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IoT Firmware Management:
Over the Air Firmware Management for Constrained Devices using IPv6 over BLE

by

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Declaration

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University of Dublin, Trinity College, 2017

Supervisor: Dr. Jonathan Dukes

The next wave driving the Internet expansion will come from Internet of Things. Bluetooth Low Energy (BLE) is considered to be a prime candidate to connect and let the device communicate with each other. Furthermore, with the advent of LoWPAN technology, it is possible to designate the IPv6 address to every "thing" in the Internet of things paradigm. As IoT is gaining traction, a number of associated challenges have surfaced. One of which is the management of the fleet of IoT devices.

Manual management of resource constrained IoT devices is not feasible. The network of wireless sensors should be controlled by a remote management framework which should take care of device control and firmware upgrade. The firmware upgrade is required to push bug fixes, security, vulnerabilities fixes and new features into the IoT devices. In the current state of the art, there exist no end to end firmware upgrade framework to remotely manage the device control and firmware upgrade on BLE devices. This dissertation establishes state of the art in IoT protocol stack and firmware upgrade mechanism.

Further, we investigate the gaps in current firmware upgrade mechanism and implements an approach which adheres the specifications of remote management standard (LwM2M) and uses CoAP block transfer for transporting the firmware image to BLE based IoT device via IPv6 over BLE channel.

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Chapter 1

Introduction

1.1 Background

The Internet of Things, or IoT, is emerging as the next technology revolution. The term "Internet of Things" was coined by Kevin Ashton while working with Auto-ID Center at MIT[1]. The Internet of Things allows small devices to be sensed or controlled across the existing internet infrastructure. The network of these connected devices would lead to the merging of physical and digital worlds, opening up a host of new opportunities and challenges for consumers, companies, and governments[1]. As estimated by various market surveys[2], billions of everyday devices ranging from wearables to industrial equipment will be connected in coming years.

A number of significant factors have given the thrust for enabling IoT in real scenarios. These include ubiquitous connectivity, widespread adoption of IP-based networking, computing economics, miniaturization, advances in data analytics, and the rise of cloud computing [2]. The applicability of IoT can be broken up into five key verticals of adoption: connected wearable devices, connected cars, connected homes, connected cities, and the industrial Internet.

In its simplest form, IoT is just about enabling connectivity between "things" or de-

[1] https://en.wikipedia.org/wiki/Internet_of_things

[2] http://www.gartner.com/technology/research/internet-of-things/

vices. In a more sophisticated form, the IoT ecosystem consists of sending data from IoT nodes via a gateway to storage servers or data analytics platform and relaying back management commands from a remote management platform. Figure 1.1 shows an overview of basic building blocks in an IoT ecosystem.

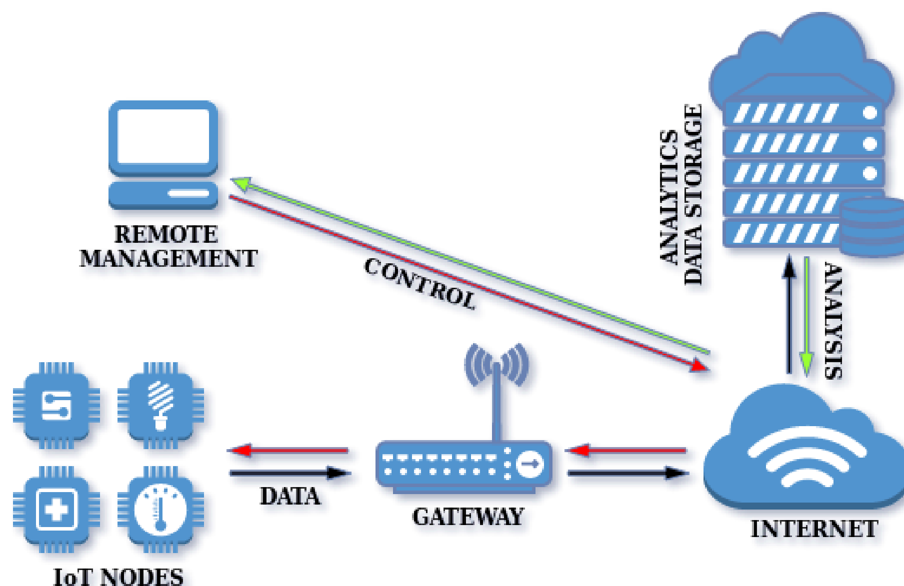


Figure 1.1: The Internet of Things Ecosystem.

In general, the IoT devices such as small sensors or actuators are resource constrained devices with low memory, processing power, reduced battery capacity. The conventional TCP/IP stack is not applicable for IoT devices[3]; therefore a redesigned light weight network stack is needed to let these devices to communicate with mainstream internet and attain a working Internet of Things. In this dissertation, we will discuss state of the art and address the challenges in the firmware update on IoT devices.

1.2 Motivation

As IoT continues to gain traction, a number of associated challenges have surfaced. These problems range from technological to business related aspects. A survey on application and challenges in IoT was carried out by S. Nalbandian [4]. Some of the key challenges

are summarized below.

- Standards: Lack of standards and documented best practices limits the potential of IoT. Without standards to guide, manufacturers or developers sometimes design the products that operate in nonstandard ways which impact the interoperability. A poorly designed and configured device can have negative consequences for the networking resources.

- Device Management and Firmware Upgrade: IoT devices are often deployed in a remote location where the manual administration of these resource constrained devices is not feasible. Upgrading the firmware on these devices is one of the key challenges in IoT ecosystem. The firmware upgrade is required to push bug fix, security vulnerabilities fix and new features into the IoT devices. For a seamless integration of connected devices, a network of wireless sensors should be controlled by a remote management server which should take care of device control and firmware upgrade.

- Connectivity: The current connectivity method relies on the centralized, server/-client paradigm to authenticate, authorize and connect different nodes in a network. With more and more devices coming into the network it will defy the very structure of current communication models and the underlying technologies.

- Privacy: More and more data generation from IoT networks creates a unique challenge to privacy. This is becoming more prevalent in consumer devices, such as tracking devices for phones and cars as well as smart televisions.

- Security: There are no stringent security standards enforced till now to prevent attacks in IoT network. With the increase in the number of connected devices increases the opportunity to exploit security vulnerabilities in the poorly designed IoT networks.

The above-discussed challenges lie in different domains of IoT. In this dissertation, we primarily focused on identifying and addressing the gaps realted to device management and firmware upgrade in IoT devices.

1.3 Research Objectives

On the commercial basis, there is a need of automating the firmware upgrade on sensor networks to reduce manual interventions. In the current state of the art, there is no end to end standardized approach for remotely managing the firmware on IoT devices and pushing new firmware when required. With the availability of energy efficient LoWPAN technology and broad adoption of BLE, this dissertation aims to investigate and implement a standard complaint end to end firmware management system for BLE based IoT devices using IPv6 over BLE compliant communication stack.

The research objective can be further divided into sub-objectives as listed below:

1. Establish state of the art for the IoT protocol stack.
2. Establish state of the art for firmware management of resource constrained devices.
3. Identify the gaps in the current state of the art for firmware management of resource constrained devices.
4. Design a standard compliant end to end firmware management architecture and for BLE based IoT devices using IPv6 over BLE compliant communication stack to address the gaps in the current state of the art.

1.4 Dissertation Structure

This section provides an outline of the structure of the thesis document.

- The current chapter provides a brief overview of the areas of research; motivation, research objectives and goals of this dissertation.

- Chapter 2 divides the objective into specific areas of research. The state-of-the-art, background and related work for each of these areas are discussed in corresponding sections.
- Chapter 3 specifies the design aspects of the proposed system. The requirements of the system, the system architecture, and high-level design are discussed in this chapter.
- Chapter 4 discusses the methods, technologies, and platform used to implement the proof of concept of a firmware management system. The specific libraries, programming tools, languages, and software setup used are specified in the chapter. A discussion on system evaluation is also presented in this chapter.
- Chapter 5 summarizes the contributions made by this research, lists future work and concludes with final remarks on the dissertation.

Chapter 2

State of the Art

2.1 Introduction

In this chapter, we will look into the communication models being followed in IoT network deployment and proposed lightweight stack for IoT devices. In the recent years, there is a lot of work done in standardizing protocols to make IoT solution inter operable. We will discuss different protocols and standards applicable in IoT stack. Finally, we will discuss the principles, challenges and acknowledge the work done by the researcher community in the field of firmware updates on resource constrained IoT devices.

2.2 Communication Models

Regarding operations, it is necessary to define how IoT devices should connect and communicate. The Internet Architecture Board (IAB)[1] released the guiding specification RFC-7452 [5] to design Internet connected smart objects, which defines a number of communication patterns utilized in the smart object environment. The discussion below presents the defined pattern with the key characteristics of each model.

[1]https://www.iab.org/

1. Device to Device communication model:

   The device to device communication model represents two or more devices that connect directly and communicate with each other. In this sort of model, devices can exchange packets directly without the need of any intermediate gateway or application server. For communication, this model encourages the use of wireless link layer technologies such as Bluetooth low energy [25], Z-wave[2], Zigbee[3] or LoRaWAN[4]. Figure 2.1 shows the communication pattern wherein two devices are connected with each other using a radio link.

   This communication model is well suited in an area where the data exchange uses small data packets of information, and the requirement of data rate is relatively low. The connected home is the prime use case for this communication model. Controlling light bulbs, switches and consumer electronics which requires relatively low data rates.

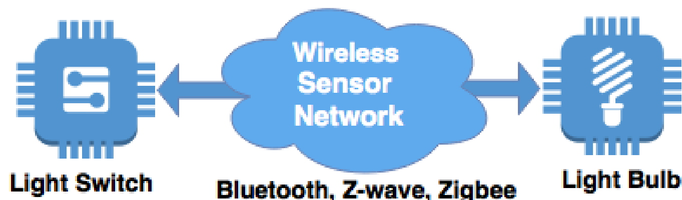


Figure 2.1: Example of device-to-device communication model [5].

2. Device to Cloud communication:

   The device to cloud communication model represent IoT devices which directly connect and communicate with an Internet cloud service and exchange data and control messages. This model allows an end to end IP based connectivity between device and cloud service using the traditional wired Ethernet or Wi-Fi connections. Figure 2.2 shows the device to cloud communication model. The IoT devices come under

[2]http://www.z-wave.com/
[3]http://www.zigbee.org/
[4]https://www.lora-alliance.org/

this model should have enough resource to allow support for traditional connectivity. Typical examples include Nest Thermostat which connects directly with the cloud service to transmit data. Further, the user can remotely control the devices using exposed cloud interfaces/services.

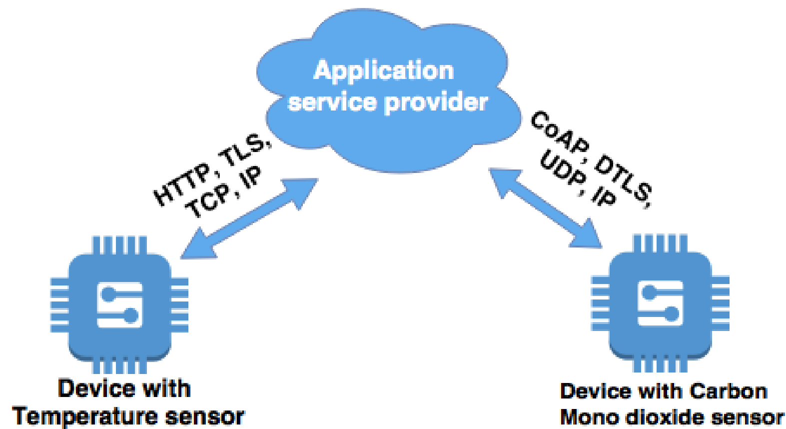


Figure 2.2: Example of device-to-cloud communication model [5].

3. Device to Gateway model:

   In the device to gateway model, the IoT devices connect with a gateway which acts as an intermediary between the device and the cloud service. In this sort of model generally, two different types of communication technologies are bridged by an intermediary gateway and provides an end to end connectivity between IoT device and cloud service. Figure 2.3 shows the device to gateway communication model. In most of the use cases, a smart phone application serves as an intermediary gateway to connect resource constrained IoT devices to connect with cloud services.

   Interoperability could be a challenge in a device to gateway communication model. Intermediate gateway should be smart enough to support a number of communication protocols so that vast number of devices can connect to these gateways.

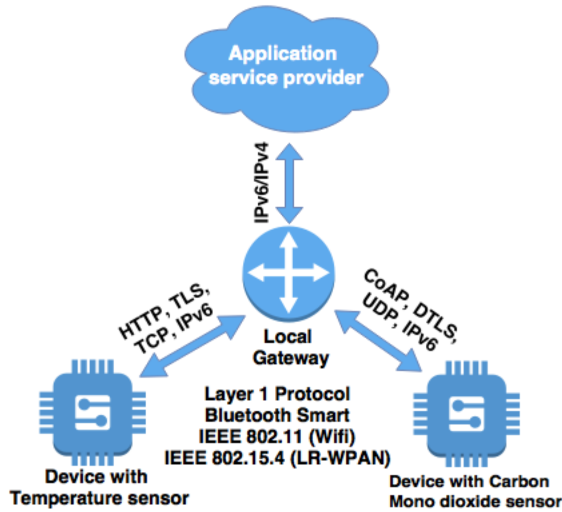


Figure 2.3: Example of device-to-gateway communication model [5].

4. Back End data sharing pattern:

   Back end data share model allows the user to export and analyze smart object data from a cloud service in combination with data from other sources. This architecture provides the authentication services which enables the user to grant access to the third party services. The patterns re-use the RESTful API designs in combination with the federated authentication and authorization technology such as OAuth 2.0 [6]. A graphical representation of this model is shown in Figure 2.4. Typical use case exists if the owner of a retail shop would like to analyze the market trends from the footfall data captured from deployed sensors in conjunction with data from a third party provider.

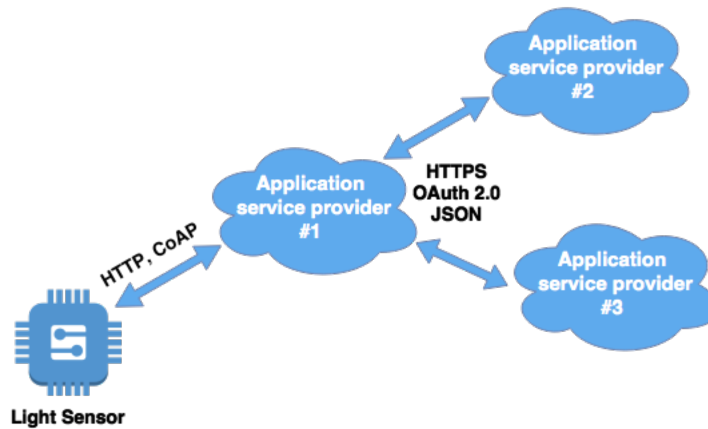


Figure 2.4: Example of back end data sharing communication model [5].

2.3 IoT Communication Stack

IoT is all about integrating machine to machine and wireless sensor network (WSN) solutions with the mainstream Internet services using existing Internet protocol (IPs). The integration would require the IoT endpoints to support IP connectivity or relay their packets via IP supported gateway. In general IoT devices are low powered, resource constrained devices which need to function long term on limited battery power and support frequent data exchange over lossy networks. Use of existing IP stack as-is make it less feasible to IoT devices [3].

Different standardization bodies and groups including government standards institutes like ETSI[5], organizations like IETF[6]/IAB, and alliances like ZigBee[3] and IPSO[7] are active in creating more inter operable protocol stacks and open standards for the IoT. With the advent of IP technologies and acceptance of IPv6 over IPv4, standardization bodies have agreed upon the idea of using IP to even the smallest device. Protocol like 6LoWPAN made it possible to extend IP connectivity to IoT endpoints. 6LoWPAN enables compressed IPv6 packets to be carried out on IEEE 802.15.4 standard [21]. Figure 2.5

[5]http://www.etsi.org/
[6]https://www.ietf.org/
[7]https://www.ipso-alliance.org/

below shows the typical web application stack and redesigned IoT network stack suitable to provide IP connectivity in low powered, resource constraint IoT nodes. This section further discusses each layer of IoT protocol stack in more detail.

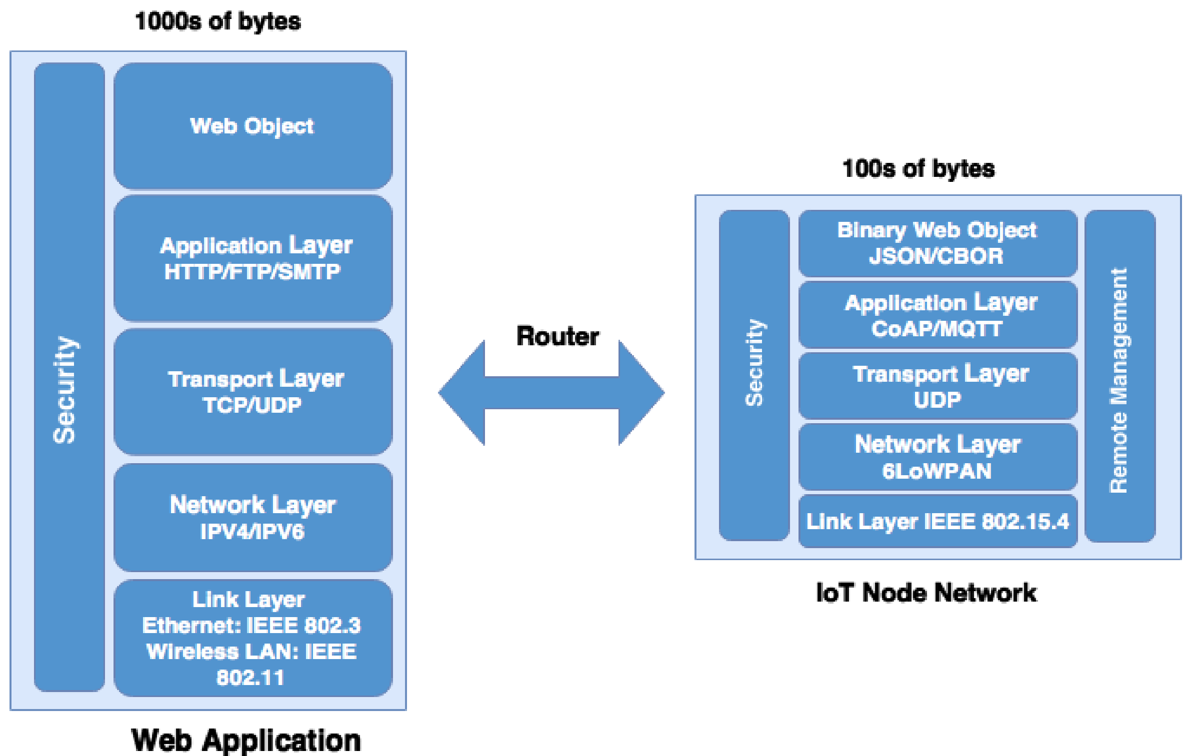


Figure 2.5: From web application to IoT node stack.

2.3.1 Data Interchange Formats

Data interchange formats are required to let the applications speak to each other in a standard format. These formats are responsible for representation of structured data. This section further discusses the formats suitable for IoT stack.

1. JAVA SCRIPT OBJECT NOTATION (JSON)

   RFC-7159 [7] defines the specification of JSON data interchange format. JSON is a lightweight text format which allows structured data interchange. It is completely language independent but uses conventions associated with conventional programming languages such as C, C++, C#, Java, JavaScript, Perl, Python, etc. It was

first introduced to the world at json.org website[8]. The syntax of JSON is a collection of braces, brackets, colons, and commas that are used to define structured data. On principle, JSON is built on two universal data structure.

(a) Collection of name value pair: Implemented as hash tables, associative arrays, or dictionary

(b) An ordered list of values: Implemented as an array, vector, or list.

These universal data structures are supported by virtually all the programming languages which make it suitable for programming languages to have a data interchange format based on standard data structures.

2. Concise Binary Object Representation (CBOR)

   RFC-7049 [8] defines the specification of CBOR data exchange format. CBOR is a binary data serialization format which is based on JSON data interchange format. The design goals of CBOR includes the possibility of minimal code size, fairly small message size, and extensibility without the need for version negotiation [8]. CBOR is a recommended data serialization layer for the CoAP IoT protocol suite[9]. Implementation of CBOR is simple and provided in various languages[10]. Internet of Things is a major factor in the development of CBOR. Binary encoding in CBOR allows faster processing.

3. IPSO Alliance

   The potential of the Internet of things can be best exploited with IP as a connectivity medium. The IPSO alliance[7] is an organization which promotes the Internet protocol (IP) for IoT device communication. With rapid integration of small devices, IETF has provided a specification for IP-enabled IoT devices to work in a web like fashion. There is a need to structured data model on top of application layer

[8]http://www.json.org/
[9]http://coap.technology/
[10]http://cbor.io/impls.html

protocol to allow seamless communication with these small devices. IPSO provides a common design pattern, an object model to provide interoperability between smart object device and connected software application on devices and services [9]. IPSO defined object model is based on Open Mobile Alliance Lightweight Specification (OMA LwM2M) [31].

The data model followed by IPSO is in the form of CoAP URI /Object/Instance/Resource and identical to one which is followed by LwM2M. Section 3.7 provide details about the Data models and object representation.

2.3.2 Application Layer

IoT is about interactions between multiple devices, things, and objects. Interaction of devices and services will exploit the actual potential of IoT. The application layer is responsible for providing services and determines a set of protocols for message passing at the application level. M. B. Yassein et al., [10] provides a survey and comparison of different application protocols based on transport layer used, architecture and communication model. This section further discusses the application layer protocol suitable for IoT.

1. CONSTRAINED APPLICATION PROTOCOL (COAP)

   Constrained application protocol (CoAP) is a request/response protocol specified by RFC-7252 [12]. CoAP is designed and well suited for a constrained environment such as low power devices and devices with constraint resources regarding CPU, RAM, and network. C. Bormann et al. in [11] explains CoAP protocol as a replacement of HTTP in the domain of Internet of things. CoAP follows REST architectural style and works upon UDP to achieve its goals with less complexity. CoAP inherits REST feature from HTTP and allows four of the request methods: GET, PUT, POST and DELETE. A typical CoAP packet consumes only 10-20 byte of header size. Graphics in figure 2.6 shows the CoAP GET request from a client to the server with the name of the resource. The server, in turn, responds with "200 OK"

response code, data format and requested data[11].

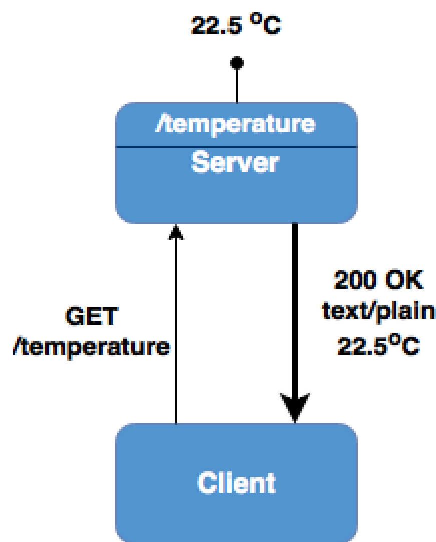


Figure 2.6: CoAP GET request elicits a 200 OK response [11].

CoAP provides three main features: Block transfer, Observe and Discover.

(a) Block Transfer: Block transfer will overcome the situation of fragments where large data needs to be transferred such as firmware update. CoAP transfers multiple blocks of information for a resource representation by simply adding a pair of "Block options."

(b) Observe: Using observe, the client will subscribe to a resource in server and server will send out a notification in case of any change in the resource.

(c) Discover: Discover will expose a "well-known" resource using which devices will be able to discover each other and their resources.

Figure 2.7 shows the inter working of CoAP with HTTP. The proxies in between can behave like intermediately which can speak both CoAP and HTTP this providing the interoperability between CoAP based network and traditional HTTP based Internet.

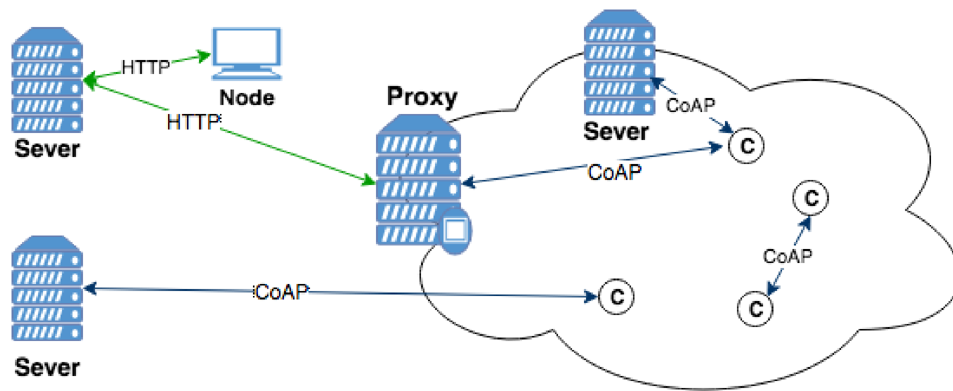


Figure 2.7: Web architecture with HTTP and CoAP [11].

2. MESSAGE QUEUE TELEMETRY TRANSPORT (MQTT)

MQTT[11] provides a publish/subscribe service model wherein the publisher publishes the information and subscriber subscribe to the information it wants. MQTT was designed for low powered and constrained devices; therefore, it is well suited for IoT deployments[12]. It is based on TCP/IP protocol. The broker in between publisher and subscriber facilitates or filters the information and allow for a loose coupling between entities. Figure 2.8 shows the pub/sub model of MQTT and data transfer between publisher and subscriber via a common broker.

The decoupling can occur in a few different ways, space, time, and synchronization.

- Space: The subscriber doesn't need to know who the publisher is, for example by IP address, and vice-versa
- Time: The two clients don't have to be running at the same time
- Synchronization: Publishing and receiving doesn't halt operations

Through the filtering done by the broker, subscribers can subscribe messages based on subject, content, or type of message. Once connected with the broker, a publisher can simply send its data to the broker and broker can relay appropriate data onto

[11]http://mqtt.org/documentation
[12]MQTT-SN_spec_v1.2.pdf

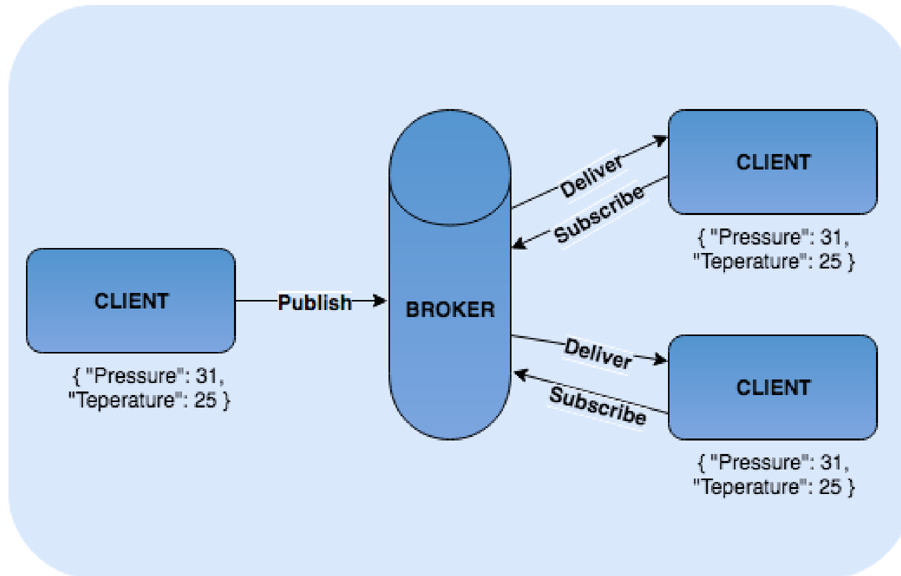


Figure 2.8: MQTT Publish/Subscribe Model

the subscribers who subscribed for that data. All this data transfer is done in a light weight fashion suitable for resource constrained devices.

2.3.3 Transport and Communication Layer

1. INTERNET PROTOCOL VERSION 6 (IPv6)

Internet Protocol version 6 (IPv6) is the latest revision of the Internet Protocol (IP) and the successor of IPv4. IPv6 was originally defined in RFC-2460 [14] by the Internet Engineering Task Force (IETF). In July 2017 RFC-2460 was obsoleted by RFC-8200 [15]. The motivation behind the development of IPv6 was to deal with the shortcoming of IPv4 and its long-anticipated problem of address exhaustion. To deploy Internet of Things it is necessary to address every "Thing" connected to the Internet. IPv4 with its 32 bits long address (2^{32} addresses) is not capable of providing required address space.

IPv6 is redesigned entirely and kept the core functionalities of IP addressing, but IPv6 is not designed to be backward compatible with IPv4. IPv6 offers following features.

- Larger Address Space [15]: The full version of IPv6 address is as long as 128 bits which is in contrast to IPv4, four times more bits to address a device on the Internet. The full address range of IPv6 can provide approximately 2^{128} different combinations of addresses. This address can accumulate the aggressive requirement of address allotment for almost everything in this world.
- Simplified Header [15]: In IPv6's header all the unnecessary information is moved to end of the header and used as an option. Wherein in case of IPv4 header the information is tied to the header. In this way, IPv6 header is more simplified and can be compressible.
- End-to-end Connectivity: Every system now has a unique IP address and can traverse through the Internet without using NAT or other translating components. After IPv6 is fully implemented, every host can directly reach other hosts on the Internet, with some limitations involved like Firewall, organization policies, etc.
- Auto-configuration [17]: IPv6 supports both stateful and stateless auto configuration mode of its host devices. This way, the absence of a DHCP server does not put a halt on inter segment communication.
- IPSec [18]: An optional feature of providing IPsec security is included in IPv6 which makes it more secure than IPv4.
- Anycast Support: In this mode, multiple interfaces over the Internet are assigned same Anycast IP address. Routers, while routing, send the packet to the nearest destination.
- Mobility [19]: IPv6 was designed keeping mobility in mind. This feature enables hosts (such as mobile phone) to roam around in a different geographical area and remain connected with the same IP address. The mobility feature of IPv6 takes advantage of auto IP configuration and Extension headers.

Z. Jun et al., [20] explained how IPv6 is could be a key enabling factor in IoT and

suitable for wireless sensor networks.

   (a) Enormous address space of IPv6 can cater every device.

   (b) Mobile IPv6 avoids triangulation and can be as efficient as normal IPv6.

   (c) Internet protocol security (IPsec) is mandatory in IPv6 which can satisfy security requirement.

   (d) Neighbor discovery meets the need of WSNs such as router discovery, parameter discovery, and address auto configuration.

   Z. Jun et al., [20] also proposes an improved, simplified IPv6 addressing scheme for addressing formats in intra-WSN communication. The full version of IPv6 address is as long as 128 bits, and the data payload in WSNs is quite small. Processing an address with full IPv6 addressing would be a big hit in the performance of WSNs thus compressing the control section is of great importance for energy. The author explained the use of IPv6 prefixes in a sensor node. Often WSNs adopts prefix 001(2000::/3) which is not suitable for WSNs as computer networks often utilize it. Author proposed prefix 0100::/8 as a new address section of WSNs. There are techniques available which compress the IPv6 address inside a WSNs networks and added to data packets when packets are directed to an external IPv6 network. One such technique is 6LoWPAN which provides IPv6 networking over IEEE 802.15.4.

2. IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN)

   6LoWPAN is an open standard defined in RFC-6282[21] by the Internet Engineering Task Force (IETF). It introduces an adaption layer between network and link layer and enables the efficient transfer of IPv6 data packets by reducing the IP overheads. 6LoWPAN works on the principle of stateless compression to elide adaptation network, and transport-layer header fields, compressing all three layers down to a few bytes. The adaptation layer has three primary elements mentioned below.

   (a) Header compression

(b) Fragmentation

(c) Layer two forwarding

W. hui et al.[22] describes the 6LoWPAN header arrangements; it uses header stacking to keep orthogonal concepts separate and enforce a clear method for expressing its capabilities. 6LoWPAN also provides support for Mesh under and Route over routing. In the former routing method network stack has no role in routing instead, the adaptation layer masks the lack of a full broadcast at the physical level by transparently routing and forwarding packets within the LoWPAN. In route over routing is done at the IP layer, with each node serving as an IP router.

Figure 2.9 shows the network architecture of 6LoWPAN including IPv6 network. The 6LoWPAN network is connected to the IPv6 network using an edge router and typically operate on the edge, acting as stub networks. The edge router handles three actions:

(a) The data exchange between 6LoWPAN devices and the Internet (or other IPv6 network).

(b) Local data exchange between devices inside the 6LoWPAN.

(c) The generation and maintenance of the radio subnet (the 6LoWPAN network).

Two other device types are included in a typical 6LoWPAN network: routers and hosts. Router do the work of routing data between the nodes in the 6LoWPAN network and hosts are the end devices and are not capable of routing data in the network. A host could be low powered devices which wake up periodically to check its parent for data.

2.3.4 Link Layer

1. Bluetooth Low Energy (BLE)

[13]http://www.ti.com/lit/wp/swry013/swry013.pdf

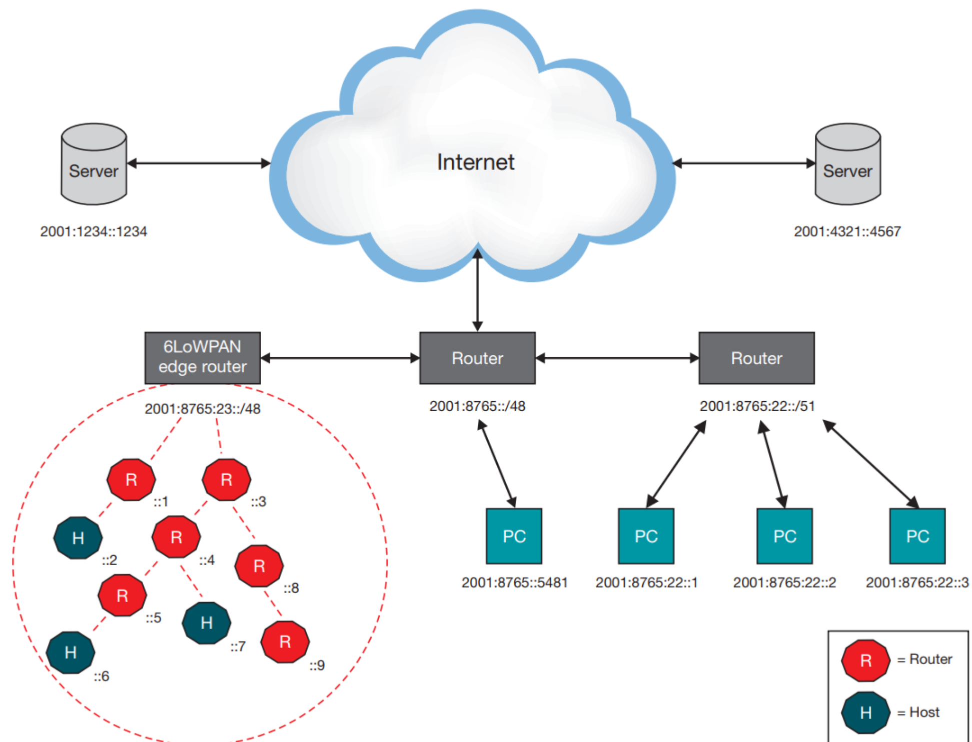


Figure 2.9: 6LoWPAN Network Architecture [13]

Bluetooth Low Energy (BLE), also referred to a Bluetooth Smart is the Bluetooth 4.0 core specification. The widespread use of BLE makes it a perfect choice to enable networking solution on Internet of thing devices. BLE is particularly designed for short range communication and monitoring applications that are expected to be incorporated into billions of devices in the next few years [24]. Bluetooth low energy is not backward compatible to the classic Bluetooth as it was designed to provide low cost, low bandwidth, low power and less complex radio standard. Since BLE is rapidly adopted in the smartphone, this gives an opportunity for a number of BLE based use cases in areas such as healthcare, consumer electronics, smart energy, and security. Furthermore, the power efficiency of BLE is considered to be a key factor which makes the BLE to be preferred choice compared to its competitors like Wi-Fi, Zigbee[3], etc.

Bluetooth protocol stack consists of two main components: The Controller and

the Host [25]. The controller takes care of physical layer and link layer of BLE stack and is typically implemented in the form of System-on-a-Chip (SoC) with an integrated radio. The host runs on application processor and includes application-level functionality. Graphics in figure 2.10 shows the BLE protocol stack and a short description of all the layers is mentioned below:

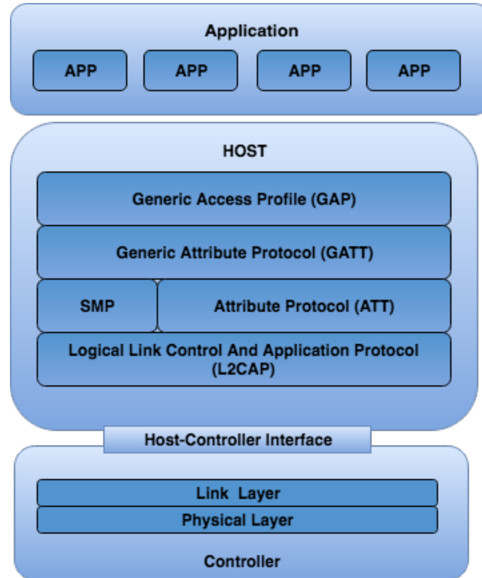


Figure 2.10: Bluetooth Low Energy Stack [24]

(a) Attribute Protocol (ATT): The ATT defines the communication between two devices playing server and client role. The server maintains a set of attributes which stores the information managed by GATT protocol. The client and server role is defined by GATT and does not relate to the role of central and peripheral. The client sends out the request to access the attribute on the server. The server responds back to the client. in terms of notification and indication messages.

(b) Generic ATT (GATT): The GATT defines the framework that uses the ATT for discovery services and exchange of characteristic from one device to another. A characteristic is defined as a set of data which includes a value and properties. The data related to services and characteristics are stored in attributes

(c) Generic Access Profile (GAP): Defines the device role, modes, and procedure for device discovery and services.

(d) Logical Link Control and Adaptation Layer Protocol (L2CAP): the primary function of L2CAP is to multiplex the data of three higher layer protocol, ATT, SMP and Link layer control signaling.

Communication between host and controller takes place using a host controller interface (HCI). BLE defines four roles in its topology which are broadcaster, observer, peripheral and central.

(a) Broadcaster: transmits data known as advertising packets. Devices like beacons and sensors cannot connect to the broadcaster during the advertisement. The purpose is to let other devices know of its presence.

(b) Observers: These are receivers which can receive advertising packets from broadcasters and peripheral devices.

(c) Peripherals: These are devices that connect in a slave role. The broadcaster will first broadcast their presence so that the central device knows of its existence and then chose to connect with the device.

(d) Central: These are sophisticated devices and support multiple connections. It initiates connections to peripherals. This device can be central and peripherals at the same time.

2. IEEE 802.15.4

IEEE 802.15.4 is a standard defined and maintained by IEEE 802.15 working group[14]. IEEE 802.15.4 specifies the operation of low-rate wireless personal area network. The standard was initially specified in 2003 but superseded by the publication of IEEE 802.15.4-2006 standard[15]. The standards specify the physical layer and mac

[14]http://www.ieee802.org/15/
[15]http://www.ieee802.org/15/pub/TG4.html

layer of LR-WPANs with a focus on resource efficient communication between devices. The emphasis is on resource constrained devices with a little cost of communication. It provides a connection with a range of 10 meters and transfer rate of 250 kbit/s. The figure 2.11 shows the protocol stack of IEEE 802.15.4. As shown in figure IEEE 802.15.4 defines the lower layers of the protocol stack. A brief explanation of each layer is mentioned below.

(a) Physical (PHY) Layer: This is the lowest layer in the stack and concerned for physical transmission on underlying radio and exchanging data bits with MAC layer. More specifically PHY layer is responsible for

- Channel assessment
- Bit-level communications

(b) Medium Access Control (MAC) Layer: This layer resides on top of PHY layer and uses the services of PHY layer. Responsibilities of this layer include the following.

- Services for registering and deregistering the device in the network.
- Access control to the shared channels
- Guaranteed time slot management
- Beacon generation.

Standards like Zigbee[3], WirelessHART[16], and Thread[17] extends the stack further and defines the upper layers of the protocol stack. IEEE 802.15.4 can be used with 6LoWPAN to determine the upper layer of protocol stack and provide IPv6 connectivity capabilities over WPANs.

[16]https://en.wikipedia.org/wiki/WirelessHART
[17]https://threadgroup.org/

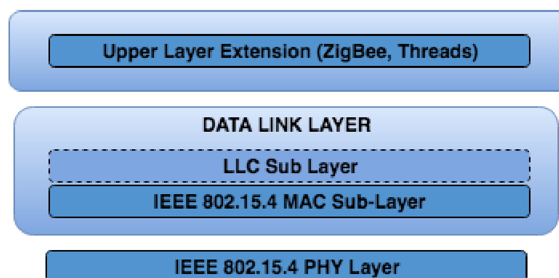


Figure 2.11: IEEE 802.15.4 Software Stack Architecture

2.3.5 Device Management

In a majority of scenarios, remote deployment model is preferred in IoT. Operators can't expect the end users to perform any troubleshoot or management operation (such as firmware updates) on remotely deployed IoT devices. For a seamless integration of connected devices, the network of wireless sensors should be controlled by a remote management server which should take care of device control and firmware updates.

S. K. Datta et al., [30] proposes an M2M device management framework that can address the challenge of managing the fleet of connected M2M devices. The architecture proposed by the authors follows the specification of open mobile alliance lightweight machine to machine (OMA LwM2M). It also adheres the CoRE link format [32] to represent the M2M device and their endpoints using resource types and attributes. The framework follows a lightweight description of M2M devices which is the key to implement an efficient and scalable design.

The framework is divided into four layers namely: Perception layer, Proxy layer, Configuration Storage layer and Service Enablement layer. Each layer performs a dedicated set of functionality to bootstrap and manage the smart and legacy device. In the initialization phase devices are registered with configuration storage database using configuration

REST APIs. Based on the requirements access control can be established in Service Enablement layer to provide access to defined user and defined devices. The integration is done in such a way that M2M device management framework can be deployed in a cloud system, M2M gateway or even inside a mobile application. Figure 2.12 depicts the M2M device management framework and illustrates the concept defined by S. K. Datta et al. Section 3.3 discuss more about the design and specification of LwM2M and firmware update object.

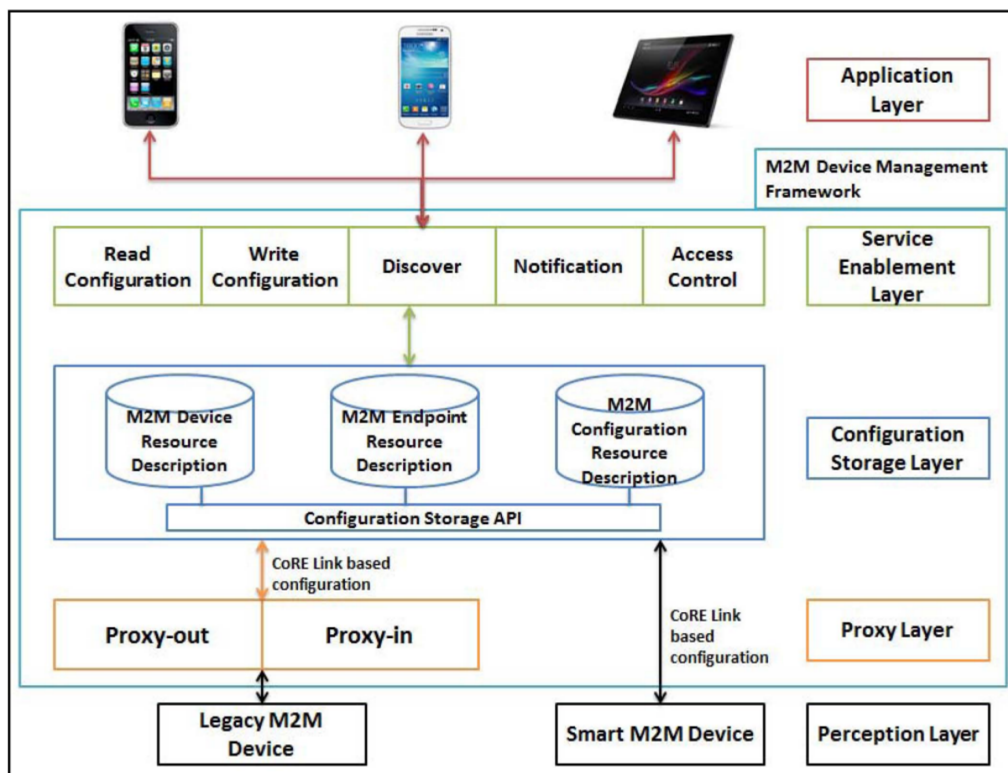


Figure 2.12: M2M device management framework [30].

2.3.6 Security

Security is a very open and key research area in IoT. S. L. Keoh et al., [33] provides a review of standardization effort made by IETF to standardize the security solution for IoT ecosystem. Firmware update in a sensor network contains three layers, Firmware update repository, Communication channel and Target Device. Two types of attacks are

considered in remote firmware updates (i) Attack on the untrusted communication channel to access the firmware image while data transport phase (ii) Attack on target device during firmware loading phase. Both attacks have similar capabilities to perform either passive (eavesdropping) or active (man-in-the-middle) attacks during firmware transport and loading phase. Remote management of sensor nodes would require communication with each node in the sensor network. CoAP which runs on UDP is a preferred choice concerning communication medium. DTLS is a prime consideration to secure the communication channel. DTLS is considered to be a complete security protocol which provides authentication, key exchange, and protection of application data. DTLS provides end to end secure session between two communicating devices in our case one inside the sensor network, and other is remote management server [33].

BLE devices are low powered and designed to run several years on a single coin cell battery. The area of the firmware update is open for vulnerabilities and attack. For a secure firmware update, it is needed to establish the authenticity of data originated from the firmware build server. The conventional way of encrypting the data with asymmetric key cryptography (Digital Signature) would not be suitable for the type of devices in consideration due to its low computational resource. Use of symmetric key cryptography would be more appropriate for such devices. A hash function with the combination of Message authentication code (MAC) could be used to establish the data integrity and authenticity of firmware update. Working with symmetric key cryptography, there is a need to ensure the safety of secure MAC key.

2.4 IPv6 Over BLE

Seeing, the widespread usage of BLE and projection of a billion BLE based device in near future, IETF 6LoWPAN WG standardized RFC-7668 [26] to provide end to end IP connectivity over BLE. RFC-7668 allows the transportation of IPv6 packets over Bluetooth low energy. Work done by J. Nieminen et al. [24] focuses on the enablement of

Bluetooth low energy in low powered sensor nodes and connecting these small devices with the Internet. Figure 2.13 shows the IPv6 over BLE stack proposed by RFC-7668 and implemented by J. Nieminen et al.

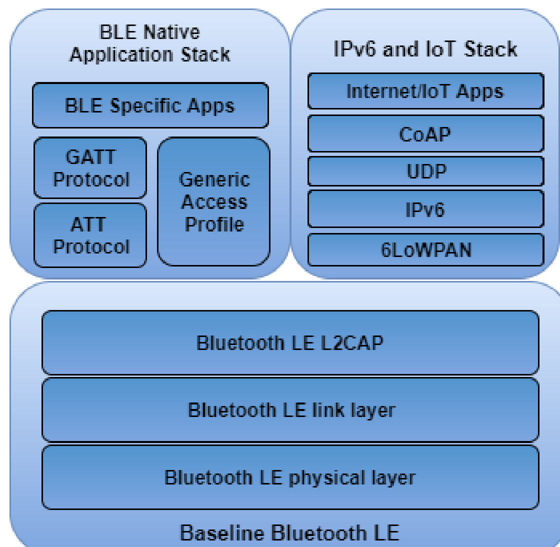


Figure 2.13: Communication Stack for IPv6 over BLE [24]

Authors presented the practical implementation of RFC-7668 (When this paper was written, RFC-7668 was in draft phase) and evaluation of its implementation. IPv6 is not directly supported over BLE, in this implementation author modifies the already implemented 6LoWPAN adaptation layer to work with BLE. Natively 6LoWPAN is designed to work with IEEE 802.15.4 standard [21], additional work done by the authors allowed the modification of 6LoWPAN stack and made it compatible with BLE layer. The author described various feature (fragmentation, header compression, and neighbor discovery) provided by 6LoWPAN in context of IEEE 802.15.4 and also talked about enabling these features in the context of BLE. As shown in figure 2.14, RFC-7668 advocates a star based topology to connect multiple BLE peripherals with a central BLE device. The central device will act as 6LBR (Border router/Gateway) as the specified topology is start based, so there is no scope is 6LR routers as in 6LoWPAN implementation in the context of IEEE 802.15.4. Further work has been identified as an action item to support mesh networking in IPv6 over BLE implementation. At present [27] provides the draft version of the

standardization work for the support mesh networking in IPv6 over BLE implementation.

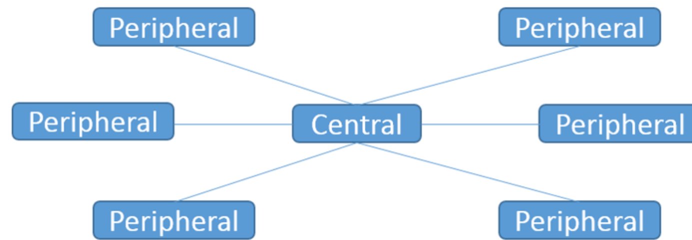


Figure 2.14: Star Topology of Bluetooth Connected Device [26]

2.5 Firmware update for Constrained Devices

This section contains the current research and solutions for firmware updates in sensor networks which is the core of this dissertation. The present state of the art spreads in different software update functionality such as: Modular updates [38], Image based updates [34], Incremental update [35]. This section also focused on fail safe techniques and error recovery [36] in case of failure in software updates.

The survey provided by S. Brown, and C.J. Sreenan [34] covers a large number of different solutions available for WSNs software updates. It is needed that software upgrades and maintenance of WSNs should be automatic without the need of manually reaching to every sensor. Working with the wireless low powered sensors uncovers major challenges regarding energy consumption, reliability, and most importantly security. Over the period the functional requirements of WSNs changed/extended. S. Brown, and C.J. Sreenan [34] provides an exhaustive list of the technical requirement.

- Need for dynamic Modification
- Need for heterogeneous node support
- Integration of new software in the running system

- Update should be reliable and reach all nodes
- Handling packet loss in context of software data dissemination in WSNs
- Special boot loader to provide support for fall back.
- Control mechanism for overall management of WSNs

The author also presented functional requirement from energy efficiency point of view. In energy reduction context techniques such as differential, modular updates are focused which ultimately reduce the traffic load. As a result, less energy consumption. Figure 2.15 shows the architecture and components of an autonomous firmware update system.

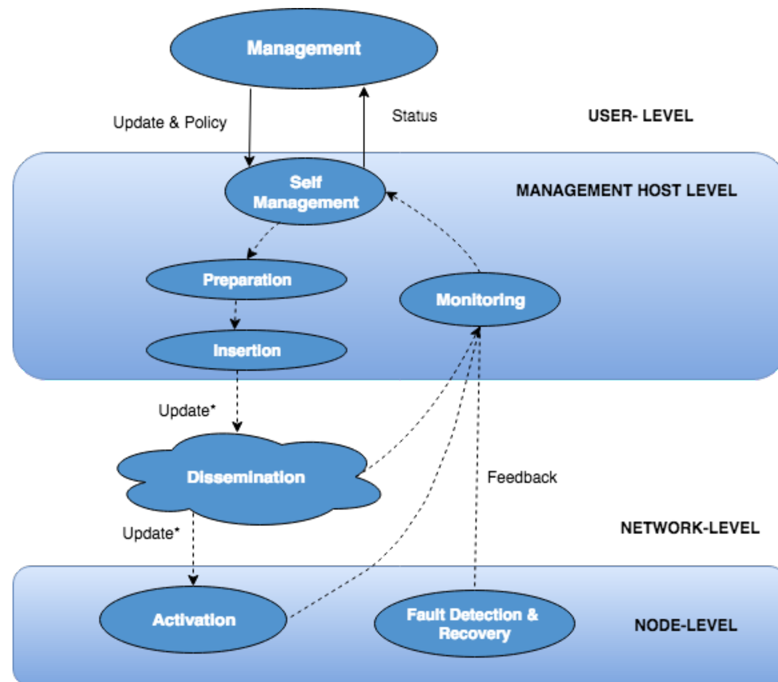


Figure 2.15: Architecture for Autonomous update [34]

M. Stolikj et al., [35] presented his work for efficient reprogramming of wireless sensor networks using the data compression techniques and incremental updates. Author exploited the fact that energy used by the processor is significantly less than wireless radio. The author emphasizes on applying data compression method to a software update in combination with any incremental update algorithm. These two approaches, could lead

to a significant reduction in energy consumption and resource usage. The author analyzed various other solution such as Contiki, Mate, OSAS, and Zephyr. Out of all only Zephyr works on principles of incremental updates and all other works on modular and Virtual machines methodology respectively.

B. Porter et al., [38] proposed a modular upgrade approach and presented Lorien which is a type-safe modular OS. Lorien is written in a minimal component oriented extension of C programming language and provides strongly modeled components for strong typing of software components. Explicit use of constructors and destructors make the dynamic component instantiation. The overall software configurations (list of modules) are represented as a collection of pre-component-instance configuration fragments that are held in a system manifest in program memory.

S. Unterschtz et al., [36] addresses the problem of error-prone software updates which can disable the update functionality on a sensor node. For a fail safe software updated author divided firmware deployment process into four sections.

1. Firmware Separation
    - Splitting the firmware image into segments and packets and transferring over the allowed limit of low powered devices such as 100 bytes for IEEE 802.15.4.
    - Maintaining a bit vector to store the status of segments and needed retransmissions.
2. Dissemination
    - A central server will control the dissemination process and based on requirement central server will contact selected nodes only instead of flooding the whole network.
3. Forward Error Correction
    - Getting acknowledgment of each received packet will flood the network. To

avoid this reed solom coding is used in which for each M packets, extra k redundant packets.

4. Boot loader and error recovery

    - Author emphasizes on the necessity of watch dog timer and locking the boot loader so that it cant be modified through software updates. Boot loader should be carefully tested at the time of deployment

We reviewed state of the art for the firmware update in IoT devices. Present work is related to energy efficient techniques and error detection mechanisms. At the best of our knowledge, there is no implementation exist which provide an end to end firmware management system for IoT devices.

2.6 A survey on IoT platforms

Traditional operating system (Windows/Unix) and RTOS does not match with the requirement of small scale IoT device. An operating system for IoT should support the protocol stack defined in section 2.3. In recent years numerous open source and proprietary IoT operating has been rolled out. Work done by O. Hahm, et al. [28] and P. Gaur, et al. [29] provides a discussion on the required features for an IoT OS and a survey of current IoT operating system. Ideally, an IoT operating system should comprise of following feature to support small IoT devices [28].

1. Architecture
2. Programming Model
3. Scheduling
4. Small Memory Footprint
5. Support for Heterogeneous Hardware

6. Network Connectivity
7. Energy Efficiency
8. Real-Time Capabilities
9. Security

Table 2.1 provides a survey of IoT operating system in terms features mentioned above. The survey is partially based on the work done by O. Hahm, et al. [28] and extended further in terms of features and updated with the current development of compared IoT operating system.

In this survey, we have analyzed various OSs targeted for resource constrained IoT device. These devices are not capable to run traditional OS such as Linux. Generally, all the OSs targeted for IoT devices have supported the minimal IoT stack and protocols defined in section 2.3. We would also like to mention that in some cases the functionality presented by maintainers of a particular OS doesnt go well with the specification. Practically, while working with some of the OSs defined in the survey, we found broken support in terms of platform or feature support. It is understandable that these OSes are developing under open source contribution and project in OSS could take time to mature in terms of both features and documentation.

Name	License	Architecture	Programming Model	Scheduler	Protocol	Platform	Language	Memory
Contiki[a]	BSD	Monolithic	Protothreads and events	Cooperative	LwM2M, MQTT, 6lowpan, RPL, CoAP, TLS, DTLS, Bluetooth, Bluetooth Low Energy	TI CC2538, nRF52832, TI MSP430x, Atmel AVR, Freescale MC1322x	C	10k RAM and 30k ROM
Zephyr [b]	Apache 2.0	Monolithic	Multi Threading	Cooperative and Preemptive	LwM2M, CoAP, HTTP, MQTT, Bluetooth, Bluetooth Low Energy, IEEE 802.15.4, 6LoWPAN, Wi-Fi, NFC	Arduino, Quark D200, CC2650, NXP FRDM, Hexiwear, nRF52, ST Nucleo	C	8K RAM
TinyOS[c]	BSD	Monolithic	Event Driven	Cooperative	Dissemination protocols: Drip, DIP, and DHV. Deluge, RPL and 6LoWPAN.	Imote2, Shimmer, IRIS, Telos Rev B, MicaZ, Mica2, Mica2dot, Mulle, TinyNode, Zolertia Z1, UCMote Mini	nesC	<1kB RAM and ROM >4KB
Mynewt[d]	Apache 2.0	Monolithic	Multi Threading	Preemptive	6lowpan, CoAP, TLS, DTLS, Bluetooth, Bluetooth Low Energy	nRF52840, nRF51 DK, BMD-300-EVAL-ES, STM32F4DISCOVERY, STM32-E407, Arduino Zero, Arduino Zero Pro, NUCLEO-F401RE, PIC32MX470, PIC32MZ2048EFG100	C	
RIOT[e]	LGPLv2	Microkernel	Multi Threading	Preemptive	6LoWPAN, IPv6, RPL, and UDP, CoAP, CBOR	Arduino-due, UDOO, CC2538DK, OpenMote, pca10005, yunjia-nrf51822, STM32 Nucleo32, telosb, chronos, Arduino Zero	C/C++	1.5kB RAM and 5kB ROM
FreeRTOS[f]	Modified GPL	Microkernel	Multi Threading	Preemptive		Altera, Atmel, Cortus, Freescale, Infineon, Microsemi, NXP, Renesas, TI, ST, Intel, Xilinx	C	<23K ROM FreeRTOS + Nabto
mbedOS[g]	Apache 2.0	Monolithic	Event Driven & Single Thread	Preemptive	Bluetooth LE, 6LoWPAN Sub-GHz Mesh, NFC, Threads, RFID, Wi-Fi , LoRa LPWAN, Ethernet, Cellular	Nordic nRF52DK, Seeed Arch Link, Realtek RT8195AM, Wizwiki, EFM32, NUCLEO F334R8, hexiwear, mbuino, mbedLPC	C/C++	2.5K RAM and 8K ROM

Table 2.1: A survey of IoT OS

[q]http://www.contiki-os.org/
[q]https://www.zephyrproject.org/
[q]https://github.com/tinyos/tinyos-main
[q]https://mynewt.apache.org/
[q]https://riot-os.org/
[q]http://www.freertos.org/FreeRTOS-Plus/Nabto/Nabto.shtml
[q]https://www.mbed.com/en/

Chapter 3

Design

So far we established state of the art for IoT protocol stack and firmware upgrade mechanism. In the current state of the art, there exist no end to end firmware upgrade framework to remotely manage the device control and firmware upgrade on BLE devices. The goal of this dissertation is to implement an end to end firmware upgrade framework which adheres the standards specified by the standardization body.

3.1 Requirement

To design the required firmware upgrade mechanism, a number of requirements have identified and mentioned below.

1. A remote management system should manage firmware upgrade and device control.
2. Use of standardized and widely accepted application layer protocol to transfer the firmware image from firmware management server to IoT device.
3. Use of IPv6 over BLE [24] as a transport layer protocol to transport firmware blocks.
4. Firmware integrity and validity check before switching to a new firmware.
5. A bootloader capable enough to execute new firmware when instructed.

The above-specified requirements are identified in such a way that each layer of protocol stack should follow the standard protocols, and overall implementation should be compatible and adheres defined standards.

3.2 System Architecture

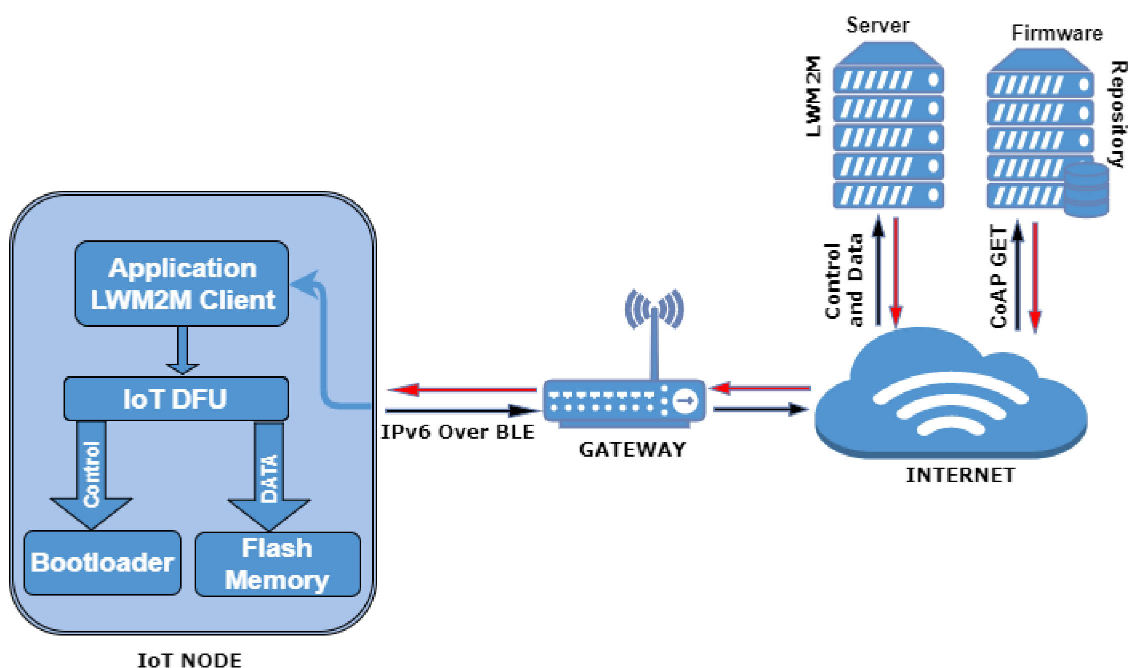


Figure 3.1: System Architecture

Figure 3.1 depicts the framework upgrade system architecture. The system contains three main components defined below.

1. LwM2M Server: This will act as a device management server which controls the device and provides the firmware management resources to the IoT device. The management server should follow the specifications given by OMA-LwM2M standard [31].

2. Firmware Repository: This will act as a server hosting a firmware repository and the expectation is that this server merely serves as a separate file server making

firmware images available to LwM2M Clients. The server should support a CoAP server implementing block-wise transfer. LwM2M management server provides the URI of firmware storage server to the IoT device.

3. Gateway: an Intermediary device which will forward the communication from device to firmware management server or vice-versa.

4. IoT device: Small resource constrained device which will act as an end point. The device will be having an LwM2M client implementation to communicate with LwM2M server. As shown in the figure 3.1 device should also have enough capability to store the new firmware into flash memory.

3.3 OMA Lightweight M2M

The sections provide the details about the device control specification given by OMA Lightweight M2M (LwM2M)[31] and further extends to a discussion on firmware update specifications. The OMA Lightweight M2M (LwM2M) defines service architecture for IoT devices and the protocol for device management. Graphics in figure 3.2 presents the application layer communication between a LwM2M server and a LwM2M client, which is present in the LwM2M device. The architecture shows the use of CoAP and SMS binding with Datagram transport layer security (DTLS) as a UDP transport layer security. LwM2M supports four interfaces between a device and server.

1. Bootstrap: Interface is used to provide required information to the LwM2M Client to enable the LwM2M Client to perform "Register" with one or more LwM2M Servers.

2. Client Registration: Interface is used by a LwM2M Client to register with one or more LwM2M Servers, maintain each registration and de-register from a LwM2M Server.

3. Device Management and Service Enablement: Interface is used by the LwM2M server to access object instances and resources available from a registered LwM2M Client. The interface provides this access through the use of “Create”, “Read”, “Write”, “Delete”, “Execute”, “Write-Attributes”, or “Discover” operations.

4. Information Reporting: Interface is used by a LwM2M server to observe any changes in a resource on a registered LwM2M client, receiving notifications when new values are available.

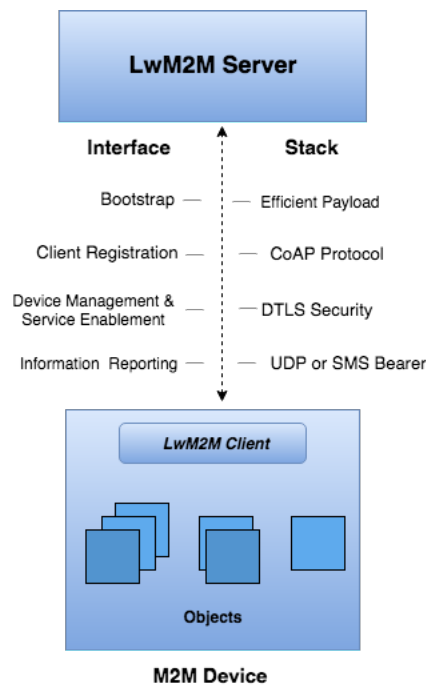


Figure 3.2: LwM2M Architecture [31]

Version 1.0 of LwM2M the specification [31] defines the following list of the object as part of core technical specification.

0. Security Object

1. Server Object

2. Access Control Object

3. Device Object
4. Connectivity Monitoring Object
5. Firmware Update Object
6. Location Object
7. Connectivity Statistics Object

3.3.1 LwM2M Firmware Upgrade Mechanism

Object 5 of LwM2M core technical specification enables firmware management on IoT device. This Object includes installing firmware package, updating the firmware, and performing actions after updating the firmware. The specification allows a version 1.0 complaint LwM2M client to connect with any LwM2M version 1.0 compliant server to upgrade the firmware using the object and resource structure defined by the technical specification. Table B.1 gives the details regarding LwM2M firmware object and its access method. The firmware object further breaks down into the resources associated with it. The specification [31] specifies nine resources related to firmware object. Table B.3 gives a detailed explanation of firmware resource with the allowed values associated with it.

Figure 3.3 depicts the state diagram specified by OMA-LwM2M specification [31] for firmware upgrade mechanism. The state diagram consists of possible states shown in rounded rectangles and their transition condition. The graphics also depicts the assertion and variable assignment. Variable "Update Result" signifies the error condition during firmware update process. "state" variable defines the current state of the system. Table B.3 defines all the possible outcome of resources associated with firmware upgrade object.

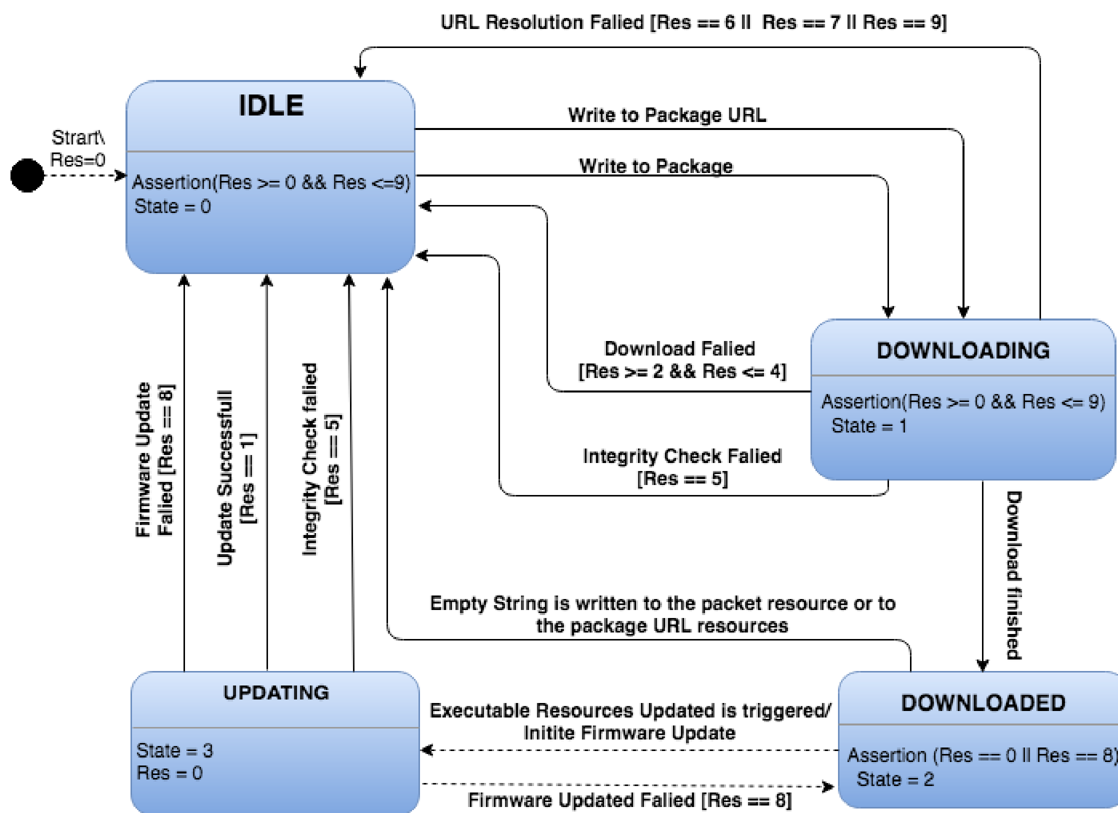


Figure 3.3: Firmware Update Mechanism [31].

State Diagram Walkthrough

Use Case #1: Successful Firmware Update

Initially, the STATE of the system remains IDLE and LwM2M server writes the "Package URI" to IoT Device. IoT device establishes a connection with firmware repository identified by URI provided by LwM2M server and starts downloading the firmware image using CoAP block wise transfer. With the start of firmware download STATE of the system should change to "DOWNLOADING". The firmware download will finish with the reception of the last block of firmware and at this point, the STATE of the system should change to "DOWNLOADED". The system will update the new firmware upon the reception of "Update" resource from LwM2M server and STATE should change to "UPDATE". After the upgrade, the system should restart with new

firmware image and state of the system should change to “IDLE” and updates the result with ‘1’ (Successfully update).

Use Case #2: Failed Firmware Update

Initially, the STATE of the system remains IDLE and LwM2M server writes the “Package URI” to IoT Device. IoT device establishes a connection with firmware repository identified by URI provided by LwM2M server and starts downloading the firmware image using CoAP block wise transfer. With the start of firmware download STATE of the system should change to “DOWNLOADING”. The firmware download will finish with the reception of the last block of firmware and at this point, the STATE of the system should change to “DOWNLOADED”. The system will update the new firmware upon the reception of “Update” resource from LwM2M server and STATE should change to “UPDATE”. The system will match the CRC received from the header of firmware with the calculated CRC of the firmware image. In case of CRC mismatch, the system will raise an assertion and update the “update result” with ‘5’ (Integrity check failure).

The above discussion presented only one failure possibility. Similarly, in other failures, the result will be updated with the type of failure given in OMA LwM2M specification table B.3.

3.4 Firmware Transfer using CoAP Block Transfer

To avoid IP fragmentation, RFC-7959 [13] extends the specification of primary CoAP with a pair of “Block” option to transfer multiple blocks of information from a resource representation in multiple request-response pairs. Both the client and server have to mutually agree on the size of the block to transfer. In general, CoAP block-wise transfer is useful in case of firmware image transfer from firmware management server to IoT device. OMA-LwM2M specification [31] mandates the use of CoAP block-wise transfer to transport the firmware image.

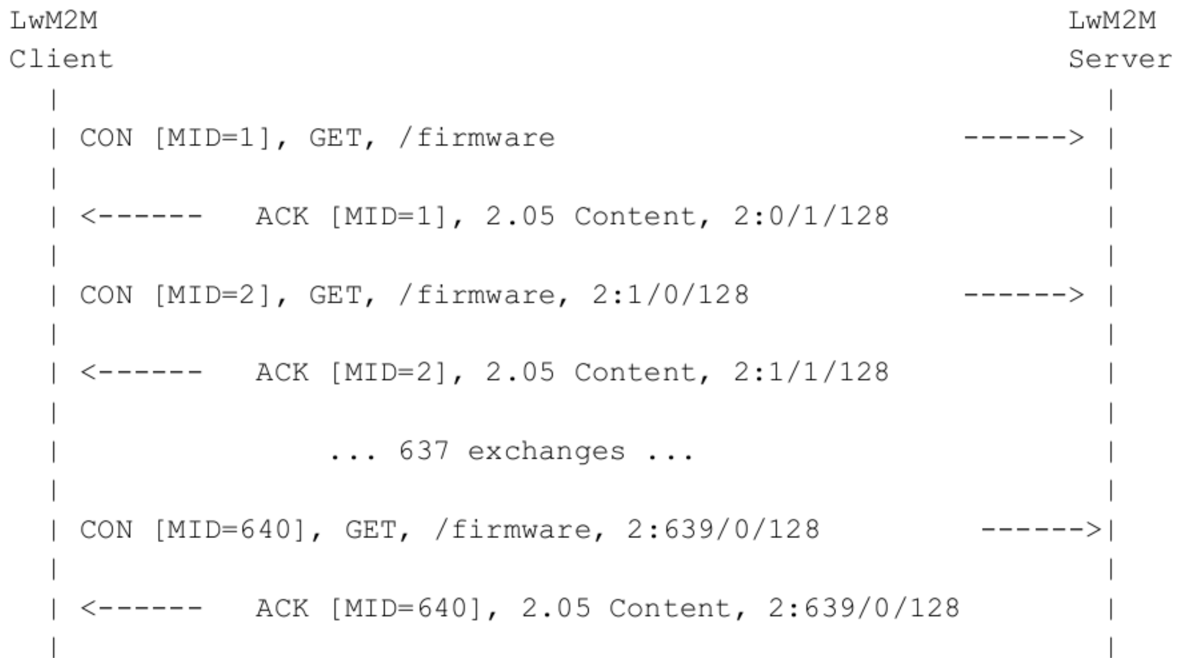


Figure 3.4: Example of client fetching firmware image [31].

The figure 3.4 shows the transfer of firmware image using CoAP block-wise transfer in a scenario where a package URI is provided to the client by LwM2M server and client fetches the firmware image from indicated firmware management server. In the example the both LwM2M client and server agreed on a block size of 128 bytes and the firmware image of 80 KiB (=81920 bytes) sent to the LwM2M Client in 640 messages with each 128 bytes payload.

3.5 Firmware Validation

Once the new firmware is completely received in the system, it is essential to check its validity. A faulty or erroneous firmware could make the system unusable after the update. S. Unterschtz, et al. in his work [36] emphasis on the importance of fail-safe over the air update and techniques to ensure system safety. In this implementation below defined methods have been used to ensure validity and integrity of new firmware.

1. Cyclic redundancy check (CRC): Used to perform firmware validation. CRC is an

error detecting algorithm used to detect changes in raw data.

2. Firmware Size: This can be used to validate the integrity of firmware.

The firmware image is extended with the meta data header which contains the server side calculated CRC value and Firmware image size. Once the firmware received at device side, these values can be matched with the values calculated from the received firmware. Figure 3.5 depicts the structure of final firmware with an extended header containing CRC value and Firmware size.

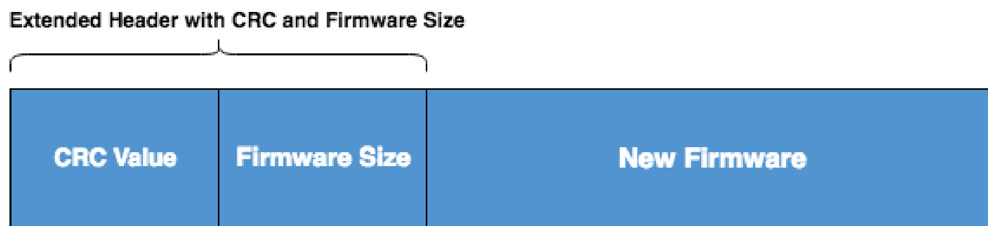


Figure 3.5: Firmware image with extended header containing.

Firmware validation would take place in "DOWNLOADED" state of firmware update state machine [31]. Any error in validation will be reported back to LwM2M server using "update result" resource of firmware upgrade object.

3.6 Flash Operation and Bootloader

The previous sections explained firmware validation and transfer mechanism of a firmware image from firmware management server to IoT device using CoAP block-wise transfer. Upon the reception in an IoT device, firmware blocks could be stored in two ways:

1. RAM Storage: The received blocks would be stored in RAM which is a volatile but faster memory.

2. Flash Storage: The received blocks would be stored in flash memory which is a nonvolatile but slower memory.

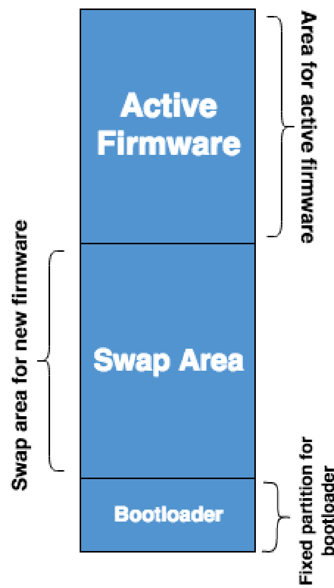


Figure 3.6: Flash bank with separate partition for new firmware.

The decision of storing the firmware depends on requirements and available resource of the system. In general, the capacity of the flash memory in a constrained device is more than RAM capacity. In this implementation, a hybrid approach is followed in which a number of firmware blocks first stored into RAM and then transferred in to flash memory. After completing the flash writing, the system will then ask for further blocks from firmware management server. As shown in figure 3.6 the system works on a dual bank approach where the new firmware would be flashed into a separate memory region in flash memory which doesn't impact the area where the current firmware is stored. From the firmware update perspective the work of the bootloader is to verify the firmware image and when instructed write the new firmware image from swap partition to active firmware area.

3.7 High Level Design

This section describes the high-level design for firmware update flow adhering the specification of LwM2M mentioned in section 3.3.1. Logically the system is divided into three parts mentioned below

1. LwM2M Client
2. Firmware Download Process
3. Firmware Upgrade Process

Upon system start, the application will wait for firmware update request from the LwM2M server and maintains the state of the system accordingly. The flow diagram in figure 3.7 describes the interaction among the LwM2M client, firmware download process, and firmware update process. The design adheres the state machine specification given by LwM2M in section 3.3.1 maintains the state of the system at any given point of time.

LwM2M Client

The LwM2M client receives the request from LwM2M server. The communication takes place using CoAP application layer protocol. Each request is in the form of CoAP URI "/Object/Instance/Resource" followed by a CoAP CRUD operation. It is the responsibility of the client to forward the request to appropriate object type with the data payload. Graphics in figure 3.8 depicts the structure of an LwM2M request. The state of the system will remains "IDLE" in this region of control flow.

Firmware Download Process

After the reception of firmware update request from LwM2M server, the LwM2M client invokes the "Firmware Download Process." The firmware download process changes the state of the system to "DOWNLOADING" and initiate a CoAP GET request to the

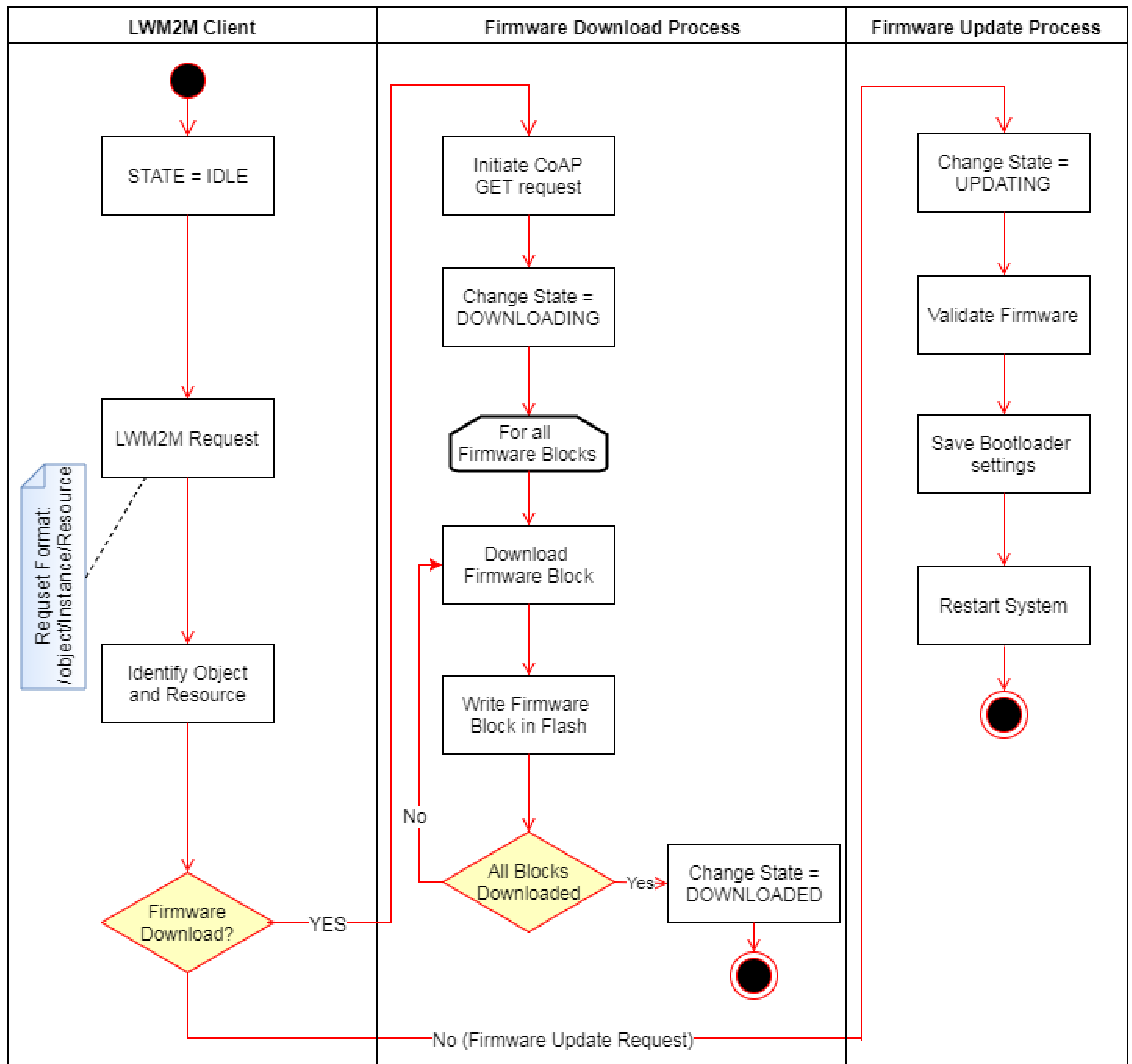


Figure 3.7: High Level Software Design

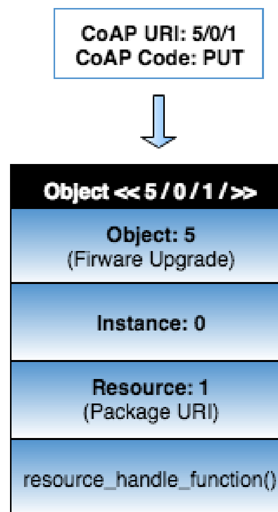


Figure 3.8: LwM2M Request Format

package URI received from the LwM2M client. At the first practical opportunity, this process downloads the firmware blocks and save it into the flash memory. The details of firmware block storage are mentioned in further sections. Once it receives all the firmware blocks, it changes the state of the system to "DOWNLOADED" and finish the process.

Firmware Update Process

In firmware upgrade specification, LwM2M defined "Update" resource (Table B.3) to upgrade the firmware package stored into flash memory in firmware download phase. This resource becomes executable only if the state of the system is "Downloaded." In this phase, firmware update process changes the state of the system to "Updating" and validates the firmware using CRC matching technique mentioned in section 3.5. The process asserts the client and updates the results as CRC error if validation gets failed otherwise it proceeds to save the boot loader settings and restarts the system.

Chapter 4

Prototype Implementation and Evaluation

4.1 Introduction

This chapter will provide a detail description of the firmware upgrade framework implementation. It includes the discussion on hardware platform used, choice of software platform along with the implementation of end to end firmware update software.

4.2 Requirement

4.2.1 Hardware Platform

Nordic Semiconductor nRF52 (nRF52832)

Nordic semiconductor's nRF52 (nRF52832)[1] is chosen as the hardware platform for this prototype due to following reason.

1. Low-cost BLE device.

2. Support for IPv6 over BLE which is the core requirement of this dissertation

[1]https://www.nordicsemi.com/eng/Products/Bluetooth-low-energy/nRF52-DK

3. Widely supported by open source RTOS such as Contiki[2], Zephyr[3].

4. Software development kit with ready made examples for the supported feature.

5. Debugging support using SEGGER Jlink toolchain[4].

Bluetooth CSR 4.0 Dongle

Bluetooth CSR 4.0 is a USB dongle which supports Bluetooth V4.0 specifications. The dongle is used to provide Bluetooth capability to a Ubuntu based server which is mentioned in next section. It has dual-mode capability and support with both Bluetooth and Bluetooth low energy. It can deliver up to 3Mbps data rate with a range of 20 meters.

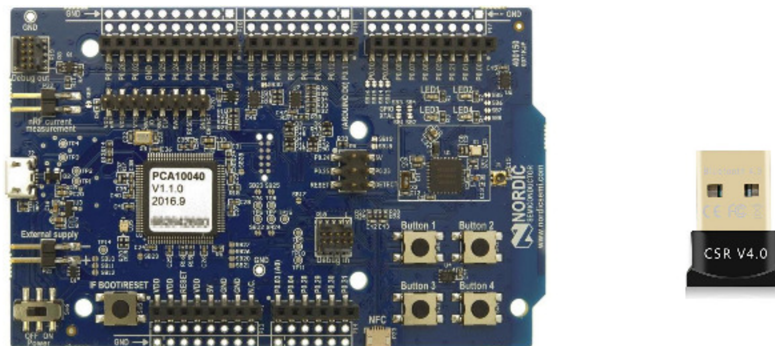


Figure 4.1: nRF52 Soc and CSR Bluetooth V4.0 Dongle.

Ubuntu based server

A Ubuntu Linux distribution version 17.04 based server is used for the following reason

1. To provide BLE connectivity to IoT device using BLE dongle.

2. To host LwM2M server for device management.

---

[2] http://www.contiki-os.org/
[3] https://www.zephyrproject.org/
[4] https://www.segger.com/products/debug-probes/j-link/

3. To host CoAP based firmware server which reads the firmware image and transfer block by block to IoT device.

4.2.2 Software Platform

Contiki operating system

Contiki [5] is an open source lightweight operating system specifically designed for Internet of Things. It connects low powered, resource constrained IoT devices to the Internet. A. Dunkels et al., [40] explained Contiki is built around an event-driven kernel but provides optional pre-emptive multithreading that can be applied to individual processes. It supports dynamic loading and replacement of different programs and services. The author described for an operating system designer primary challenge lies in finding lightweight mechanisms and abstractions that provide a rich enough execution environment while staying within the limitations of the constrained devices. Contiki is implemented in the C language and has been ported to a number of micro controller architectures, including Nordic Semiconductor nRF52 series, Texas Instruments MSP430, Atmel AVR and much more. Contiki can load and unload individual applications or services at run-time so an incremental technique could be used to save transmission data and bandwidth. Figure 4.2 depicts the Contiki network stack and its corresponding implementation.
Contiki provides a dynamic structure which allows programs and drivers to be replaced during runtime and without relinking. The kernel consists of a lightweight event scheduler that dispatches events to running processes and periodically calls process polling handlers[40]. Contiki kernel supports two kinds of events: asynchronous and synchronous events, and it only provides the most basic CPU multiplexing and event handling features. The rest of the system is implemented as system libraries that are optionally linked with programs. The communication stack is implemented as a service

[5] http://www.contiki-os.org/
[6] http://anrg.usc.edu/contiki

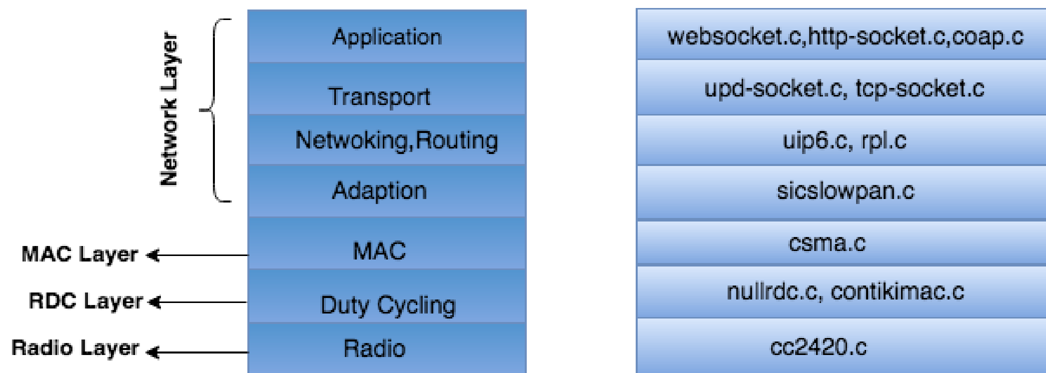


Figure 4.2: Contiki Network Stack.[6]

to enable run-time replacement.

Nordic IoT SDK

The nRF5 IoT SDK [7] is an IPv6 capable Bluetooth low energy software stacks that enable nRF5 series devices to connect and communicate directly to cloud services and other devices over the IP-based network using Bluetooth low energy. It includes an IPv6 over Bluetooth low energy adaptation layer (6LoWPAN) and a complete Internet Protocol Suite including IPv6, ICMP, UDP, TCP, DTLS, TLS, CoAP, and MQTT. It provides the support of required features in the form of drivers, libraries, examples, and APIs which makes it general purpose tool for getting started with IoT. IPv6 addresses are assigned to all IoT devices, and the BLE link is used to transmit the IPv6 packages. The graphic in figure 4.3 shows the IoT devices that are connected to the Internet through BLE enabled router.

[7] https://www.nordicsemi.com/eng/Products/Bluetooth-low-energy/nRF5-SDK-for-IoT

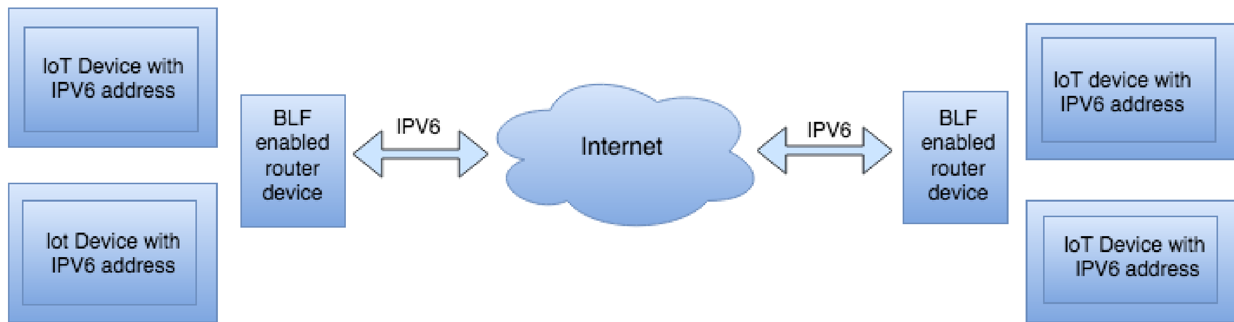


Figure 4.3: BLE enabled IoT Network.[8]

The SDK also included various examples for configuring nR52 devices as a Bluetooth low energy 6LoWPAN node and configuring it with the above transport layer (UDP and TCP) with security (DTLS and TLS), to the application layer CoAP, MQTT, and LwM2M. Figure 4.4 depicts the protocol stack of Nordic IoT SDK which is required to route IPv6 packets to and from IoT devices.

Layer			
Application Layer	CoAP	MQTT	
Transport Layer	UDP	TCP	
Network Layer	IPv6	ICMPv6	RPL
Adaptation Layer	BLE 6LoWPAN		
Physical And Link Layer	IPSP		
	Application Programming Interface (API)		
	SoftDevice		

Figure 4.4: Protocol stack of Nordic IoT SDK.footnotemark[8]

SoftDevices are precompiled, pre-linked libraries that can be programmed into Nordic nRF series devices. It is an abstraction layer for the BLE radio and lets the application integrate with lower layer radio technology. The SoftDevice provide the facility to develop application code as ARM Cortex-M0 project and access the toolchain of ARM

[8] http://infocenter.nordicsemi.com

Cortex-M0 for application development. The examples given in NRF IoT SDK requires a modified SoftDevice. "S1xx_iot"[9] supports L2CAP Connection Oriented Channels, which is needed for transport of IP packets.
The APIs exposed by SoftDevice is composed of C function which makes the application completely independent of compiler and linker[8]. The APIs are based on SuperVisor Calls (SVC) and defined in a set of a header file. In ARM architecture SVCs are software triggered interrupts and in Nordic's implementation SVCs conforms to a standard procedure call and allows parameter passing and return values. By calling a Softdevice API, triggers an SVC interrupt which in turn calls the SVC interrupt handler. The application compiles without any function address information at compile time and this removes the application linking dependency with the SoftDevice. The header files contain all information required for the application to invoke the API functions. This SVC interface makes SoftDevice API calls thread-safe.

ARM GNU Toolchain

The GNU Embedded Toolchain [10] for ARM is a collection of packages featuring ARM Embedded GCC compiler, binutils, GNU debugger (GDB) and other GNU libraries necessary for bare-metal software development. It is a ready-to-use, open source suite of tools for C, C++, and Assembly programming targeting devices based on the ARM Cortex-M and Cortex-R processors. Based on Free Software Foundation's (FSF) GNU Open source tools and newlib, these toolchains are available for cross-compilation on Microsoft Windows, Linux and Mac OS X host operating systems.
The toolchains support code generation for non-OS or 'bare-metal' environments. It supports ARM Cortex-M0, Cortex-M0+, Cortex-M3, Cortex-M4, Cortex-M7, Cortex-R4, Cortex-R5, Cortex-R7, Cortex-R8 processors and ARMv8-M baseline and mainline architectures.

[9] nRF5 IoT SDK v. 0.9.0 Release Notes
[10] https://developer.arm.com/open-source/gnu-toolchain/

Leshan (OMA Lightweight M2M server)

Leshan is an open source OMA Lightweight Machine to Machine (LwM2M) java client and server implementation[11]. It provides libraries to develop an LwM2M client and server using the Java programming language. Leshan project contains a client, a server, and a bootstrap server as an example to demonstrate Leshan APIs and for testing purpose. Below mentioned are some of the salient features of Leshan

- Eclipse project since 2014
- Modular Java libraries
- Based on Californium CoAP implementation
- Based on Scandium DTLS implementation
- IPSO objects support

As shown in the figure 4.5, Leshan provides a very simple UI to get the list of connected clients and interact with clients resources.

[11] http://www.eclipse.org/leshan/

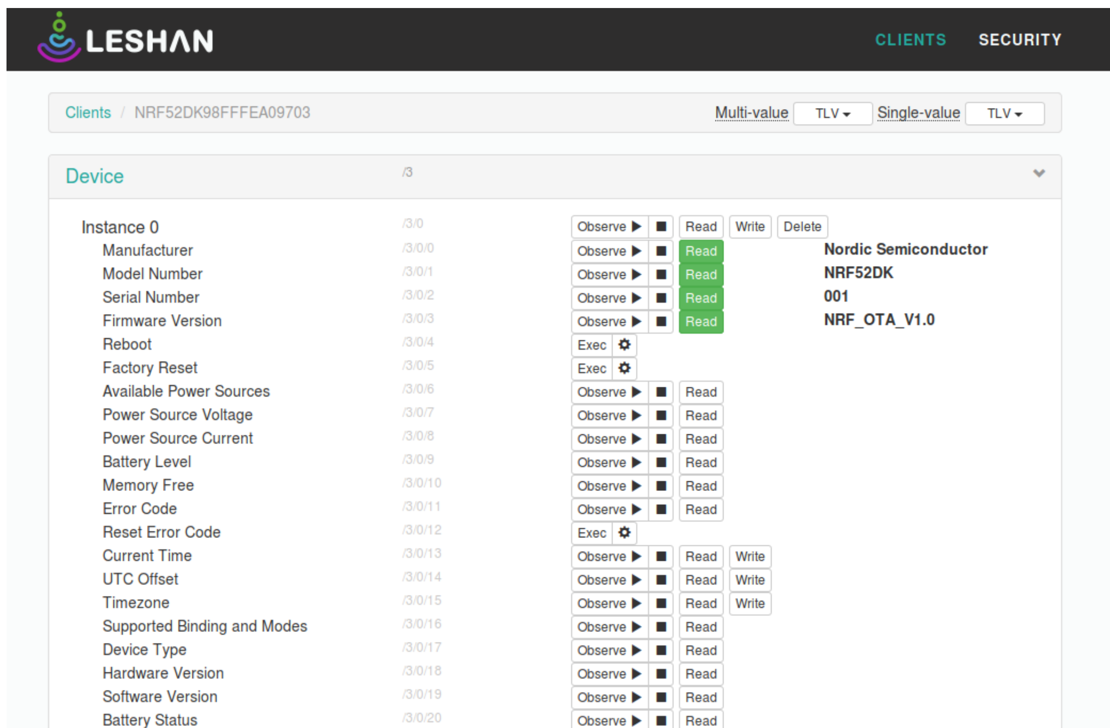


Figure 4.5: UI of Leshan Server shows interaction with NRF device.

4.3 Software Setup and Configurations

Connecting Devices to the Router

Ubuntu version 17.04 has a pre-compiled 6LoWPAN module. To establish a connection between an nRF52 device and Linux router following procedure need to follow.

```
# Log in as a root user.
$ sudo su
# Mount debugfs file system.
$ mount -t debugfs none /sys/kernel/debug
# Load 6LoWPAN module.
$ modprobe bluetooth_6lowpan
```

```
# Enable the bluetooth 6lowpan module.
$ echo 1 > /sys/kernel/debug/bluetooth/6lowpan_enable
# Look for available HCI devices.
$ hciconfig
# Reset HCI device - for example hci0 device.
$ hciconfig hci0 reset
# Read 00:AA:BB:XX:YY:ZZ address of the nRF5x device.
$ hcitool lescan
# Connect to the device.
$ echo "connect 00:AA:BB:XX:YY:ZZ 1" >
        /sys/kernel/debug/bluetooth/6lowpan_control
# Check if you have established a connection.
$ ifconfig
# Try to ping the device using its link-local address,
  for example, on bt0 interface.
$ ping6 -i bt0 fe80::2aa:bbff:fexx:yyzz
# Disconnect from the device.
$ echo "disconnect 00:AA:BB:XX:YY:ZZ" >
/sys/kernel/debug/bluetooth/6lowpan_control
# Check if there are active connections left.
$ ifconfig
```

Creating Link-Local IPv6 addresses

A link local IPv6 address must be assigned to a device to identify it uniquely in the network. This address is based on the interface identifier (IID), which derives from the Bluetooth Device address. Link-local addresses contain the prefix FE80::/10 and a 64-bit

interface identifier (IID) [16]. Link-local addresses are used for addressing on a single link if no router present in the network or the case of automatic address configuration. Creating an IPv6 link-local address comprises three steps:

1. Transforming the Bluetooth device address into Modified EUI-64 format
2. Transforming the Modified EUI-64 address into an IID
3. Transforming the IID into a link-local address

For example, link-local address for the Bluetooth device address C0:11:22:33:44:55 is FE80:0000:0000:0000:C011:22FF:FE33:4455, or simpler FE80::C011:22FF:FE33:4455.

Global IPv6 Prefix Distribution

By using a link-local source or destination address, routers are not allowed to forward any packets to other links. It is required to distribute a global IPv6 prefix to the connected devices to expose Bluetooth devices outside the link-local network. For this purpose, Router Advertisement Daemon (RADVD) can be used on Linux. RADVD can periodically or on solicitation send a Router Advertisement message. There are two ways of obtaining global IPv6 prefix.

1. Stateful auto-configuration (using DHCPv6).
2. Stateless auto-configuration.

The figure illustrates how an IPv6 global address is constructed using stateless 4.6 auto-configuration.
RADVD Configuration as follows:

```
# Set IPv6 forwarding (must be present).
$ sudo echo 1 > /proc/sys/net/ipv6/conf/all/forwarding
```

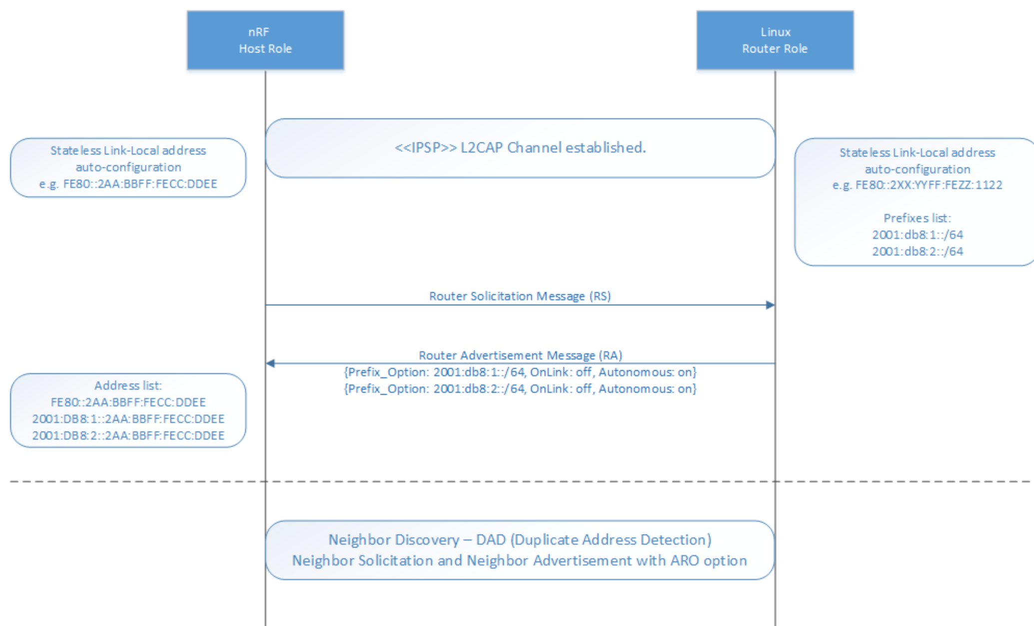


Figure 4.6: IPv6 Stateless Auto-Configuration.[8]

```
# Run radvd daemon.
$ sudo service radvd restart
# Assign prefix to btX interface
$ sudo ifconfig btX add 2001:db8::1/64
```

Leshan Server Initialization

The Leshan bootstrap and LwM2M standalone server have to be compiled from source code. After compilation libraries and example server would be ready to use. Following commands will execute Leshan bootstrap and LwM2M server.

```
# Multiplex port
$ ifconfig bt0 add 2001:db8::1/64
$ ifconfig bt0 add 2001:db8::2/64
```

```
# Execute Leshan LwM2M server
$ java -jar leshan-server-demo/target/leshan-server-demo-*-SNAPSHOT
-jar-with-dependencies.jar --coaphost 2001:db8::1 --coapport 5683

# Execute Leshan bootstrap server
$ java -jar leshan-server-demo/target/leshan-server-demo-*-SNAPSHOT
-jar-with-dependencies.jar --coaphost 2001:db8::1 --coapport 5683
```

4.4 Software Implementation and Interaction

Figure 4.7 depicts the interaction between the components of the system. The interaction is logically divided into five parts and described in further sections.

1. Initialization phase
2. Firmware Update Request
3. Firmware Download phase
4. Firmware Update phase
5. Firmware Swap phase

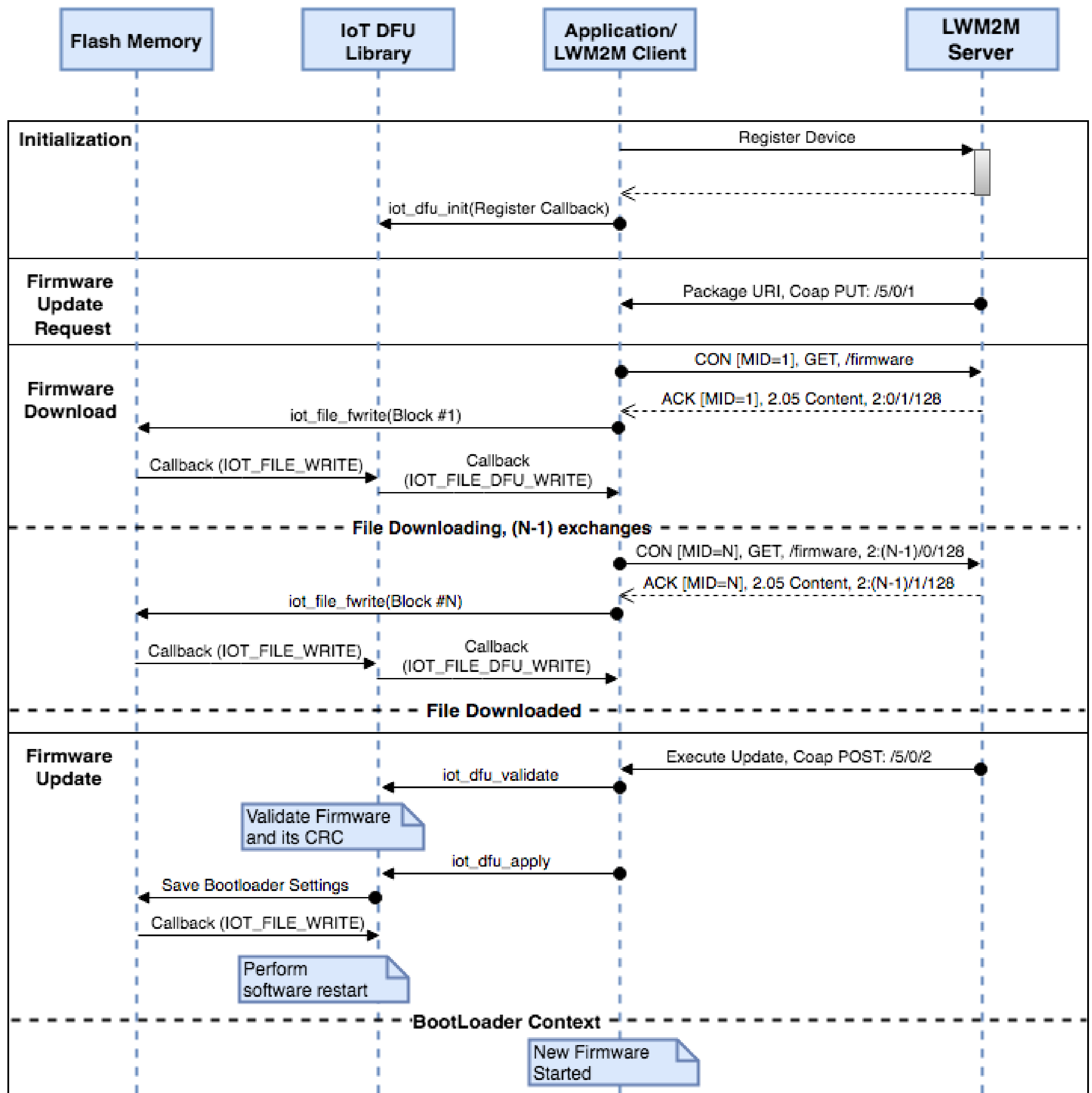
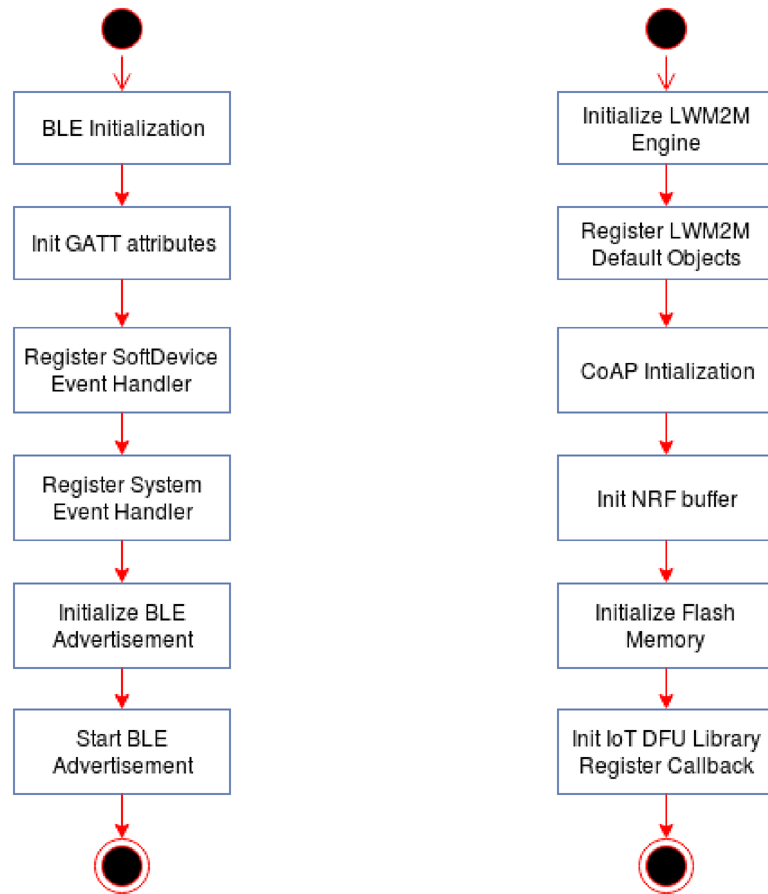


Figure 4.7: Master Sequence Diagram.



(a) BLE module initialization

(b) Application Initialization

Figure 4.8: System Initialization Flow

Initialization phase

Once started the application initializes the BLE module and flash memory to store the firmware. BLE requires initialization of GATT attributes and its advertisement packet. After the initialization phase, BLE starts advertisement and waits for a connection. The advertisement period can be configured in advertisement initialization which directly affects the energy consumption.

The flow diagram in figure 4.8a describes the initialization sequence of BLE module and registration of callback functions to handle the generated event. The application initialization sequence in figure 4.8b represents the initialization of required libraries such as LwM2M engine, CoAP library, IoT DFU library and Flash Memory.

LwM2M client initiates the communication and register its identity with LwM2M

server. This mode refers as "Bootstrapping" phase where the LwM2M client receives server information from a bootstrap server and registers its identity with LwM2M server. Graphics shown in figure 4.9 shows the registered IoT device with Leshan LwM2M server. The application also performs initialization task such as CoAP initialization, LwM2M engine initialization, Registering default LwM2M resources, BLE initialization, Nordic's IoT DFU library initialization and flash memory initialization. The flow diagram in the figure illustrates the initialization of various subsystem.

Figure 4.9: Device Registration with Leshan Server.

Firmware Update Request

The user can issue a firmware update request using the "Package URI" object of LwM2M firmware resource. Package URI will generate a CoAP "POST" request and provides the URI of firmware to the application. With the next practical opportunity the CoAP server issues CoAP "GET" request to block-wise download the package into the system. More details on LwM2M firmware resource can be found in table B.3. Graphics in figures 4.10 shows the UI of Leshan LwM2M server with firmware update object.

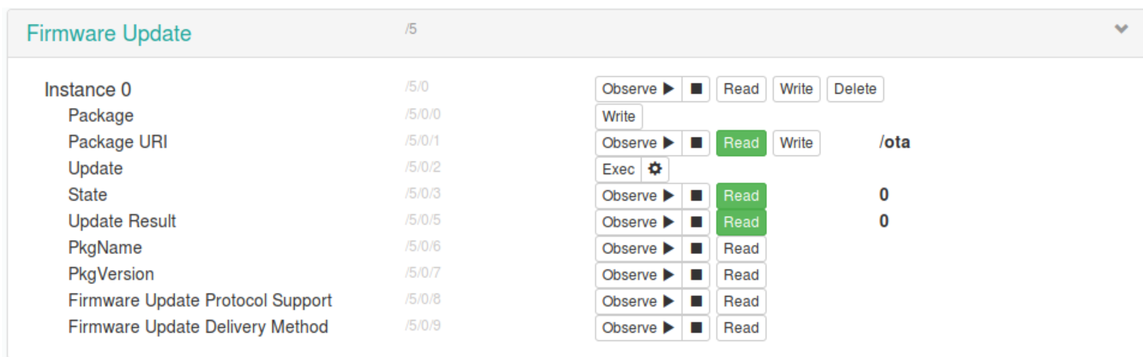


Figure 4.10: Firmware Update UI of Leshan Server

Firmware Download phase

CoAP blockwise transfer is used for transporting the firmware from firmware management server to IoT device. Section 3.4 explains the mechanism of CoAP block transfer where both server and client mutually agree on the size of the block to transfer and client initiates the transfer process. Wireshark[12] logs in figure 4.11 signifies the transfer of CoAP blocks from firmware management server to IoT device.

Upon reception of firmware block, it needs to be written into flash memory. As illustrated in figure 4.12, in this implementation a number of blocks first collected into RAM buffer and then written into flash memory. Writing of firmware blocks into flash memory is implemented using the "IoT File" library provided by Nordic

[12]https://www.wireshark.org/

No.	Time	Source	Destination	Protocol	Length	Info
12	39.376031236	2001:db8::2	2001:db8::206:98ff:fea0:9703	ICMPv6	127	Destination Unreachable (Port unreachable)
13	51.905413564	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41948, GET, End of Block #0, /ota (text/plain)
14	51.905503380	2001:db8::2	2001:db8::206:98ff:fea0:9703	ICMPv6	127	Destination Unreachable (Port unreachable)
15	76.894251589	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41948, GET, End of Block #0, /ota (text/plain)
16	76.927036771	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41948, 2.05 Content, Block #0 (text/plain)
17	77.034394845	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41949, GET, End of Block #0, /ota (text/plain)
18	77.043567664	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41949, 2.05 Content, Block #0 (text/plain)
19	77.664217862	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41950, GET, End of Block #1, /ota (text/plain)
20	77.666486948	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41950, 2.05 Content, Block #1 (text/plain)
21	78.154200741	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41951, GET, End of Block #2, /ota (text/plain)
22	78.156238793	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41951, 2.05 Content, Block #2 (text/plain)
23	78.644144478	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41952, GET, End of Block #3, /ota (text/plain)
24	78.645983060	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41952, 2.05 Content, Block #3 (text/plain)
25	79.134132320	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41953, GET, End of Block #4, /ota (text/plain)
26	79.135441194	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41953, 2.05 Content, Block #4 (text/plain)
27	79.700700826	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41954, GET, End of Block #5, /ota (text/plain)
28	79.701951458	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41954, 2.05 Content, Block #5 (text/plain)
29	80.324038359	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41955, GET, End of Block #6, /ota (text/plain)
30	80.326053839	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41955, 2.05 Content, Block #6 (text/plain)
31	80.884026238	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41956, GET, End of Block #7, /ota (text/plain)
32	80.886728119	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41956, 2.05 Content, Block #7 (text/plain)
33	81.374018388	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41957, GET, End of Block #8, /ota (text/plain)
34	81.375930839	2001:db8::2	2001:db8::206:98ff:fea0:9703	CoAP	331	ACK, MID:41957, 2.05 Content, Block #8 (text/plain)
35	81.933993016	2001:db8::206:98ff:fea0:9703	2001:db8::2	CoAP	79	CON, MID:41958, GET, End of Block #9, /ota (text/plain)

Figure 4.11: CoAP block transfer messages in wireshark

semiconductor[8]. IoT file abstraction library provides the APIs for accessing any object, which can be treated as a file. Applications can use the APIs provided by libraries for read and write operations to the memory block. The provided APIs are implemented in an asynchronous fashion and to support that the library defines the event structure where an application callback is assigned in the initialization phase of specified file instance. The callback notifies the application when the data is ready, or operation is completed which in turns could be useful to unlock another procedure. Message passing using events and callbacks is shown in the "firmware download" and "firmware update" phase of figure 4.7

In the SoftDevice implementation provided by the Nordic semiconductor, the underlying flash operations are performed using the SoC library API. The flash memory access is scheduled by SoftDevice in between the protocol radio events[8]. The flash access time could be larger with short connection or advertisement intervals. The access may also be slightly delayed to minimize the disturbance of the BLE radio protocol. In some case, the flash memory access may fail with a timeout event:
NRF_EVT_FLASH_OPERATION_ERROR.

Firmware Update phase

The importance of firmware validation is mentioned in section 3.5. Firmware validation is implemented using the "IoT DFU" library provided by Nordic semiconductor[8]. IoT DFU exposes a common API for configuration and checksum validation. The library is

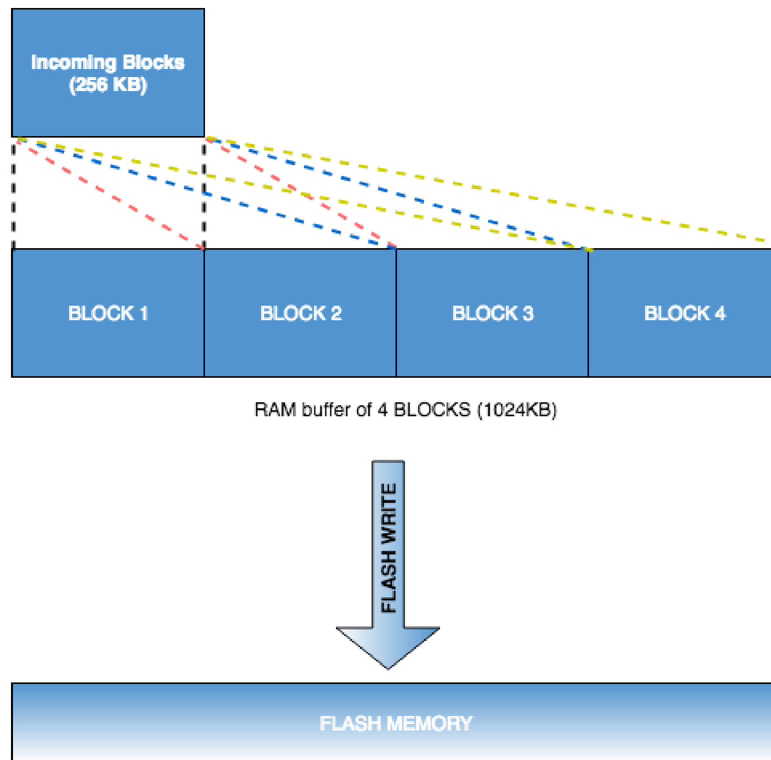


Figure 4.12: Firmware blocks collection into RAM buffer

also responsible for triggering a swap procedure by writing into the "boot flags" which indicates bootloader to swap firmware image. IoT DFU library is implemented in an asynchronous fashion and hence required an application callback to notify the user-level application. The library also provides support to validate the checks for multi firmware update scenario, for example, updating softdevice and application together.

Firmware Swap phase

In this phase, the system will be in bootloader context. During initialization, the bootloader will either initiate the firmware swap mode or request the softdevice to launch the application. The configuration settings define if a new valid firmware present in the flash memory. The bootloader initiates a firmware swap mode if the configuration settings (boot flags) indicates to swap the firmware. The flash memory partitioned logically for the different component. The figure 4.13 depicts the memory layout of a

512kB nrf52 device.

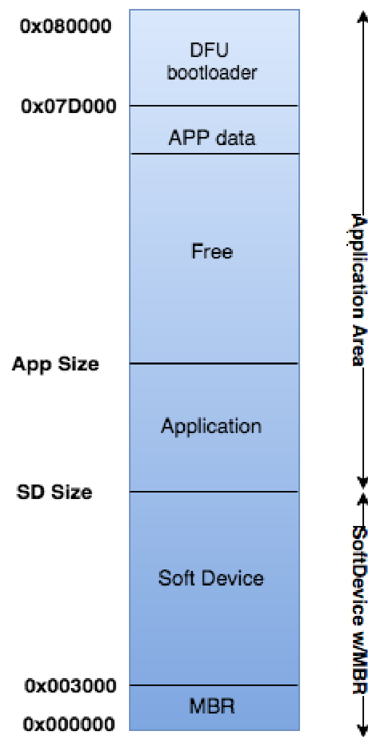


Figure 4.13: Flash Memory Layout of a 512kB nrf52 device.[8]

4.5 Data Structure

Below defined table 4.1 lists the major data structure used in this implementation.

Data Structure	Description
Coap_packet_t	CoAP Packet structure
Lwm2m_object_t	Describes the structure for LwM2M object
Lwm2m_resource_t	Describes the structure for LwM2M resource
Lwm2m_instance_t	Describes the structure for LwM2M Instance
Lwm2m_firmware_t	Describes the resources of LwM2M firmware object
iot_file_evt_t	Asynchronous event of IoT File library
iot_file_struct_t	Describes the structure for file abstraction
iot_dfu_firmware_block_t	Description of single block of firmware
iot_dfu_firmware_desc_t	Description of the new firmware that has been written into flash memory
bootloader_settings_t	Structure holding bootloader settings for application and bank data
ble_enable_params_t	BLE GATTS init options
ble_gap_addr_t	BLE address
ble_advdata_t	Data structure for BLE advertising packet.
ble_ipsp_handle_t	Structure contains information regarding IPSP profile

Table 4.1: Data Structures.

4.6 Evaluation

4.6.1 Firmware Download and Firmware Update

Objective

This experiment is a qualitative analysis to evaluate the functional requirement of the implementation. The test issues the firmware download and update commands from LwM2M server and assess the state of the system and update result.

Methodology

1. Configure the software and related services as mentioned in section 4.3.
2. Access Leshan server UI and check the firmware version and state of the system.
3. provide "package URI" and check the state of the system.
4. The system state should change after the package download.
5. Execute update and check the firmware version after device reboot.

Results

The results are measured and mentioned below for each given test case in section 4.6.1.

1. Initially Firmware version was "NRF_OTA_V1.0, " and state of the system was "IDLE."
2. After providing the "package URI," the state of the system was changed to "DOWNLOADING."
3. After package download, the system state was changed to "DOWNLOADED."
4. After execution of update device rebooted and firmware version changed to "NRF_OTA_V2.0."

Discussion

This experiment provides a qualitative analysis of the implemented framework. We tested all the functional requirement and states of the system.

4.6.2 Firmware download time with different size of RAM buffer

Objective

As shown in figure 4.12 firmware blocks are first downloaded into RAM buffer and then transferred into flash memory. The size of the RAM buffer depends on the application. The objective of this experiment is to measure the firmware download time with different sizes of RAM buffer.

Methodology

An experiment was conducted with different size of RAM buffers shown in table 4.2. Five iterations of firmware download for each RAM buffer size was performed, and the average value was taken for the final result.

Results

The results are tabulated in the table below.

Iteration	**256 Bytes**	**512 Bytes**	**1024 Bytes**	**2048 Bytes**
1	161	153	147	145
2	162	153	147	146
3	161	153	146	145
4	161	154	147	145
5	162	153	147	146

Average	161.4	153.2	146.8	145.4

Table 4.2: Results for Experiment #1.

Discussion

In this experiment, it was expected to gain substantial time difference with the change in RAM block size. As shown in table 4.2 there is a marginal change in time with the change in RAM block size. The reason for this anomaly could be the use of Nordic Semiconductor SoftDevice implementation for flash writing. As discussed in section 4.4 flash device operation could be effected with BLE radio events. This performance evaluation needs an investigation of the underlying implementation of Nordic semiconductor and hence it is deferred for future work.

Chapter 5

Conclusion and Future Work

5.1 Introduction

We identified the gaps in the current state of the art for firmware update and proposed the design for an end to and firmware solution adhering to specified standards. Further, we implemented a working prototype of the proposed design and evaluated the implementation. The final chapter concludes the dissertation by highlighting the features of the implementation, challenges faced during the implementation and future work that can be done.

5.2 Prototype

This dissertation presents a working prototype of an end to end firmware upgrade framework which adheres the standard specifications. The prototype provides the implementation of firmware upgrade state machine specified by OMA LwM2M [31]. The prototype was tested with a number of different new firmware images to upgrade and it was concluded that the approach is successfully allowing the new firmware upgrade on a BLE device and also presenting the state of the system at any given point of time.

5.3 Contributions

In this dissertation, we established state of the art for current IoT standards and specifications. Further, we identified the gaps in the current firmware update solution. We addressed these deficiencies by implemented an end to end solution for the firmware upgrade on a BLE device using IPv6 over BLE which adheres the current standards. The implementation is ready for an open source contribution. Below mentioned are the novel contributions of this dissertation.

1. Coding and implementation for LwM2M firmware state machine.

2. Coding and implementation CoAP block transfer client in IoT device.

3. Integration of Nordic IoT DFU library with open source Contiki RTOS.

5.4 Challenges

1. The code base involved two different SDKs, Nordic IoT SDK[7] and Contiki operating system[5]. Integration of Nordic's IoT DFU libraries with Contiki SDK became a problem. Each relevant code file was manually selected and added into Contiki code base.

2. Support for NRF52 DK in the current version of Contiki is broken. The issue is already reported, but no action is taken yet. This dissertation is implemented using the previous version of Contiki in which NRF52 DK is supported.

3. Less documentation regarding the flash usage of nrf52 DK causes the loss of time while integrating flash writing support to Contiki OS.

4. Testing and debugging on actual hardware was time-consuming. For debugging purpose, most of the time we had to rely on message prints on the serial terminal.

5. Reading and understanding the specification was time-consuming.

5.5 Future Work

5.5.1 Energy Efficient Updates

Energy is a major constraint in IoT devices. In general updating, a firmware means pushing a fix or new feature into the device. A major part of the firmware remains same. In this implementation, we are sending a new firmware with every update which required more energy with every update. Approaches like incremental or modular Updates could be used for an energy efficient firmware upgrade. These methods reduce the traffic load by sending only a part of firmware to upgrade; as a result less energy consumption. In section 2.5 we mentioned few approaches which follow an incremental or modular update fashion. In future, these approaches could be integrated with current prototype to make it more robust and energy efficient solution.

Incremental Update

In incremental update approach, a compressed incremental patch could be sent in the existing system. This would reduce the bandwidth usage as compared to image based update. To generate the delta (change of old and new firmware) a number of techniques are available namely, RDIFF, VCDIFF, and BSDIFF. The delta can be compressed on the server side using Lempel-Ziv (LZ) variant of data compression algorithm. Upon reception of delta on IoT device, it can be decompressed and patched with the active firmware updates. The required downtown of the system would depend on the application of the system and method of patching. At present Zephyr[1] supports incremental updates and development is on going for IPv6 support over BLE. Zephyr could be a potential platform to work with to support incremental update. However, from device management side, specification given by LwM2M supports only image based update. It would be challenging to handle an end to end upgrade for a single patch of firmware.

[1] https://www.zephyrproject.org/

Modular Update

In a Modular update, the OS should support the dynamic linking and instantiation of modules. Contiki is one such platform which supports dynamic module loading. Again in this solution, the challenge would be from device management side, specification given by LwM2M supports only image based update. It would be challenging to handle an end to end upgrade for a single module of the system.

5.5.2 Firmware Upgrade in a mesh network

In December 2016, Bluetooth SIG released the specification for Bluetooth V5.0[2]. Bluetooth V5.0 adopted the mesh topology which allows devices to become a hub and communicating directly or indirectly with other devices. In this dissertation, the current firmware upgrade prototype is focused on a peer to peer firmware upgrade. The mesh support of Bluetooth V5.0 could be used to extend this prototype and allowing the firmware upgrades on peer nodes using the IoT device in picture as a hub.
As described in section 1.2 the traditional communication paradigm of client/server model is not appropriate for IoT. In mesh network nodes can communicate with each other and from firmware upgrade prospective neighboring nodes can fetch latest firmware from its peer nodes. This will eliminate the single point of failure possibility and introduce resiliency in the network.

5.5.3 Security implication of firmware upgrade

Security is an open area of research in the domain of Internet of things. There are vulnerabilities exposed in each layer of IoT ecosystem. In case of firmware upgrades security needs to be implemented from firmware management server till the IoT device. The report provided by S.Farell et al.,[3] mentions a large number of concerns when it

[2]https://www.bluetooth.com/specifications/bluetooth-core-specification
[3]https://tools.ietf.org/html/draft-farrell-iotsu-workshop-00

comes to securing the ecosystem. This dissertation could further be extended to address the security concerns and provide a "secure end to end firmware upgrade framework."

5.5.4 Performance Evaluation

We performed the performance evaluation in section 4.6.2. Further investigation is required to identify the cause of anomaly caused in download time with the different size of firmware blocks. One such indication is the interference of SoftDevice with flash writing while ongoing radio event. This could be further analyzed with the good knowledge of Nordic's SoftDevice implementation.

5.6 Conclusion

The aim of implementing a standard compliant, end to end firmware upgrade solution on a BLE device using IPv6 over BLE was successfully achieved using Nordic NRF52 platform and support provided by Contiki operating system. To the best of the writers knowledge, this is the first time such an approach where an inter operable solution for firmware upgrade in IoT device had been implemented.
The framework and its further extension would provide a solution for long running problems in IoT ecosystem to manage and upgrading a fleet of devices. The specification followed by this framework would make it inter operable and extend its reach to work with different vendors and services. This approach is a one step forward to envisage the Internet of Things.

Appendix A

Abbreviations and Acronyms

Short Term	Expanded Term
IoT	Internet of Things
IP	Internet Protocol
IPv6	Internet Protocol Version 6
OS	Operating System
SDK	Software Development Kit
HDK	Hardware Development Kit
API	Application Programming Interface
RFC	Request for Comments
SIG	Special Interest Group
WSN	Wireless Sensor Network
REST	Representational state transfer
IETF	Internet Engineering Task Force
IAB	Internet Architecture Board
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks
CoAP	Constrained Application Protocol
CoRE	Constrained RESTful Environments
LwM2M	Lightweight M2M

Appendix B

LwM2M Firmware Update Specification

Object Definition

Name	Object ID	Instances	Mandatory	Object URN
Firmware Update	5	Single	Optional	urn:oma:lwm2m:oma:5

Table B.1: Firmware Object Definition [31].

Resource Definition

ID	Name	Operations	Instances	Mandatory	Type	Range	Description
0	Package	W	Single	Mandatory	Opaque		Firmware package
1	Package URI	RW	Single	Mandatory	String	0-255 bytes	URI from where the device can download the firmware package by an alternative mechanism. As soon the device has received the Package URI it performs the download at the next practical opportunity. The URI format is defined in RFC 3986. For example, coaps://example.org/firmware is a syntactically valid URI. The URI scheme determines the protocol to be used. For CoAP this endpoint MAY be a LwM2M Server but does not necessarily need to be. A CoAP server implementing block-wise transfer is sufficient as a server hosting a firmware repository and the expectation is that this server merely serves as a separate file server making firmware images available to LwM2M Clients.
2	Update	E	Single	Mandatory	none		Updates firmware by using the firmware package stored in Package, or, by using the firmware downloaded from the Package URI. This Resource is only executable when the value of the State Resource is Downloaded.
3	State	R	Single	Mandatory	Integer	0-3	Indicates current state with respect to this firmware update. This value is set by the LwM2M Client. 0: Idle (before downloading or after successful updating) 1: Downloading (The data sequence is on the way) 2: Downloaded 3: Updating If writing the firmware package to Package Resource is done, or, if the device has downloaded the firmware package from the Package URI the state changes to Downloaded. Writing an empty string to Package Resource or to Package URI Resource, resets the Firmware Update State Machine: the State Resource value is set to Idle and the Update Result Resource value is set to 0. When in Downloaded state, and the executable Resource Update is triggered, the state changes to Updating. If the Update Resource failed, the state returns at Downloaded. If performing the Update Resource was successful, the state changes from Updating to Idle. Firmware Update mechanisms are illustrated below in Figure 29 of the LwM2M version 1.0 specification.
5	Update Result	R	Single	Mandatory	Integer	0-9	Contains the result of downloading or updating the firmware 0: Initial value. Once the updating process is initiated (Download /Update), this Resource MUST be reset to Initial value. 1: Firmware updated successfully, 2: Not enough flash memory for the new firmware package. 3. Out of RAM during downloading process. 4: Connection lost during downloading process. 5: Integrity check failure for new downloaded package. 6: Unsupported package type. 7: Invalid URI 8: Firmware update failed 9: Unsupported protocol. A LwM2M client indicates the failure to retrieve the firmware imagine using the URI provided in the Package URI resource by writing the value 9 to the /5/0/5 (Update Result resource) when the URI contained a URI scheme unsupported by the client. Consequently, the LwM2M Client is unable to retrieve the firmware image using the URI provided by the LwM2M Server in the Package URI when it refers to an unsupported protocol.

ID	Name	Operations	Instances	Mandatory	Type	Range	Description
6	PkgName	R	Single	Optional	String	0-255 bytes	Name of the Firmware Package
7	PkgVersion	R	Single	Optional	String	0-255 bytes	Version of the Firmware package
8	Protocol Support	R	Multiple	Optional	Integer		This resource indicates what protocols the LwM2M Client implements to retrieve firmware images. The LwM2M server uses this information to decide what URI to include in the Package URI. A LwM2M Server MUST NOT include a URI in the Package URI object that uses a protocol that is unsupported by the LwM2M client. For example, if a LwM2M client indicates that it supports CoAP and CoAPS then a LwM2M Server must not provide an HTTP URI in the Packet URI. The following values are defined by this version of the specification: 0 CoAP (as defined in RFC 7252) with the additional support for block-wise transfer. CoAP is the default setting. 1 CoAPS (as defined in RFC 7252) with the additional support for block-wise transfer 2 HTTP 1.1 (as defined in RFC 7230) 3 HTTPS 1.1 (as defined in RFC 7230) Additional values MAY be defined in the future. Any value not understood by the LwM2M Server MUST be ignored.
9	Delivery Method	R	Single	Mandatory	Integer		The LwM2M Client uses this resource to indicate its support for transferring firmware images to the client either via the Package Resource (=push) or via the Package URI Resource (=pull) mechanism. 0 Pull only 1 Push only 2 Both. In this case the LwM2M server MAY choose the preferred mechanism for conveying the firmware image to the LwM2M Client.

Table B.3: Firmware Resource Definition [31].

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