the other nodes all got an increase in packet delivery ratio. Delay is also an increasing problem after the two mechanisms but still better than the mesh topology. For fairness, Jain's index results show that packet delivery ratio is apparently improved than normal cluster, aggregation and intra-cluster fairness. Fairness for delay got a 0.17 decrease than normal cluster because of the excess processing time for waiting and joining a new cluster.

Chapter 7

Conclusion

7.1 Conclusion

In this thesis, the performance of ZigBee networks and related work is firstly introduced. Taking into account packet delivery ratio and delay, the performance of mesh and cluster-tree topology is analyzed. Moreover, burst traffic in smart home is simulated as a real life traffic case which shows the similar performance as exponential traffic.

The impact of node amount, packet size, packet interarrival time, retransmissions and depths on packet delivery ratio and delay is simulated and analyzed in Chapter 2. As can be seen in the results, packet delivery ratio in the cluster-tree is higher especially for the amount of end nodes below 50 than in mesh topology. Retransmissions could increase the performance when there is not too much traffic. If there are no retransmissions, larger size of packet could also achieve a higher performance. Small size of packet can get the best performance in packet delivery ratio no matter how many nodes existing in the network. If all the nodes don't transmit the packet frequently, the network could stay on a high level of performance even for large packet size of 800 bits.

In Chapter 3, data packet aggregation is adopted to release the load of the network and integrate several packets into a super packet. The packet delivery ratio could get to more than 50% when 200 nodes are sending a 100 bits packet which is 40% and 25% higher than the mesh and cluster topology respectively. Packet aggregation improves the performance of the ZigBee network significantly when the packet size is smaller than 200 bits in a large size of network. The packet aggregation also improves the ratio to 90% especially when the end node nodes don't send the packet frequently.

After introducing the concept of fairness, all the members in the same cluster can achieve almost the same ratio around the average level by intra-cluster fairness mechanism, especially in the case with large packet size and large amount of end nodes. However, Unfairness amongst different clusters still can be found. Therefore, the inter-cluster fairness mechanism is proposed. The results of Jain's index show that packet delivery ratio is apparently improved than normal cluster, aggregation and intra-cluster fairness. Fairness for delay got a 0.17 decrease than normal cluster because of the excess processing time for waiting and joining a new cluster. The average packet delivery ratio got a slight decrease as a trade-off for fairness.

To sum up, our mechanism and algorithms can be used in more occasions such as monitor sensors in smart home, healing controller in hotels, lamp sensors in the streets, which require a high level of packet delivery ratio and delay with a large amount of end nodes.

7.2 Further works

Admittedly, during the research, some problems still. For example, all the simulation results are done with OPNET. In real ZigBee network, the results might be slightly different. Our packet aggregation mechanism directly integrates the packets as a super packet. It allows nodes to aggregate the packets regardless of the environment. For a future research, the scheme can consider the environments by including entire query definitions within interest messages. Some features such as interest transformation, layered data aggregation and dynamic data aggregation could improve overall system performance [39].

From the results of inter-cluster fairness mechanism, the increased delay and the decreased packet delivery ratio is the trade-off with fairness. How to improve fairness without losing the performance of delay and packet delivery ratio is still an open issue. Coexistence with the other wireless technologies sharing the same band should be considered in further work too, such as 802.11b/g Wi-Fi and Bluetooth. With the interference of these devices, coexistence issues arise and ZigBee is potentially vulnerable to the interference by these technologies [40]. Therefore, it is desirable to improve the performance and robustness of ZigBee networks.

Reference

[1] ZigBee Alliance. ZigBee Overview. September 2003.
[2] A. Sikora and V. F. Groza, "Coexistence of IEEE802.15.4 with other Systems in the 2.4GHz-ISM-Band," in IEEE Instrument and Measurement Technology Conference, vol. 3, pp. 1786-1791, Ottawa, Canada, May 2005.
[3] K. Shuaib, M. Boulmalf, F. Sallabi and A. Lakas, "Co-existence of ZigBee and WLAN, A Performance Study, " Wireless Telecommunications Symposium, 2006. WTS '06, page 1 – 6,2006
[4] IEEE Standard for Information technology— Telecommunications and information exchange between systems— Local and metropolitan area networks— Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)
[5] http://www.opnet.com/solutions/network_rd/modeler.html
[6] http://isi.edu/nsnam/ns/
[7] Patrick Kinney, "ZigBee Technology: Wireless Control that Simply Works", Communications Design Conference,2 October 2003
[8] ZigBee Alliance .ZigBee Specification. December 14th, 2004
[9] http://www.mobilenetx.com/zigbee-vs-bluetooth
[10] Jun Huang1; Guoliang Xing1; Gang Zhou2; Ruogu Zhou1, "Beyond Co-existence: Exploiting WiFi White Space for ZigBee Performance Assurance" IEEE ICNP, Kyoto, Japan, 2010
[11] I. S. Hammoodi, B. G. Stewart, A. Kocian1, S. G. McMeekin, "A Comprehensive Performance Study of OPNET Modeler For ZigBee Wireless Sensor Networks," 2009 Third International Conference on Next Generation Mobile Applications, Services and Technologies
[12] Mathioudakis, I et al, "Wireless Sensor Networks: A case studyfor Energy Efficient Environmental Monitoring", Proceedings of Eurosensors conference 2008, Dresden, Germany, September2008.
[13] Sokullu, R.; Donertas, C, "Combined effects of mobility, congestion and contention on network performance for IEEE 802.15.4 based networks", Computer and Information Sciences, 2008. ISCIS '08. 23rd International Symposium on, 27-29 Oct. 2008, page 1-5
[14] Harsh Dhaka, Atishay Jain, Karun Verma, "Impact of Coordinator Mobility on the throughput in a ZigBee Mesh Networks", 2010 IEEE 2nd International Advance Computing Conference, Thapar University, Patiala
[15] Petr Jur_ík, Anis Koubaa, Mário Alves, Eduardo Tovar, Zden_k Hanzálek, "A Simulation Model for the IEEE 802.15.4 Protocol: Delay/Throughput Evaluation of the GTS Mechanism,"
[16] Mikko Kohvakka, Mauri Kuorilehto, Marko Hännikäinen, Timo D. Hämäläinen, "Performance analysis of IEEE 802.15.4 and ZigBee for large-scale wireless sensor network applications," Energy Efficient algorithms, Pages: 48 – 57,2006
[17] Sofie Pollin, Mustafa Ergen, Sinem Coleri Ergen, Bruno Bougard, "Performance Analysis of Slotted Carrier Sense, IEEE 802.15.4 Medium Access Layer," IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 7, NO. 9, SEPTEMBER 2008
[18] Nelson I. Dopico, Carlos Gil-Soriano, I ˜nigo Arrazola and Santiago Zazo, "Analysis of IEEE 802.15.4 Throughput in Beaconless Mode on micaZ under TinyOS 2."
[19] Brunelli, D., Maggiorotti, M., Benini, L., Bellifemine, F.L. "Analysis of Audio Streaming Capability of ZigBee Networks." Wireless Sensor Networks, ch. 12, pp. 189–204. Springer, Heidelberg (2008)

[20] G. Zhou, C. Huang, T. Yan, T. He, J. Stankovic, and T. Abdelzaher. Mmsn: Multi-frequency media access control for wireless sensor networks. In INFOCOM, 2006.
[21] C. Liang, R. Musaloiu-Elefteri, and A. Terzis. Typhoon: A reliable data dissemination protocol for wireless sensor networks. In EWSN, pages 268–285, 2008.
[22] Österlind, Fredrik and Dunkels, Adam (2008) Approaching the maximum 802.15.4 multi-hop throughput. In: The Fifth ACM Workshop on Embedded Networked Sensors (HotEmNets 2008), 2-3 June 2008, Charlottesville, Virginia, USA.
[23] T. R. Burchfield, S. Venkatesan, and D. Weiner, "Maximizing throughput in ZigBee wireless networks through analysis, simulations and implementations," in Proc. of the International Workshop on Localized Algorithms and Protocols for Wireless Sensor Networks, 2007, pp. 15–29.
[24] Bougard, B., Catthoor, F., Daly, D.C., Chandrakasan, A., Dehaene, W., Energy efficiency of IEEE 802.15.4 standard in dense wireless microsensor networks: modeling and improvement perspectives, in Proceedings of Design, automation and test in Europe (DATE'05) (Munich, Germany, March 7-11, 2005). IEEE, 2005, Vol. 1, 196-201.
[25] OPNET software version 16.0 A modeler
[26] Bhaskar Krishnamachari, Deborah Estrin, Stephen B. Wicker, The Impact of Data Aggregation in Wireless Sensor Networks, IEEE Computer Society Washington, DC, USA ©2002 table of contents ISBN:0-7695-1588-6
[27] RAMESH RAJAGOPALAN AND PRAMOD K. VARSHNEY, SYRACUSE UNIVERSITY,DATA-AGGREGATION TECHNIQUES IN SENSOR NETWORKS: A SURVEY, The Electronic Magazine of Original Peer-Reviewed Survey Articles, 4TH QUARTER 2006, VOLUME 8, NO. 4
[28] W. R. Heinzelman, "Application-Specific Protocol Architectures for Wireless Networks," Ph.D. thesis, Massachusetts Institute of Technology, June 2000.
[29] S. Lindsey, C. Raghavendra, and K. M. Sivalingam, "Data Gathering Algorithms in Sensor Networks Using Energy metrics," IEEE Trans. Parallel and Distributed Systems, vol. 13, no. 9, Sept. 2002, pp. 924–35.
[30] Huaizhou Shi, R.R. Venkatesha Prasad, Ertan Onur, I.G.M.M. Niemegeers, Fairness in Wireless Networks, WMC group, Department of Telecommunications, Technology University of Delft (TU Delft)
[31] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems, Digital Equipment Corporation," Technical Report DEC-TR-301, Tech. Rep., 1984.
[32] C. Shannon and W. Weaver, "The mathematical theory of communication," Urbana: University of Illinois Press, 1949
[33] J. Jaffe, "Bottleneck flow control," IEEE Transactions on Communications, vol. 29, no. 7, pp. 954–962, 1981.
[34] D. Bertsekas, R. Gallager, and T. Nemetz, Data networks. Prenticehall Englewood Cliffs, NJ, 1987.
[35] E. Hahne, "Round-robin scheduling for max-min fairness in data networks," IEEE Journal on Selected Areas in communications, vol. 9, no. 7, pp. 1024–1039, 1991.
[36] Xianren Wu, Hui Xu, Hamid R. Sadjadpour and J.J. Garcia-Luna-Aceves, "proactive or Reactive Routing: A Unified Analytical Framework in MANETs", ICCCN 2008: 649-655
[37] Tian-Wen Song, Chu-Sing Yang, A Connectivity Improving Mechanism for ZigBee Wireless Sensor Networks, 2008 IEEE/IFIP International Conference on Embedded and Ubiquitous Computing,page::495-500
[38] Yanying Gu, Personal Networks: Mobility and Clustering, phd thesis, Delft University of Technology.
[39] Supriyo Chatterjea and Paul Havinga, "A Dynamic Data Aggregation Scheme for Wireless Sensor Networks", Ubiquitous Computing Systems Lecture Notes in Computer Science (2007) ,Springer Berlin / Heidelberg, Pages: 699-701
[40] Xiaolei Cui, "Improving ZigBee Networks Robustness with Multi-channel Capability",Distributed Sensor System Group, Faculty of Electrical Engineering, Philips Research

Glossary

MAC	Medium Access Control
PHY	Physical Layer
PAN	Personal Area Network
LR WPAN	Low-Rate Wireless Personal Area Networks
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
GTS	Guaranteed Time Slot
CAP	Contention Access Period
CFP	Contention Free Period
AODV	Ad hoc On Demand Distance Vector
ETE	End-To-End
SO	Superframe Order
BO	Beacon Order
CW	Contention window
BE	Backoff Exponent
NB	Number of Backoffs
PPDU	Presentation protocol data unit
ZC	ZigBee Coordinator
ACK	ACKnowledge
FIFO	First-In-First-Out
RFD	Reduced Function Device
FFD	Full Function Device

Appendix

802_15_4_mac_pk_router_fairness

```
 /* This is a data packet.                                          */
 op_pk_fd_get_int32 (pk, pan_id_index, &pk_pan_id);
 op_pk_fd_get_int32 (pk, next_hop_address_index, &pk_next_hop);
OPC_FIELD_SIZE_UNCHANGED);
                op_pk_fd_get (pk, WPANC_MAC_SEQ_NUM_FIELD_INDEX, &seq_number);
 strncpy(to, &devicename+7, 4);
 no_router=atoi(to);
/*
 strncpy(to1, &devicename+7, 1);
 router_select=atoi(to1);
op_ima_obj_attr_get (parent_id, "model",&devicemodel);
        */
   if (op_sim_time ()>20&&time_flag==0)
          {printf("\nstart");
           time_flag=1;
          }
        if (pk_size==372.0)
      {
         if (temp_pk==0)
         {temp_pk=829;
         //printf("%s \n",&devicename);
         }
 for (i = 0; i < 201; i++)
                {
             if (packet_source_addr[i]==0)
                    {packet_source_addr[i]=temp_pk;
                    address_count[i]++;
                    //printf("new,%d,%d,%d\n",i,packet_source_addr[i],address_count[i]);
                    temp_count=address_count[i];
                    //printf("new,%d,%d,%d\n",i,packet_source_addr[i],address_count[i]);
                    i=201;
                    }
             else if (packet_source_addr[i]==temp_pk)
```

```
                    {
                    if (count_f[i]==0)
                         {
                    address_count[i]++;
                    }
                    else
                         {count_f[i]=0;
                         }
                    temp_count=address_count[i];
                    this_i=i;
OPC_FIELD_SIZE_UNCHANGED);
                    i=201;
                    }
               }
          for (i=0;i<40;i++)
                  {
                  sum_router=sum_router+address_count[i];
                  if (address_count[i]==0)
                       {
                       avg_count[no_router]=sum_router;
                       temp_i=i;
                       sum_router=0;
                       i=40;
                       }
                  }
  if (temp_count*temp_i<=avg_count[no_router])
  {
   if (pk_count_flag[no_router]<2)
     {
     pk_count_flag[no_router]++;
                    printf("\nrouter:%d:%d:%d",seq_number,router_pk[no_router],no_router);
     }
   else
     {
     pk_size=572.0;
name_list[no_router],                    OPC_FIELD_SIZE_UNCHANGED);
          printf("\nrouter:%d:%d:%d:%f",seq_number,router_pk[no_router],no_router,pk_size);
        router_pk[no_router]++;
     pk_count_flag[no_router]=0;
     }
   }
   else
        {printf(":des");
```

```
            pk_count_flag[no_router]=1;
            count_f[this_i]=1;
            }
          }
 if    (pk_count_flag[no_router]==0)
        {
        wpan_mac_rcvd_stats_update1 (pk_size);
        op_pk_total_size_set (pk, (OpT_Packet_Size) pk_size);
        pk_size = (double) op_pk_total_size_get (pk);
        /* Update recieved stats                                          */
                /* Process the packet only if it is destined for this node      */
        /* or is a broadcast packet.                                       */
        if ((pk_pan_id == my_pan_id && pk_next_hop == my_network_address) ||
                (my_pan_id == -1 && pk_next_hop == my_network_address)        ||
                (pk_pan_id == my_pan_id && pk_next_hop == BROADCAST_CODE_ALL) ||
                (pk_pan_id == my_pan_id && pk_next_hop == BROADCAST_CODE_RC))
                {
                if (op_prg_odb_ltrace_active ("wpan_mac"))
                        {
                        sprintf (message_str, "Received a packet from the wireless medium, sending it upto the
networklayer.\n");
 op_prg_odb_print_major (message_str, OPC_NIL, OPC_NIL, OPC_NIL);
                        }
                /* At this point we are quite sure that old network    */
                /* address is no longer needed and hence its safe to  */
                /* reset it back to an invalid value.                    */
                old_network_address    = WPANC_INVALID_ADDRESS;

                /* Reduce the packet size of the physical layer          */
                /* overhead                                                      */
                pk_size = (double) op_pk_total_size_get (pk) - WPAN_MAC_DATA_OVERHEAD;
                //printf("%f\n",pk_size);
                op_pk_total_size_set (pk, (OpT_Packet_Size) pk_size);

                /* Update the throughput and delay statistics.            */
                wpan_mac_thput_and_e2e_stats_update1 (pk);

                /* Send an ACK if the sender has requested fot it.         */
                if (op_pk_fd_is_set (pk, WPANC_MAC_ACK_FIELD_INDEX) == OPC_TRUE)
                        wpan_mac_send_ack1 (pk);
                /* Strip the packet of the fields that have local          */
                /* significance and may affect the MAC behavior once      */
```

```
			/* the packet is resent to this MAC by the upper layer. */
			wpan_mac_fields_strip1 (pk);

			/* Send the packet to network layer.			*/
			op_pk_send (pk, NWK_STRM);
			}
		else
			{
			/* If we still receive a packet with old network		*/
			/* address then its   mostly going to be retransmissions	*/
			/* of JOIN repsonse which is expecting an ACK back.		*/
			if ((my_pan_id == pk_pan_id) && (old_network_address == pk_next_hop))
				{
				/* Send an ACK if the sender has requested fot it.	*/
				if (op_pk_fd_is_set (pk, WPANC_MAC_ACK_FIELD_INDEX) == OPC_TRUE)
					wpan_mac_send_ack1 (pk);
				}

			op_pk_destroy (pk);
			}
}
```

802_15_4_mac_pk_router

```
		/* This is a data packet.						*/
		op_pk_fd_get_int32 (pk, pan_id_index, &pk_pan_id);
		op_pk_fd_get_int32 (pk, next_hop_address_index, &pk_next_hop);
		//op_pk_fd_set_int32	(pk,NAME_COUNT_INDEX,		5.0,
 OPC_FIELD_SIZE_UNCHANGED);
			op_pk_fd_get (pk, WPANC_MAC_SEQ_NUM_FIELD_INDEX, &seq_number);
				//printf("%d \n",seq_number);
 //op_ima_obj_attr_get (parent_id, "model",&devicemodel);
//printf("%s \n",&devicemodel);
 strncpy(to, &devicename+7, 4);
 no_router=atoi(to);
/*
 strncpy(to1, &devicename+7, 1);
 router_select=atoi(to1);
op_ima_obj_attr_get (parent_id, "model",&devicemodel);
		//printf("%d    \n",no_router);
		*/
 //if (strcmp(&devicemodel,"ZigBee_router")==0&&router_select!=0)
```

```
//{
  if (op_sim_time ()>20&&time_flag==0)
        {printf("start\n");
         time_flag=1;
        }

    if (pk_size==372.0)
   {
   if (pk_count_flag[no_router]<2)
      {
      //pk_size_router[no_router]=pk_size_router[no_router]+pk_size;
      pk_count_flag[no_router]++;
                          printf("router:%d:%d:%d\n",seq_number,router_pk[no_router],no_router);
      }
   else
      {
      //pk_size_router[no_router]=pk_size_router[no_router]+pk_size;
      //op_pk_total_size_set (pk, (OpT_Packet_Size) 1272.0);
      pk_size=572.0;
      //pk_size_router[no_router]=0.0;

      //name_list[no_router]=34.0;
      //op_pk_fd_set_dbl       (pk, WPANC_BEACON_NAME_COUNT_INDEX,
name_list[no_router],                     OPC_FIELD_SIZE_UNCHANGED);
              printf("router:%d:%d:%d:%f\n",seq_number,router_pk[no_router],no_router,pk_size);
           router_pk[no_router]++;
      pk_count_flag[no_router]=0;

      }
        }
```

802_15_4_mac_pk_router_fairness

```
      /* This is a data packet.                                    */
      op_pk_fd_get_int32 (pk, pan_id_index, &pk_pan_id);
      op_pk_fd_get_int32 (pk, next_hop_address_index, &pk_next_hop);
      //op_pk_fd_set_int32     (pk,NAME_COUNT_INDEX,          5.0,
OPC_FIELD_SIZE_UNCHANGED);
              op_pk_fd_get (pk, WPANC_MAC_SEQ_NUM_FIELD_INDEX, &seq_number);
                          //printf("%d \n",seq_number);
//op_ima_obj_attr_get (parent_id, "model",&devicemodel);
```

```
//printf("%s \n",&devicemodel);
 strncpy(to, &devicename+7, 4);
 no_router=atoi(to);
/*
 strncpy(to1, &devicename+7, 1);
 router_select=atoi(to1);
op_ima_obj_attr_get (parent_id, "model",&devicemodel);
        //printf("%d    \n",no_router);
        */
 //if (strcmp(&devicemodel,"ZigBee_router")==0&&router_select!=0)
 //{
   if (op_sim_time ()>20&&time_flag==0)
         {printf("start\n");
          time_flag=1;
         }
       if (pk_size==372.0)
      {
      if ((op_sim_time ()-time_router[no_router])<0.03)
         {
         num_time_count[no_router]++;
                printf("router:%d:%d:%d\n",seq_number,router_pk[no_router],no_router);
                //op_pk_fd_set_dbl         (pk, WPANC_BEACON_NAME_COUNT_INDEX,                          5.0,
 OPC_FIELD_SIZE_UNCHANGED);
         //printf("%f    %d    \n",op_sim_time (),num_time_count[no_router]);
 //WPANC_BEACON_NAME_COUNT_INDEX     = op_pk_nfd_name_to_index (pk, "name_count");
         //printf("%d,%d \n",seq_number,no_router);
         }
      else
         {
         pk_size=num_time_count[no_router]*200+272;
         num_time_count[no_router]=0;
                printf("router:%d:%d:%d:%f\n",seq_number,router_pk[no_router],no_router,pk_size);
         time_router[no_router]=op_sim_time ();
              router_pk[no_router]++;

         }
```

Data collection

```
Sub Macro1()
'
' Macro1 Macro
```

```
' Macro recorded 18-3-2011 by localadmin
'
    Sheets("Sheet1").Select

    Cells.Select
    Range("J25").Activate
    Selection.ClearContents
    With ActiveSheet.QueryTables.Add(Connection:= _
        "TEXT;C:\Documents and Settings\localadmin\Desktop\802_15_4_mac", Destination _
        :=Range("A1"))
        .Name = "802_15_4_mac"
        .FieldNames = True
        .RowNumbers = False
        .FillAdjacentFormulas = False
        .PreserveFormatting = True
        .RefreshOnFileOpen = False
        .RefreshStyle = xlInsertDeleteCells
        .SavePassword = False
        .SaveData = True
        .AdjustColumnWidth = True
        .RefreshPeriod = 0
        .TextFilePromptOnRefresh = False
        .TextFilePlatform = 437
        .TextFileStartRow = 1
        .TextFileParseType = xlDelimited
        .TextFileTextQualifier = xlTextQualifierDoubleQuote
        .TextFileConsecutiveDelimiter = False
        .TextFileTabDelimiter = True
        .TextFileSemicolonDelimiter = False
        .TextFileCommaDelimiter = False
        .TextFileSpaceDelimiter = False
        .TextFileOtherDelimiter = ":"
        .TextFileColumnDataTypes = Array(1)
        .TextFileTrailingMinusNumbers = True
        .Refresh BackgroundQuery:=False
    End With
    Rows("1:92").Select
    Range("A92").Activate
    Selection.Delete Shift:=xlUp
    Columns("E:E").Select
    Range("E310").Activate
    Selection.Copy
    Columns("G:G").Select
```

```
        Range("G310").Activate
        ActiveSheet.Paste
        'Columns("A:A").Select
        'Selection.Delete Shift:=xlToLeft

maxrow = Worksheets("Sheet1").Range("A65536").End(xlUp).Row
maxrow_b = Worksheets("Sheet1").Range("e65536").End(xlUp).Row

'For i = 1 To maxrow
'a_find = Range("a" & maxrow - i + 1)
'a_addr = Range("b" & maxrow - i + 1)
With Worksheets(1).Range("a1:a800")
        Set c = .Find("start", LookIn:=xlValues)

        If Not c Is Nothing Then
          firstAddress = c.Address

        End If
End With
Range("h3") = firstAddress
                Range("h4") = "=LEFT(RIGHT(R[-1]C[0],3),3)"
                Range("h5") = "=LEFT(RIGHT(R[-2]C[0],2),1)"
                Range("h6") = "=LEFT(RIGHT(R[-3]C[0],3),1)"
                Range("h7") = "=LEFT(RIGHT(R[-3]C[0],4),1)"

        Rows("1:" & Range("h4")).Select
        Range("A" & Range("h4")).Activate
        Selection.Delete Shift:=xlUp
        Columns("A:M").Select
        Selection.ColumnWidth = 12.71
        Range("A1").Select
        Columns("I:l").Select
        Selection.ClearContents
For l = 1 To maxrow
        If Range("a" & l) = "delay" Then
          Range("e" & l) = "=LEFT(RIGHT(R[0]C[-3],5),5)"
        End If
        If Range("e" & l) = "des" Then
        Rows(l & ":" & l).Select
        Application.CutCopyMode = False
        Selection.Delete Shift:=xlUp
        l = l - 1
        End If
```

```
Next
For i = 1 To maxrow

If Range("a" & i) = "node" Then

        node_num = Range("c" & i)
        node_row = Worksheets("Sheet1").Range("i65536").End(xlUp).Row
        For m = 1 To node_row
           If Range("i" & m) = node_num Then
           node_exist = 1
           node_find = m
           m = node_row
           End If

        Next

        If node_exist = 0 Then
        Range("i" & node_row + 1) = node_num
        node_find = node_row + 1
        End If

        Range("j" & node_find) = Range("j" & node_find) + 1
        node_exist = 0
        If Range("a" & i + 1) = "start" Then
        i = i + 1
        End If
    If Range("a" & i + 1) = "router" Then
        Range("k" & node_find) = Range("k" & node_find) + 1
        packet_find = Range("c" & i + 1)
        router_find = Range("d" & i + 1)
         If Range("E" & i + 1) > 0 Then
               For K = 1 To 20

                  If Range("a" & i + K + 1) = "sink " And Range("E" & i + K + 1) > 0 Then
                  Range("l" & node_find) = Range("l" & node_find) + 1
                     If Range("a" & i + K + 1 + 1) = "delay" Then
                        Range("n" & node_find) = Val(Range("e" & i + K + 1 + 1)) / 1000000 + Range("n" &
node_find)
                     End If
                  'Range("E" & i + K + 1) = 0
                  K = 500
                  End If
```

```
                    Next
              Else
              For j = 1 To 200
                    If Range("d" & i + j) = router_find And Range("c" & i + j) = packet_find And Range("E" & i + j) > 0
Then
                     For K = 1 To 10

                        If Range("a" & i + j + K) = "sink " And Range("E" & i + j + K) > 0 Then
                        Range("l" & node_find) = Range("l" & node_find) + 1
                          If Range("a" & i + j + K + 1) = "delay" Then
                          Range("n" & node_find) = Val(Range("e" & i + j + K + 1)) / 1000000 + Range("n" & node_find)
                          End If
                        'Range("E" & i + J + K) = 0
                        K = 500
                        j = 200
                        End If
                     Next

                    End If
                'End If

               Next
               End If
    End If
End If
'Next
'Next
Next
    ActiveWindow.SmallScroll Down:=3
    Range("J201").Select
    ActiveCell.FormulaR1C1 = "=SUM(R[-199]C:R[-1]C)"
    Range("J201").Select
    Selection.AutoFill Destination:=Range("J201:L201"), Type:=xlFillDefault

    Range("M2").Select
    ActiveCell.FormulaR1C1 = "=RC[-1]/RC[-3]"

    Range("M2").Select
    Selection.AutoFill Destination:=Range("M2:M201"), Type:=xlFillDefault
    Range("K203").Select
    ActiveCell.FormulaR1C1 = "=R[-2]C/R[-2]C[-1]"
```

```
For l = 1 To maxrow
If Range("a" & l) = "sink " Then
sink_count = sink_count + 1
End If
Next

sink_avg = sink_count / 39
  Range("l202") = sink_count
  'Range("l202") = "sink_avg"

  Range("M202") = sink_avg
  Range("k202") = "sink_avg"

        Range("m201").Activate

For l = 1 To maxrow
        If Range("a" & l) = "delay" Then
          Range("e" & l) = "=LEFT(RIGHT(R[0]C[-3],5),5)"
          Range("f" & l) = Val(Range("e" & l)) / 1000000
        delay = delay + Val(Range("e" & l))
        delay_count = delay_count + 1
        End If
Next
        Range("n201") = delay
          Range("n202") = delay_count
          Range("n203") = delay / 1000000 / delay_count
        For i = 1 To 200 - 1
    For j = 200 To i + 1 Step -1
        If Range("i" & j) < Range("i" & j - 1) Then
              temp1 = Range("i" & j)
              Range("i" & j) = Range("i" & j - 1)
              Range("i" & j - 1) = temp1
              temp2 = Range("j" & j)
              Range("j" & j) = Range("j" & j - 1)
              Range("j" & j - 1) = temp2
              temp3 = Range("k" & j)
              Range("k" & j) = Range("k" & j - 1)
              Range("k" & j - 1) = temp3
              temp4 = Range("l" & j)
              Range("l" & j) = Range("l" & j - 1)
              Range("l" & j - 1) = temp4
                     temp5 = Range("n" & j)
```

```
            Range("n" & j) = Range("n" & j - 1)
            Range("n" & j - 1) = temp5
                Range("o" & j - 1).Select
        ActiveCell.FormulaR1C1 = "=RC[-1]/RC[-3]"
        '     temp5 = Range("m" & j)
          ' Range("m" & j) = Range("m" & j - 1)
          ' Range("m" & j - 1) = temp5

        End If

      Next
    Next
                Range("o" & 200).Select
        ActiveCell.FormulaR1C1 = "=RC[-1]/RC[-3]"

        Range("N204").Select
        ActiveCell.FormulaR1C1 = "=SUM(R[-203]C:R[-4]C)"
        Range("O204").Select
        ActiveCell.FormulaR1C1 = "=RC[-1]/R[-3]C[-3]"
        Range("O205").Select

        Range("O:O,M:M,j:j").Select
        'Range("L186").Activate
        Selection.Copy
        Columns("Q:Q").Select
        Range("p1").Activate
        ActiveSheet.Paste
    If Range("o200").Text = "#DIV/0!" Then
    Range("o200") = 0
    End If
    max1 = Range("m200")
    min1 = Range("m200")
    max2 = Range("j200")
    min2 = Range("j200")
    max3 = Range("o200")
    min3 = Range("o200")
        For i = 199 To 1 Step -1
            If Range("m" & i).Text <> "#DIV/0!" Then
              If Range("o" & i).Text <> "#DIV/0!" Then
                If Range("m" & i) > max1 Then
                max1 = Range("m" & i)
```

```
            End If
            If Range("j" & i) > max2 Then
            max2 = Range("j" & i)
            End If
            If Range("o" & i) > max3 Then
            max3 = Range("o" & i)
            End If
            If Range("m" & i) < min1 Then
            min1 = Range("m" & i)
            End If
            If Range("j" & i) < min2 Then
            min2 = Range("j" & i)
            End If
            If Range("o" & i) < min3 Then
            min3 = Range("o" & i)
            End If
           End If
        Else
        i = 1
      End If
Next
Range("r205") = max1
Range("r206") = min1
Range("r207") = max1 - min1
Range("q205") = max2
Range("q206") = min2
Range("q207") = max2 - min2
Range("s205") = max3
Range("s206") = min3
Range("s207") = max3 - min3
Range("Q207:S207").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("maxmin").Select
maxrow = Worksheets("maxmin").Range("b65536").End(xlUp).Row

Range("B" & maxrow + 1).Select
ActiveSheet.Paste
```

```
    'Sheets("Sheet1").Select
End Sub
```