ZigBee-based Firmware Updating Algorithms in Smart Home Environment

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Abstract

Smart home system is comprised of two parts: the home gateway and a number of home appliances. ZigBee technology has great advantage (or IEEE 802.15.4) and is widely used in this system. Therefore, updating the smart home ZigBee firmware is essential in the practice. Since the ZigBee network contains massive nodes and many sensors are battery powered,resource-efficiency, multi-node concurrent congestion and other ZigBee nodes' interference become challenges during the firmware updating. A lot of research has been done regarding updating optimizations for a single updating mode, such as firmware image compression algorithms and routing request strategies updating. Most optimizations are implemented in either wire or wireless updating avenue. However, there is a limited research on updating solution in combined wired and wireless methods. This dissertation proposes an integrated ZigBee network firmware updating solution scheme that uses the gateway to conduct the ZigBee network firmware updating by the wired method (Serial bootloader (SBL)) and the wireless method (Over-the-air (OTA)). Considering the ZigBee nodes' resource limitation, this dissertation designs a nimble image decompression algorithm, namely Huffman Hamilton-circuit decompression (HHD) to optimize the ZigBee SBL wired updating. MATLAB simulations show that the decompression algorithm saves storage space and time, when compared to the traditional Huffman image compression. For wireless updating, a distributed priority page-request OTA (DPPOTA) algorithm is proposed which will reduce the OTA network data redundancy and duration of updating. This dissertation implements the DPPOTA, Optimization OTA (OOTA) and TI's original OTA updating

schemes on the NS2 simulator. The results show that the DPPOTA algorithm outperforms the OOTA and TI's OTA. Compared with the related OTA optimization work, DPPOTA has a better performance on reducing network jitter and transmission delay. Under the different application scenarios, this dissertation proposes the combined updating solution which can exert the advantages of each single mode and outperforms any single mode.

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Acronyms / Abbreviations

AODV Ad hoc On-Demand Distance Vector Routing

APS Application Sub Layer

Cmd Command

CRC Cyclic Redundancy Check

DPPOTA Distributed priority page-request OTA

HHD Huffman Hamilton decompression

IAP In application programming

IDE Integrated Development Environment

ISP In system application

MAC Media Access Layer

NS2 Network Simulator version 2

NWK Network Layer

OAD Over the air download

OOTA Optimization over the air

OTA Over the air

PHY Physical Layer

pktloss packet loss rate

TI Texas Instruments

UART Universal Asynchronous Receiver/Transmitter

ZCL ZigBee Cluster Library

ZNP ZigBee Network Processor

Chapter 1

Introduction

1.1 Background

The modern smart technologies make individuals' living environment more convenient, comfortable, automatic and secure, which leads to the birth of smart home. Smart Home [1] is defined as a home monitoring or control system that is simple to install and to operate friendly. Few technologies, such as Bluetooth, WIFI, ZigBee, and 6LoWPAN, have already been applied in smart home system. Featuring close range, low complexity, self-organization, low power consumption and low data rate, ZigBee technology introduced in [2] is mainly suitable for automatic control, remote control and being embedded in a variety of equipment. Therefore, the ZigBee technology is majorly applied in the smart home environment. The network structure is shown in Fig. 1.1.

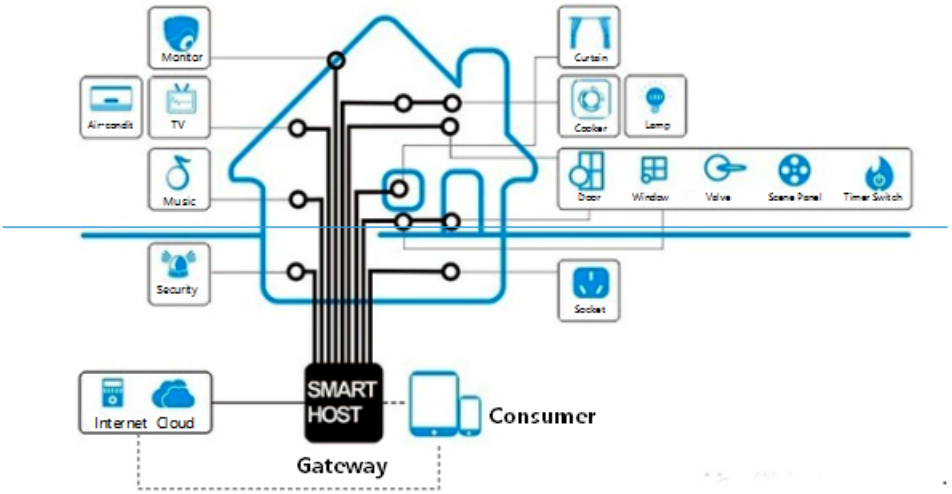


Fig. 1.1 ZigBee Smart Home Environment

Smart home belongs to Internet of things technology applications. By connecting the home devices with the internet, people can control the devices by phone or monitor them through the wireless network. Google, Apple and other world-famous companies have already published their relevant smart home products. Google Home for instance, is a hands-free smart speaker powered by the Google Assistant. Consumers can control the home devices by voice to release people's hands and feet. Not only hardware has been overwhelmingly concerned, the software of things is developed rapidly as well. Like OpenHub and home assistant, many smart home frames are open source. IBM designs the MQTT protocol to perform as an ISO standard of machines' connection. Smart home is almost based on the IEEE 802.15 communication protocols such as ZigBee, Bluetooth and WIFI that all work in the 2.4GHz frequency range. There are many different firmware update technologies when it refers to the practical updating applications. This article chooses the Microprocessor Control Unit (MCU) update programming to conduct the case study and experiment. Through analyzing the different MCU programming technologies, the author selects the In-Application programming to actualize the ZigBee dongle and endpoints' firmware update downloading.

1.2 Firmware Updating Technologies

The rapid development of semiconductor technology leads to the continuous upgrading of various chip technologies. In terms of data storage, from the initial mask ROM to the development of Flash technology, storage technology continues to improve and the corresponding programming technology is also in constant development.

1.2.1 In-system Programming

To update the chip firmware without removing the core chip, an In-system programming (ISP) technology was invented. [3] explains ISP is that the board level can be programmed without dismantling chip down to write the entire program by the ISP interface. In-system programming uses the serial port or other common generic communication interface to program the chip. People can reserve a serial port on product. If firmware updating is needed, people can simply plug the product into the computer and transfer the program through the serial port into the chip, and the update operation will soon be completed. The achievement of ISP technology depends on the chip's bootloader program which is pre-programmed in the factory. There are many different terminologies for bootloader such as ISP service program (STC macro crystalline microcontroller 51 so called), bootstrap (MSP430 programming of BSL so called) and so on, but the essence is the same. When chips are reset or powered, the bootloader will make precedence run over the user's own code. This code will firstly check whether the specified pin of chip has the specific signal. If not, the code will jump into the user program execution. According to the bootloader specific communication protocol, bootloader sends handshake commands to the computer and the computer will eventually trigger a new program through the common interface (such as serial port) to the chip. Then the bootloader erases the user program area by software way as this paper [4] (hardware support is certainly needed), then a new program is written to the specified location. In addition, bootloader is written by their own various chip manufacturers, so it is not all-purpose for

different chips. Although they all use the serial port, the communication protocol is different such as some STC microcontroller, communication protocols are even confidential. Thus, the special ISP software usually requires manufacturers to provide flash loader in order to program the chip.

1.2.2 In-application Programming

A technology that is more advanced than the ISP technology is called In Application Programming (IAP). [5], [6], [7] introduce that the IAP is a method of updating firmware program of the embedded products. It is now becoming more and more popular to update the firmware of the embedded products via the network remotely. IAP technology allows users to modify flash. In other words, the IAP technology allows users to customize one bootloader, or there will be two bootloaders: a default bootloader and a user-defined one. Maybe someone wonders whether the user customizing the bootloader program is just the user program . In fact, the difference comparing with the ordinary user program is that bootloader will not be so easily erased. The general idea is to use special software calling the cured bootloader to write custom bootloader and then use custom bootloader which can read and write flash to write a new program for the chip. A question is why we need a custom bootloader. The default bootloader needs fixing pin through the serial port and a fixed transfer protocol program. If we are dissatisfied with any point of the process, we can customize the bootloader ourselves. The author [8] will brief on the Device Firmware Upgrade (DFU), which is usually reserved for the USB device. Because many products are basically USB device and less serial port, many MCUs have the built-in USB support. DFU is an abbreviation and the DFU mode is used to support the USB bootloader. DFU Mode usually requires a specific driver since USB interface chips typically operate in VCP (Virtual COM Port) mode and convert into a virtual serial device after inserting into computer. The DFU mode is different at this point. Under the VCP mode, PC client is a serial port driver, MCU is the user program. While in the DFU

mode, PC client is DFU driver and MCU side is bootloader. Bootloader of DFU mode is typically user-defined through the curing bootloader brush into chip by the serial port.

Usually there are two ways to enter bootloader program. The first one is hardware reset (or down) that pushes the reset button on the board. After reset it will first execute bootloader. The second way is the software reset, which is typically sent by a series of specified instruction through PC. The user program will detect and deal with these instructions by the interrupt service routine. When the trigger condition occurs, the chip will perform a soft reset and load the specified address into the PC register which jumps into the bootloader program by the software.

1.3 Dissertation Objectives and Contributions

Over a serial time, people need to update the smart home devices' firmware. But many devices such as battery powered socket, switch and alarm are embedded on the wall, people cannot take down them from wall to update them hand by hand. In addition, smart home gateway device needs the more reliable and fast updating. To solve these problems, this dissertation proposes a updating scheme combined wired and wireless firmware updating methods. The remote battery powered end devices on the wall apply the wireless OTA firmware updating and the core gateway device applies the SBL wired firmware updating. Wireless method avoids the disassembly work and the wired method ensures reliability and speed of the firmware updating. However, the wired and wireless methods' performances are not very well such as updating time, image decompression time cost and multi-nodes' failed concurrent updating. According to these problems, this dissertation propose a nimble decompression algorithm called HHD to decompress the firmware's Huffman coding compression image.The HHD algorithm can cost less storage space and decompression time. Moreover, this dissertation also propose a DPPOTA algorithm for the OTA wireless updating method in the ZigBee network. The DPPOTA algorithm can cut down the ZigBee network's

data redundancy and congestion. This algorithm make the network more orderly so that multi-nodes can update their firmware faster.

This dissertation is arranged as below: Chapter 2 introduces the smart home firmware updating IAP technologies based on TI's CC2530 Chip. It also analyzes the different progresses on the firmware image compression algorithms and the OTA optimization methods. Chapter 3 prepares the ZigBee updating scheme of smart home system such as the ZigBee Linux gateway design and the ZigBee network applications configurations. Chapter 4 demonstrates the wired and wireless firmware update schemes (SBL and OTA) of the ZigBee-based smart home. Chapter 5 proposes the optimization algorithms of the SBL and the OTA. A nimble image decompression algorithm named Huffman Hamilton-circuit decompression of the SBL is proposed and this dissertation proposes the DPPOTA algorithm to optimize the OTA updating process. Chapter 6 presents the simulations of HHD and DPPOTA algorithms and some experiments also evaluate their optimization performances. This dissertation uses NS2 simulator to evaluate the network jitter and transmission delay of TI's OTA, Optimizatin OTA and DPPOTA. In addition, it also provides the comparison results.The last part of the dissertation summarizes the optimization algorithms and point out that the updating scheme combining wire and wireless performs much better than any single updating mode.

Chapter 2

Related Work

The major work is to carry out the smart home firmware updating that needs a gateway can download the ZigBee firmware image to the local and track the remote nodes' firmware updating in the ZigBee network. According to the different ZigBee device types , the wired and wireless in-application programming methods can perform well in their own work environments. To optimize the firmware update, the image compression has been considered.

2.1 Smart Home Firmware Updating Technologies

Smart home system contains many technologies such as WIFI, Bluetooth and ZigBee. These technologies have their own advantages in the different application conditions. When consumers need the big data transmission applications such as watching movie and the mobile entertainment, WIFI can meet these requirements. But many other applications such as switch, lamp and reading temperature sensor are simpler to operate, sensitive to energy consumption data and require less data transmission. In this scenario, the ZigBee technology performs better than other technologies. The smart home system mainly contains applications which need to work in a home mesh network, so this dissertation builds up the wireless sensors network of smart home with these ZigBee devices.

Tiny enough, the ZigBee-based smart home network refers to the network transmission information commands grading data, such as a sensor's switch. But when it processes the updating services, the net transmission data will be a large data volume of updating image so that the original ZigBee network cannot have relatively good performances. Thus, this dissertation uses the Huffman lossless compression algorithm to compress the image data, reduce the network congestion and upgrade transmission duration. For the entire firmware update system, the compression work is done on the smart home gateway console, which makes it possible to handle the resource restrictions. The decompression process is working on the ZigBee endpoints as well. Because of memory storage endpoint chips and computing power limitation, the dissertation designs a slight decompression algorithm to meet the needs of the terminal nodes decompressing update data.

ZigBee is a wireless data transmission protocol by which devices use to connect to one another. In fact, ZigBee can work in the home to improve individual's comfort and make home secure. It is convenient to extend the management with many advantages such as reliability, interoperability and energy conservation. The ZigBee Wireless Networking [9] introduces how to plan and develop applications and networks in detail. ZigBee sensors have many applications including industrial automation, medical sensing, remote controls, and security. Developers have a project at hand may benefit the most from the texts and examples. All the ZigBee technology details are recorded in the ZigBee specification [10]. Smart home energy management system [1] presents the design of a multi-sensing, heating and actuation application, as well as the home users: a sensor network-based smart light control system for smart home and energy control production. The z-stack developer's guide [11] explains some components of the Texas Instruments ZigBee stack and their functioning. It also explains the configurable parameters in the ZigBee stack and how they adapt to the application requirements. The author's first task is to set up the smart home environment through studying TI's documents.

TI provides the ZigBee hardware solutions CC2530 chips and z-stack protocol stack. The smart home contains the z-stack logic node types: coordinator, router and endpoint. A smart home ZigBee network has a coordinator that sets up the first network which later turns to be a router. In the smart home simulation scene, the ZigBee dongle performs as a coordinator and works on the ZigBee network gateway. The other endpoints transfer information and commands through the dongle gateway to the internet.

According to the ZigBee network process (ZNP) cluster, developers can use the CC2531 as a ZNP dongle to manage the whole smart home network. The gateway is developed based on the ZNP dongle and the MT layer APIS in the z-stack. Z-Stack 3.0 is TI's ZigBee 3.0 compliant protocol stack for the cc2530, cc2531, and cc2538 system-on-chip. It has the features as below: Based on ZigBee pro 2015 and base device behavior specifications, with enhanced security and new, application-agnostic device commissioning methods; Incorporated support for the cc2592 and cc2590 RF front ends which support +22dBm and +14dBm transmit power respectively, and provide improved receiver sensitivity; Z-Stack 3.0 combines multiple previous ZigBee profiles into a single profile, and provides an interoperable ecosystem for every device type. Then base device behavior defines a common set of mechanisms for network commissioning to be used by all devices. In the ZigBee PRO 2015, it provides new and improved security modes, including installing codes for out-of-band key exchange and distributed security networks for coordinator-less network topology. The most important update of the new version ZigBee is the Green Power Proxy support. Every ZigBee 3.0 routing device (router and coordinator) will support green power which allows energy-harvesting and ultra-low power devices to connect seamlessly. Z-Stack provides serial bootloader (SBL) for the wired upgrading method through the serial port. In addition, it also supports Over-the-air (OTA) firmware upgrade and allows future updates of deployed systems. If the smart home gateway hosts an OTA server, it can update the ZigBee nodes' firmware wirelessly. Both

these two embedded firmware upgrading methods are the in-application-programming. Thus, the following part will introduce the embedded programming technologies.

2.2 In-application Programming of ZigBee CC2530 Chip

In the smart home environment, this dissertation applies the IAP technology to update the ZigBee nodes' firmware. CC2530 is the 8051-core chip and the IAP method is a very convenient and reliable update firmware technology. The chip itself (or through the periphery of the chip) can write code through a series of operations. The microcontroller is divided into three program areas: boot loader, the program working area and downloading area. Chip receives the IAP commands and enters the guide area to run the bootstrap through the serial ports. The program will download new code into the relevant area as the guidance of the bootloader. When the downloading finishes and passes check, bootloader would copy the download content into working area and run the reset program so that IAP will be completed. It is now becoming more and more popular to update the firmware of the embedded products via the network remotely. Q.Xu designed a new IAP method based on LwIP stack on the platform of STM32F107, that is the IAP method based on HTTP through the Ethernet interface of STM32F107 in paper [12]. After introducing the overview of the system model, this dissertation shows how to port LwIP stack to STM32F107 and how to implement this IAP program in details. At the end, the performance of the IAP method evaluation shows that comparing to other on-line programming methods, this IAP method has a lot of advantages and can be used for general embedded products. Upon the IAP theory and technology, a new method of program remote online upgrading for the embedded device based on Real View MDK compiler is introduced in [13]. Initially, the IAP theory for online upgrading is analyzed. Then the difficult problems of the flash division, the program linking and location and the old or new procedures jump are explained in the LPC2138 chips as an example. At last, the advantage and disadvantage of the new method are described by comparing

with the previous methods. With the IAP function, the new method realizes that the remote upgrading through Ethernet is simple and convenient. It simplifies the cumbersome work of the conventional upgrading method, such as removing chips. The efficiency and reliability of updating program is improved greatly without additional hardware cost. From the point of software's or hardware's code sign, this dissertation [14] describes the implement of ISP/IAP system in the microcontroller without using Mask Rom. In the microcontroller, the software is designed by assembly language and the hardware logic is designed by Verilog HDL. This system combines with other modules, in the whole MCU system, building test bench on which the ISP/ IAP system is tested entirely. Simulation, synthesis and verification are successfully done. The design method of this system shows up the basic principle of MCU's function development. IAP technology can achieve wired update download that is Serial Bootloader upgrading method in z-stack and Over the Air wireless update download method. The smart home firmware update system supports these two IAP update methods.

Part of the this dissertation's main research work is to implement the ZigBee-based efficient firmware updating for smart home applications. After studying the methods of firmware updating of the Z-stack CC2530-2.5.0-1.4.0, this dissertation applies the wired update method: SBL and the wireless update: the OTA. The combined wire and wireless solution is based on the IAP technology. ZigBee nodes can be updated by wired method through the serial port on the chips. The OTA Upgrade Cluster provides a standard mechanism for wirelessly upgrading the ZigBee device's firmware. OTA upgrading sessions take place between clients and a server. The OTA Client downloads an OTA Upgrade Image. The images are hosted by the OTA server. Texas Instruments' Z-Stack ZCL: ZigBee Cluster Library provides the support for clients and server operation of the OTA Upgrade Cluster. Thus, the section 4 is to study details of communication and protocol between the client and the server. In addition, another part of the author's work is to optimize the SBL and OTA upgrading technologies. The SBL optimization is to use the HHD algorithm to compress the

firmware size and nimbly decompress the image on the ZigBee endpoints. First of all, the author introduces the traditional image compression processing.

2.3 Firmware Image Compression Processing

In the smart home network environment, the ZigBee embedded chips build network and transmit commanding grading data information in a very small amount like switch on or off for sensors. When ZigBee network multi-nodes concurrently update their firmware, the network will transmit a large number of image data. The original ZigBee network cannot have very good performances. Compression of the image data can reduce the network congestion and upgrade transmission period that can have a better performance. This thesis builds the smart home environment based on CC2530 chips and adopts Huffman lossless compression algorithm to compress image data in the paper [15].

In the ZigBee smart home system, the firmware image compression work is conducted on the gateway which has many resources such as big storage and electricity powered. Because the decompression is working on the ZigBee remote endpoints and the ZigBee embedded chips have the limited memory storage as well as the computing power, designing a slight decompression algorithm is an important target. [16] first presents a new two-dimension array data structure to represent the Huffman tree and confirms an efficient Huffman decoding algorithm based on the designed data structure. When given a Huffman code, the search time for finding the source symbol is T. This Huffman tree data structure could improve the average T performance about twenty times in the section 6 simulations.

2.3.1 Firmware Image Compression: Huffman Coding

There are many algorithms are used in the firmware image compression. Because the Huffman coding is the very traditional compression algorithm and very popular used in modern text

compression. Our firmware is the coding text so the Huffman coding is very suitable for this condition. LZ algorithm is proposed in [17] which is the better lossless compression algorithm than the Huffman coding. But they have more complexity and computation. So this dissertation choose the Huffman coding to compress the firmware image.

There are two main algorithms for data compression: loss compression and lossless compression in the book [18]. Loss compression algorithm removes the need for fidelity in the case of large amounts of data to store small details and the file is smaller. In the loss compression process, removing some necessary data and restoring the original file is impossible. Lossless compression also makes the file smaller, while the corresponding decompression functions can accurately restore the original file without losing any data. The basic principle of lossless data compression is widely used in the computer field. Lossless compression algorithm is feasible: any non-random file contains duplicate data. Duplicating these data can determine the occurrence probability of a character or phrase statistical modeling techniques to compress.

Huffman coding [19] is a lossless compression coding which can perform well in the text file compression process. Huffman (D.A. Huffman) proposed a coding method in 1952. Sometimes called the best coding, it is completely based on the character occurrence probability to construct the shortest average length terminal. The idea of Huffman coding is that shorter codes represent the bigger probability source symbols, and longer codes reflect a smaller probability of source symbols to construct the shortest average length of words. The header of each code is different.

Huffman coding is an optimal prefix code technology, but its shortcomings restrict its direct application. Firstly, the decoding time is positive proportional to the average length code word; Secondly and more importantly, the decoder needs to know the Huffman coding tree structure which must be saved as an encoder or decoder transmission Huffman coding tree. For a small amount of compressed data, this is a big overhead. Therefore, it is critical to

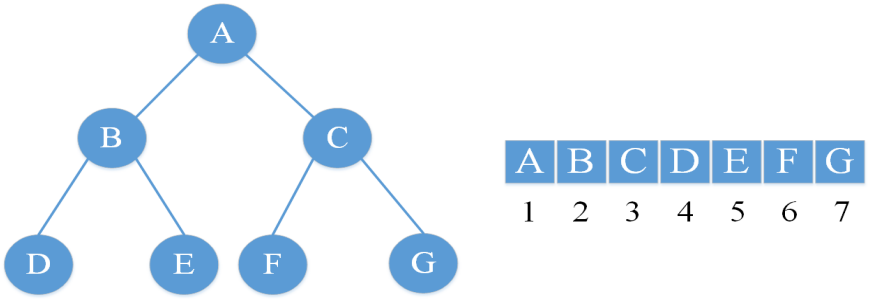
figure out how to reduce storage space in Huffman coding Huffman coding tree. An adaptive Huffman coding Huffman coding tree in which the storage space reduces to zero was proposed in [20]. In the case of convention using, the decoder can dynamically reconstruct the encoder synchronization and Kazakhstan Huffman coding tree without additional data, which leads to increased time overhead. Another technique is to use an encoder and decoder prior agreement of the code tree. This method can only apply to specific data which is not versatility. Alternatively, and most common method is the paradigm Huffman coding. Nowadays many popular compression methods use the paradigm Huffman coding techniques such as PNG, GZIB, and JPEG.

2.3.2 Huffman Compression Data Storage Structure

There are many methods to record Huffman tree nodes information. Huffman trees discussed above are all static. Huffman decoding needs Huffman tree or reconstruct Huffman tree by the decoder through a certain algorithm. Therefore, Huffman tree is contained in the compression file. The following part discusses two kinds of Huffman tree storage structure [21] sequential storage and chain list storage.

Sequential Storage

Sequential storage binary tree is a set of contiguous memory locations to store the binary tree nodes. Therefore, all binary tree nodes are arranged in proper sequence. The mutual position of the nodes in this sequence can reflect their logical relationship. Start from the root with numbering orderliness: from the upper to the lower layer, from left to right on all nodes. The disadvantage is that it is likely to cause a great waste of storage space. In the worst case, a depth of k and only k nodes right single branch tree requires 2k -1 nodes of storage space.



(a) A Complete Binary Tree **(b) Sequential Storage Structure**

Fig. 2.1 Complete Binary Tree Stored in the Order Schematic

Based on binary nature, full binary tree and complete binary use sequential storage more appropriately. Number of nodes in the tree can uniquely reflect the logical relationships among nodes. In this way, it can use the index value of the array elements to determine the nodes' positions and their relationships. Fig. 2.1(a) is a complete binary tree. Its sequential storage structure is presented as in Fig. 2.1(b).

For general binary tree, the order of the nodes in the tree is stored in a one-dimensional array based upon the top-down and left-right order. The relationship among the elements of an array index does not reflect the logical relationships of nodes in the binary tree. However, one can add some empty nodes that are not exist in reality to change this binary tree to a complete binary tree form. People can then use one-dimensional array stored sequentially. Fig. 2.2 shows a general binary tree complete binary tree form after transformation and their order status storage schematic. Obviously, it needs to increase the number of empty storage nodes in order to construct a complete binary tree storage which will cause a lot of wasted space. This condition should not use sequential storage structure. The worst case is the right single tree, as shown in Fig. 2.3, a depth of k right single branch tree, only k nodes are allocated, but 2k-1 memory cell is needed as well.

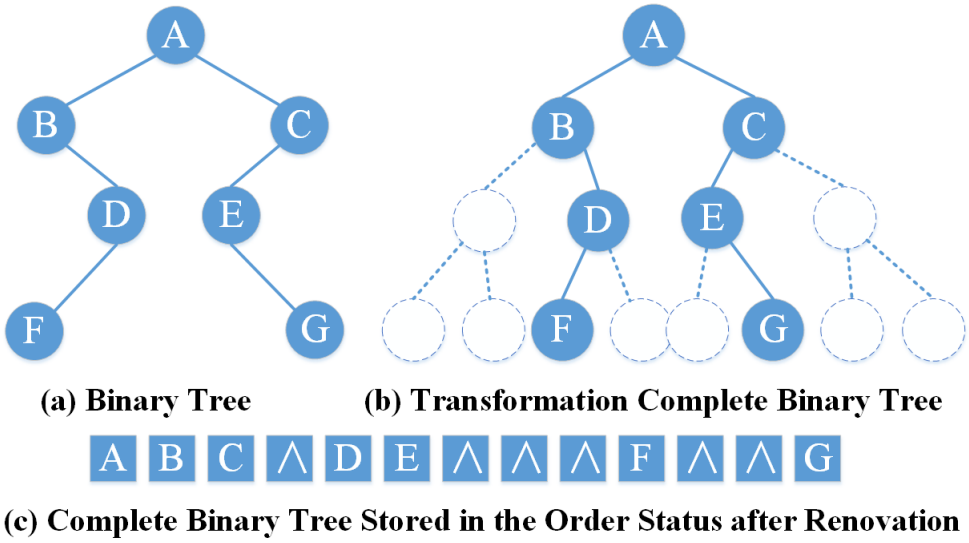


Fig. 2.2 General Binary Transformation Complete Binary Tree

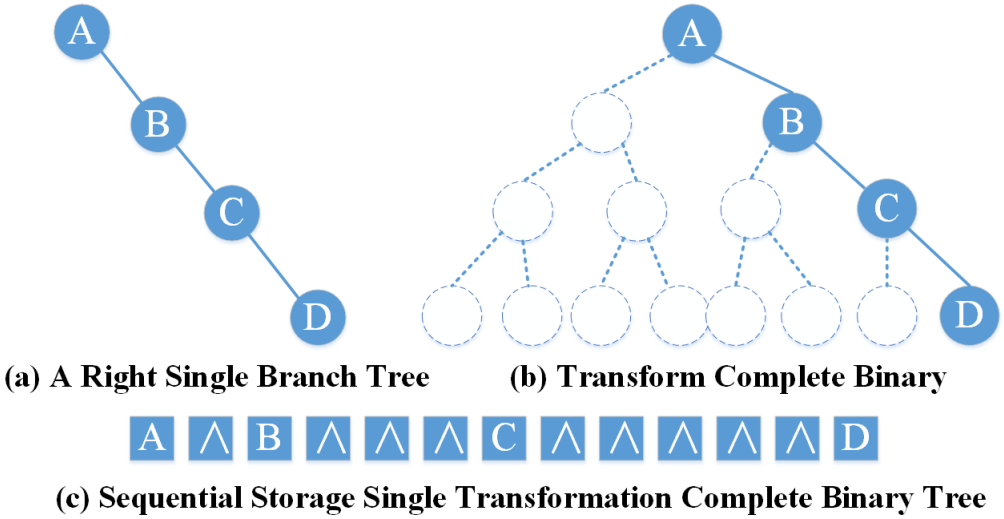


Fig. 2.3 Single Binary Transformation Complete Binary Tree

Chain List Storage

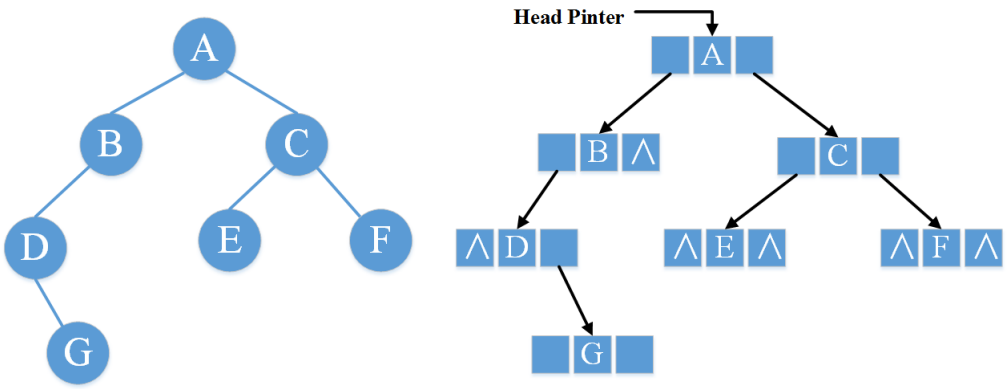
Chain list storage binary tree structure is to represent a binary tree that used to indicate a chain of logic elements. The usual pattern is to list each node consists of three domains, domain and data about the target domain, were used to give the pointer around the left

child node and the right child's link points stored address. Its junction structure is shown as Table 2.1.

Table 2.1 CHILDREN STRUCTURE

LCHILD	DATAI	RCHILD

In this structure, data field contains the value of a node; LCHILD and RCHILD are stored pointing to the left child and right child pointers. When the left and right children do not exist, the corresponding value is the null pointer domain (represented by the symbol ∧ or NULL). Such binary tree node structure represents the chain storage structure as a binary list as the example shown in Fig. 2.4. The right chain storage structure shows that the LCHILD is the same as the RCHILD that points to the next left or right child data unit.



(a) Binary Tree **(b) Binary Linked List Storage Structure**

Fig. 2.4 Binary Tree Binary Schematic

In order to facilitate the process of accessing to a parent node, some researchers also add a node to the linked list of parent field parent that directs to its parent node address. Each node consists of four domains and the node structure changes as in Table 2.2:

Table 2.2 CHILDREN AND PARENT STRUCTURE

LCHILD	DATAI	RCHILD	PARENT

It is easy to find both child nodes and the parent node in this storage structure. But it increases the space overhead regarding the binary list storage structure. Such binary tree node structure that represents the chain storage structure is called the trigeminal list. Fig.6 shows a binary representation of the trigeminal list.

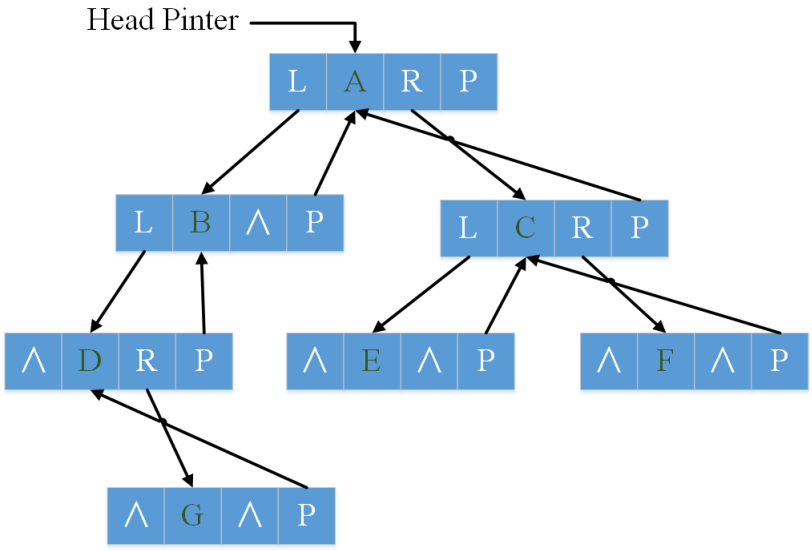


Fig. 2.5 Binary tree diagram showing the trigeminal list

2.3.3 Traditional Huffman Decompression Algorithm

The traditional Huffman decompression algorithm [22] is to rebuild the Huffman coding tree and to decode the compression data. In a nutshell, the decompression of the Huffman code tree is the conversion of the prefix Huffman code back to the symbol, usually by step-by-step tracing of the received bits stream reduction. But in order to track the tree, the Huffman tree must be built first. In some cases, if the weight of each symbol can be predicted in advance, the Huffman tree can be pre-built and stored to reuse. Otherwise, sender end must pre-send Hoffman tree related information to the receiver.

The simplest way is to count the weights of the symbols at first and then add them to the compressed bit string. But the amount of computations in this method is considerable and not suitable for practical applications. Canonical Huffman coding was first proposed by

Schwartz which is a subset of the Huffman coding. Its central idea is that by using certain mandatory convention, with only a few data, the Huffman coding tree will be able to be reconstructed. One very important convention is the digital sequence attribute (numerical sequence property), which requires the consecutive integers binary description with the code word of same length. If the Canonical Huffman coding is used, it is possible to know the exact amount of data reconstructed by the tree only for $B * 2^B$ bits (where B is the number of bits per bit). If the bit of the received bit string is simply a bit, for example: '0' represents the parent node and '1' represents the terminal node. If each reads 1, the next 8 bits will be interpreted as the terminal node (assuming the data is 8-bit letters) and Huffman Tree can be rebuilt. In this way, the amount of data may be the size of $2 \sim 320$ bytes. Although there are many ways to rebuild the Huffman tree, as the compressed data string contains "trailing bits", do not restore them to the wrong value when the reduction decides when to stop, for example in case the data is compressed with the length of the data Traditional algorithms operate by bit, therefore it is inefficient. Fast decoding algorithm is developed to solve two kinds of speed bottlenecks. The advantage of a small improvement of the algorithm is not bit by bit operations, but to some extent, to enhance the decoding efficiency. For this algorithm, the code length is determined in the code but improvements can also be made if the minimum value develops into a binary tree, and code length can then be determined more quickly if using the binary tree.

While these improvements are intended to ease the bottleneck of by-bit operation, the code length is still needed to calculate. Therefore, this paper discusses the need to calculate the code length lookup table algorithm. Assuming the length of the longest code word is the maximum, each fixed decoding algorithms can read at least the max number. The read bit string contains zero or more interpretable but uudecoded "surplus" sections of code words, which are the prefix of next code word. Based on the interpretable code word, corresponding symbols will be output, and by using the "surplus" partial index lookup table, the next bit

string can be read. This method requires the number of the look-up table is equal to that of different code word prefixes, i.e. the number of internal nodes of Huffman: N-1. Thus, each lookup table has 2^k records with k binary number string of corresponding length.

Huffman decoding needs to search the Huffman tree to decompress data. There are many efficient Huffman decoding algorithms, but they are not very suitable for the embedded environment. Due to the complexity of above decoding algorithms and poor function of the space cost scenes in the smart home applications, this dissertation is originally inspired by the literature and designs an efficient decoding algorithm. Both the compression and decompression consider the data storage structure. A nimble and fewer space-cost storage structure design has always been the goal to pursue. This dissertation proposes a flexible Huffman tree storage structure to present the binary tree. It uses a recorded array of N-1 node information that contains each node's logic and physical positions information. Then the decompression algorithm can use the array to decode the bits string.

2.4 OTA Updating Optimization Progress

Texas Instruments provides an Over-air-download (OAD) firmware update method in the z-stack [11] before ZigBee OTA firmware update specifications are formulated by ZigBee Alliance [23]. Admittedly, the z-stack OTA is more standardized and mature in conforming to the OTA specifications.

Many researchers and developers have made some optimizations about the ZigBee OTA update technology based on different hardware platforms. In the z-stack [24], TI provides a page requesting to reduce the image block commands as article [25]. But developers need to implement it by themselves in the z-stack applications. Paper [26] presents a kind of image data compression algorithm and voluntary nodes request method for the OTA upgrading. The compression algorithm can make firmware image smaller so as to abbreviate the transmission data and cut down the transmission duration. The voluntary nodes request method can assort

the performance of backbone data circulation. But the firmware compression algorithm will increase the complexity of OTA server workload computation and the OTA client needs to decompress the image data, thus requiring more workload and power consumption. It is not very suitable for ZigBee embedded chips' strict requirements for low-power consumption. Moreover, the nodes can voluntarily request method to close the pooling function and it is an awful scheme that only OTA process can transmit data but the ZigBee's natural functions cannot work normally. In this paper [27], authors propose a multi-node concurrent upgrade scheme which is to solve the efficiency problem with broadcast upgrade based on the tree-type ZigBee network. It defines a new node's logic type who has child nodes named the slave server of the ZigBee OTA. When multi nodes of the ZigBee network concurrently update the firmware, all nodes will send the request to the father slave server nodes other than the OTA server and the slave server will decide whether to conduct the children nodes' updating. This method addresses the redundancy of firmware data and reduces the workload of the OTA server. It allows the ZigBee OTA to update P2P scheme in an orderly manner other than arbitrarily obstruct the OTA server's backbone. However, as the self-healing function permits the ZigBee network which is generally in the meshes to dynamically transform structure so the father slave server in the tree may not be the befitting node. In addition, excessive orderliness may not lead to the optimal efficiency. The nodes at the bottom of the tree network will send vain polling commands if the slave server does not complete the firmware updating and squander more energy when the multiple nodes are concurrently updating themselves.

All those leads to a complicity of the OTA update and make ZigBee OTA mesh network need to cut the data redundancy and improve the update efficiency. Meanwhile, the OTA update can work with the normal functions of ZigBee network [28] and features low power consumption, self-healing and mesh network architecture. Therefore, this dissertation proposes the dynamic page-request distributed OTA upgrade algorithm (DPPOTA) which implements the image page request method in the z-stack to decrease the image block

commands and modifies the ZigBee routers' OTA applications to make the mesh network dynamically process multi-node concurrent updating efficiently. In a way, this algorithm is like a sort of the greedy algorithm: the OTA progress is based on the ZigBee mesh network's basic route choice and each thread is currently the best choice. In addition, the routers must complete their own OTA process at first and then transmit other nodes' OTA upgrading commands. Therefore, each route path is dynamic and sequential and performs as an orderly mesh network to cut down the massive data redundancy.

Chapter 3

Preparing ZigBee Network for Firmware Updating

In this dissertation, ZigBee technology is used to build the smart home system which mainly contains two parts: the ZigBee gateway and the ZigBee wireless mesh network nodes. ZigBee gateway consists of a Linux host and a CC2531 as a ZigBee's network coordinator. CC2531 chip performs as a ZNP device that can manage the ZigBee network such as building up the ZigBee network, adding or moving devices, and setting the network security key. The Linux host performs as an important role that parses the ZNP incoming information from bottom layer and pushes the information to the upper different server applications for treatment in progress. In addition, the gateway also needs to present a user interface or application interface to be inserted into the internet. It is just like a bridge that connects the remote ZigBee endpoints and people's mobile devices through the internet. On the other side, the ZigBee 3.0 came into consumers' sight in June 2016. Comparing with the traditional ZigBee standards, the ZigBee 3.0 has created a breakthrough technology named "Green Power" which can make sensors consume less power and even some companies claimed that the sensor can work in your life. ZigBee 3.0 evidently expands the power saving advantage of the ZigBee technology than other 2.4GHz technologies. Smart home devices with ZigBee 3.0

can perform very well in the remote end-point environment. According to the implementation of the technology, this dissertation selects TI open source solution – Z-Stack to build the ZigBee 3.0 mesh network as the basic smart home devices network and builds the Z-Stack Linux gateway as the smart home gateway.

3.1 Updating Server: ZigBee Linux Gateway

Z-Stack Linux gateway is TI's ZigBee Home ZigBee Home gateway solution for Linux systems. One of the main points of this gateway is to integrate ZigBee into the IP internet world with simplified APIs over socket communication. The ZigBee middleware abstracts a variety of smart home applications and conducts multiple automation application cases such as lighting control, alarm, security, energy management, network management and over-the-air firmware upgrade. It can be fast prototyped on Beagle Bone Black platform which is powered by TI's leading Sitara-Am335x Cortex-A8 processor and is able to run on most Linux or Android platforms. This gateway solution can also support the green power nodes of ZigBee 3.0.

The gateway's upper level uses Google protocol buffers that are Google's language-neutral, platform-neutral and extensible mechanism for serializing structured data such as XML, but it is smaller, faster, and simpler. Developers can define how they want to the data to be structured, then they can use the special generated source code to easily write and read your structured data to and from a variety of data streams and use a variety of languages such java, C# and python. After that developers can use the protocol buffers to communicate with other message queue servers such as Rabbit MQ broker for future development.

Home gateway can receive ZIGBEE nodes' information and send commands to control home devices. In addition, the gateway can serve as a bridge to support the ZIGBEE data inserting into the internet. ZNP can perform as a home ZIGBEE devices dongle and an application needs to be developed on the ZNP layer which is named ZIGBEE network

application (ZPI). TI has provided a solution of ZNP using the CC2531 USB dongle as a coordinator. Afterwards, we can develop our own application to manage home through CC2531. There are many programming languages provided for developers to make their dream come true. In this dissertation, node.js is chosen to build the ZPI and node.js can develop a web server easily and communicate with brows in a friendly way. It is a truly convenient method to build the gateway server. There are so many open-source ZIGBEE scheme and we choose ZigBee-shepherd to build the gateway interface rapidly. The ZPI is designed as Fig. 3.1.

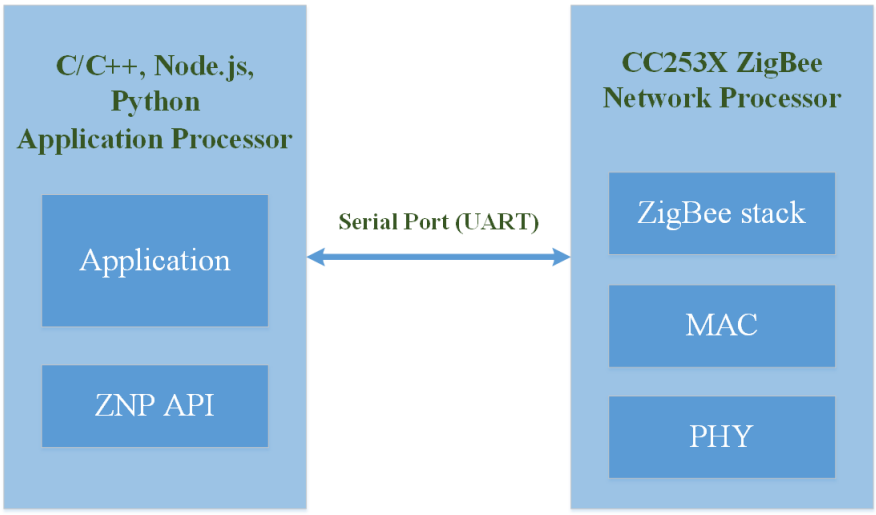


Fig. 3.1 Smart Home Gateway ZPI Scheme

Node.js is very popular and can be applied for developing on embedded computer platforms such as Raspberry Pi and Beagle Bone Black. We can firstly develop the gateway on PCs and explant the other small computer board because node.js has a good cross-platform feature. Only ZPI cannot work as a gateway itself, and it must communicate with the internet. ZigBee-shepherd provides abundant interfaces of ZNP written by java scripts for upper level callback. Thus, the ZIGBEE coordinator function can be realized and the ZIGBEE's endpoints can be mapped to the logical variable for a web or phone to operate. The article of gateway is shown as Fig. 3.2.

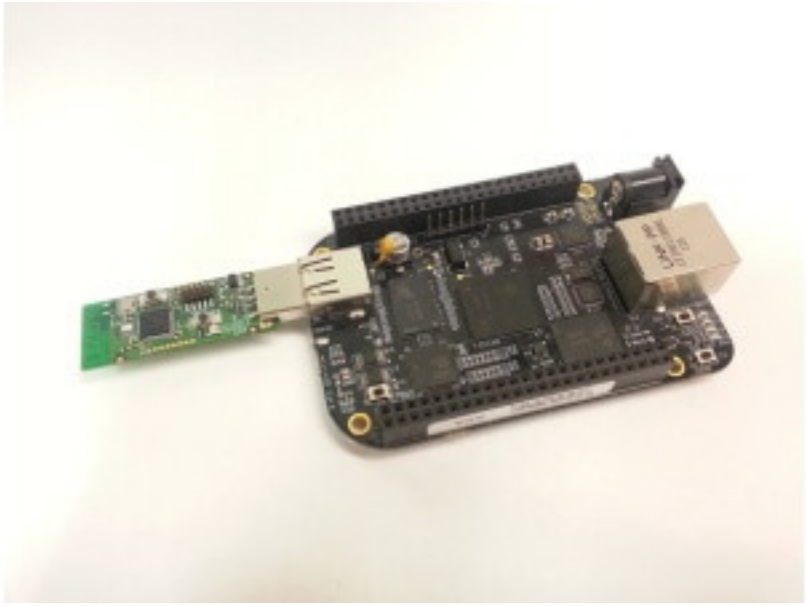


Fig. 3.2 ZigBee Smart Home Gateway

TI provides an open source ZigBee gateway solution for developers to build their own gateway applications. Because the CC2530 chips have been chosen as the endpoint radio scheme, the CC2531 naturally becomes the ZNP device and Beagle Bone Black board performs as the Linux host. According to the z-stack documents, my smart home gateway-level block is that the bottom layer of ZNP's gateway which is the Z-Stack ZigBee Network Processor, running on the TI CC2531 wireless MCU. It is a ZigBee application that contains the Z-Stack's core functions and is logically configured as the smart home's coordinator. The ZNP CC2531 device connects with the Linux host through serial interface in the software module and achieves hardware connection by UART. Upper layer is NPI's server that is the ZigBee network processor application interface. NPI supports the socket communication modality connecting with the ZNP device that abstracts the physical serial communication mechanism of UART. In addition, the SBL tool is located at this layer because the tool needs to update the ZNP firmware image by UART. Afterwards, there is a middle layer whose function is to wrap ZigBee's stack data and build a TCP socket to serve top server applications. There are mainly three servers over the middle layer: home gateway server,

network manager server and over-the-air update server. The core of the firmware update of the smart home is the OTA server which provides devices with firmware update service listed in the gateway ZigBee network such as the lamp, the switch and other devices. The network manager server uses ZigBee's stack services to manage its facilities on the network and creates a facility database that contains information such as IEEE address, device ID and other parameters for all ZigBee's facilities. The gateway server offers the primary function of the gateway. It encapsulates the ZigBee's endpoint registration, simple descriptor of devices and the endpoints attribute table. For instance, if consumers want to read their home temperature and control their home lamps, the gateway server will provide these services. These three servers are the core of the smart home gateway and a user application layer will be developed to combine these servers to serve individuals. C language is able to make binary data coding and well communicate with GPU. So, C language is used in developing many embedded systems to run application fast. When the upper layer application does not much limit machine running speed demand, C language is not a very suited programming language in web and mobile application development. However, if other developers want to use another developing language, the problem will be how different programming languages work together with each other.

In views of this situation, Google has designed a structured data encapsulation named protocol buffers that are Google's language-neutral, platform-neutral, extensible mechanism for serializing structured data. To refer to the serializing data structure, there are many popular technologies such as XML and JSON. The protocol buffer is smaller, faster and simpler than them. People can define how they want the data to be structured and use the special generated source code to easily write and read the structured data through the proto file and using a variety of languages. The advantage of protocol buffer is that these three servers socket interfaces can be encapsulated into three proto files and python and java can be used to develop the web application communicating with servers. But the disadvantage

is that the proto file needs a compiler to produce the python class file and its readability is poor. Recently the gateway user application can be developed to communicate with servers by different languages using these three proto files.

Above all, the smart home has been built. User can send commands and receive attributes of devices on the gateway application via the CC2531 ZNP layer. The next step is to establish the endpoints' ZigBee network applications.

3.2 Updating Client: ZigBee Network Applications

In 2016, ZigBee Alliance officially launched the ZigBee 3.0 protocol which was an open, global standard for the Internet of Things based on the IEEE 802.15.4 standard and working on the 2.4GHz frequency band. The difference compared with the precious ZigBee standard is that ZigBee PRO network has the Green Power feature. The same protocol structure as the previous ZigBee version is: the physical layer (PHY), media access layer (MAC), network layer (NWK) and application layer (APL) from bottom to up. In the past fourteen years, ZigBee Alliance has developed many APL applications such as home automation, building automation and ZigBee light link, but the ZigBee 3.0 has integrated and simplified these different applications as discussed in this paper [29]. Just as the ZigBee Alliance web said, ZigBee is the only global, standards-based wireless solution that can conveniently and affordably control the widest range of devices to improve comfort, security and convenience for consumers. It is the choice of technology for world-leading service providers, installers and retailers who bring the benefits of the Internet of Things into the Smart Home. It has the following main features: frequently and agilely operating over sixteen channels in the 2.4GHz frequency, multiple star topology and inter-personal area network communication. ZigBee 3.0 utilizes the industry standard AES-128 security scheme, incorporates power saving mechanisms for device of all classes and provides support for battery-less devices. Those features allow the energy harvest devices to securely join ZigBee's pro networks. It is

the eco-friendliest way to power ZigBee products such as sensors, switches, flame and many others. Devices can currently be powered by using widely available but frequently untapped sources of energy: motion, light, click, vibration and temperature alternation, just to name a few. The energy used to flip a typical switch via common energy harvesting techniques is powerful enough to generate and send the ZigBee PRO commands. For instance, we can use switch to turn on or off the lamp in the past circuit, but now we can use the battery-less switch to control lamp with ZigBee battery-less radio chip instead.

In this dissertation, the TI z-stack 3.0 is chosen as the ZigBee protocol implement scheme. TI ZigBee solution chips are CC2530 and CC2538. CC2530 is a true system-on-chip solution for IEEE802.15.4 and RF4CE application. It combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8041 MCU. CC2538 is more powerful and contains an ARM Cortex-M3-based MCU. Considering the cost, CC2530 is more suitable for the smart home devices' radio module. To sum up, the CC2530 hardware chips and z-stack software are used to build up the smart home environment.

Initially, the ZigBee network nodes have three logical types: coordinator, router and end device. Coordinator is the first node to be started and is the only one node responsible for forming the network by allowing other nodes to join the network through it. Coordinator has all the functions of router. After it builds the network and the other ZigBee nodes have joined the network, the coordinator only performs as a router. If the ZigBee network needs to reset, the coordinator start the coordinator's functions. As mentioned above, the gateway application on the coordinator is set to be the smart home pivot. Router is another ZigBee node's logical type which has routing capability. It is also able to send and receive data as a smart home device and allows other nodes to join the network. One ZigBee network contains many routers that always wait to be on call. The last node type is an endpoint that is the most common device type. It is only capable of sending and receiving data and cannot route other commands. A mesh network is illustrated in the Fig. 3.3.

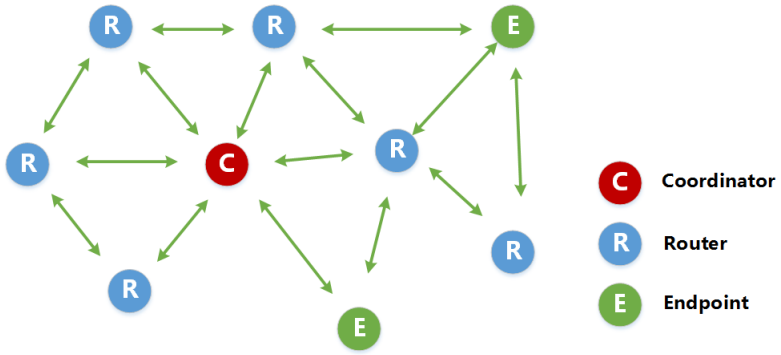


Fig. 3.3 ZigBee Mesh Network Topological Graph

The smart home contains many kinds of ZigBee nodes and they can be roughly divided into three kinds: controller, sensor and binary sensor. To facilitate my study, this dissertation uses just two devices as samples. If open the z-stack in IAR IDE, we can see that it does not only contain the ZigBee protocol layers but also some other auxiliary layers as shown in the Fig.3.3. To omit the developing progress, this dissertation abstracts two types' devices: switch and light. The switch can be turned on or off and bind with the light application in a group. Both of them can be routers or endpoints. Then we can update their firmware by upgrading the technologies of the ZigBee firmware in the next section.

Chapter 4

Approaches to ZigBee Network Firmware Updating

This dissertation applies the TI CC2530 chips and z-stack platform to build the smart home sensor network. When it comes to the smart home devices firmware update solutions, it needs to upgrade the ZigBee firmware without removing core chips. If consumers need to update devices' firmware themselves by using the programmer to burn the image, the workload is so massive and any consumer will not buy these products. The ZigBee IAP technology can realize a convenient update and z-stack has provided two methods: Serial Bootloader wired upgrading scheme and the Over-the-Air wireless upgrading scheme.

4.1 Wired ZigBee Firmware Updating: Serial Bootloader

Serial Bootloader (SBL) is provided as a value-enhancing sample solution that enables the updating of code in devices without the cost of maintaining any download-related code in the user's application other than ensuring a compatible flash memory mapping of the final output. SBL process is working as a managed client-server mechanism which requires a serial master to drive the process and it has a generic feature that should deviate as little

as possible. Many implementations only support the idiosyncrasies of the specific medium (e.g. USB) crucial to the level of service necessary to complete a code image download in a reasonable amount of time. For the sake of example, the USB SBL specific references will be made in this document, although merely changing the medium-specific verbiage and paths should allow this document to sufficiently describe any Z-Stack SBL.

4.1.1 ZigBee SBL Server

TI has provided the SBL client application on CC2530 chips and a console tool as an .exe server based on PC Windows. But developers cannot see SBL server's operational principles. If the smart home's gateway wants to support the SBL service as a server end, it must make the communication process clear. My contribution is providing the details of communication between the server and the client through monitoring the serial communication. SBL updating is a wired firmware updating method and it is generally used to upgrade the ZNP device. I summarize the communication commands and implement a python SBL server on the gateway to upgrade the CC2531 ZNP.

Firstly, when the consumer has a new version firmware of ZNP, the gateway can be reliable and fast for transforming the firmware image to CC2531 ZNP device. The SBL server communicates with the client in half-duplex operation. The gateway gives the SBL server essential environment of port parameters such as baud rate, port number and so on. Then the gateway sends a SBL request to ask ZNP to prepare for SBL updating. When it receives a response command, the next step is to make handshake with ZNP. After the handshake succeeds, ZNP client turns into a SBL client model and continues to receive the firmware data. Then the gateway can write the hex or binary firmware data into ZNP by UART. When the gateway receives the success response, it sends the next block data, or resends the failing data frame. At last, the whole firmware image will be sent out and the gateway sends a CRC command to make ZNP start the new firmware. Above all, it

is the basic SBL communication process between the server and the client. The diagrams below show the basic request and response commands of the communication process (see Table 4.1).

Table 4.1 SERVER BASIC COMMAND AND CLIENT BASIC COMMAND PATTERN

SOF	Length	CmdO	Cmd1	D1	D2	...	Dn	XOR

SOF	Length	CmdO	Cmd1	Error Flag/D1 Dn	XOR

According to the SBL status, the Z-Stack defines many states as shown in Table 4.2.

In the Z-Stack protocol, the biggest transform data size is 64 bytes. The gateway can send the 0xF8 command to force boot load into in-application-programming model and send the 0x07 command to force the system to run. This is the same case for Cmd0:0x4D by using the SBL process. In the definitions of ZNP clusters, the high three bits represent three models: the synchronous request model for 0x02, the asynchronous request model for 0x04 and synchronous response model for 0x06. Subsystem command over 0x0D is given by SBL's subsystem. Then Cmd0: 0x4D means the client jumping into SBL's asynchronous subsystem. Server will first send the cmd1: 0x10 to start the ZNP SBL model. Then the server will send the Cmd1: 0x04 to make handshake with ZNP. After receiving the Cmd0:90 and ErrorFlag: 0x00, it will successfully begin flash programming.

Table 4.2 ERROR FLAGS

Error Flag	Meanings
0	SB_SUCCESS: Success.
1	SB_FAILURE: Failure.
2	SB_INVALID_FCS: XOR error.
3	SB_INVALID_FILE:Invalid file.
4	SB_FILESYSTEM_ERROR
5	SB_ALREADY_STARTED
6	SB_NO_RESPOSNE
7	SB_VALIDATE_FAILED
8	SB_CANCELED

Table 4.3 HANDSHAKE COMMAND PATTERN

Server		Client	
Name	Content	Name	Content
SOF	0xFE	SOF	0xFE
Length	0x01	Length	0x01
Cmd0	0x4D	Cmd0	0x4D
Cmd1	0x04	Cmd1	0x84
Data	0x02	ErrorFlag	0x00 (Success)
XOR	0x4A	XOR	0xC8

Table 4.4 FLASH PROGRAMMING COMMAND PATTERN

Server		Client	
Name	Content	Name	Content
SOF	0xFE	SOF	0xFE
Length	0x42	Length	0x01
Cmd0	0x4D	Cmd0	0x4D
Cmd1	0x01	Cmd1	0x81
FlgAddr	0x00 0x00		
Data	Data	ErrorFlag	0x00 (Success)
XOR	0x38	XOR	0xCD

When SBL begins to flash the firmware, the server will send Cmd1:0x01 and flash start address: 0x00 0x00. When the client receives the correct firmware image block, it will send the 0x00 success response. Then the server begins to send 64-bit firmware image block and the last block less than 64 bits are filled with 0xFF. After successfully flashing the last firmware image block, the server will send the read command Cmd1:0x02 to read back the data from address: 0x00 0x00 to check the firmware validity.

When the server reads back the whole firmware image correctly, the server will send the CRC Cmd1:0x03 to make ZNP jump to run on the application system. When the server writes the CRC command Cmd1:0x03, if the CRC's result is incorrect, the Error Flag will present SB_VALIDATE_FAILED or SB_SUCCESS. As the gateway design is based on the TI CC2530 z-stack protocol, the commands will follow ZigBee's cluster specification.

Table 4.5 READ BACK COMMAND PATTERN

Server		Client	
Name	Content	Name	Content
SOF	0xFE	SOF	0xFE
Length	0x02	Length	0x43
Cmd0	0x4D	Cmd0	0x4D
Cmd1	0x02	Cmd1	0x82
FlgAddr		0x00 0x00 Data... ErrorFlag	
Data	Data		
XOR	0x54	XOR	0xCD

Table 4.6 CRC RUN APPLICATION SYSTEM COMMAND PATTERN

Server		Client	
Name	Content	Name	Content
SOF	0xFE	SOF	0xFE
Length	0x00	Length	0x01
Cmd0	0x4D	Cmd0	0x4D
Cmd1	0x03	Cmd1	0x83
Data		ErrorFlag	0x00 (Success)
XOR	0x4E	XOR	0xCF

Based on above all, the ZigBee SBL server can be implemented based on the special protocol in different programming language. According to the upper application development in the future, python is used to build the same function script as C programming SBL server on the Beagle Bone Black which can be a widget for the gateway to abstract the SBL service.

4.1.2 ZigBee SBL Client

When developing the gateway application, the ZNP firmware needs to be updated frequently. The SBL firmware update method can provide a reliable and convenient service. However, SBL must possess wired communication by UART that is a big limit of application in the wireless communication network. Thus, the CC2531 ZNP is a just perfect fit client device in this condition.

The SBL solution requires the use of boot code to check the integrity of the active code image before jumping to it. This check guards against an incomplete or incorrect programming of the active image area. The SBL boot code provides the following functionality: 1. Boot Code will be the target of the reset vector (as well as any vector necessary for communicating on the chosen serial bus), and therefore contains startup and ISR code; 2. When the serial bus connection is detected and the master application commands it, Boot Code will program the SBL image into the active image area and will thusly complete the final step of the SBL process: code instantiation; 3. (Optional) Boot Code will guard against interrupted, incomplete or incorrect programming of active image areas by checking the validity of the active application code image via CRC. If the image is not valid then the boot code will not allow it to run.

An SBL-compatible Z-Stack is implemented as a standard ZigBee application built with the exception of the linker command file and some ancillary settings. The serial ports update is completed in the sample application. By analyzing interaction of serial data frames, the z-stack SBL update command is found between PC and CC2530. It can work with z-stack boot loader application with fast speed. The frame and command are as Table 4.7

Each CC2530 chip runs as a ZigBee node radio chip that sends and receives wireless data or commands for smart home devices. ZNP is an important device as a coordinator to build and manage network or device. In this dissertation, CC2531 ZigBee Network Processer is used as the solution to connect with Beagle Bone Black by UART as a home gateway. When consumers want to update the ZNP firmware, SBL is a reliable and fast update method. Our gateway has provided an SBL server to track the ZNP SBL update, and what ZNP needs to do is to communicate with the server and make handshake. Then the ZNP client waits to receive a block firmware data from the server and send a success response command to the server to tell that it can send the next block image. After receiving the whole firmware data, the client will receive a CRC to transform the new firmware to the memory bank. Counting several

Table 4.7 OTA UPGRADE CLUSTER COMPENENTS

| Data Header: SOF | Data Length: LEN | Command 1 | Command 2 | data | CRC: FCS|

For example:FE 01 4D 10 00 5C

In the SBL program has the following definition:
// Bootloader Serial Interface Subsystem
#define SB_RPC_SYS_BOOT 0x4D
// Commands to Bootloader
#define SB_WRITE_CMD 0x01
#define SB_READ_CMD 0x02
#define SB_ENABLE_CMD 0x03
#define SB_HANDSHAKE_CMD 0x04

seconds, the ZNP will restart and run the new firmware. The logical interacting process is shown in a figure and the communication commands are present in a table. However, if ZNP wants to implement the SBL service, it needs to program the serial boot code into the CC2531 in advance. The boot code is located from 0x0000 to 0x2000 in the memory bank. Thus, the ZNP application code will start from bank: 0x2000 in the memory to keep the boot code invariant. The CC2531 inner memory bank programming address allocation is showed as Fig. 4.1.

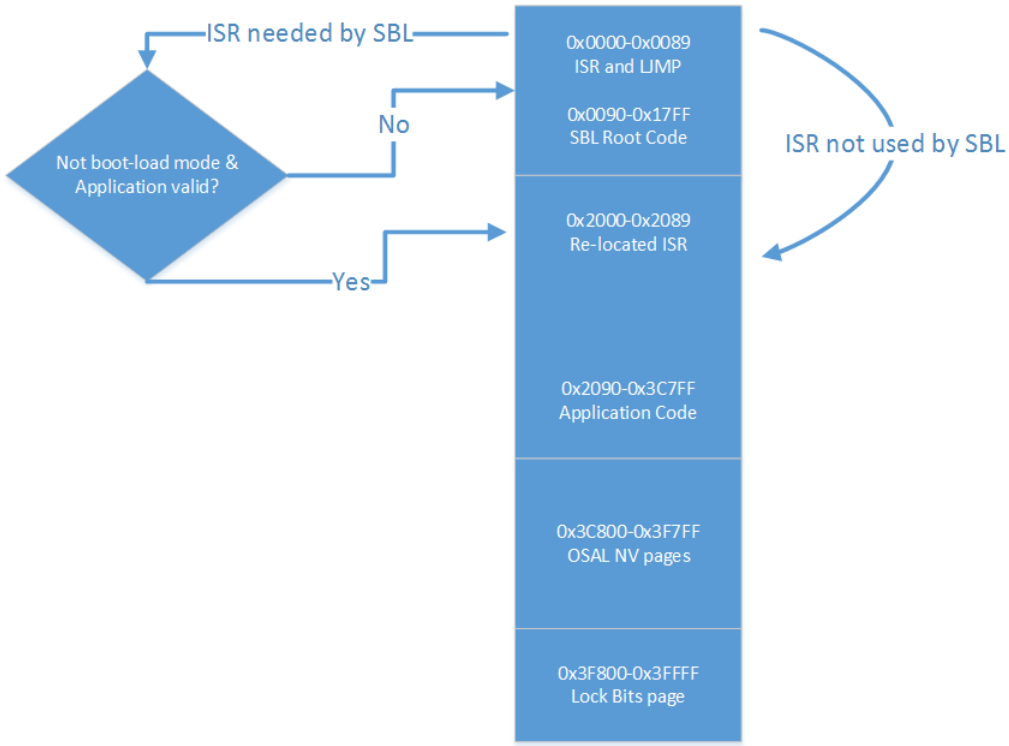


Fig. 4.1 SBL Programming Bank Address

As the Serial Boot loader may run on the different platform, when developers use C/C++ in windows, they will write files to make it run on the Linux system because many embedded computers are Linux system. For this cross-platform need, Python is a good programming language choice. Therefore, a Serial Bootloader python script is developed to provide wired firmware update service. It can work with the z-stack Linux gateway to update the ZNP device's firmware without any other servers running. This SBL server can work well with the ZigBee network applications. The CC2531 dongle runs as not only a ZNP device on the gateway but also a SBL client same as other ZigBee applications.

4.2 Wireless ZigBee Firmware Updating: Over-the-Air

This dissertation applies ZigBee technology to build a smart home In-Application programming update environment as Fig.4.2. In this environment, the dongle is connecting the

computer through wired method. The ZigBee network nodes connect with each other by wireless method. Then the dongle and other nodes should choose a different method to update so that the whole network update is more efficient. After the z-stack data sheet is studied, three methods can be used to update the ZigBee nodes firmware: Serial Bootloader (SBL), Over the Air Download (OAD) and Over the Air (OTA). The OAD uses TI's protocol and the OTA use the ZigBee Alliance protocol. So, the OAD is the same as the OTA in principle and it only chooses the OTA method to update. The above sections has introduced the SBL technology, the OTA technology that is one of the In-Application programming (IAP) technologies, same as the SBL, but the OTA is a wireless IAP.

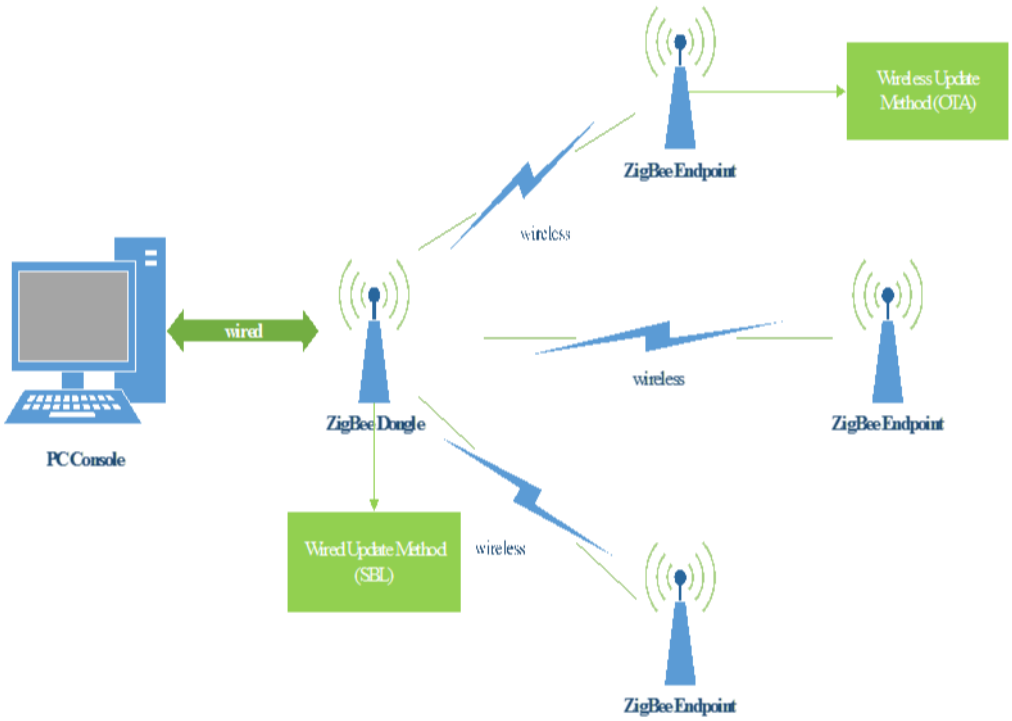


Fig. 4.2 A Simple ZigBee Firmware Upgrading Process

The OTA (Over-the-Air) Upgrade Cluster provides a standard mechanism to wirelessly upgrade a ZigBee device's firmware. Over-the-air updating sessions take place between a client and a server. The OTA Client downloads an OTA Updating Image from the OTA Server that hosts new firmware images.

4.2.1 ZigBee OTA Server

ZigBee alliance formulates the Over-the-Air update standard that is providing a standard mechanism for wirelessly upgrading a ZigBee device firmware in the ZigBee upgrade cluster. Over-the-air update wireless sessions are processed between a client and a server. In addition, the server needs to produce the firmware image data from the upper machine such as a home gateway by wired method. Texas Instruments z-stack of ZigBee Cluster Library (ZCL) provides the applications' technical support for the client and the server operation in the OTA Upgrade Cluster. It provides a simple description of how the OTA Upgrade Cluster is used to renovate a device firmware. In simple terms, the OTA Upgrade Cluster communication between a client and a server takes place using some message commands as shown in Fig.4.3.

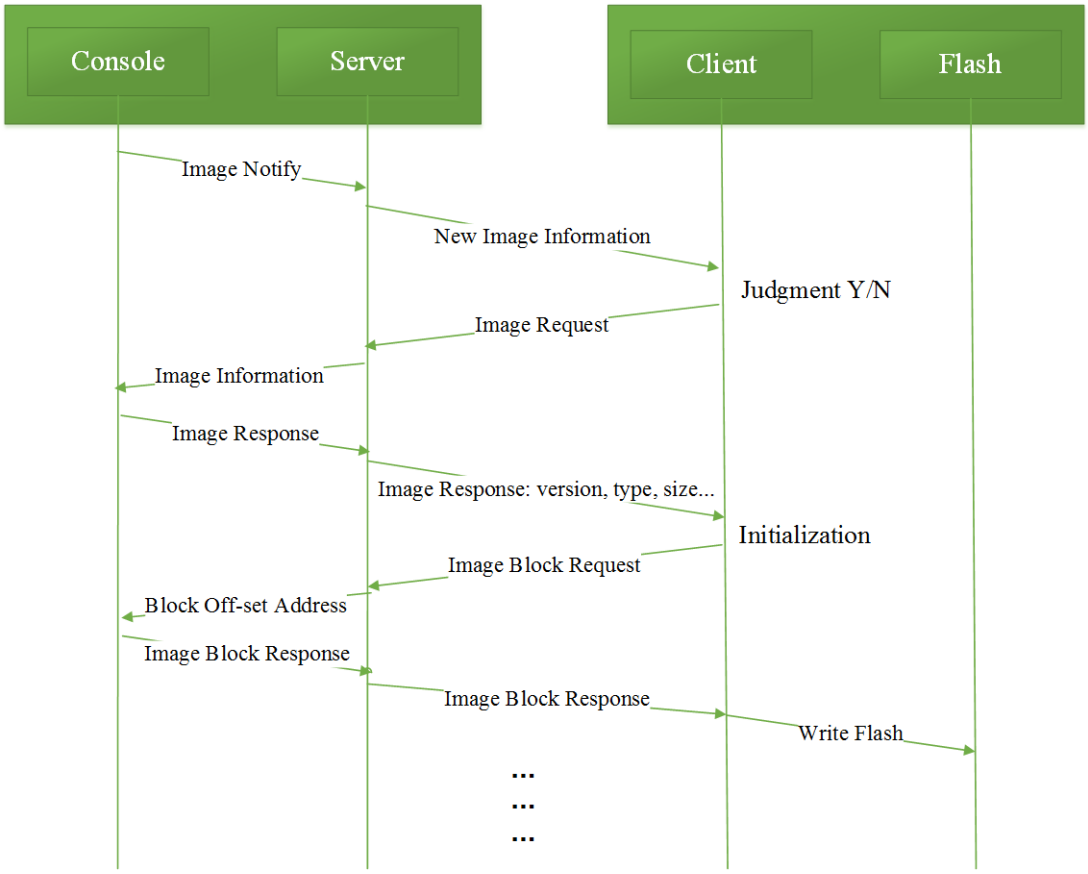


Fig. 4.3 OTA Process Communication Commands

From the above diagram, it shows that the OTA updating is a kind of data request and response dependable communication. If only considering the wireless communication session, the ZigBee OTA Cluster commands are be presented as bellow. Basically, adding OTA function can be sectioned into three parts: inserting OTA and related events, handling OTA MSG, environment setup and updated image generation. The followings are steps to change the Z-stack sample application, Simple Sensor EB, into an OTA-enabled application. Increase in the data payload can speed up the update.

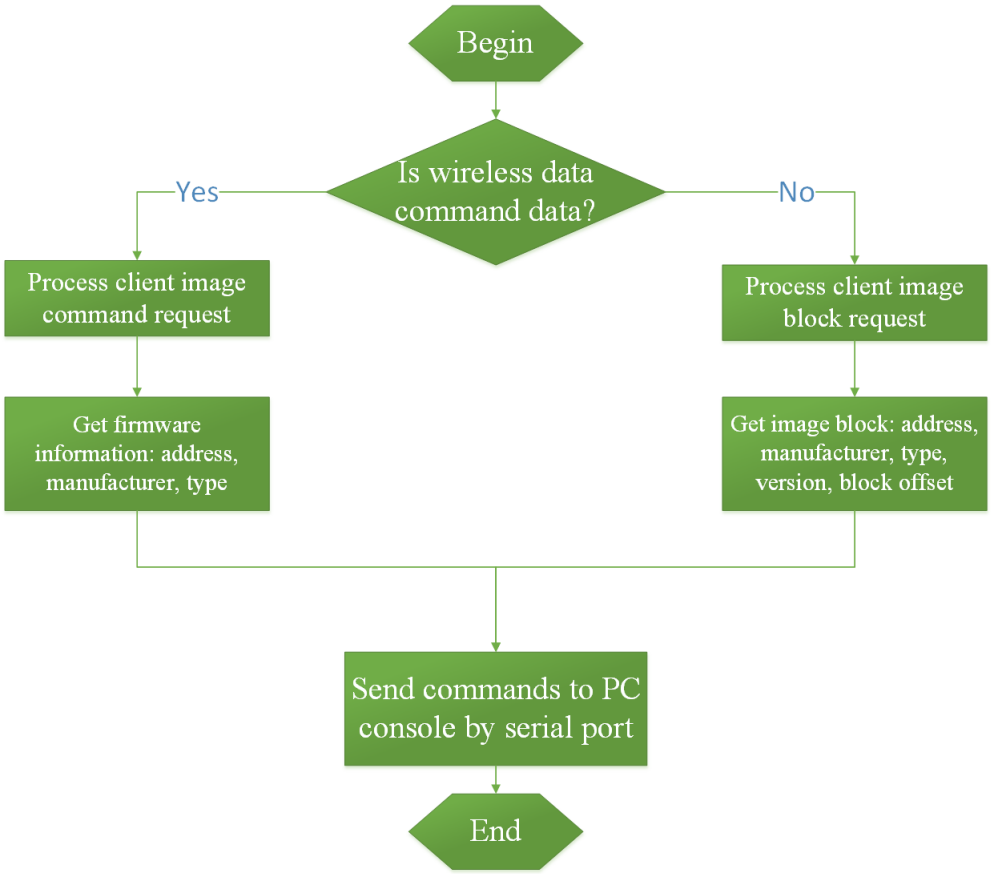


Fig. 4.4 OTA Server Wireless End

The server is a ZigBee device such as a CC2531 ZNP dongle that performs as an OTA boot device by which the *Image Notify* message is sent broadcast or unicast to notify the OTA clients that there are some new firmware images available. In the Fig.4.4, the server receives the wireless data. If the wireless data is the command data then go left path to send commands

to PC console. If the data is the block image request then go right path to get the image block from the PC console. This message command does not contain any information about new images and it is just an OTA inspiration. Then the OTA clients determine whether they need to update the new firmware image by sending the *Query Next Image* request command and receiving the response messages. This request message contains the currently running firmware version on the client device and the server decides whether an image should take place and which image the client should update by checking this message. Then the server sends the *Query Next Image Response* message to instruct the client to download the new firmware or inform the firmware that it is not available. Afterwards, the download process begins to run after the clients sending the *Image Block Request* message. The server sends chunks of firmware image data in the *Image Block Response* message. The clients write the received image blocks to a secondary storage location which can be in the on-chip or off-chip flash memory. Depending on the CC2530 chips that only have 256k RAM, an external flash is needed to communicate with the chip by SPI. Periodically, after a client requests the entire firmware image data, the client sends the Upgrade End Request message to the server. The *Upgrade End Response* message sent by the server contains information about what time the client can switch to the new firmware, immediately or waiting a specified period. Above all, it is the chief communication process of the OTA update. The detailed functions and implementation of the OTA server and clients are presented in the following section.

The OTA server contains the upper machine that hosts firmware image and the OTA boot loader. As the frontal home gateway design scheme, the ZigBee gateway hosts the OTA update firmware image and provides the OTA update service. The ZNP CC2531 becomes the OTA boot device like an assistant that produces the image data from the gateway and sends the firmware data to the clients. The z-stack provides the OTA function solution but it cannot work in the sample applications. Firstly, open the z-stack software file and find the OTA dongle file. Because the ZNP device performs as a coordinator, the OTA dongle will be

programmed in the IAR IDE tool. Switch the C/C++ Compiler and Linker options in the IAR and configure the parameters as shown in the figure. Then rebuild all endpoint codes of the coordinator and download them into the ZNP dongle device. In the Fig.4.5, OTA server serial port end can receive three types serial port data. One is the command from the PC console which it the image notify. Second is the client's commands from the PC console. The last one is the client's image block response.

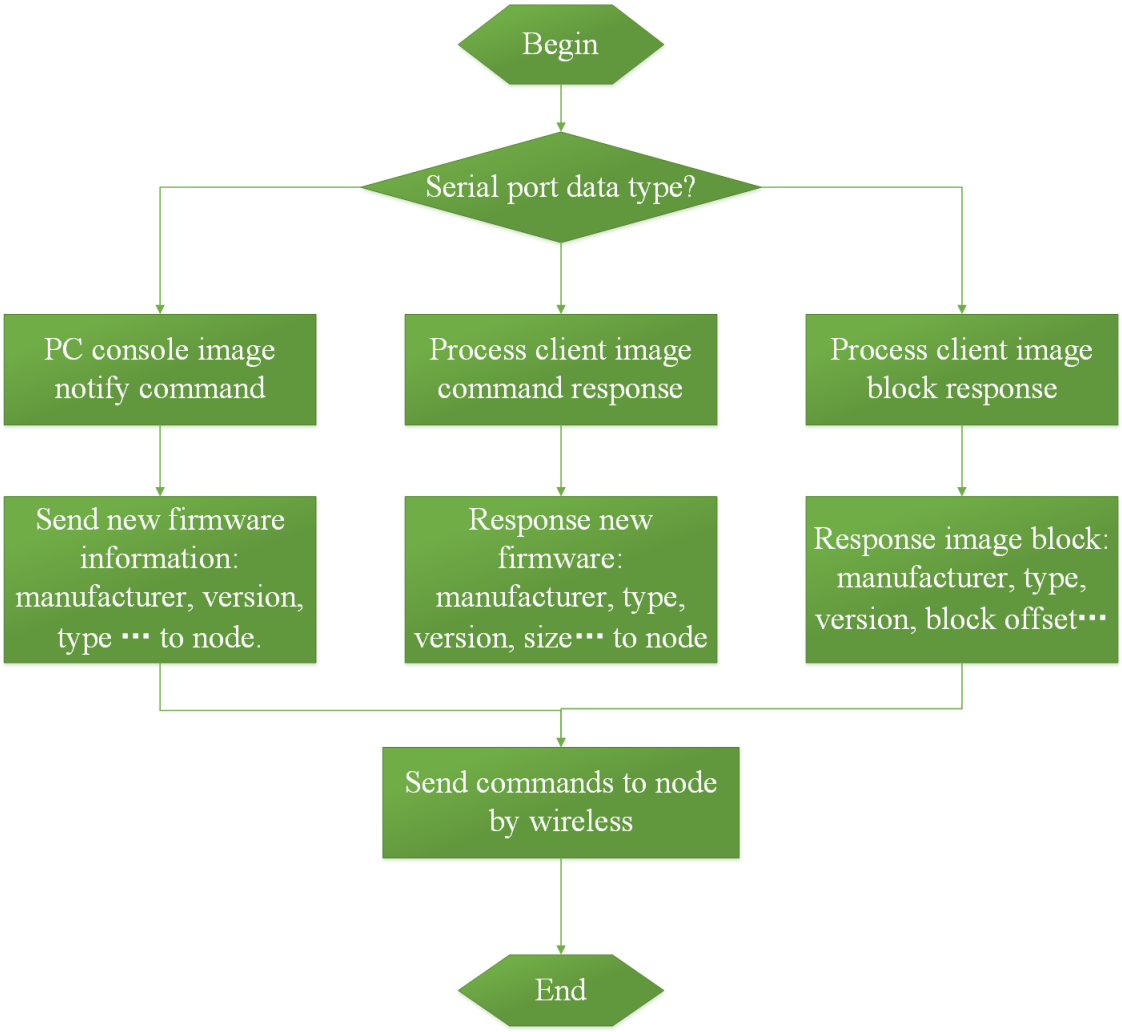


Fig. 4.5 OTA Server Serial Port End

The gateway OTA server provides firmware upgrade services in the Gateway ZigBee network and uses the ZigBee stack services provided by the Z-stack server. The server provides

some API interfaces to the user application over a TCP socket that allows maintenance of device in upgrading images and controls the air operations through the ZNP coordinator. In the figure, there are three communication components: gateway application, the OTA subsystem and ZNP device. Firstly, the gateway application sends the update registration request to the OTA subsystem and the OTA enables request. When it receives the confirmation command, the ZNP dongle produces the firmware data from the gateway database. Then the ZNP dongle processes the OTA updating. After the update is finished, the OTA subsystem will inform the gateway application that the remote device to finish the downloading of the firmware image. Consumers can send the image-applying request to instruct the remote devices that they can apply a previously downloaded image.

To sum up, the OTA upper server contains two components: the gateway application and the ZNP dongle. Consumers can use the gateway application to update the remote ZigBee devices firmware through the ZNP dongle assistant.

4.2.2 ZigBee OTA Client

The OTA clients are the ZigBee endpoint devices. Each ZigBee endpoint runs a z-stack software on chip and the OTA updating is also based on the z-stack cluster. The advantage is that the ZigBee endpoints can normally work and update OTA. If the devices want to implement the OTA update function, they must start the booting application. To open the z-stack OTA boot file, the CC2530 chips need to download the boot code firstly. The parameters in the Linker option as shown in the figure are also needed to be checked. ZigBee endpoint applications cannot work only by starting the boot application and it needs to add the boot application to the SOAL system. Firstly, add the *zcl*_Init (*taskID*++) and *zcl_event_loop* functions to the task of the sample application OSAL. Then add the OTA variables such as program length, manufacturer ID, image's type and image version to the global variables declaration field. In the normal application profile, it does not have the *zcl* and *zcl_ota* files.

At last, it just needs adding an OTA callback function to the application function. The OTA service is turned on at the endpoint chips. More operation and settings are provided in the handbook [30]. If the programming compiles successfully, it can be downloaded into the ZigBee endpoint device over the boot code. Currently, the ZigBee endpoint device can perform the OTA update with the ZNP dongle.

The OTA process works as below: At the beginning of the OTA update, the server sends an *Image Notify* message to one device or multiple devices by unicast or broadcast respectively. It informs the devices that a new image is available. Then the server decides if or not to update the client's current firmware based on the information contained in the *Query Next Image Request* message, which is sent by the client. After this, a *Query Next Image Response* message is transmitted to inform the client that whether the firmware is available and whether and when to follow the client manages and start the firmware's downloading procedure. During the downloading process, *Image Block Request* and *Image Block Response*, which include the image block, are transmitted between the server and the client. The client writes the image block to its secondary storage, which can be internal or external flash memory. In the end, an *Upgrade End Request* is sent to the server when the client has received the entire image. For response, the server sends back an *Upgrade End Response* message to inform the client when to switch to the new firmware.

Basically, adding OTA function can be sectioned into three parts: inserting OTA and related events, handling OTA MSG, environment setup and updated image generation. The followings are steps to change the Z-stack sample application, Simple Sensor EB, into an OTA-enabled application. Increase in the data payload can speed up the update. But there is also a range. Texas Instruments' Z-Stack ZCL, ZigBee Cluster Library, provides support for client and server operation of the OTA Upgrade Cluster. The Texas Instruments' Z-Stack implementation of the OTA Upgrade Cluster consists of the following components (see Table 4.8) .

Table 4.8 OTA UPGRADE CLUSTER COMPENENTS

1	OTA Console Application
2	OTA Image Converter Application
3	ZCL Implementation of the OTA Protocol
4	Boot loaders for the supported platforms
5	Sample OTA Application

This section provides a simple description of how the OTA Upgrade Cluster is used to update a device's firmware. For more detail, see the ZigBee Alliance Document 095264 [10], ZigBee OTA Upgrade Cluster Specification. Communication via the OTA Upgrade Cluster takes place using the following command messages in Table 4.9.

Table 4.9 OTA UPGRADE CLUSTER COMMANDS

1	Image Notify
2	Query Next Image Request
3	Query Next Image Response
4	Image Block Request
5	Image Block Response
6	Update End Request
7	Update End Response

The *Image Notify* message is sent unicast or is broadcast by an OTA Server to notify OTA Clients that new images are available. The *Image Notify* does not contain information about the new images. The *Image Notify* only indicates new available images. OTA Clients will determine if these new images apply to them by using the *Query Next Image* request and response messages.

Periodically, or after receipt of an *Image Notify* message, an OTA Client sends a *Query Next Image Request* message to an OTA Server. The *Query Next Image Request* message contains the version of the firmware which is currently running on the client. On receiving the *Query Next Image Request*, the server decides if an image update should take place and which image the client updates. The server responds to the query for next image request with a *Query Next Image Response* message. This command may instruct the client to download new firmware, or it may inform the client that no firmware is available. During the downloading process, the client sends *Image Block Request* messages to the server and receives *Image Block Response* messages from the server with chunks of the upgraded image. The client writes the image blocks to a secondary storage location. In the Z-Stack's sample applications, this secondary storage can be in on-chip or off-chip flash memory, depending on the hardware platform.

After the client has downloaded the entire upgrade image, the client sends the *Upgrade End Request* message to the server. The server then responds with an *Upgrade End Response* message. The *Upgrade End Response message* contains information about when the client should switch to the new firmware. The client may switch to the new firmware immediately or it may be instructed to wait for a specified period. In the z-stack's sample applications, when it is the time for a client to switch the new image, the client writes a nonvolatile (NV) memory location indicating new firmware is available. Then the client reboots and a boot loader on the client sees the new available image. The boot loader copies the new image from secondary storage to the operational memory space and the new firmware is started on the chips.

The existing OTA upgrade methods available are platform specific, not OTA interoperable and do not provide a common framework for upgrading networks that support a mix of devices from multiple 426 platforms and ZigBee Stack vendors. The intent of this document is to provide an interoperable OTA upgrade of new image for devices deployed in the field. As

long as the device supports the OTA Upgrade cluster and it is certified by an approved test house, its image shall be upgradeable by another device from the same or different manufacturer that also implements and certifies the OTA Upgrade cluster. The OTA Upgrade cluster will also require that in order to support OTA upgrade, the device will need to have an application boot loader installed as well as sufficient memory (external or internal) to store the newly loaded image. An application boot loader uses the running ZigBee stack and application to retrieve and store a new image. Depending upon the manufacturer, the image may consist of a boot loader image, a ZigBee stack image or only a patch to the application image. Whatever comprises the OTA upgrade image being sent to the node does not concern the ZigBee OTA cluster and it is outside the scope of this document. To use an application boot loader, the device is required to have sufficient memory (internal or external) to store the newly downloaded OTA upgrade image. By doing so, the current running image is not overwritten until the new image has been successfully downloaded. It also allows the possibility of a node saving an image in its memory and forwarding that image to another node. Application boot loader provides flexibility of when the device decides to download new OTA upgraded images as well as when the device decides to switch to running the new image. Since the boot loader is done at the application level, it automatically makes use of various features already offered by the ZigBee Network Layer and Application Sub Layer (APS) including the ability to load a device that is multiple hops away, message retries to increase reliability and security. It also allows the network to continue to operate normally while the boot loader is in progress. In addition, it supports boot loader of sleeping (Rx on When Idle=FALSE) devices. The application boot loader messages are built upon typical ZigBee messages, with additional ZigBee Cluster Library (ZCL) header and payload and ZigBee OTA cluster specific payload.

Chapter 5

ZigBee Firmware Updating Optimization Algorithms

Apart from the functions mentioned above, SBL can even update the ZNP's firmware out of question through the serial port from the ZigBee gateway server. It can compress the firmware image to reduce the update duration in the large firmware image condition. Correspondingly, this dissertation designs a nimble image decompression algorithm to the ZigBee chips.

Over-the-Air technology can upgrade the ZigBee nodes' firmware wirelessly. The original OTA upgrade scheme is that, as a TI z-stack solution, the OTA clients communicate with OTA server end-to-end. No matter ZigBee endpoints and routers send the OTA requests directly to the OTA server that makes the OTA update serious congestion so that many nodes update slowly and even failed. To solve this problem, this dissertation proposes the distributed priority page-request (DPP) OTA algorithm to update firmware. The algorithm designs a dynamic update priority orderliness to cut down the massive data redundancy by using the page-request mode to ask for the firmware image. Then, this dissertation presents the data redundancy mathematics model and the update duration mathematics model of the ZigBee OTA network. Proved by the simulation results of the CC2530 experiments, the DPPOTA algorithm has the advantages of lower data redundancy and shorter update duration. Last,

this dissertation concludes the DPPOTA features and provides the suggestions for future optimization work.

5.1 Wired SBL Optimization: HHD Algorithm

Because the ZigBee end nodes have some limitations in memory storage, communication bandwidth and processing capability, resource-efficiency firmware update becomes the top challenge. A commonly used method presented in Section 2.3 is to compress the firmware image before sending it to the ZigBee endpoints which need firmware update. The endpoints could decompress the firmware image and use it to upgrade the current application in the chips. The sender is typically a home gateway where resources are relatively abundant. In Section 2.4, this dissertation designs a Hamilton Huffman decompression algorithm that endpoints can easily decompress the firmware image data.

5.1.1 HHD Algorithm's Data Storage Structure

The Section 2.1 and 2.2 present the traditional image compression technology, data storage structure and the related decompression method. The sequential storage structure is more suitable for embedded scenarios as it takes up less memory. In addition, it can read and decode original data randomly so decoding is more efficient. Because the storage structure is designed based on the Huffman tree that is stored in the sequence array one of the disadvantages of sequence storage is that when the code is longer and the Huffman tree structure is a special single branch, the sequential storage space will be significant huge. The decoding process is traversing the Huffman binary tree and sequential storage structure should traverse binary tree for each input bite to decode the code word. This method wastes a lot of time on traversing and contrasting computation.

However, the chain list storage takes a lot of space to store the node pointer. Coding word data can decompress directly by reading the bit stream. According to the advantages and disadvantages of the above two kinds of Huffman tree data structures, this dissertation designs a new Huffman tree data storage structure. Through contrasting with the new Huffman tree storage array, it can easily decompress the coding word.

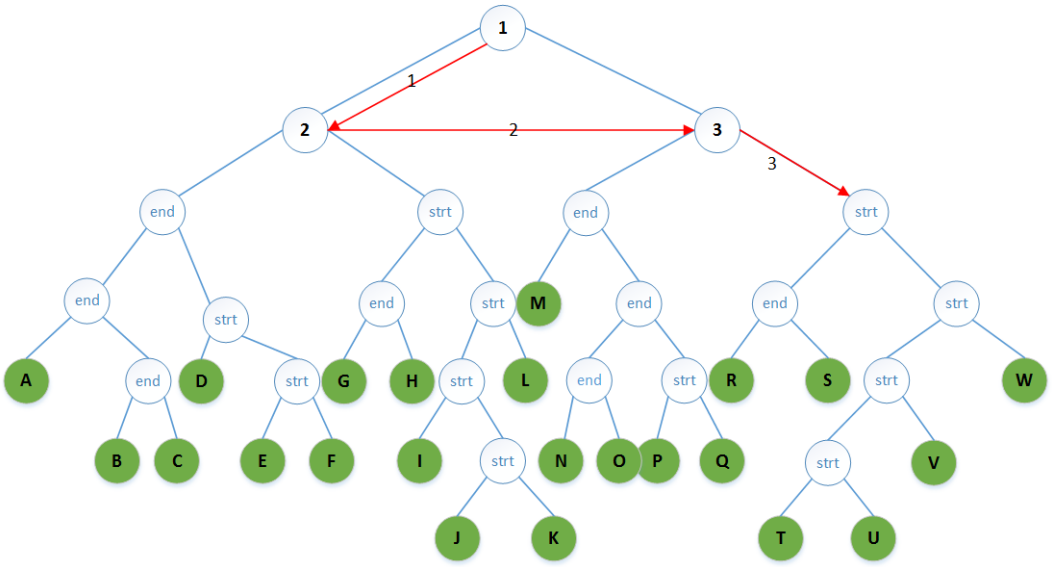


Fig. 5.1 Mark Huffman's Binary Tree Nodes

The idea of designing the new Huffman tree storage structure is that the array can be used to record the nodes properties such as left child node's address, left child node value, right child node's address and right child node's value. If we only record nodes instead of leaf nodes, the total storage space will be O (N-1). Even though applying the sequence storage structure can read decoding word quickly and easily, how the nodes' logic position projects its physical position will be a problem, which in Huffman binary tree is just a Hamilton circuit problem. In the mathematical field of graph theory, a Hamiltonian path (or traceable path) is a path of an undirected or directed graph that visits each vertex exactly once. A Hamilton cycle (or Hamilton circuit) is a Hamiltonian path that is a cycle. It will be determined whether such paths and cycles that exist in graphs are the Hamiltonian path problem, which is NP-complete. If we can design a Hamilton circuit of all the Huffman tree

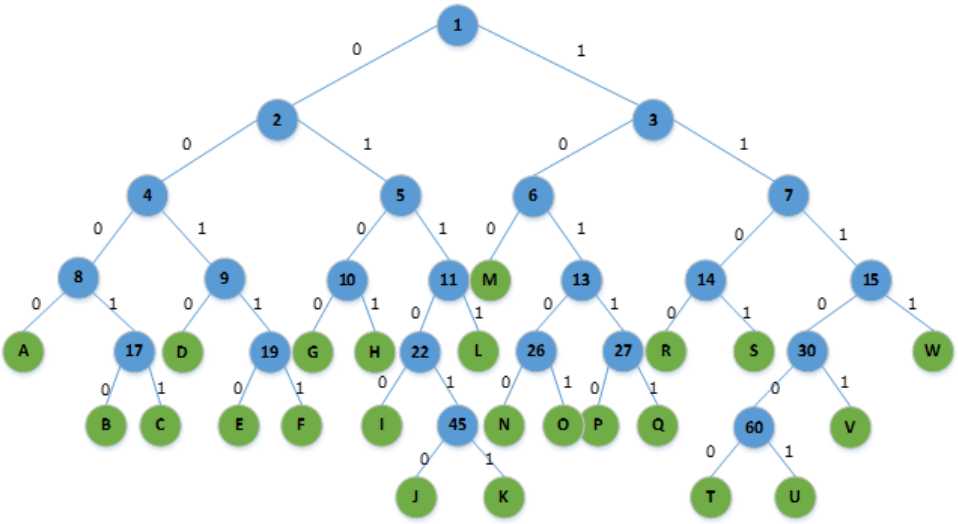


Fig. 5.2 Numbering Zero and One of Binary Tree

nodes, its logic position matches its position in the circuit. This paper takes the Huffman coding tree in the Fig. 5.1 for an example to explain the generation algorithm. First, the prerequisite is that we can confirm the Huffman tree and set the left child as 0 and the right child as 1 to draw the Huffman tree as showed in 5.2. Our target is to build an ordered configuration code table and demand its logic position to close. Whether it is closed or not is the key to the success of the design. The problem can be solved by using the Hamilton circuit: arranging the first root node number as 1, 2 as the left child and 3 as the right child. The right child nodes are marked as end nodes. The left child nodes are marked as start nodes. We set the lower layer's start nodes with higher priority and the lower layer's end nodes with lower priority. Then the Huffman tree should be marked as Fig. 5.2 and the marking rules for a unit binary tree are as below: the left child node is marked as the ending of binary and the right child node is labeled as a starting point. When only one of the two children nodes is a leaf node, the other node inherits its parent node's quality mark; when the two children nodes are both leaf nodes, its value will be marked. Starting nodes in higher layer have higher priority and ending nodes in higher layer have lower priority. After marking all the nodes, the Hamilton circuit will be built. As is shown in Fig 5.3, the seeking rules

of Hamilton circuit are: Branch searching direction of starting nodes is from top to bottom, the ending nodes' direction is from bottom to top; On the same branch, any starting node's priority is greater than any end node; The higher priority of node is the first number; and the nodes sequentially will be numbered following the path search.

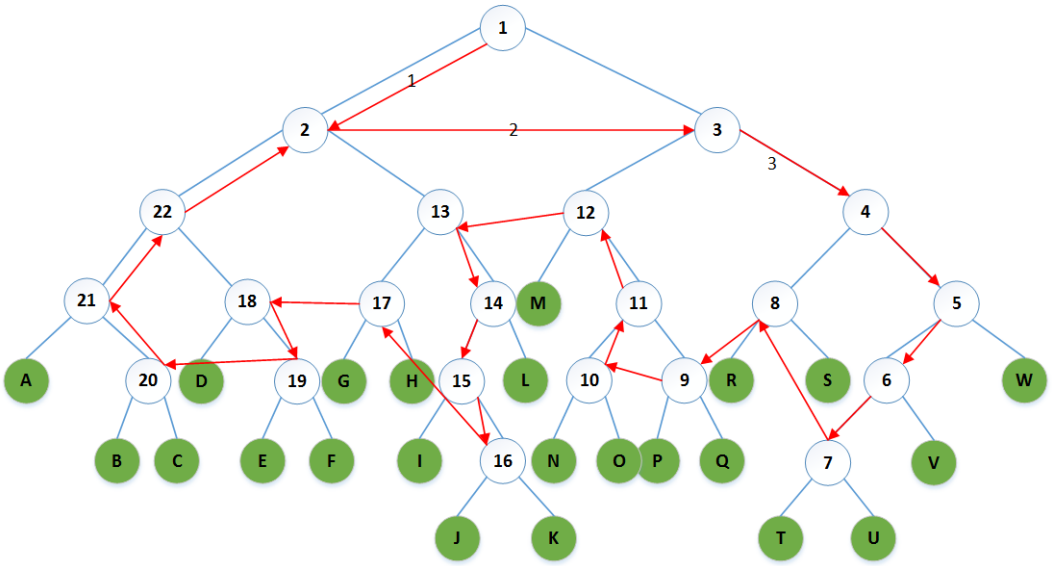


Fig. 5.3 Huffman Tree Hamilton Circuit Path Search

5.1.2 Huffman Tree Hamilton-circuit Path Algorithm

Based on the Huffman binary tree depicted in Fig. 5.3, a specified Hamilton Huffman serial number algorithm has been proposed its pseudo code, as can be seen in Algorithm 1. Essentially, this dissertation provides a common Hamilton-circuit path-finding strategy in the Huffman tree.

Algorithm 1 Huffman Tree Hamilton-circuit Path Algorithm.

Input: Huffman Binary Tree; Left is 0, right is 1;

Output: Hamilton numbering Huffman Tree ;

Node's number is N;
Root $N \leftarrow 1$;
Root left child $N \leftarrow 2$; ;
Root right child $N \leftarrow 3$
while *mark unit tree process* **do**
    if $leftnode\&rightnode = non-leaf$ **then**
        $Mark : rightnode \leftarrow startingpoint$
        $Mark : leftnode \leftarrow endingpoint$
    end if
    if $leftnode||rightnode = leaf$ **then**
        $Mark : leafnode \leftarrow value$
    end if
    if $(leftnode = leaf\&rightnode = non-leaf)||(leftnode = nonleaf\&rightnode = leaf)$ **then**
        $Mark : non-leafnode \leftarrow rootquality$
    end if
    if $node = higherlayer$ **then**
        $startingpointpriority \leftarrow higher$
        $endingpointpriority \leftarrow lower$
    end if
end while
while *number Huffman tree process* **do**
    path finding sequence: from starting to ending
    path finding priority: from higher to lower
    number nodes N as sequence, N>=3
end while

Specific steps to solve the time complexity of the algorithm are: Firstly, find the basic algorithm in the statement. The sentence that has the most execution times in the algorithm is the basic statement, usually the loop body of the innermost loop. Secondly, calculate the order of magnitude of the number of basic sentences. Only the order of magnitude of basic statement executions needs to be calculated, which means that all coefficients of the lower and highest powers can be ignored as long as the highest power in the function that guarantees the execution of the basic statements is correct. This simplifies algorithmic analysis and focuses attention on the most important point: growth rate. Thirdly, symbol with a large O that the algorithm's time performance. Put the order of magnitude of basic statement execution into the O mark. If the algorithm contains nested loops, the basic statements are usually the innermost ones, and if the algorithm contains juxtaposed loops, the temporal complexity of the juxtaposed loops is summed. Algorithm's time complexity only concerned about the worst case of running time that is the longest time algorithm.Focus only on the most important level of growth.So in the Algorithm 1, the time complexity of the first While loop is O(n) and the If loop's time complexity in the first While is O(n2). The time complexity of second While loop is O(n). So the total algorithm time complexity is O$(n^2+n+n) = O(n^2)$.

As the Hamilton circuit is closed, the calculation is completed. Then it is necessary to use an array to record the nodes' property. For instance, N[x][y] can indicate the array $0 < x < 5$ and $0 < y < N$.

The definition of this two-dimensional array is as follows. Node property can be recorded by using a row: N[1][y] stores the left child node value; N[2][y] stores the right child node value; N[3][y] stores the left child node number; N[4][y] stores the right child node number. When the nodes are non-leaf, the value is null. Otherwise, the value is its decoding word, and its number is zero, indicating this stream decoding has become an end. When it comes to the end of a segment decoding, it starts decoding the new segment bit stream from N[1][y]. The sample N[x][y] for above Huffman tree is shown as TABLE 5.1.

Table 5.1 HHD ALGORITHM DECOMPRESSION ARRAY

Number	**lv**	**rv**	**ln**	**rn**
1	∧	∧	2	3
2	∧	∧	22	13
3	∧	∧	12	4
4	∧	∧	8	5
5	∧	W	6	0
6	∧	V	7	0
7	T	U	0	0
8	R	S	0	0
9	P	Q	0	0
10	N	O	0	0
11	∧	∧	10	9
12	M	∧	0	11
13	∧	∧	17	14
14	∧	L	15	0
15	I	∧	0	16
16	J	K	0	0
17	G	H	0	0
18	D	∧	0	19
19	E	F	0	0
20	B	C	0	0
21	A	∧	0	20
22	∧	∧	21	18

5.1.3 HHD Algorithm Decompression Array

According to the HHD array generating algorithm, the Huffman tree regenerates a decoding array under the structure of sequential storage. Thus, the physical address is mapped with the logical address, and the decompression clients can randomly decode data. The decoding process contains the stream of binary bits and the Huffman tree, as presented in Table 5.1. Also, Section 2 has discussed the reconstruction of the array. The process is as follows. Set the left to the binary tree 0 and the right one 1. Input the binary bit stream, such as *10110101110000....* Search the array in Table5.1. When the first bit is 1, read *N[4][1]* and *y=N[4][1]*. Then the bit is 0, read *N[3][y]* and *y=N[3][y]*. Until the bit is 0, $y = 0$, *Decoding =N[1][y]* or the bit is 1, $y = 0$, *Decoding =N[2][y]*. Afterwards, read the next bit and start from *N[x][1]* and do the cyclic operation until the decoding is completed. The decompression algorithm can be seen in Algorithm 2. The *"lv"* is left child node's value and the *"rv"* is right child node's value. The *"ln"* is left child node's number and the *"rn"* is right child node's number. The pseudo code of the Hamilton Huffman decompression algorithm is also shown in Algorithm 2. The time complexity of the first loop is O(n) and the time complexity of second If loop is O(n^2). The time complexity of the While loop in the else sentence is O(n^3). So the total algorithm time complexity is O($n^3 + n^2 + n$) = $O(n^3)$. Algorithm 1 has a better time complexity than the Algorithm 2.

Algorithm 2 Hamilton Huffman Decompression

Input: Two-dimensional decompression array:$N[x][y]$;

coding bit stream B;

Output: decoding word M ;

```
1:  begin
2:  loop(n=0; n++)
3:      x=1
4:      if N[x][3] = 0 then
5:          M = N[x][1];
6:          x = 1
7:      else if N[x][4]= 0 then
8:          M=N[x][2];
9:          x=1
10:     else
11:         while B[n] =1 do
12:             x=N[x][4]
13:         end while
14:         while B[n] =0 do
15:             x=N[x][3]
16:         end while
17:     end if
18:     B is null
19: end loop
20: end
```

The key of building the two-dimensional array is how to generate a Hamilton circuit according to Huffman coding tree. Based on the circuit, the decoding array can accelerate

decompress data process. Since most of the computation cost is in the process of creating decompression array, it is nimble to meet the contribution target.

To sum up, the HHD algorithm uses the structure of array storage to store the Huffman binary tree and realize the logic address mapping the array index address. In other words, it uses array to achieve the pointer function. In this way, ZigBee endpoints can nimbly decompress the update firmware image.

5.2 Wireless OTA Optimization: DPPOTA Algorithm

Based on the IEEE 802.15.4 Protocol, ZigBee technology[31] defines the network layer (NWK) and the application layer (APL). Over-the-Air is a wireless in-application programming (IAP) [6] [32] technology in the ZigBee protocol framework. ZigBee Alliance [10] proposes the Over-the-Air technical specifications for the ZigBee firmware upgrade on the APL. Texas Instruments releases the semi-open source, namely, the z-stack protocol stack, which implements the holonomic ZigBee protocol specifications and provides the OTA solution cluster interfaces [33] in the ZigBee clusters library layer (ZCL). It can remotely and wirelessly upgrade the TI ZigBee nodes' firmware, thus fulfilling the OTA specifications. However, the OTA is just a solution scheme in the z-stack where developers need to refer to handbooks [34] in order to work it out.

As an added consideration, when a large number of devices simultaneously process the OTA firmware update, even though the z-stack implements the basic one, its performance is not stable. Initially, the OTA update rate is limited by the ZigBee technology which is characterized as low data transmission rate. According to the general measurement experiment, the z-stack OTA inefficiently takes fifteen minutes to upgrade 120k image data. Subsequently, the OTA uses the P2P method [35] to update the remote devices: each ZigBee OTA client device requests the image data from a unique OTA server. Both ZigBee routers and endpoints are OTA clients, when the ZigBee network is organized in a deeper depth and

bigger scale, the backbone is congested. In addition, the undisciplined redundancy requests not only disturb the backbone, but can lead to the OTA firmware update failure.

5.2.1 DPPOTA Algorithm

To solve the above problems, the distributed priority page-request OTA (DPPOTA) upgrade algorithm adopts the page-request method firstly. In the z-stack, the OTA clients request the image block data from the OTA server. As the augmented number of nodes upgrades synchronously, the time of all the nodes fulfilling the OTA update will increase. Correspondingly, the more nodes being updated, the bigger probability of wireless conflict. The ZigBee data retransmission mechanism increases time cost in the client nodes OTA update. Even worse, the OTA client nodes will reset the network parameters, and restart the OTA update service under repeated void request. This situation wastes massive updating time and energy as the redundancy data requests. In the reality application, the z-stack just can upgrade two nodes at the same time because of the ZigBee network congestion.

Despite that the page image request method can reduce the image block request commands, it cannot make a big difference in the redundancy data requests. The OTA priority orderliness update scheme is a useful solution, but it is necessary to consider the excessive orderliness problem as mentioned [27]. In the ZigBee mesh form network, all the nodes can update in a dynamic suitable path to reduce the time and energy waste. Similarly, the priority orderliness OTA update scheme reduces the network's backbone transmission redundancy data and solves the excessive orderliness problem with the same method.

The DPPOTA algorithm is designed as Algorithm 3 shows. One DPPOTA request combines n numbers block image data requests as the page image request. This method can reduce the total request command times of the OTA and cut down the OTA update duration. Afterwards, when it comes to the router logic type nodes, it will process the DPPOTA exceptional choice strategy. When the router completes the OTA update, it can

receive the child page image requests and send them to the upper router, until to the OTA server. This algorithm follows the ZigBee normal data transmission principle and possesses all the ZigBee mesh network functions and features.

Algorithm 3 Distributed Priority Page-request OTA

Input: Firmware image request type: *Img[t]*; Image response:*Imgblock[t]*.

Output: *OTA_status: Success=1, Failure=0.*

```
1: begin
2: Image[page]=Img[block]*n
3: if Logic[t]==router then
4:     if OTA_status==1 then
5:         while receive Img[page] from child do
6:             send Img[page] to father
7:         end while
8:         while receive Imgblock[t] from father do
9:             send Imgblock[block to child
10:        end while
11:    end if
12:    if OTA_status==0 then
13:        ignore Img[page]from child
14:        send Img[page] to father
15:        flash Imgblock[t]
16:    end if
17: else if Loic[t]== endpoint then
18:    if OTA_status==0 then
19:        send Img[page] to father
20:        receive Imgblock[t] from father && flash Imgblock[t]
21:    end if
22:    if OTA_status==1 then
23:        return
24:    end if
25:    end
26: end if
```

When the multi-node concurrent updating command broadcast to the ZigBee mesh network, the OTA will build a plethora of tree network paths to the OTA server, which is similar to any remote ZigBee node request data from the coordinator on the AODV routing path.Each node that needs to process the OTA updating sends the image data request to the OTA server. However, OTA client does not consider the path choice, for example, which father node should be chosen next and which request line is better. Since the ZigBee network has solved the routing problem in the dynamic mesh network, there is need for OTA service to follow the route path and keep it as the dynamic suitable scheme, but differentiated from the OTA end-to-end scheme, every router cannot optionally retransmit the lower child request commands. Each ZigBee node has its unique logic type, and the routers can process the OTA updating shortly since the endpoints have the sleep function to save power while routers do not. The DPPOTA algorithm makes the upper routers have the higher OTA update priorities to update firmware preferentially, and when the upper routers complete the OTA update, it turns to be an OTA router to unseal the lower nodes' OTA update service. This OTA update process can be seen in Fig.5.4: the coordinator is set to be the OTA server and the blue dots are routers. When the ZigBee sleepy end device and routers concurrently process the OTA update, each path to the server is filled with image data requests and other commands. Upper routers that are closer to the coordinator have the higher priority, and the paths close to the coordinator are more crowded and thick.

The DPPOTA algorithm can alleviate the OTA server backbone workload and reduce its congestion degree. In Fig.18, it firstly upgrades the nearest three routers to the coordinator who run an OTA thread on each line. When the updating is completed, these three paths turn on to the next OTA update level. This network contains ten nodes and the OTA nodes take up six. The three backbones averagely run two OTA threads as well. When these six nodes finish the OTA update, the other seven nodes will begin to process the OTA update. In this circumstance, the whole network contains seventeen nodes, but the three server backbone

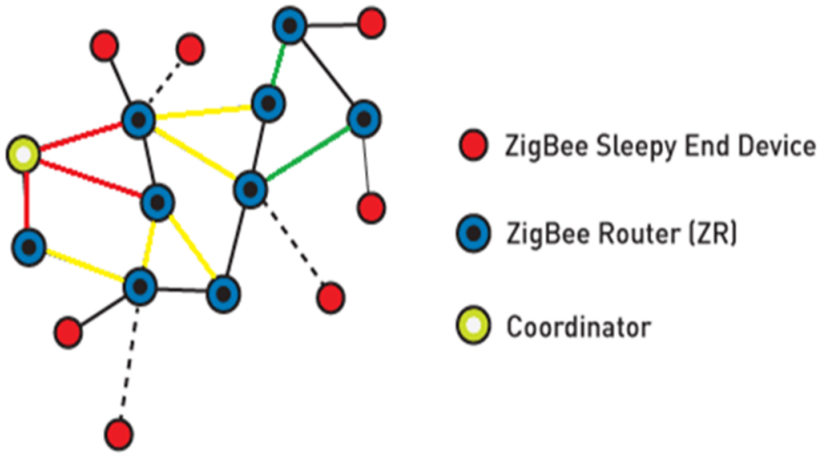


Fig. 5.4 Dynamic Page-request Distributed OTA Update Network

paths only run seven threads. As the traditional OTA update end-to-end scheme, the server backbone paths need to run sixteen OTA threads, but the DPPOTA algorithm only implements two OTA threads in this example. The following sections will present two mathematical parameters models to establish the DPPOTA algorithm's attributes, namely, data redundancy model and update duration model.

Data Redundancy Model

Data redundancy can reflect both the OTA updating path congestion and its energy efficiency to a certain extent. Obviously, the OTA network with redundant data leads to frequent path congestion and reduces the efficiency of OTA update. In the above OTA example, the data redundancy is related to the ZigBee network range which contains two parameters: the network depth and the path quantity. It uses d_k to represent the network depth and the k means the path quantity. In addition, the network depth d_k equals to the nodes quantity of each path. Set each node sending the data redundancy unit as d_u. Ideally, in one multi-nodes concurrent OTA request process, each path's total data redundancy $\widetilde{D_{po}}$ of original OTA update can be represented as in Equation (5.1). The data redundancy accumulation of growth

is as the depth increases: the next path's data redundancy will add the previous one. For instance, the number k path section runs d_k OTA threads.

$$\widetilde{D_{po}}=d_u*\left(\begin{array}{c}1+2+\cdots+\\ d_k\end{array}\right)=\frac{(1+d_k)*d_k}{2}*d_u \tag{5.1}$$

$$\widetilde{D_{pd}}=d_u*\left(\underbrace{1+1+\cdots+1}_{d_k}\right)=d_u*d_k \tag{5.2}$$

$$D(t)=d_e+d_o+\int_{p=1}^{k}\widetilde{D_p} \tag{5.3}$$

When OTA update data redundancy of each path meets Equation (5.2), it becomes the ideal DPPOTA algorithm. Because of the OTA router decision mechanism, each path section only runs one OTA thread and the total data redundancy $\widetilde{D_{po}}$ is supposed to meet Equation (5.2). Expressions of each path's data redundancy can be given to the OTA server and then the OTA network total data redundancy mathematical model can be calculated, as can be seen in Equation (5.3). The d_e parameter in Equation (5.3) is network error of the retransmission data redundancy and d_o means that the OTA client nodes reset OTA network data redundancy.

Update Duration Model

The update duration can directly show the OTA update efficiency, in a common sense, and frequent upgrading duration leads to lower efficiency. Meanwhile, all the OTA network nodes that need more duration to complete updating will consume more energy. The update duration model is also important to represent the OTA network update performances. Ideally, one image block request duration unit has been set to be equal to the image block response duration as t_b, and the page-request image duration t_r=t_b. Next, set the total firmware image size as $block * m$ and the page image data size $page = block * n$. The original OTA scheme update duration T_o is presented in Equation (5.4).

$$T_o = \int_{p=1}^{k} m * t_{rp} + \int_{p=1}^{k} m * t_{bp} + t_{eo} \tag{5.4}$$

$$T_d = \int_{p=1}^{k} \frac{m}{n} * t_{rp} + \int_{p=1}^{k} \frac{m}{1} * t_{bp} + t_{ed} \tag{5.5}$$

The original OTA update needs m times request and response duration units. The DPPOTA update cuts down the request duration times and receives the same times of block image as the origin. Both two equations' ends have the t_e variable that represents the network error of retransmission image duration. The proportion to the path data redundancy is positive-related which can follow the data redundancy model results, as shown in Equation (5.6).

$$t_{eo} = K * \frac{1+d_k}{2} * t_{ed} \quad (K > 0,\ t_{eo} \propto \widetilde{D_{po}},\ t_{ed} \propto \widetilde{D_{pd}}) \tag{5.6}$$

Equation (5.6) shows that the original OTA scheme has more data redundancy to keep its update duration longer. However, the DPPOTA can not only reduce the data redundancy, but also curtail the update duration. Next, this dissertation will actualize the DPPOTA algorithm based on the CC2530 z-stack platforms and illustrate the evaluations and simulations of these two mathematical models.

5.2.2 Implement DPPOTA Algorithm Based on Z-Stack

TI has published the open source z-stack that provides the OTA service interface. But developers need to call these OTA functions in the OSAL [33] on chip system and modify the z-stack project application under the guidance of handbook [30]. This dissertation is based on the TI CC2530 chip experiment [36] and z-stack 2.5.1a [37]. After turning on the OTA service to the z-stack, it needs to modify the routers' OTA transmission functions. Different from the literature [27] in which all the OTA clients still send the request commands to the OTA server, it has the natural advantage of the ZigBee network. Accordingly, a data transmission judgement function has been added that the routers will not send the received

OTA type request commands until the routers' own OTA update has been completed. Under other circumstances, the nodes only send their own OTA updating commands to the upper, then the OTA update process of the whole network will have the orderliness that cuts the data redundancies and request conflicts.

On top of that, the page-request node also needs to modify the OTA client's z-stack. In the *zcl_ota.c* and *zcl_ota.h*, the image data block request function has been found and the page request function has been added as the block request. Its difference from the block image request is that the page request send number n image blocks' request only once. Meanwhile, it also needs to modify the OTA server application and add the manipulation page-request function. The DPPOTA algorithm is similar to Go-Back-N algorithm, which is a dependable communication based on the ZigBee network. The main DPPOTA z-stack functions are presented as in Fig. 5.5.

```
1114 static ZStatus_t sendImagePageReq(afAddrType_t *dstAddr)
1115 {
1116   zclOTA_ImagePageReqParams_t req;
1117
1118   req.fieldControl = 0;
1119   req.fileId.manufacturer = zclOTA_ManufacturerId;
1120   req.fileId.type = zclOTA_ImageType;
1121   req.fileId.version = zclOTA_DownloadedFileVersion;
1122   req.fileOffset = zclOTA_FileOffset;
1123   req.pageSize=6400;//page-request size
1124   req.responseSpacing=30;//interval
1125   PageCount=req.pageSize;
```

Fig. 5.5 DPPOTA Z-stack Functions Codes

The page-request function defines how many image blocks are contained in a page image request. In addition, the image blocks request interval in one page is an added consideration. If the interval becomes too small, it may lead to failure of the update. On the other hand, the interval cannot be too big to influence the efficiency of upgrading. According to the CC2530 chip serial port buffer, the block number n should not be relatively large. This dissertation implements the dynamic page-request based on the CC2530 chips as shown in Fig.17 as well

Table 5.2 DPPOTA EVALUATION PARAMETERS

Symbol	Description	Conversion equation
$\widetilde{D_{po}}$	Original OTA data redundancy	$d_u * (1+2+\cdots+d_k)$
$\widetilde{D_{pd}}$	DPPOTA data redundancy	$d_u * d_k$
$D(t)$	Total network data redundancy	$d_e + d_o + \sum_{p=1}^{k} \widetilde{D_p}$
T_o	Original OTA upgrading duration	$\sum_{p=1}^{k} m * t_{rp} + \sum_{p=1}^{k} m * t_{bp} + t_{eo}$
T_d	DPPOTA upgrading redundancy	$\sum_{p=1}^{k} \frac{m}{n} * t_{rp} + \sum_{p=1}^{k} \frac{m}{1} * t_{bp} + t_{ed}$
t_{eo}	Original network-error retransmission duration	$K * \frac{1+d_k}{2} * t_{ed}$
t_{ed}	DPPOTA error retransmission duration	$t_{eo} \div (K * \frac{1+d_k}{2})$
Image	Image total size	118253 bytes
Block	Image block size	64 bytes
Page	Image page size	640 bytes, 320 bytes, 128 bytes
n	Each page contains block number	10, 5, 2
K	Positive proportional coefficient	$K > 0$

as summarizes the OTA clients updating page-request function parameters and the DPPOTA evaluations' parameters as can be seen in Table 5.2. The normal ZigBee networks are the mesh architecture ones, such as smart home and energy. As P2P model, when the original OTA update starts, OTA clients communicate with the OTA server in all of the Zig Bee nodes. In the physical structure, it keeps the mesh network architecture, but the clients logically request and response data with the server in the endpoint-to-endpoint model.

Therefore, the DPPOTA changes the logical communication mode and designs the OTA update priority orderliness, which makes all the router nodes judge the incoming data type. The higher upper routers have the top priority to update, so the lower remote nodes need to wait for their top routers completing the OTA updating. Moreover, the remote nodes can choose the updated router to process their OTA update dynamic. If the used router is power off or moves away, it can dynamically carry on another optimal suitable router. This priority orderliness improves the OTA update network self-healing and overall optimization.

It can support the multi-node concurrent OTA update and save the global energy as much as possible.

Chapter 6

Performance Evaluations

6.1 HHD Algorithm Evaluations

The evaluation process of the algorithm is as below. The first set prerequisites are that the ZigBee firmware source file contains 256 elements and the image has been compressed according to Huffman. The longest coding length is 11 and the average coding length is 6. The unit data array space is 1byte and the pointer space occupies 2bytes.

Storage Space Cost

In order to avoid repeated affiliation from different authors, a template has been designed for two affiliations which are supposed to be as succinct as possible (for example, do not differentiate among departments of the same organization).

The sequence storage Huffman tree size depends on its longest coding length k. In this dissertation, all the Huffman tree number sequence is from top to bottom and left to right. If the longest coding length is the single left branch, its size is minimized:

$$\left(2^{k-1}+2^{k-1}+1\right) * 1\text{byte} \tag{6.1}$$

If the longest coding length is single right branch, its size is maximized:

$$\left(2^{k}+2^{k}-1\right)*1\text{byte} \tag{6.2}$$

Generally, the longest coding length would be more than 8. In the case of compressing the ZigBee image file, k=11. So the minimum size is: $(2^{10}+2^{10}+1)*1byte. = 2049bytes$;

If the chain list storage only uses children pointers without parent pointer, the general chain list storage structure space cost is:

$$y1=(2bytes+1bytes+2bytes)*(N+N-1) \tag{6.3}$$

Only when the children pointers without paint pointer data structure has been recorded does the smaller space cost size of chain list apply: *(2bytes+1byte+2bytes) ∗ (256+256-1)=2555bytes;* HHD algorithm records the non-leaf nodes information, and its items have just N-1, each of which takes up 4bytes memory space. Therefore, the HHD Huffman tree total space cost is:

$$y2=(N-1)*4bytes \tag{6.4}$$

Accordingly, this decompression algorithm space cost size is: *(256-1) × 4bytes=1020 bytes.*

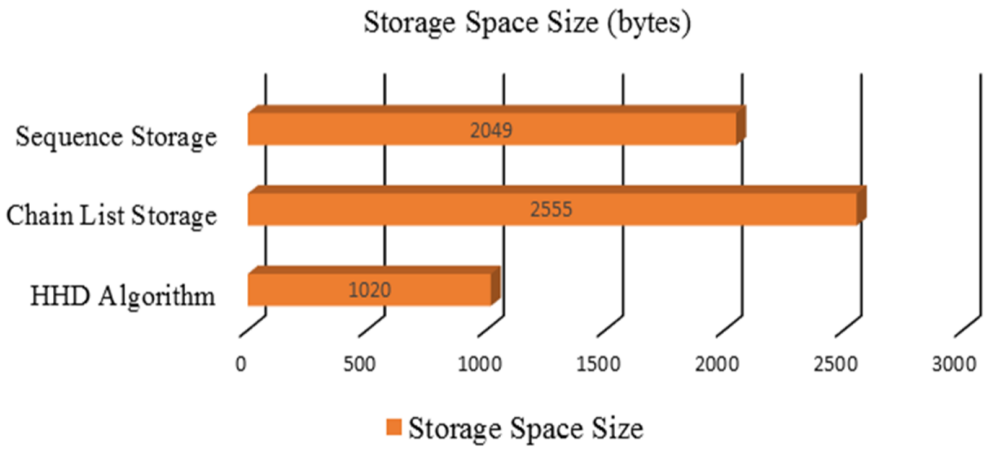


Fig. 6.1 Sequence, Chain List and HHD Space Cost Comparison

Fig. 6.1 compares three storage space sizes and the result is clear. In addition, Fig. 6.2 indicates the relationship between the space cost y and the element N, and Fig. 6.3 shows the relationship between the longest coding length k and space cost y, in which y1 represents chain list storage's space cost and y2 represents HHD decompression algorithm's space cost. In Fig. 6.1 y1 bigger than y2. Since the sequence storage space cost is confined by the longest coding length, HHD decompression algorithm costs smaller space than others.

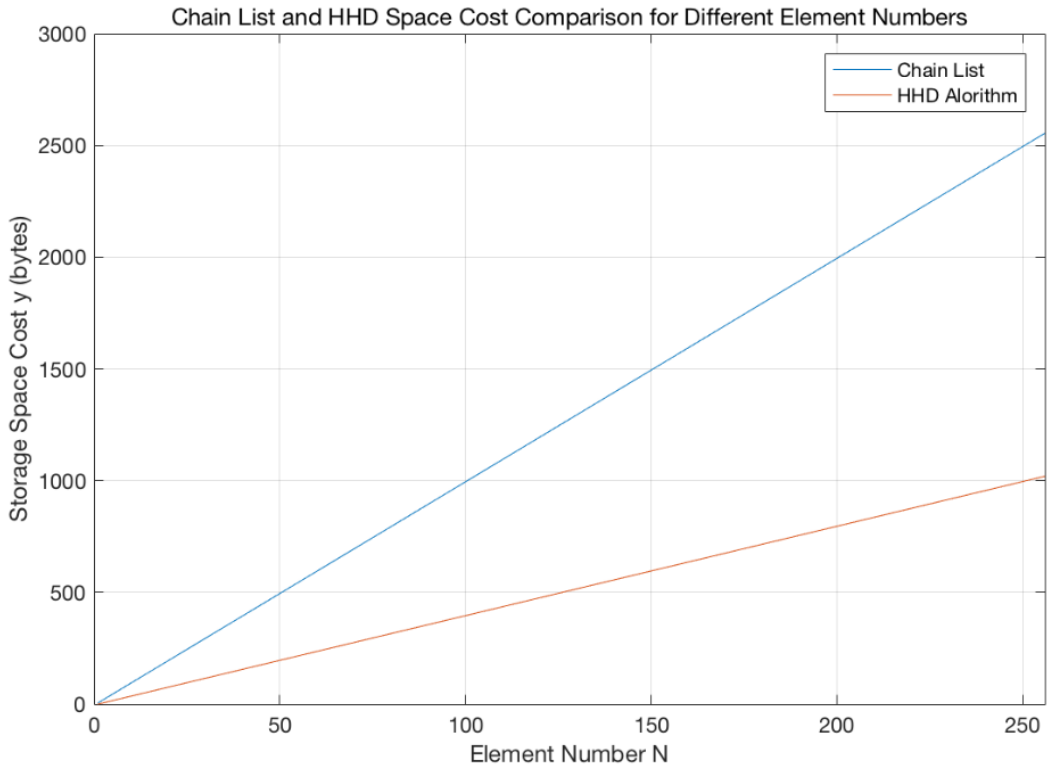


Fig. 6.2 Space Cost Comparison: Chain List vs HHD

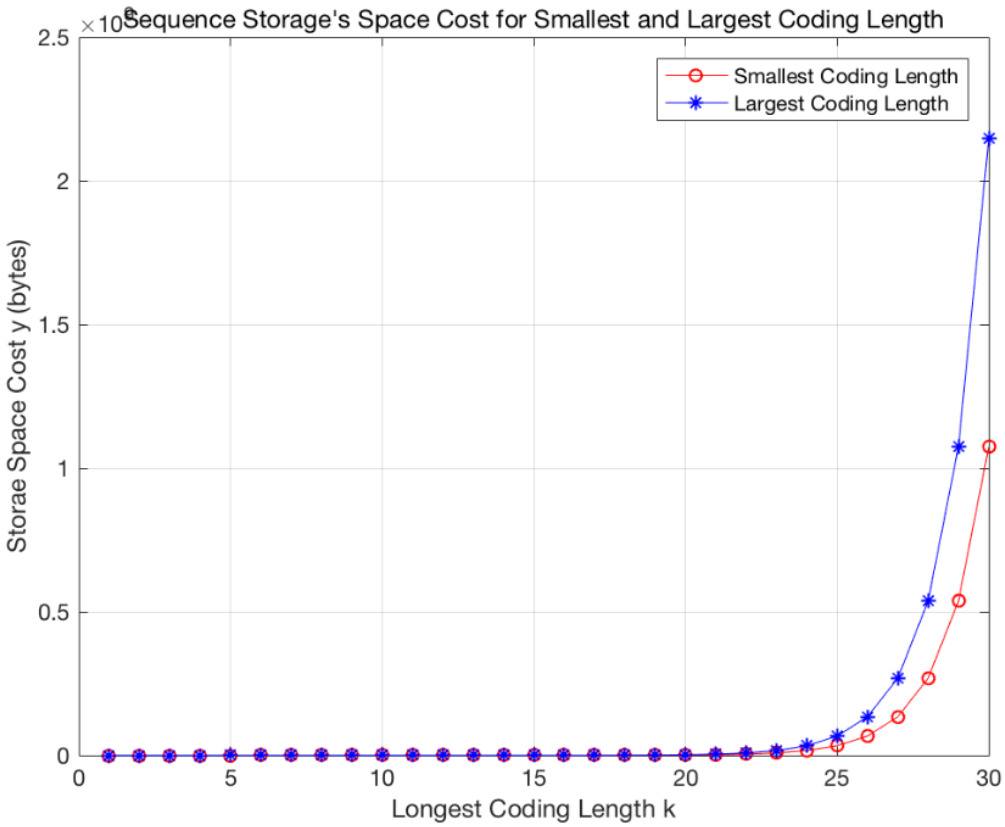


Fig. 6.3 Sequence Storage Largest and Smallest Space Cost Comparison for Different Coding Longest Length

Generally, the longest coding length is almost bigger than 8 and each file has different longest coding length. Fig.22 shows its interval value with longest coding length k. If the longest coding length is 11, the smallest space cost of sequence storage is 2049bytes, which is still bigger than HHD 1020bytes.

Decompression Time Cost

The decompression algorithm realizes the pointer function in array by reading logic address mapped with the index number. If the average coding length is 6 , it indicates that it takes six steps to decode a coding word. Accordingly, the average time cost is $6 * t$. The result is shown in Fig. as 6.4.

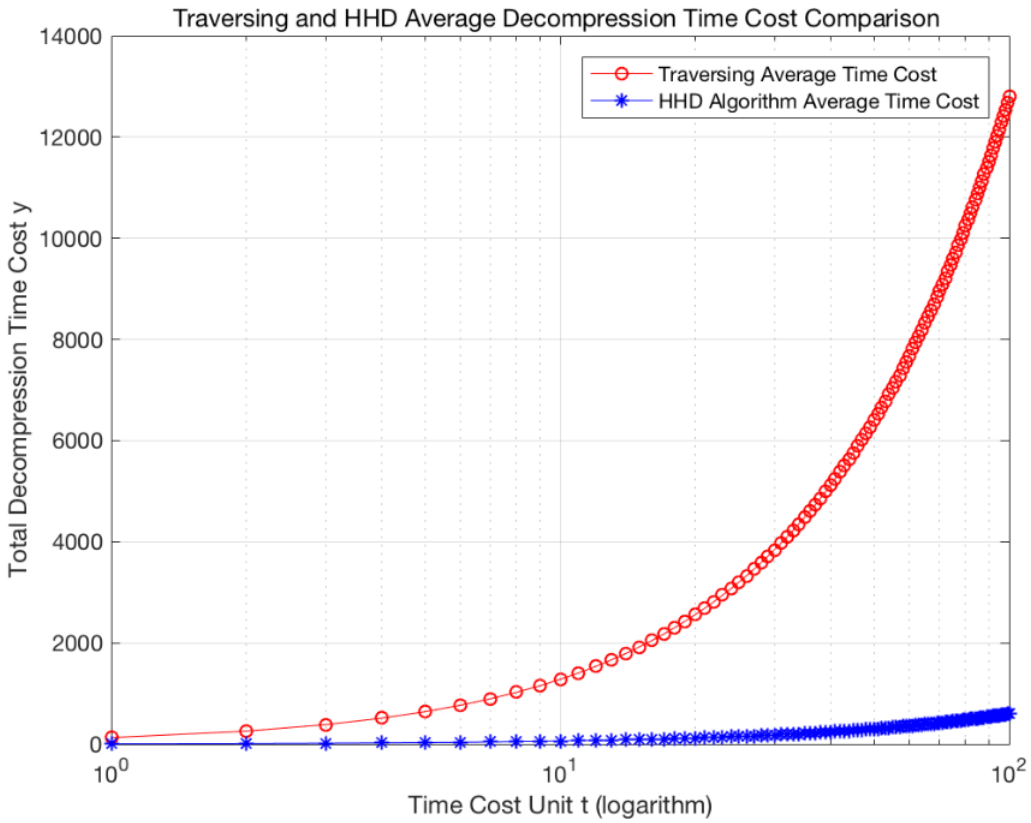


Fig. 6.4 Traversing and HHD Average Decompression Time Cost Comparison

In the experiment, the file has 256 elements and the searching unit time is set as t. Traditional Huffman decoding is traversing the binary tree. According to the coding table, all elements and their codes ought to be searched, and successfully traversing them to decode coding word could not be better. In terms of the average probability, one word cost time of the traditional coding table storage searching Huffman tree is $(256/2)*t$. If we use the sequence to store and traverse the Huffman tree, the searching time will be bigger than $(256/2)*t$. The types of traversing binary tree are classified as pre-order traversal, in-order traversal and post-order traversal, all of which take more steps to locate the decoded word. Under better circumstance, the average coding length is 6 and it will take another six times to locate a decoded word. However, since there are 256 elements to be traversed, the average decoding time cost is $(256/2)*6t$. In HHD algorithm, it just cost $6*t$ to decode a coding word. Due

to the traversing time cost of Huffman tree is bigger than coding table, Fig.7 compares the traversing coding table time cost and the HHD algorithm time cost, from which HHD has much better performance on average decompression time cost about twenty folds.

6.2 DPPOTA Evaluation Models

Section 2.4 has discussed that the data redundancy and update duration are two representative mathematical models to evaluate the ZigBee OTA upgrade scheme's performance. This dissertation provides these two model simulations by using MATLAB. Initially, the evaluation considers the data redundancy of the ZigBee OTA network. Equation 5.1, 5.2 and 5.3 represent the OTA network data redundancy simulation attributes. The original z-stack OTA update scheme's data redundancy simulation result is shown in Fig. 6.5 where the blue line represents the original OTA update scheme and the red line is the DPPOTA simulation.

Data Redundancy Model

The ZigBee network's range becomes larger as the depth d_k of the network increases. Having influence on the network range, the path number k is a co-efficient parameter of the network d_k. Fig. 6.5 has shown the increase of the DPPOTA's data redundancies as the network deepens. When it transforms the network depth to the linearity, the original OTA update grows exponentially and the DPPOTA is in the linear growth. Ideally, when the depth in the Fig. 6.5 becomes 2, where the blue line and the red line meet, their data redundancies reach the same level. Then, the original update data redundancy will rise sharply over the DPPOTA update with the depth increasing. In the experiment, the original OTA update can only support two ZigBee nodes upgrading and their firmware at the same time. It does not mean that the OTA cannot support the multi-nodes upgrading, instead, the OTA server cannot synchronously support more than two nodes upgrading. If another ZigBee node needs to process the upgrading, it must wait or break off other nodes upgrading frequently.

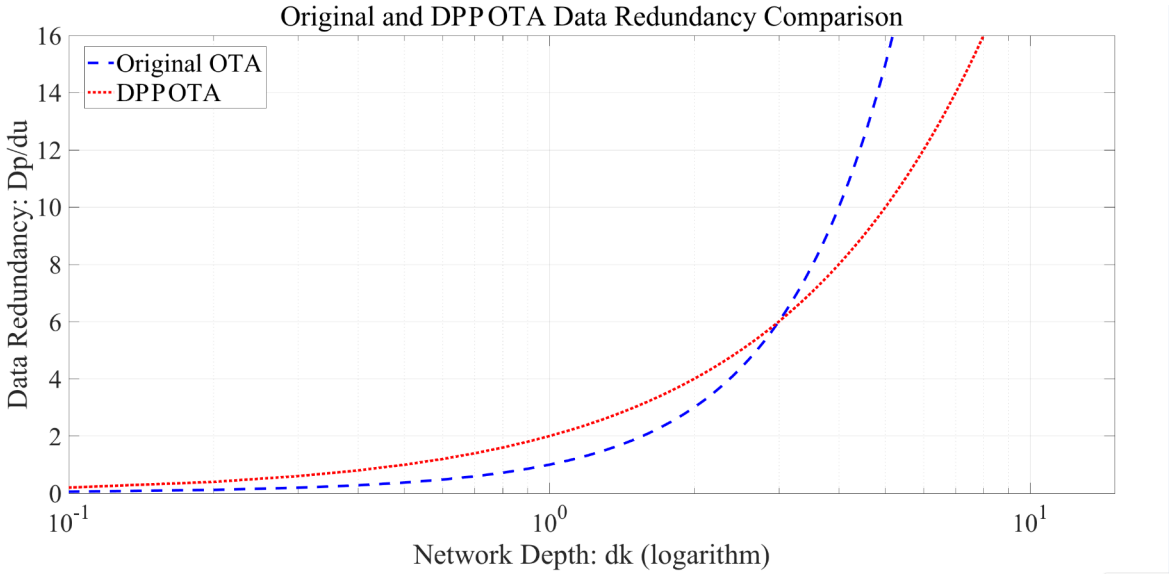


Fig. 6.5 Original Scheme and DPPOTA Data Redundancy Comparison

Certainly, all the experiments are based on the original z-stack OTA update scheme without any optimization. The OTA update performances are also related to the chip's hardware workmanship. Although the result of this experiment is not as stable as other developers show, it proves the validity of the data redundancy model as provided in the simulation. After the network depth reaches 2 when the ZigBee nodes number is 2 in one path, the DPPOTA algorithm accordingly embody better. It not only cuts down massive redundancy request commands, but also sharply reduces the probability of the ZigBee OTA network conflict. The network conflict or congestion *de* and the restarted OTA command data do are the major factors to influence the OTA update. As an added consideration, the network congestion error and the OTA clients restarting OTA service are the positive proportion relation of the data redundancy. The more data redundancy of the network self has, the more congestion errors appear and the more times the restarting take. This wrongly spiral condition explains why the original OTA update cannot support more than 2 nodes concurrent update, even when it influences the accumulative request commands redundancy data. On the other hand, the DPPOTA algorithm provides an excellent solution to deal with the congestion errors and restarting request. It cuts down output capacity of the data in the network path

and improves the efficiency of OTA update by formulating the OTA nodes' update priority orderliness.

Update Duration Model

The DPPOTA algorithm makes the remote endpoints wait for their turns. However, increasing the OTA update duration as it may look like, it cuts down the chaotic congestion error and reduces the update duration. When it comes to the update duration model, the DPPOTA algorithm compared with the original z-stack OTA scheme simulation are shown in the Fig. 6.6. Y-Axis presents the T/tb, tb is the unit updating duration which can be seen as 1ms. To make the X-Axis only has one variabls dk, I just let the equation divide the tb. So Y-Axis is T/tb which can directly reflect the updating duration. Firstly, the DPPOTA uses the image page-request mode to request the firmware image and it reduces some redundancy request duration from the origin. When there are more nodes in the network, the page-request mode will reduce a larger number of request duration and it is impressive to save the accumulative duration.

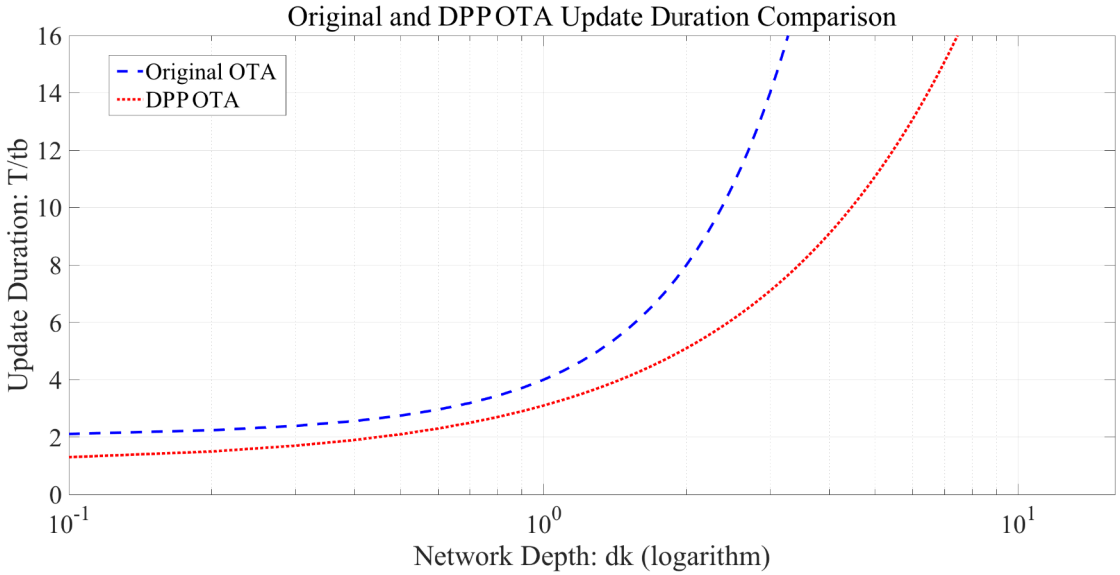


Fig. 6.6 Original Scheme and DPPOTA Update Duration Comparison

In addition, as the same problem as the data redundancy has, the congestion errors duration and restart duration increase as redundancy of the network rises, which are also the positive proportion relation. From the data redundancy model, it also can reflect the update duration's relationship with the redundancy data. But it needs to add other modulus variables as shown in the Table 5.2, such as redundancy duration modulus K and the origin request and response duration t_{rp}. Then the duration model follows the data redundancy model and is expressed as Equation 5.4 and 5.5. Fig. 6.6 shows that the original OTA update scheme duration is over on DPPOTA. As the depth of network and number of nodes increase, the redundancy duration overwhelmingly rises and the total update duration also increases fast. When the number of nodes gets the threshold, the redundancy duration will be the main influence. In the duration simulation, the DPPOTA duration threshold is bigger than the original OTA update scheme, which reflects the DPPOTA algorithm interior interference immunity. In the experiment, more noises improve the duration redundancy and the DPPOTA can reduce the influence of noises to improve the network tolerance.

DPPOTA Simulations and Experiments

Above all, the two simulations prove that the DPPOTA algorithm has great advantages on the data redundancy and update duration. When the network range has been extended, the original OTA cannot work well, but the DPPOTA can still process multi-nodes concurrent OTA update. Moreover, this DPPOTA algorithm is easy to realize complexity. As it shows in the Fig. 6.7, compared to the original experiments, this dissertation illustrates the CC2530 chips' DPPOTA upgrading. Due to the limit of the hardware nodes, it just evaluates two DPPOTA nodes: server and client. Fig. 6.5 shows that the DPPOTA page-request mode has about duple duration optimization over the original, and the more contained blocks (n) in one page-request, the shorter update duration.

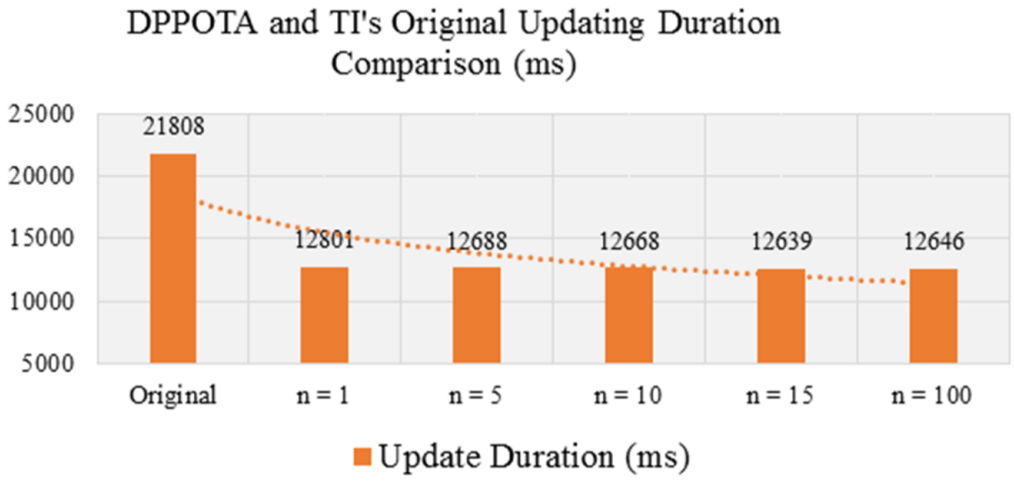


Fig. 6.7 TI's Original Scheme and DPPOTA Updating Durations Comparison

The following Fig. 6.8 shows the different block request intervals' OTA performances under the different numbers of blocks contained in one page. When the interval is 10ms, the less block request interval is, the less OTA update duration takes. But the bigger interval may be better as n is bigger. The reason is that when the block requests increasingly grows, more frequent requests may congest the serial port communication. In addition, when more blocks are contained in one page-request, the duration is also shortened. When the interval is uniform, the blocks' number n is bigger, and the update duration is shorter. If one page just contains all the blocks image requests, it will become the server propelling update. The results of the CC2530 platforms from these two experiments suggest the advantages of DPPOTA algorithm that it can shorten the data redundancy and update duration.

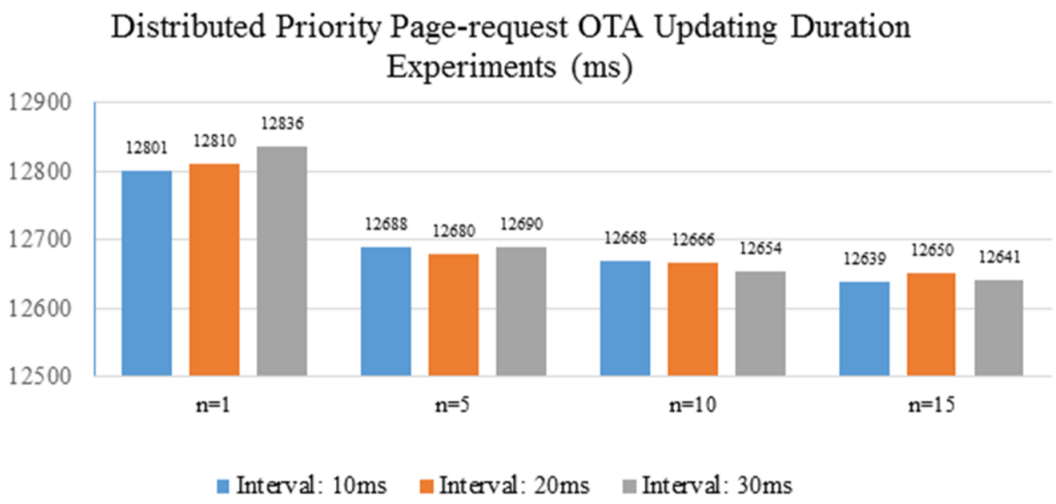


Fig. 6.8 Different Intervals of Page-request Mode Update Durations Comparison

6.3 DPPOTA Updating NS2 Simulations

ZigBee OTA NS2 Simulation [38] Parameters

1. Data Flow Parameters

   Data type: The Constants Bit Rate (CBR) has been chosen as data flow. CBR has one-way transmission, packet size and transmission interval, which is more conducive to the analysis of network transmission performance.

   Packet size: The Optimization OTA packet size is defined as 1000 bytes and DPPOTA packet size is 2000 bytes, beacons and other flags not included.

   Transmission direction: All the data information is unidirectional transmission from node 3 to coordinator 0.

   Channel selection: The simulation only uses the first three channels of the 2.4 GHz band.

2. Node Parameters

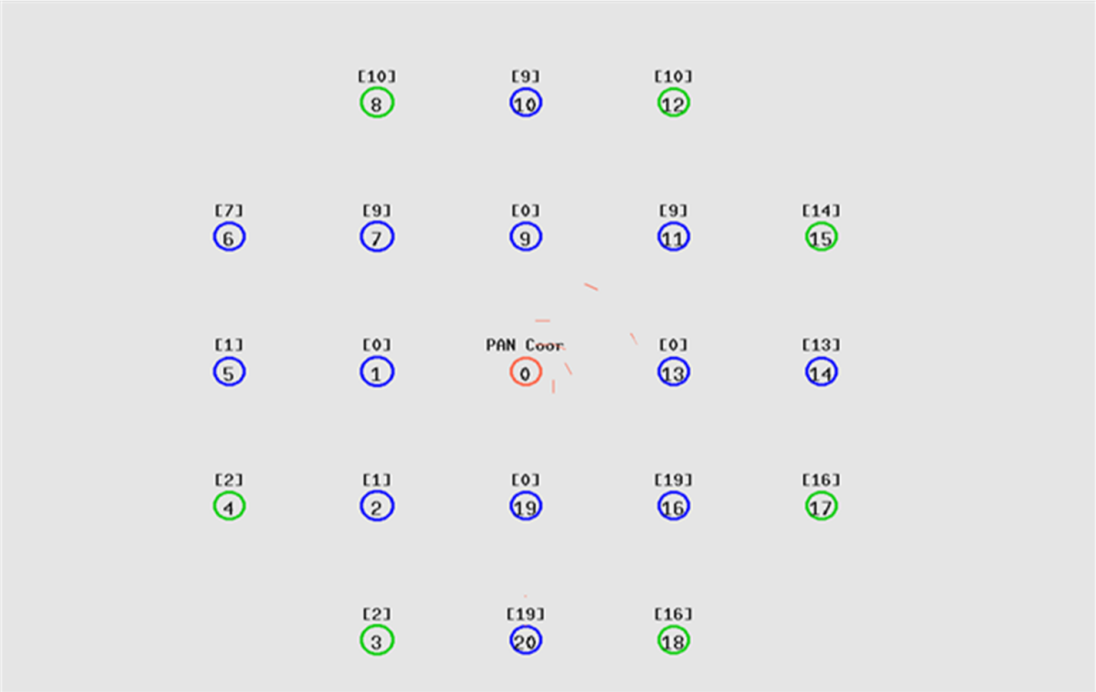


Fig. 6.9 ZigBee Network NS2 Simulation Graph

Number of nodes: The simulation environment consists of 21 nodes, including one coordination node, fourteen router nodes and seven endpoints , as shown in Fig. 6.9.

Node state: All nodes are stationary.

Node location: The distribution of all nodes is plane, as shown in Fig. 6.9. The central node 0 is the ZigBee coordinator.

3. Physical parameters

Broadcast model: As the distribution of nodes in the simulation of a larger range, the relationship between the equipment and the coordination position is more complicated, hence the use of the Shadowing model.

Antenna type: Omni Antenna. It can use the same power to send the around data.

Path loss: The signal energy will produce attenuation by the distance, obstructions and antenna height effects. But in the experiment where the attenuation is zero, the path loss is 1.0 .

Table 6.1 ZIGBEE NETWORK NS2 SIMULATION PARAMETERS

Data flow:	CBR	Broadcast type:	Shadowing
Coordinator/Routers/Nodes:	1/14/21	Antenna type:	Omni Antenna
Node motion state:	None	Queue model:	Drop Tail
Node distance:	10m	Queue length:	50
Packet size:	1000bytes	Send gain:	1.0
Band selection:	2.4GHz	Receive gain:	1.0
Channel numbers:	3	Path loss:	1.0
Data transmission mod:	Direct	Routing protocol:	AODV

Range: 50 x 50 m2. Neighbor Distance: 10 m. Tx Range: 12 m.

4. Routing layer parameters

   Queue type: The simulation uses the tail drop algorithm (Drop Tail), which is to follow the "first in first out" principle of queue management techniques: The packets that first entered the queue will be processed firstly; when the packet number exceeds the upper limit of the queue, the last packet into the queue will be discarded.

   Queue length: The standard queue length used in the simulation is 50 packets, and once this limit is exceeded, the excess will be discarded. As the performance of the network only depends on the effective utilization of resources, increasing the queue length for network performance has not a large impact.

   Routing Protocol: The simulation uses the AODV routing protocol.

Performance Parameters

In order to measure the different algorithms' OTA performance of ZigBee network, the simulation defines a number of performance indicators, through which the running status and reliability of the ZigBee network can be reflected. It should be noted that the performance indicators mentioned here are mainly concerned with the transmission of data, while other aspects are not an added consideration.

1. Transmission jitter rate

The transmission jitter rate is the Delay Variance of the transmission delay. As the network traffic changes at any time, when the traffic is large, many packets must be waiting in the queue, so each packet from the transmitter to the destination takes different time. The difference is the so-called jitter rate which reflects the stability of the network, and the greater the jitter rate, the worse the stability of the network. The formula to calculate the jitter rate is as follow:

$$Jitter = ([receive\,(m) - sent\,(m)] - [receive\,(n) - sent\,(n)]) \div (m - n) \tag{6.5}$$

The m and n are the packet numbers; receive (m) and receive (n) are the packet reception time; sent (m) and sent (n) are the packet transmission time.

2. Transmission delay

Propagation Delay refers to the time it takes for a packet to be sent from one reception to another. The transmission delay relates to each individual data packet, as long as the packet transmission is successful, there will be different degrees of delay, where the data packets are sent repeatedly. The average transmission delay for all packets can be used to measure the overall transmission performance of the network. In addition, the transmission delay can also reflect the capacity of the media access control sublayer. The longer the delay, the smaller the capacity. The transmission delay and the average transmission delay can be obtained based on the following formula:

$$Packet\_delay = Time\_receive - Time\_transmit \tag{6.6}$$

$$Average\_delay = Sum\_Packet\_delay \div Sum\_Packets\_receive \tag{6.7}$$

Packet_delay is the packet transmission delay while time_receive is the packet reception time; time_transmit means the packet transmission time and average_delay is the

average transmission delay; Sum_Packet_delay represents the sum of the transmission delays for all packets whereas Sum_Packets_receive is the sum of the number of packets received.

3. Packet loss rate

   Packet loss rate refers to the amount of discarded packets in the simulation process that the following can be sent: the packet ratio, usual packet loss rate, packet length and packet transmission frequency. Packet loss is out of network transmission errors or network congestion. For example, when the network within the forwarding device to receive the wrong packet or CRC check, frame positioning error will occur when the data packet is discarded. Similar to the transmission delay, as an added consideration, the packet lost in the calculation will lead to the repeated transmission. When a data packet waits for the next transmission, if the simulation process is successful, then the packet before the discard is not calculated. Packet loss will also affect the real-time performance of the network in terms of the transmission delay. In some connection-oriented applications, packet loss will lead to data retransmission, thereby increasing the transmission delay. The network equipment cannot work or the network load is too large when the packet loss rate is considerably large, but it does not necessarily mean that the network is faulty, because many businesses in the case of a small amount of packet loss can continue. The packet loss rate is calculated as follow:

$$Packet\_loss\_rate = (Packet\_drop)/(Packet\_sent) * 100\% \tag{6.8}$$

The above performance indicators are calculated in the same Gawk program, each of which is written to a different file, and then by Gnuplot it will be presented in the form of a coordinate map.

Simulation Results

1. The comparison among DPPOTA, OOTA and OTA's Jitter

   Initially, the OTA, the Optimization OTA (OOTA) and DPPOTA have been implemented. The NS2 simulator defines the network Jitter as Equation 6.5. Fig. 6.10 shows that the DPPOTA updating grows from time 10.3s to 100s when the node number is one. After 100s, the updating change to the TI's original OTA. Y-Axis is the Jitter which represents a rate. The unit of Y-Axis is a number such as 1. Meanwhile, the DPPOTA algorithm's jitter is thin and stable from the time 10.3s to 100s, but the TI's original OTA has a significant wide jitter.

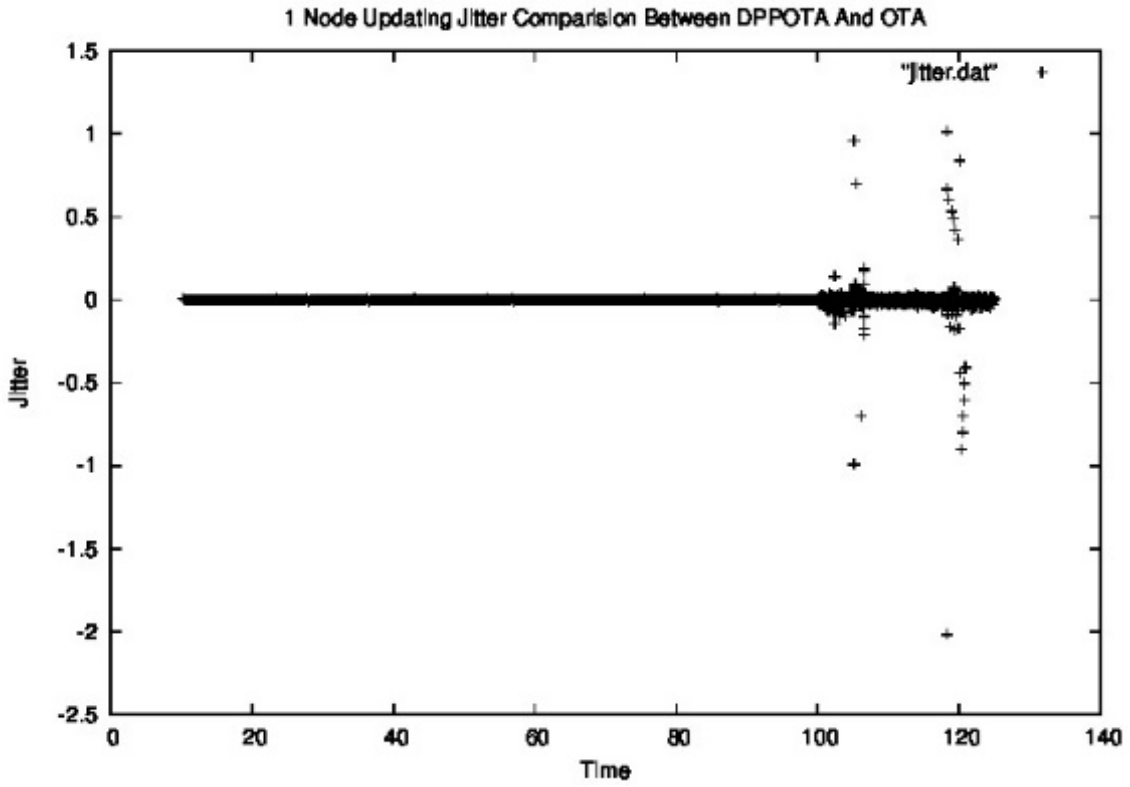


Fig. 6.10 One Node's DPPOTA and OTA Jitter Comparison

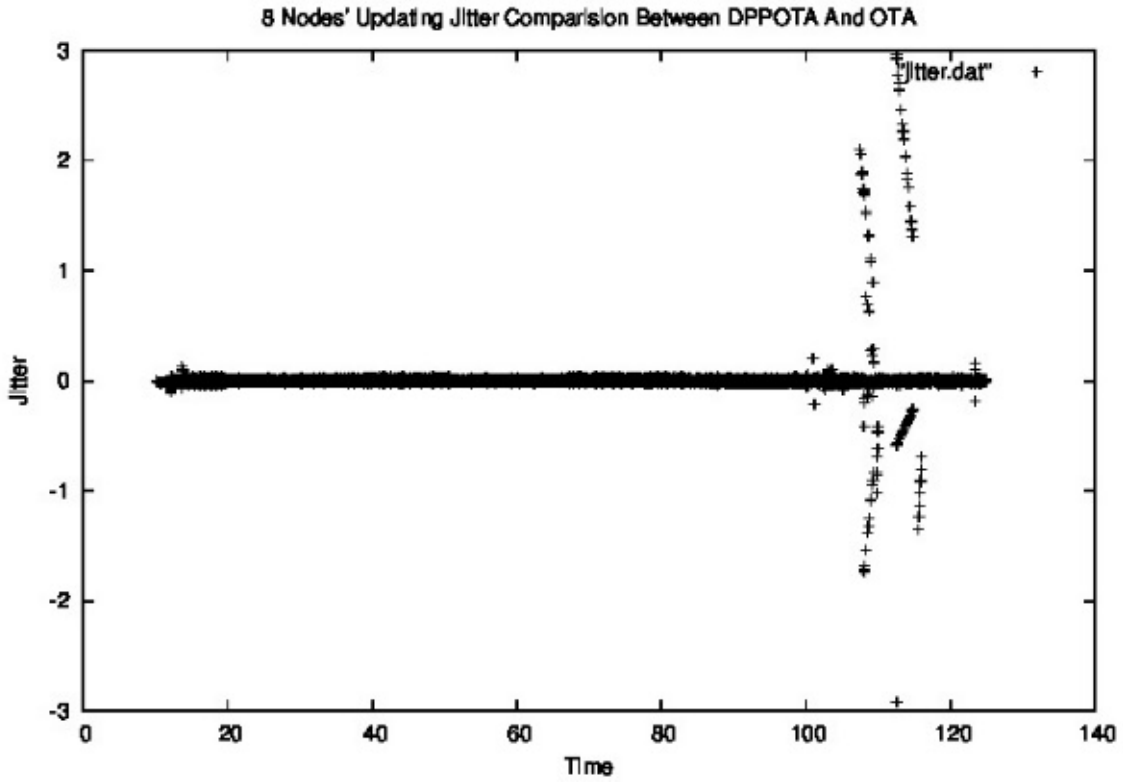


Fig. 6.11 Eight Node's DPPOTA and OTA Jitter Comparison

Afterwards, I simulate the comparison under the 4 nodes concurrent OTA updating and the 8 nodes concurrent OTA updating, as shown in Fig. 6.11 and Fig. 6.12, where the 8 nodes' DPPOTA jitter line is thicker than the one node's. It indicates that the more nodes in the DPPOTA, the more effect jitter of the ZigBee network. Fig 6.11 has enlarged the jitter simulation to 100s, the interchange time of these two algorithms. The OTA's jitter shock density is bigger than the previous DPPOTA. Thus, no matter how many nodes there are, DPPOTA's network is always more stable than TI's OTA.

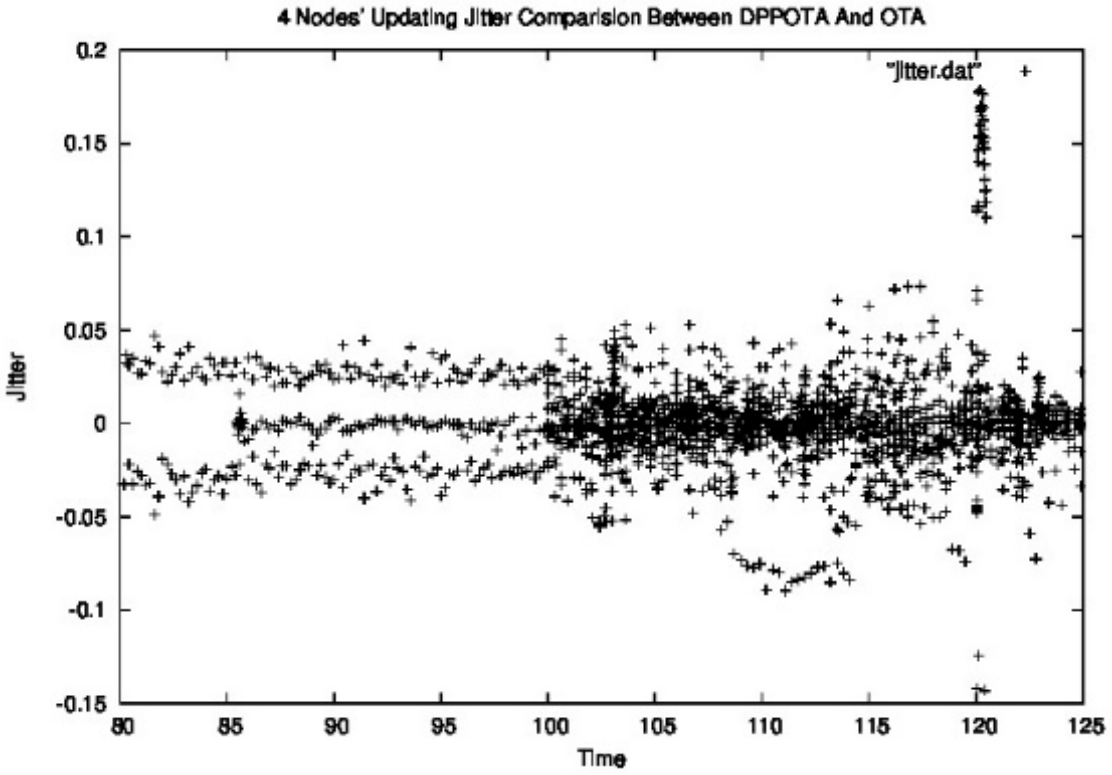


Fig. 6.12 Four Node's DPPOTA and OTA Jitter Comparison

The OOTA also outperforms the TI's original OTA, as discussed in Section 2.4. [27] has proposed an optimization OTA to reduce the data redundancy. In my simulation, the data redundancy is proportional to the jitter rate in some cases. Since the data redundancy reflects the network congestion degree, the more congestion degree, the more jitter. So the jitter can as the performance's comparison between the DPPOTA and the OOTA. The implemented DPPOTA updating and the OOTA updating can be seen from Fig. 6.13 and Fig. 6.14, where most of DPPOTA jitter's distribution are in the positive 0.005 and negative 0.005, and that the distribution of density is larger than the OOTA's in Fig. 6.14. Therefore, this simulation can suggest that the DPPOTA algorithm outperforms the OOTA on the ZigBee network's stability. The redundancy congestion degree of DPPOTA is less than the OOTA's as well.

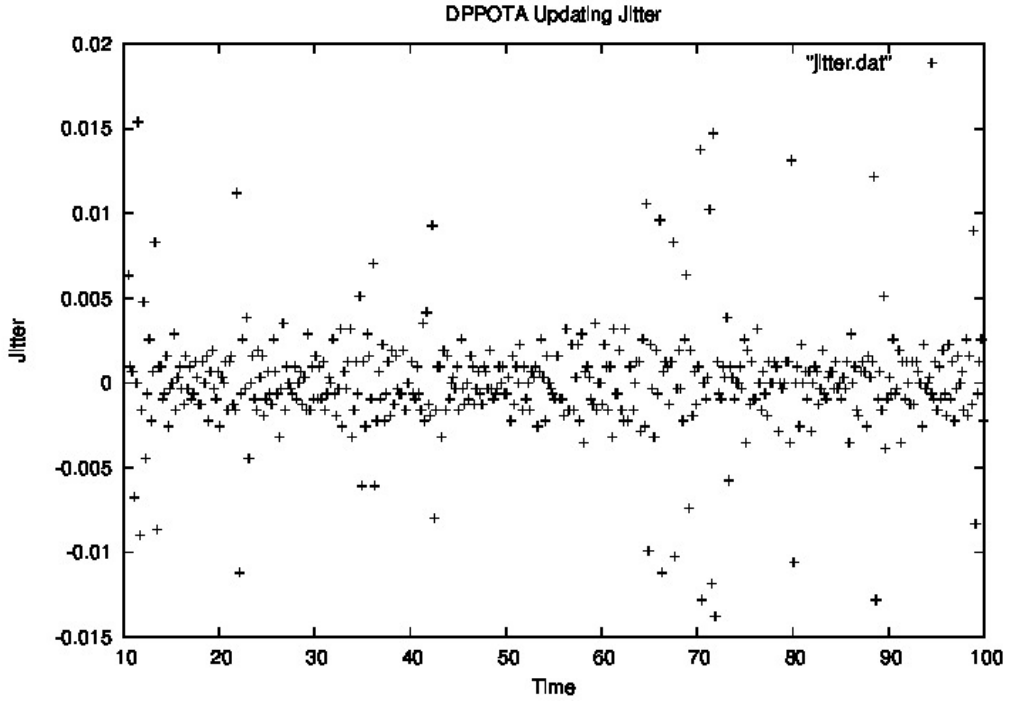


Fig. 6.13 DPPOTA Updating Jitter

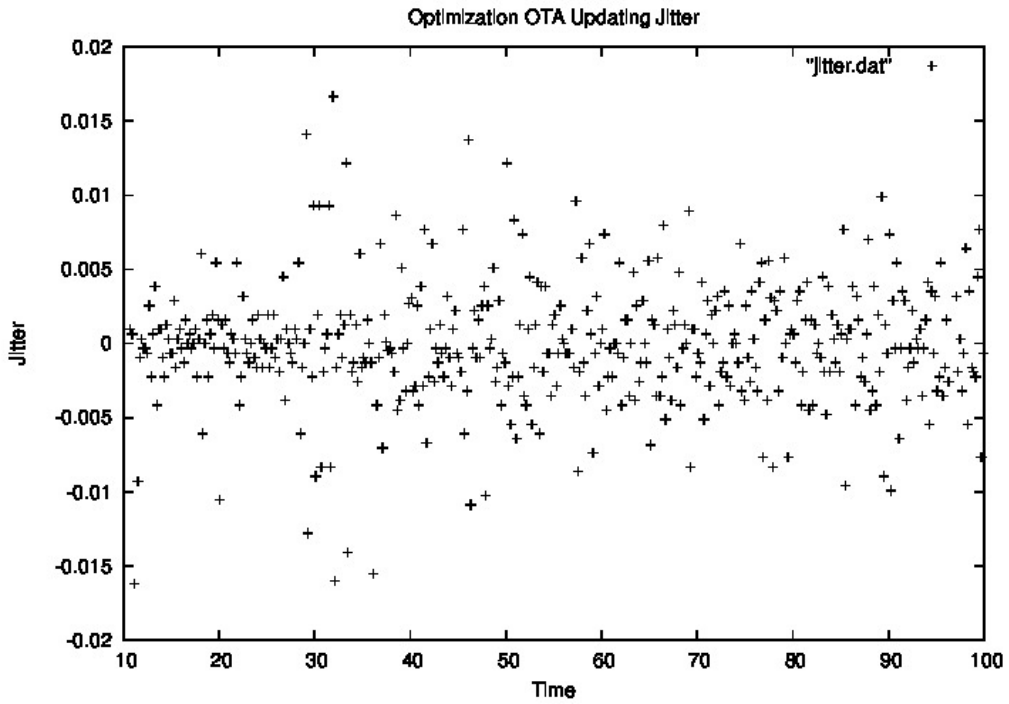


Fig. 6.14 Optimization OTA Updating Jitter

2. Comparison between DPPOTA and OOTA's Delay

   In this simulation section, the DPPOTA and OOTA updating request to the coordinator has been implemented. As discussed before, the packet's transmission delay is from node 3 to the ZigBee network coordinator in Fig. 6.9. The following Fig. 6.15 shows that the distribution of DPPOTA updating transmission delay is mostly between 0.004s and 0.01s, whereas the OOTA transmission delay is distributed between 0.01s and 0.03s in Fig. 6.16. Thus, DPPOTA uses the page-request cut most request commands and reduces the packet transmission delay. In other words, the DPPOTA updating duration is ideally smaller than that of OOTA

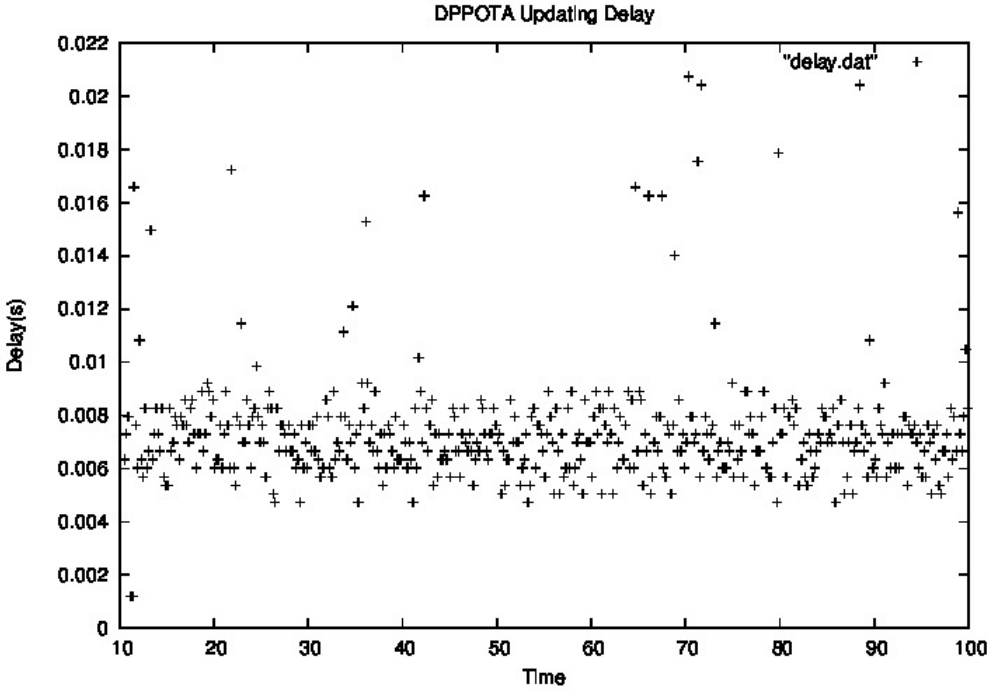


Fig. 6.15 DPPOTA Updating Transmission Delay

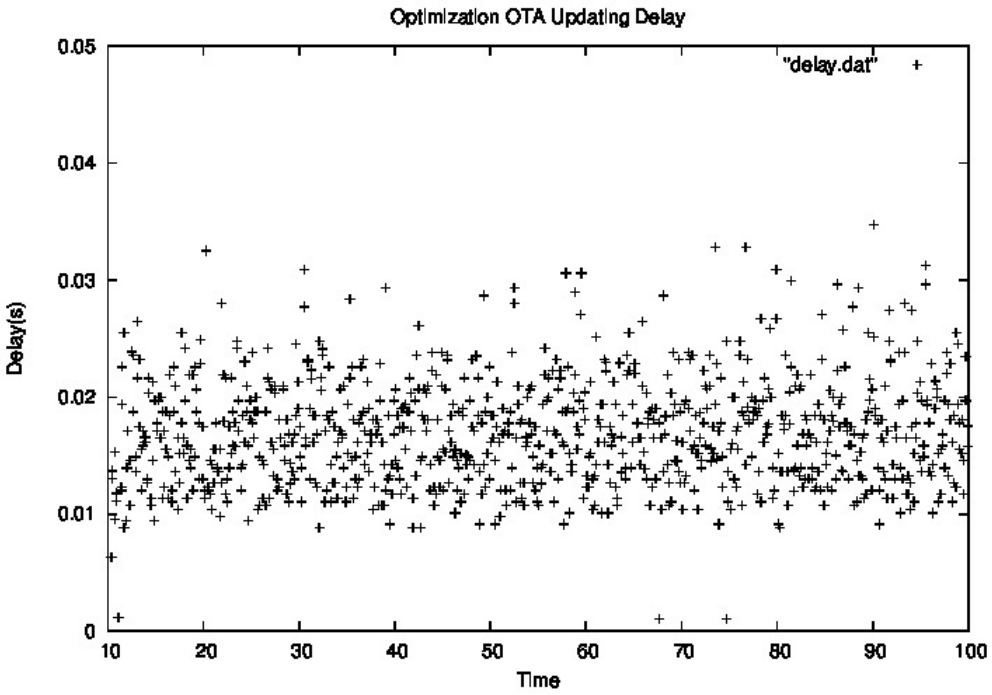


Fig. 6.16 OOTA Updating Transmission Delay

3. Packet Loss Rate

The above simulations can lead to the result of the packet loss rate, as the following table (see Table 6.2) shows. In terms of the packet loss rate, the DPPOTA is the best, followed by the OOTA and TI's OTA on the network congestion. If the network is more congested, there are more data redundancy in the ZigBee network. So the more data redundancy, the bigger packet loss rate. The DPPOTA algorithm outperforms the OOTA and TI's OTA.

Table 6.2 DPPOTA, OOTA AND OTA PKTLOSS RATE COMPARISON

DPPOTA	sent=13082	drop=1000	pktlossrate=0.076441%
OOTA	sent=9308	drop=1760	pktlossrate=0.189085%
TI's OTA	sent=8400	drop=3300	pktlossrate=0.392857%

Chapter 7

Conclusions

The array constructed in this dissertation records the non-leaf nodes property as a data unit. It shows that the HHD algorithm has two benefits. Firstly, the right leaf node does not require heavy outside storage, which can further optimize. According to the experimental results, the compressed average code length is about 6. So it takes average six steps to get to the decoded values whose performance improves more than 20 times. By decreasing the amount of calculation, the transmission time is shortened. Correspondingly, energy has also been saved for the physical transmission layer. The other benefit is that the storage space with arrays is smaller than storing the list and sequence array. Significantly, this algorithm saves the Huffman decoding space cost. Since there are plenty of empty place for holder data, it provides space for further optimization. The innovation of the paper is that the algorithm decodes the Huffman tree into an array, which can directly decode data according to subscript random read, decoding efficiency increases faster than the traditional method. However, the cost of this design is that the compression increases the amount and complexity of client computing and coding processes. In the upgrading process, the sensors' nodes and the coding process is done on the PC, which fits the application environment. However, the array is a big challenge for decoding. According to the Huffman coding tree or table creation, using the recursive algorithm can solve the problem. Since it is difficult to implement the algorithm and

a certain amount of code is requested, the programming complexity also increases. Therefore, the idea and design of this algorithm would be seen as an innovation.

As an added consideration, both the data redundancy and update duration mathematical model simulation, along with the CC2530 platform experiments, present the advantage of the DPPOTA algorithm: lower data redundancy and shorter update duration than the original OTA. These two features can improve the OTA update efficiency, save the nodes' power and increase the interference immunity and network tolerance. In addition, compared with other paper's solution, this dissertation designs the priority orderliness to update and processes the dynamically distributed update in the ZigBee network. All the simulations and experiments prove the DPPOTA algorithm's advantages. Besides, the page-request parameter configuration is a pending problem in the large-scale network. However, the optimal solution of block numbers of page and the block request interval configuration is confined in the reality application. The NS2 simulations present that DPPOTA algorithm has the better performances on network Jitter and transmission delay over TI's OTA and Optimization OTA. Overall, the DPPOTA is a creative solution to ZigBee OTA firmware update optimization.

To sum up, this dissertation contributes to designing a creative nimble image decompression algorithm HHD to run on the remote ZigBee smart home endpoints and proposes a distributed priority page-request OTA (DPPOTA) updating algorithm for the whole ZigBee network. These algorithms help the smart home firmware updating more efficient and stable. Combining the wired and wireless updating method can exert each mode's advantage. This updating solution outperforms any single updating mode. The 2.4GHz interference is another factor to improve the ZigBee OTA updating in the future work.

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Appendix A

The Z-stack OTA Updating project files and NS2 simulation codes are attached in the Appendix CD.