UG103.11: Thread Fundamentals

This document includes a brief background on the emergence of Thread, provides a technology overview, and describes some key features of Thread to consider when implementing a Thread solution.

Silicon Labs' *Fundamentals* series covers topics that project managers, application designers, and developers should understand before beginning to work on an embedded networking solution using Silicon Labs chips, networking stacks such as EmberZNet PRO or Silicon Labs *Bluetooth*®, and associated development tools. The documents can be used as a starting place for anyone needing an introduction to developing wireless networking applications, or who is new to the Silicon Labs development environment.

KEY POINTS

- Introduces Thread and provides a technology overview.
- Describes some of the key elements of Thread, including its IP stack, network topology, routing and network connectivity, joining a network, management, persistent data, security, and application layer.
- Discusses custom application layer development and development using Zigbee Cluster Library over IP.
- Contains updates for Silicon Labs Thread 2.0 and Thread Specification 1.2.
- Includes next steps for working with the Silicon Labs Thread offering.

1. Introduction

1.1 Silicon Labs and the Internet of Things

Internet Protocol version 4 (IPv4) was defined in 1981 in RFC 791 (http://tools.ietf.org/html/rfc791: *DARPA Internet Program Protocol Specification*). ("RFC" stands for "Request for Comments.") Using 32-bit (4-byte) addressing, IPv4 provided 2^{32} unique addresses for devices on the internet, a total of approximately 4.3 billion addresses. However, as the number of users and devices grew exponentially, it was clear that the number of IPv4 addresses would be exhausted and there was a need for a new version of the IP. Hence the development of IPv6 in the 1990s and its intention to replace IPv4. With 128-bit (16-byte) addressing, IPv6 allows for 2^{128} addresses, more than 7.9×10^{28} addresses than IPv4 (http://en.wikipedia.org/wiki/IPv6).

The challenge for companies in the embedded industry like Silicon Labs is to address this technology migration and more importantly the demands of customers as we move to an ever-connected world of devices in the home and commercial space, what is often referred to as the Internet of Things (IoT). At a high level the goals of IoT for Silicon Labs are to:

- Connect all the devices in the home and commercial space with best-in-class networking, whether with Zigbee PRO, Thread, Bluetooth, or other emerging standards.
- Leverage the company's expertise in energy-friendly microcontrollers.
- Enhance established low-power, mixed-signal chips.
- Provide low-cost bridging to existing Ethernet and Wi-Fi devices.
- Enable cloud services and connectivity to smartphones and tablets that will promote ease of use and a common user experience for customers.

Achieving all of these goals will increase adoption rates and user acceptance for IoT devices.

1.2 Thread Group

Thread Group (https://www.threadgroup.org/) was launched on July 15, 2014. Silicon Labs was a founding company along with six other companies. Thread Group is a market education group that offers product certification and promotes the use of Thread-enabled device-to-device (D2D) and machine-to-machine (M2M) products. Membership in Thread Group is open.

The current veersion of theThread Specification is 1.1 and may be downloaded after submitting a request here: https://www.threadgroup.org/ThreadSpec. Version 1.2 is close to final, although some features are still being modified.

1.3 What is Thread?

Thread is a secure, wireless mesh networking protocol. The Thread stack is an open standard that is built upon a collection of existing Institute for Electrical and Electronics Engineers (IEEE) and Internet Engineering Task Force (IETF) standards, rather than a whole new standard (see the following figure).

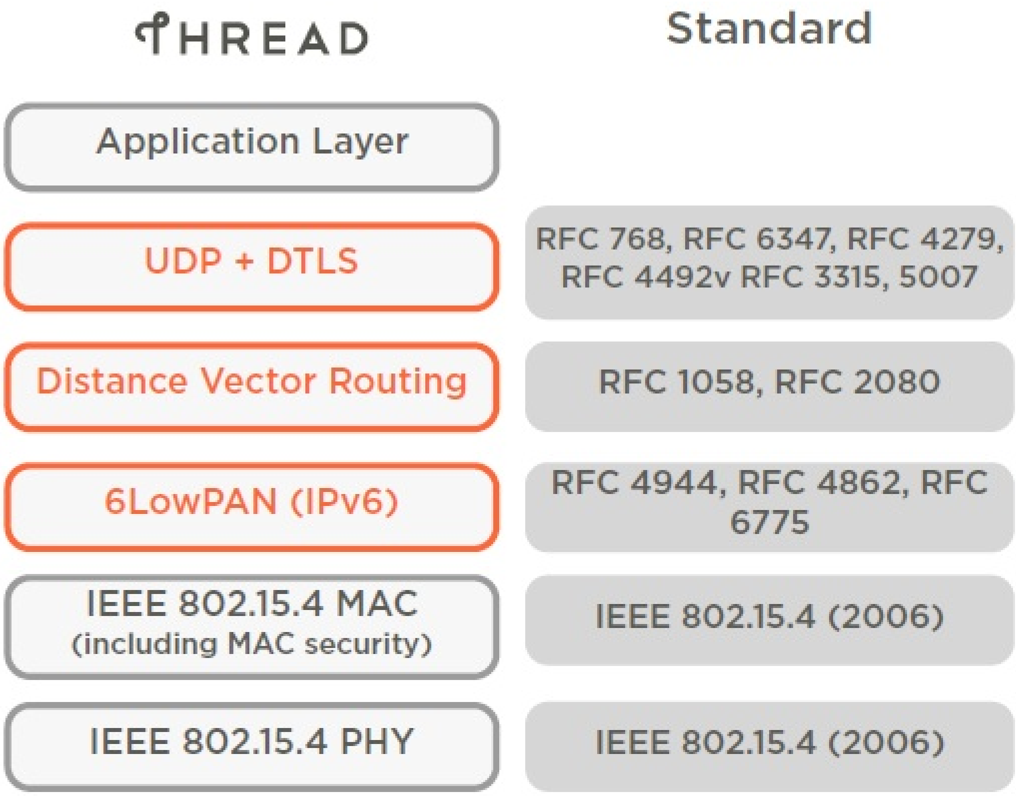


Figure 1.1. Thread Stack Overview

1.4 Thread General Characteristics

The Thread stack supports IPv6 addresses and provides low-cost bridging to other IP networks and is optimized for low-power / battery-backed operation, and wireless device-to-device communication. The Thread stack is designed specifically for Connected Home and commercial applications where IP-based networking is desired and a variety of application layers can be used on the stack.

These are the general characteristics of the Thread stack:

- **Simple network installation, start-up, and operation:** The Thread stack supports several network topologies. Installation is simple using a smartphone, tablet, or computer. Product installation codes are used to ensure only authorized devices can join the network. The simple protocols for forming and joining networks allow systems to self-configure and fix routing problems as they occur.
- **Secure:** Devices do not join the network unless authorized and all communications are encrypted and secure. Security is provided at the network layer and can be at the application layer. All Thread networks are encrypted using a smartphone-era authentication scheme and Advanced Encryption Standard (AES) encryption. The security used in Thread networks is stronger than other wireless standards the Thread Group has evaluated.
- **Small and large home networks:** Home networks vary from several to hundreds of devices. The networking layer is designed to optimize the network operation based on the expected use.
- **Large commercial networks:** For larger commercial installations, a single Thread network is not sufficient to cover all the application, system and network requirements. The Thread Domain model allows scalability up to 10,000s of Thread devices in a single deployment, using a combination of different connectivity technologies (Thread, Ethernet, Wi-fi, and so on).
- **Range:** Typical devices provide sufficient range to cover a normal home. Readily available designs with power amplifiers extend the range substantially. A distributed spread spectrum is used at the Physical Layer (PHY) to be more immune to interference. For commercial installations, the Thread Domain model allows multiple Thread networks to communicate with each other over a backbone, thus extending the range to cover many mesh subnets.
- **No single point of failure:** The Thread stack is designed to provide secure and reliable operations even with the failure or loss of individual devices.
- **Low power:** Devices efficiently communicate to deliver an enhanced user experience with years of expected life under normal battery conditions. Devices can typically operate for several years on AA type batteries using suitable duty cycles.
- **Cost-effective:** Compatible chipsets and software stacks from multiple vendors are priced for mass deployment, and designed from the ground up to have extremely low-power consumption.

2. Thread Technology Overview

2.1 IEEE 802.15.4

The IEEE 802.15.4-2006 specification is a standard for wireless communication that defines the wireless Medium Access Control (MAC) and Physical (PHY) layers operating at 250 kbps in the 2.4 GHz band, with a roadmap to subGHz bands (IEEE 802.15.1-2006 Specification, http://standards.ieee.org/findstds/standard/802.15.4-2006.html). Designed with low power in mind, 802.15.4 is suitable for applications usually involving a large number of nodes.

Note: While some Thread 1.2 low power features depend on the latest version of IEEE 802.15.4, these features are not yet supported by Silicon Labs Thread stack version 2.10.0.

The 802.15.4 MAC layer is used for basic message handling and congestion control. This MAC layer includes a Carrier Sense Multiple Access (CSMA) mechanism for devices to listen for a clear channel, as well as a link layer to handle retries and acknowledgement of messages for reliable communications between adjacent devices. MAC layer encryption is used on messages based on keys established and configured by the higher layers of the software stack. The network layer builds on these underlying mechanisms to provide reliable end-to-end communications in the network.

2.2 Thread Network Architecture

2.2.1 Residential Architecture

Users communicate with a residential Thread network from their own device (smartphone, tablet, or computer) via Wi-Fi on their Home Area Network (HAN) or using a cloud-based application. The following figure illustrates the key device types in the Thread network architecture.

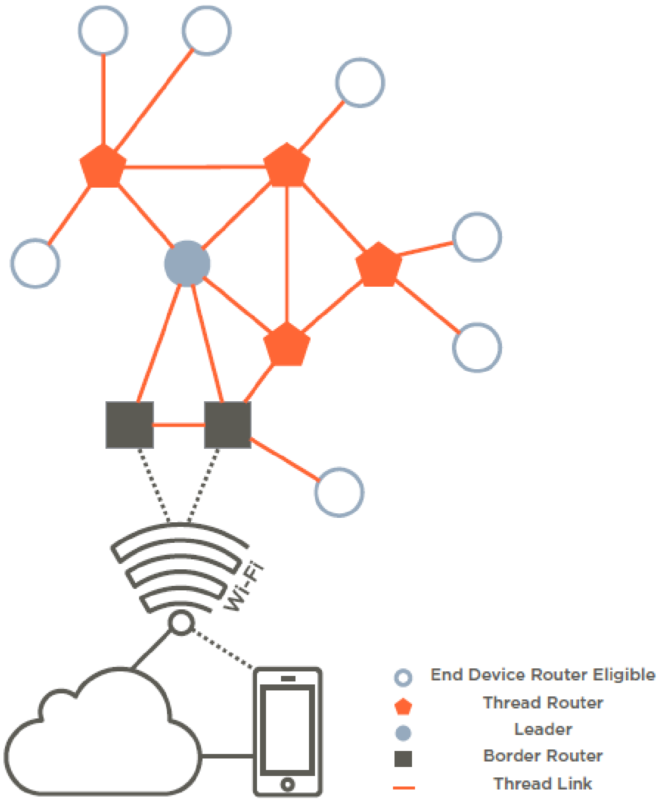


Figure 2.1. Thread Network Architecture

The following device types are included in a Thread network, starting from the Wi-Fi network:

- **Border Routers** provide connectivity from the 802.15.4 network to adjacent networks on other physical layers (Wi-Fi, Ethernet, etc.). Border Routers provide services for devices within the 802.15.4 network, including routing services for off network operations. There may be one or more Border Routers in a Thread network.
- A **Leader**, in a Thread network partition, manages a registry of assigned router IDs and accepts requests from router-eligible end devices (REEDs) to become routers. The Leader decides which should be routers, and the Leader, like all routers in a Thread network, can also have device-end children. The Leader also assigns and manages router addresses using CoAP (Constrained Application Protocol). However, all information contained in the Leader is present in the other Thread Routers. So, if the Leader fails or loses connectivity with the Thread network, another Thread Router is elected, and takes over as Leader without user intervention.
- **Thread Routers** provide routing services to network devices. Thread Routers also provide joining and security services for devices trying to join the network. Thread Routers are not designed to sleep and can downgrade their functionality and become REEDs.
- **REEDs** can become a Thread Router or a Leader, but not necessarily a Border Router that has special properties, such as multiple interfaces. Because of the network topology or other conditions, REEDs do not act as routers. REEDs do not relay messages or provide joining or security services for other devices in the network. The network manages and promotes router-eligible devices to routers if necessary without user interaction.
- **End devices** that are not router-eligible can be either FEDs (full end devices) or MEDs (minimal end devices). MEDs do not need to explicitly synchronize with their parent to communicate.
- **Sleepy end devices** communicate only through their Thread Router parent and cannot relay messages for other devices.

2.2.2 Commercial Architecture

The Thread Commercial model takes the key device types for a residential network and adds new concepts. Users communicate with a commercial network through devices (smartphone, tablet, or computer) via Wi-Fi or through their enterprise network. The following figure illustrates a commercial network topology.

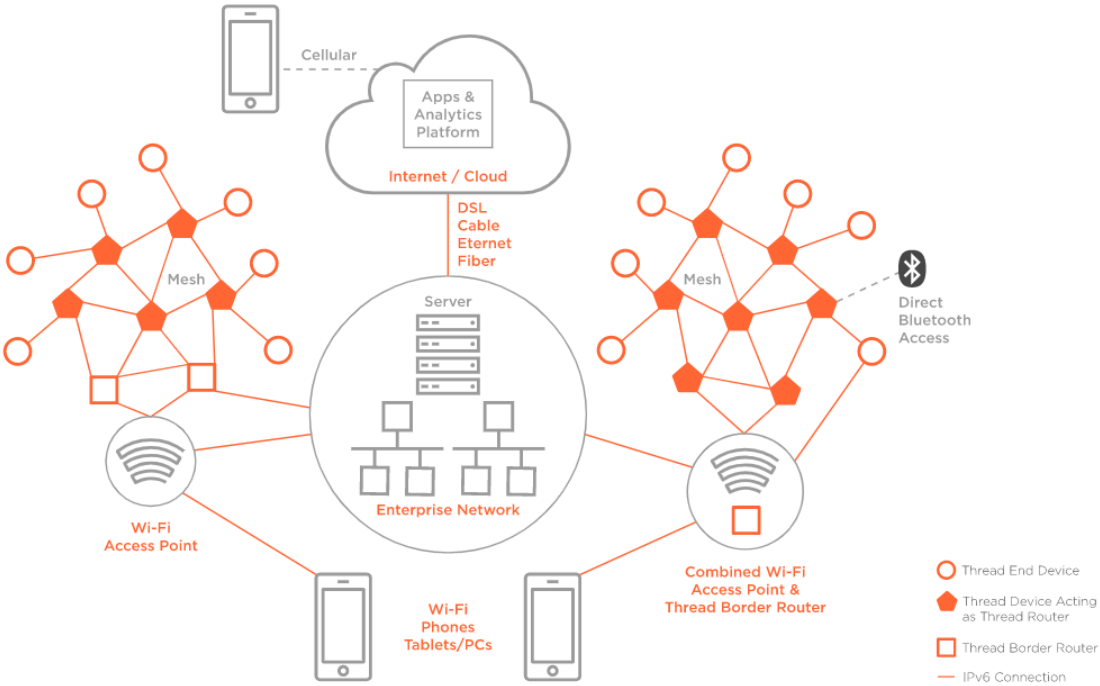


Figure 2.2. Commercial Network Topology

The new concepts are:

- The **Thread Domain model** supports seamlessly integration of multiple Thread Networks as well as seamless interface to non-Thread IPv6 networks. The main benefit of the Thread Domain is that devices are to some extent flexible to join any available Thread Network configured with a common Thread Domain, which reduces the need for manual network planning or costly manual reconfigurations when network size or data volume are scaled up.
- **Backbone Border Routers** (BBRs) are a class of Border Router in the commercial space which facilitate Thread Domain synchronization of multiple network segments, and allow large scope multicast propagation into and out of each single mesh in a Thread Domain. A Thread network that is part of a larger domain must have at least one “Primary” BBR, and can have multiple “Secondary” BBRs for fail-safe redundancy. The BBRs communicate with each other over a backbone which connects all the Thread networks.
- A **Backbone Link** is a non-Thread IPv6 link to which a BBR connects using an external interface used to implement the Thread Backbone Link Protocol (TBLP) to synchronize with other BBRs.
- Thread Devices in a commercial implementation are configured using Thread Domains and **Domain Unique Addresses** (DUAs). A device’s DUA never changes over its lifetime of being part of a Thread domain. This facilitates migration across different Thread networks in a single domain, and makes sure that the respective BBRs facilitate routing across multiple Thread networks.

These concepts are illustrated in the following figure:

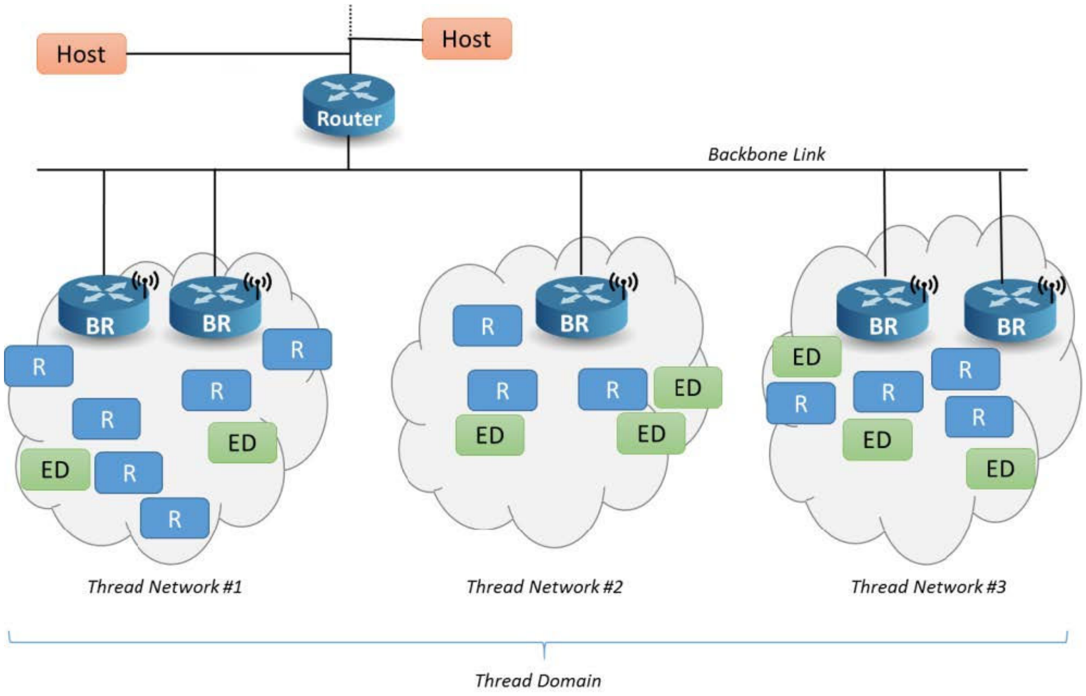


Figure 2.3. Thread Domain Model

2.3 No Single Point of Failure

The Thread stack is designed to not have a single point of failure. While there are a number of devices in the system that perform special functions, Thread is designed so they can be replaced without impacting the ongoing operation of the network or devices. For example, a sleepy end device requires a parent for communications, so this parent represents a single point of failure for its communications. However, the sleepy end device can and will select another parent if its parent is unavailable. This transition should not be visible to the user.

While the system is designed for no single point of failure, under certain topologies there will be individual devices that do not have backup capabilities. For example, in a system with a single Border Router, if the Border Router loses power, there is no means to switch to an alternative Border Router. In this scenario, a reconfiguration of the Border Router must take place.

3. IP Stack Fundamentals

3.1 Addressing

Devices in the Thread stack support IPv6 addressing architecture as defined in RFC 4291 (https://tools.ietf.org/html/rfc4291: *IP Version 6 Addressing Architecture*). Devices support a Unique Local Address (ULA), a Domain Unique Address (DUA) in a Thread domain model, and one or more Global Unicast Address (GUA) addresses based on their available resources.

The high-order bits of an IPv6 address specify the network and the rest specify particular addresses in that network. Thus, all the addresses in one network have the same first N bits. Those first N bits are called the "prefix". The "/64" indicates that this is an address with a 64-bit prefix. The device starting the network picks a /64 prefix that is then used throughout the network. The prefix is a ULA (https://tools.ietf.org/html/rfc4193: *Unique Local IPv6 Unicast Addresses)*. The network may also have one or more Border Router(s) that each may or may not have a /64 that can then be used to generate a ULA or GUA. The device in the network uses its EUI-64 (64-bit Extended Unique Identifier) address to derive its interface identifier as defined in Section 6 of RFC 4944 (https://tools.ietf.org/html/rfc4944: *Transmission of IPv6 Packets over IEEE 802.15.4 Networks*). The device will support a link local IPv6 address configured from the EUI-64 of the node as an interface identifier with the well-known link local prefix FE80::0/64 as defined in RFC 4862 (https://tools.ietf.org/html/rfc4862: *IPv6 Stateless Address Autoconfiguration)* and RFC 4944.

The devices also support appropriate multicast addresses. This includes link-local all node multicast, link local all router multicast, solicited node multicast, and a mesh local multicast. With the presence of a backbone border router in a domain model, devices can also support higher scope multicast addresses if they register for them.

Each device joining the network is assigned a 2 byte short address as per the IEEE 802.15.4-2006 specification. For routers, this address is assigned using the high bits in the address field. Children are then assigned a short address using their parent's high bits and the appropriate lower bits for their address. This allows any other device in the network to understand the child's routing location by using the high bits of its address field.

3.2 6LoWPAN

6LoWPAN stands for "IPv6 Over Low Power Wireless Personal Networks." The main goal of 6LoWPAN is to transmit and receive IPv6 packets over 802.15.4 links. In doing so it has to accommodate for the 802.15.4 maximum frame size sent over the air. In Ethernet links, a packet with the size of the IPv6 Maximum Transmission Unit (MTU) (1280 bytes) can be easily sent as one frame over the link. In the case of 802.15.4, 6LoWPAN acts as an adaptation layer between the IPv6 networking layer and the 802.15.4 link layer. It solves the issue of transmitting an IPv6 MTU by fragmenting the IPv6 packet at the sender and reassembling it at the receiver.

6LoWPAN also provides a compression mechanism that reduces the IPv6 header sizes sent over the air and thus reduces transmission overhead. The fewer bits that are sent over the air, the less energy is consumed by the device. Thread makes full use of these mechanisms to efficiently transmit packets over the 802.15.4 network. RFC 4944 (https://tools.ietf.org/html/rfc4944) and RFC 6282 (https://tools.ietf.org/html/rfc6282) describe in detail the methods by which fragmentation and header compression are accomplished.

3.3 Link Layer Forwarding

Another important feature of the 6LoWPAN layer is link layer packet forwarding. This provides a very efficient and low overhead mechanism for forwarding multi hop packets in a mesh network. Thread uses IP layer routing with link layer packet forwarding.

Thread uses the link layer forwarding to forward packets based on the IP routing table. In order to accomplish this, the 6LoWPAN mesh header is used in each multi-hop packet (see the following figure).

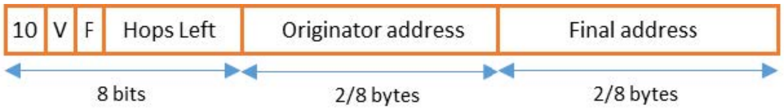


Figure 3.1. Mesh Header Format

In Thread, the 6LoWPAN layer fills the Mesh Header information with the originator 16-bit short address and final destination 16-bit source address. The transmitter looks up the next hop 16-bit short address in the Routing Table, and then sends the 6LoWPAN frame to the next hop 16-bit short address as destination. The next hop device receives the packet, looks up the next hop in the Routing Table / Neighbor Table, decrements the hop count in the 6LoWPAN Mesh Header, and then sends the packet to the next hop or final destination 16-bit short address as destination.

3.4 6LoWPAN Encapsulation

6LoWPAN packets are constructed on the same principle as IPv6 packets and contain stacked headers for each added functionality. Each 6LoWPAN header is preceded by a dispatch value that identifies the type of header (see the following figure).

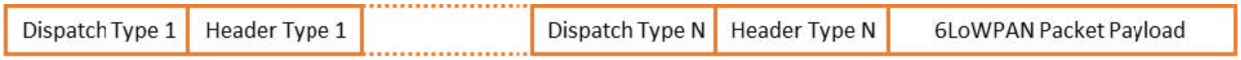


Figure 3.2. General Format of a 6LoWPAN Packet

Thread uses the following types of 6LoWPAN headers:

- Mesh Header (used for link layer forwarding)
- Fragmentation Header (used for fragmenting the IPv6 packet into several 6LoWPAN packets)
- Header Compression Header (used for IPv6 headers compression)

The 6LoWPAN specification mandates that if more than one header is present they must appear in the order mentioned above.

The following are examples of 6LoWPAN packets sent over the air.

In the following figure, the 6LoWPAN payload is composed of the compressed IPv6 header and the rest of the IPv6 payload.

Figure 3.3. 6LoWPAN Packet Containing IPv6 Payload with Compressed IPv6 Header

In the following figure, the 6LoWPAN payload contains the IPv6 header and part of the IPv6 payload.

Figure 3.4. 6LoWPAN Packet Containing Mesh Header, a Fragmentation Header, and a Compression Header

The rest of the payload will be transmitted in subsequent packets per the format in the following figure.

Figure 3.5. 6LoWPAN Subsequent Fragment

3.5 ICMP

Thread devices support the Internet Control Message Protocol version 6 (ICMPv6) protocol as defined in RFC 4443 and ICMPv6 error messages (https://tools.ietf.org/html/rfc4443: *Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 (IPv6) Specification*). They also support the echo request and echo reply messages.

3.6 UDP

The Thread stack supports User Datagram Protocol (UDP) as defined in RFC 768 for messaging between devices (https://tools.ietf.org/html/rfc768: *User Datagram Protocol)*.

4. Network Topology

4.1 Network Address and Devices

The Thread stack supports full mesh connectivity between all routers in the network. The actual topology is based on the number of routers in the network. If there is only one router then the network forms a star. If there is more than one router then a mesh is automatically formed (see 2.2 Thread Network Architecture).

4.2 Mesh Networks

Embedded mesh networks make radio systems more reliable by allowing radios to relay messages for other radios. For example, if a node cannot send a message directly to another node, the embedded mesh network relays the message through one or more intermediary nodes. As discussed in section 5.3 Routing, all router nodes in the Thread stack maintain routes and connectivity with each other so the mesh is constantly maintained and connected. There is a limit of 64 router addresses in the Thread network, but they cannot all be used at once. This allows time for the addresses of deleted devices to be reused.

In a mesh network, the sleepy end devices or router-eligible devices do not route for other devices. These devices send messages to a parent that is a router. This parent router handles the routing operations for its child devices.

5. Routing and Network Connectivity

The Thread network has up to 32 active routers that use next-hop routing for messages based on the routing table. The routing table is maintained by the Thread stack to ensure all routers have connectivity and up-to-date paths for any other router in the network. All routers exchange with other routers their cost of routing to other routers in the network in a compressed format using Mesh Link Establishment (MLE).

5.1 MLE Messages

Mesh Link Establishment (MLE) messages are used to establish and configure secure radio links, detect neighboring devices, and maintain routing costs between devices in the network. MLE operates below the routing layer and uses one hop link local unicasts and multicasts between routers.

MLE messages are used to identify, configure, and secure links to neighboring devices as the topology and physical environment change. MLE is also used to distribute configuration values that are shared across the network such as the channel and Personal Area Network (PAN) ID. These messages can be forwarded with simple flooding as specified by MPL (https://tools.ietf.org/html/draft-ietf-roll-trickle-mcast-11: *Multicast Protocol for Low power and Lossy Networks (MPL)*).

MLE messages also ensure asymmetric link costs are considered when establishing routing costs between two devices. Asymmetric link costs are common in 802.15.4 networks. To ensure two-way messaging is reliable, it is important to consider bidirectional link costs.

5.2 Route Discovery and Repair

On-demand route discovery is commonly used in low-power 802.15.4 networks. However, on-demand route discovery is costly in terms of network overhead and bandwidth because devices broadcast route discovery requests through the network. In the Thread stack, all routers exchange one-hop MLE packets containing cost information to all other routers in the network. All routers have up-to-date path cost information to any other router in the network so on-demand route discovery is not required. If a route is no longer usable, the routers can select the next most suitable route to the destination.

Routing to child devices is done by looking at the high bits of the child's address to determine the parent router address. Once the device knows the parent router, it knows the path cost information and next hop routing information for that device.

As route cost or the network topology change, the changes propagate through the network using the MLE single-hop messages. Routing cost is based on bidirectional link quality between two devices. The link quality in each direction is based on the link margin on incoming messages from that neighboring device. This incoming Received Signal Strength Indicator (RSSI) is mapped to a link quality from 0 to 3. A value of 0 means unknown cost.

When a router receives a new MLE message from a neighbor, either it already has a neighbor table entry for the device or one is added. The MLE message contains the incoming cost from the neighbor so this is updated in the router's neighbor table. The MLE message also contains updated routing information for other routers which is updated in the routing table.

The number of active routers is limited to the amount of routing and cost information that can be contained in a single 802.15.4 packet. This limit is currently 32 routers.

5.3 Routing

Devices use normal IP routing to forward packets. A routing table is populated with network addresses and the appropriate next hop.

Distance vector routing is used to get routes to addresses that are on the local network. When routing on the local network, the upper six bits of this 16-bit address define the router destination. This routing parent is then responsible for forwarding to the final destination based on the remainder of the 16-bit address.

For off network routing, a Border Router notifies the Router Leader of the particular prefixes it serves and distributes this information as network data within the MLE packets. The network data includes prefix data which is the prefix itself, the 6LoWPAN context, the Border Routers, and the Stateless Address Autoconfiguration (SLAAC) or DHCPv6 server for that prefix. If a device is to configure an address using that prefix, it contacts the appropriate SLAAC or DHCP server for this address. The network data also includes a list of routing servers that are the 16-bit addresses of the default Border Routers.

Additionally, in a commercial space with a Thread Domain model, a Backbone Border Router notifies the router leader of the Domain Unique Prefix it serves, to indicate that this mesh is part of the larger Thread domain. The network data for this includes prefix data, 6LoWPAN context, and the border router ALOC. There are no SLAAC or DHCPv6 flags set for this prefix set, however the address assignment follows the stateless model. Additionally, there are also service and server TLVs indicating the “backbone” service capability of this border router. Duplicate address detection capability over the backbone exists for any device that registers its Domain Unique Address (DUA) with the BBR. A device’s DUA never changes over its lifetime of being part of a Thread domain. This facilitates migration across different Thread networks in a single domain, and makes sure that the respective BBRs facilitate routing across multiple Thread networks. Over the backbone, standard IPv6 routing technologies such as IPv6 Neighbor Discovery (NS/NA as per RFC 4861) and Multicast Listener Discovery (MLDv2 as per RFC 3810) are used.

A Leader is designated to keep track of router-eligible devices becoming routers or allowing routers to downgrade to router-eligible devices. This Leader also assigns and manages the router addresses using CoAP. However, all information contained in this Leader is also periodically advertised to the other routers. If the Leader goes off the network, another router is elected, and takes over as Leader without user intervention.

Border Routers are responsible for handling 6LoWPAN compression or expansion and addressing to off network devices. Backbone Border Routers are responsible for handling MPL with IP-in-IP encapsulation and decapsulation for larger scope multicasts going into and out of the mesh.

For more information on Border Routers, consult *UG116*: *Developing Custom Border Router Applications*.

5.4 Retries and Acknowledgements

While UDP messaging is used in the Thread stack, reliable message delivery is required and completed by these lightweight mechanisms:

- MAC-level retries–each device uses MAC acknowledgements from the next hop and will retry a message at the MAC layer if the MAC ACK message is not received.
- Application-layer retries– the application layer can determine if message reliability is a critical parameter. If so, an end-to-end acknowledgement and retry protocol can be used, such as CoAP retries.

6. Joining a Network

Thread allows two joining methods:

- Share commissioning information directly to a device using an out-of-band method. This allows steering the device to the proper network using this information.
- Establish a commissioning session between a joining device and a commissioning application on a smartphone, tablet, or the web.
- <future>For a commercial network with a Thread domain model, an Autonomous Enrollment process without user intervention that provisions operational certificates on joiners after authentication is being defined in the Thread 1.2 specification, but is not yet supported in Silicon Labs Thread version 2.10.0. The operational certificate encodes the domain information for the device and allows secure Network Master Key provision. This model requires a registrar or Thread Registrar Interface (TRI) on a backbone border router, and facilitates communication with an external authority (MASA) using the ANIMA/BRSKI/EST protocols. A network that supports this commissioning model is called a CCM network.

The frequently used 802.15.4 method of joining with the permit joining flag in the beacon payload is not used in Thread networks. This method is most commonly used for push button type joining where there is no user interface or out-of-band channel to devices. This method has issues with device steering in situations where there are multiple networks available and it can also pose security risks.

In Thread networks, all joining is user-initiated. After joining, a security authentication is completed at the application level with a commissioning device. This security authentication is discussed in section 9. Security.

Devices join a network as either a sleepy end device, end device (MED or FED), or a REED. Only after a REED has joined and learned the network configuration can it potentially request to become a Thread Router. Upon joining, a device is provided a 16-bit short address based on its parent. If a router-eligible device becomes a Thread Router, it is assigned a router address by the Leader. Duplicate address detection for Thread Routers is ensured by the centralized router address distribution mechanism which resides on the Leader. The parent is responsible for avoiding duplicate addresses for host devices because it assigns addresses to them upon joining.

6.1 Network Discovery

Network discovery is used by a joining device to determine what 802.15.4 networks are within radio range. The device scans all channels, issues an MLE discovery request on each channel, and waits for MLE discovery responses. The 802.15.4 MLE discovery response contains a payload with network parameters, including the network Service Set Identifier (SSID), extended PAN ID, and other values that indicate if the network is accepting new members and whether it supports native commissioning.

Network discovery is not required if the device has been commissioned onto the network because it knows the channel and extended PAN ID for the network. These devices then attach to the network using the commissioning material provided.

6.2 MLE Data

Once a device has attached to a network, there is a variety of information required for it to participate in the network. MLE provides services for a device to send a unicast to a neighboring device to request network parameters and update link costs to neighbors. When a new device joins, it also conducts a challenge response to set security frame counters as discussed in Section 9. Security.

All devices support transmission and reception of MLE link configuration messages. This includes "link request", "link accept", and "link accept and request" messages.

The MLE exchange is used to configure or exchange the following information:

- The 16-bit short and 64 bit EUI 64 long address of neighboring devices
- Device capabilities information, including if it is a sleepy end device and the sleep cycle of the device
- Neighbor link costs if a Thread Router
- Security material and frame counters between devices
- Routing costs to all other Thread Routers in the network
- Collecting and distributing Link Metrics about various link configuration values

Note: MLE messages are encrypted except during the initial node bootstrapping operations when the new device has not obtained the security material.

6.3 CoAP

Constrained Application Protocol (CoAP) as defined in RFC 7252 (https://tools.ietf.org/html/rfc7252: *The Constrained Application Protocol (CoAP)*) is a specialized transport protocol for use with constrained nodes and low-power networks. CoAP provides a request/response interaction model between application endpoints, supports built-in discovery of services and resources, and includes key concepts of the web such as URLs. CoAP is used in Thread to configure mesh-local addresses and multicast addresses required by devices. Additionally, CoAP is also used for management messages such as to get and set diagnostic information and other network data on active Thread routers.

6.4 DHCPv6

DHCPv6 as defined in RFC 3315 is used as a client-server protocol to manage configuration of devices within the network. DHCPv6 uses UDP to request data from a DHCP server (https://www.ietf.org/rfc/rfc3315.txt: *Dynamic Host Configuration Protocol for IPv6 (DHCPv6)*).

The DHCPv6 service is used for configuration of:

- Network addresses
- Multicast addresses required by devices

Because short addresses are assigned from the server using DHCPv6, duplicate address detection is not required. DHCPv6 is also used by Border Routers that are assigning addresses based on the prefix they provide.

6.5 SLAAC

SLAAC (Stateless Address Autoconfiguration) as defined in RFC 4862 (https://tools.ietf.org/html/rfc4862: *IPv6 Stateless Address Autoconfiguration*) is a method in which a Border Router assigns a prefix, and then the last 64 bits of its address are derived by the router. The IPv6 stateless autoconfiguration mechanism requires no manual configuration of hosts, minimal (if any) configuration of routers, and no additional servers. The stateless mechanism allows a host to generate its own addresses using a combination of locally available information and information advertised by routers.

7. Management

7.1 ICMP

All devices support Internet Control Message Protocol for IPv6 (ICMPv6) error messages, as well as the echo request and echo reply messages.

7.2 Device Management

The application layer on a device has access to a set of device management and diagnostics information that can be used locally or collected and sent to other management devices.

At the 802.15.4 PHY and MAC layers, the device provides the following information to the management layer:

- EUI 64 address
- 16-bit short address
- Capability information
- PAN ID
- Packets sent and received
- Octets sent and received
- Packets dropped on transmit or receive
- Security errors
- Number of MAC retries

7.3 Network Management

The network layer on the device also provides information on management and diagnostics that can be used locally or sent to other management devices. The network layer provides the IPv6 address list, the neighbor and child table, and the routing table.

8. Persistent Data

Devices operating in the field may be reset accidentally or on purpose for a variety of reasons. Devices that have been reset need to restart network operations without user intervention. For this to be done successfully, non-volatile storage must store the following information:

- Network information (such as PAN ID)
- Security material
- Addressing information from the network to form the IPv6 addresses for the devices

9. Security

Thread Networks are wireless networks that need to be secured against over-the-air (OTA) attacks. They are also connected to the internet and therefore must be secured against internet attacks. Many of the applications being developed for Thread will serve a broad range of uses that require long periods of unattended operation and low power consumption. As a result, the security of Thread networks is critical.

Thread utilizes a network-wide key that is used at the Media Access Layer (MAC) for encryption. This key is used for standard IEEE 802.15.4-2006 authentication and encryption. IEEE 802.15.4-2006 security protects the Thread network from over-the-air attacks originating from outside the network. Compromise of any individual node could potentially reveal the network-wide key. As a result, it is usually not the only form of security used within the Thread network. Each node in the Thread network exchanges frame counters with its neighbors via an MLE handshake. These frame counters help protect against replay attacks. (For more information on MLE, see the Thread Specification.) Thread allows the application to use any internet security protocol for end-to-end communication.

Nodes obfuscate both their mesh-wide IP address interfaces and their MAC extended IDs by randomizing them. The stock EUI64 assigned to the node is used as a source address only during the initial join phase. Once a node is joined to a network, the node uses as its source either an address based on its two-byte node ID, or one of its randomized addresses mentioned above. The EUI64 is not used as a source address once the node is joined to a network.

Network management also needs to be secure. A Thread network management application can be run on any internet-connected device. If that device is not itself a member of a Thread network, it must first establish a secure Datagram Transport Layer Security (DTLS) connection with a Thread Border Router. Every Thread network has a management passphrase that is used in establishing this connection. Once a management application has been connected to the Thread network, new devices can be added to the network.

9.1 802.15.4 Security

The IEEE 802.15.4-2006 specification describes wireless and media access protocols for PANs and HANs. These protocols are intended for implementation on dedicated radio devices such as those available from Silicon Labs. IEEE 802.15.4-2006 supports a variety of applications, many of which are security-sensitive. For example, consider the case of an alarm system application that monitors building occupancy. If the network is not secure and an intruder gains access to the network, messages could be broadcast to create a false alarm, modify an existing alarm, or silence a legitimate alarm. Each of these situations poses significant risks to the building occupants.

Many applications require confidentiality and most also need integrity protection. 802-15.4-2006 addresses these requirements by using a link layer security protocol with four basic security services:

- Access control
- Message integrity
- Message confidentiality
- Replay protection

The replay protection provided by IEEE 802.15.4-2006 is only partial. Thread delivers additional security using MLE handshakes between nodes discussed above to complete the replay protection.

9.2 Secure Network Management

Network management also needs to be secure. A Thread network management application can be run on any internet-connected device. There are two parts to the security:

- Over-the-air security which 802.15.4 takes care of. Thread implements 802.15.4-2006 level 5 security.
- CCM networks: If a device is not itself a member of a CCM network, it must establish a connection with a backbone border router in order to obtain its operational certificate to establish itself as part of the Thread domain.
- Non-CCM networks: Internet security: If a device is not itself a member of a Thread network, it must first establish a secure Datagram Transit Layer Security (DTLS) connection with a Thread Border Router. Every Thread network has a management passphrase that is used for establishing secure connections between external management devices and Border Routers. Once a management application has been connected to the Thread network, new devices can be added to the network.

9.3 Non-CCM Device Commissioning

Thread uses the Mesh Commissioning Protocol (MeshCoP) to securely authenticate, commission, and join new, untrusted radio devices to a mesh network. Thread networks comprise an autonomous self-configuring mesh of devices with IEEE 802.15.4 interfaces and a link-level security layer that requires each device in the mesh to possess the current, shared secret master key.

The commissioning process begins when a Commissioner Candidate, typically a mobile phone connected via WiFi, discovers the Thread network through one of its Border Routers. Border Routers advertise their availability to Commissioners using whatever service location is appropriate. The discovery mechanism must provide a Commissioner Candidate both a communication path and the network name, because the network name is used later as a cryptographic salt for establishing the Commissioning Session.

The Commissioner Candidate, after having discovered the Thread network of interest, securely connects to it using the Commissioning Credential (a human-selected passphrase for use in authenticating). The Commissioner Authentication step establishes a secure client/server socket connection between the Commissioner Candidate and a Border Router via DTLS. This secure session is known as a Commissioning Session. The Commissioning Session uses the assigned UDP port number advertised during the discovery phase. This port is known as the Commissioner Port. The credential used to establish the Commissioning Session is known as the Pre-Shared Key for the Commissioner (PSKc).

The Commissioner Candidate then registers its identity with its Border Router. The Leader responds by either accepting or rejecting the Border Router as a viable forwarder to the Commissioner. Upon acceptance, the Leader updates its internal state to track the active Commissioner, and the Border Router then sends a confirmation message to the Commissioner Candidate informing the device that it is now the Commissioner.

When there is an authorized Commissioner associated with the Thread Network, it becomes possible to join eligible Thread Devices. These are known as Joiners before they become part of the Thread network. The Joiner first creates a DTLS connection with the Commissioner to exchange commissioning material. It then uses the commissioning material to attach to the Thread network. The node is considered part of the network only after these two steps are complete, and may then participate in the join process for future nodes. All of these steps confirm that the correct device has joined the correct Thread network, and that the Thread network itself is secure against wireless and internet attacks. For more information on the Mesh Commissioning Protocol, see the Thread specification.

10. Application Layer

Thread is a wireless mesh networking stack that is responsible for routing messages between different devices in the Thread network described in section 2.2 Thread Network Architecture. The following figure illustrates the layers in the Thread protocol.

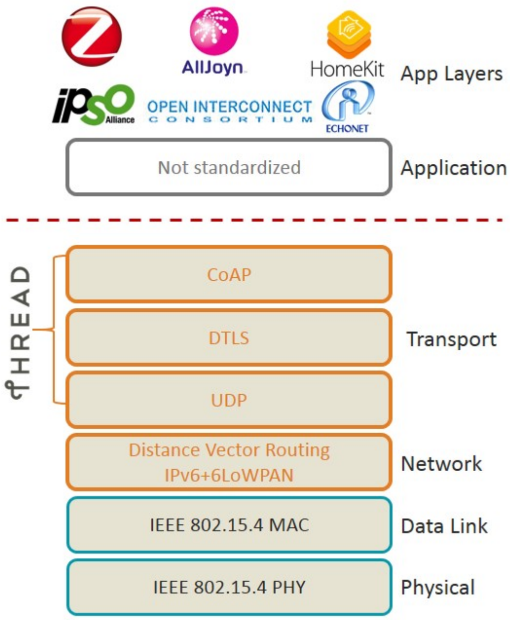


Figure 10.1. Thread Protocol Layers

A standard definition of an application layer is an “abstraction layer that specifies the shared protocols and interface methods used by hosts in a communications network” (https://en.wikipedia.org/wiki/Application_layer). Put more simply, an application layer is the “language of devices,” for example, how a switch talks to a light bulb. Using these definitions, an application layer does not exist in Thread. Customers build the application layer based on the capabilities in the Thread stack and their own requirements. Although Thread does not supply an application layer, it does provide basic application services:

- UDP messaging

  UDP offers a way to send messages using a 16-bit port number and an IPv6 address. UDP is a simpler protocol than TCP and has less connection overhead (for example, UDP does not implement keep-alive messages). As a result, UDP enables a faster, higher throughput of messages and reduces the overall power budget of an application. UDP also has a smaller code space than TCP, which leaves more available flash on the chip for custom applications.
- Multicast messaging

  Thread provides the ability to broadcast messages, that is, sending the same message to multiple nodes on a Thread network. Multicast allows a built-in way to talk to neighbor nodes, routers, and an entire Thread network with standard IPv6 addresses.
- Application layers using IP services

  Thread allows the use of application layers such as UDP and CoAP to allow devices to communicate interactively over the Internet. Non-IP application layers will require some adaptation to work on Thread. (See RFC 7252 for more information on CoAP.)

Often, one of the key requirements for an application layer is multivendor interoperability. Defining a multivendor, interoperable application layer is a major undertaking, and customers have several options. Silicon Labs believes that for IoT devices, one of the most promising and complete application layers for Thread is dotdot, which the zigbee alliance released in 2017. dotdot is a common language for smart objects, so they can speak to each other effortlessly on any network. Using dotdot, Silicon Labs has developed an application layer based on the zigbee Cluster Library (ZCL), as described in section 11. dotdot and ZCL over IP. The implementation is provided with the Silicon Labs Thread stack.

Silicon Labs has developed two example applications, client and server, that demonstrate basic interoperability features of the Thread network and how to build a simple client and server example, including a sleepy end device. Two other example applications, light and switch, demonstrate use of the ZCL over IP application layer to make a simple network. See *QSG113: Getting Started with Silicon Labs Thread* for more information on working with example applications in Simplicity Studio.

11. dotdot and ZCL over IP

dotdot is developed and certified by the Zigbee Alliance. It is a generalization of all of the application layer functionality developed both in Zigbee PRO and the Zigbee Cluster Library (ZCL) for use over a variety of transports. The first transport to implement dotdot outside of Zigbee PRO is ZCL over IP (ZCL/IP). This implementation provides the functionality of ZCL using a RESTful (representational state transfer) interface. REST-compliant Web services allow requesting systems to access and manipulate textual representations of Web resources using a uniform and predefined set of stateless operations.

Silicon Labs includes this implementation as part of the Silicon Labs Thread stack. This section provides general background on dotdot and ZCL/IP. For more details see *UG278: ZCL over IP User's Guide*. For more details about the Zigbee protocol see *UG103.02: Zigbee Fundamentals*.

11.1 About Zigbee PRO and the Zigbee Cluster Library

Because ZCL/IP is essentially an implementation of the functionality in the Zigbee PRO protocol stack, and in particular ZCL, discussions of dotdot use some standard Zigbee terminology.

- Endpoints: Represent different applications on a device.

  Example: A light strip could have multiple lights each with its own endpoint.
- Zigbee Device Profile (ZDP)

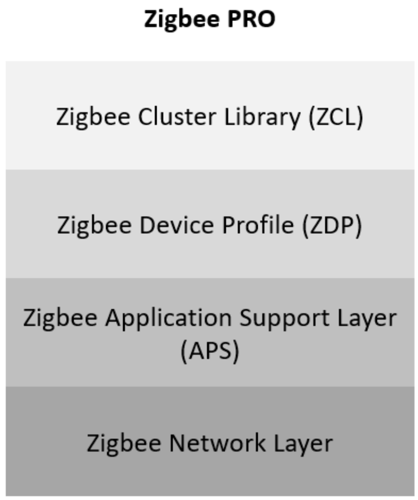
  In Zigbee, entities like bindings and device discovery services are managed through the APS layer and its ZDP management commands.

  In Zigbee, the ZDP is accessible on a special endpoint, Endpoint 0 using ZDP commands.
- Clusters (ZCL): Represent different aspects of a device's functionality on a given endpoint.

  For example: The On/Off Cluster contains all the functionality related to turning a device on and off and saving its on/off state.
- Commands: Used to take action on a device. Commands come in two flavors:
  - General Commands: Take action on the resources on a device.
  - Cluster Commands: Take action on a specific piece of functionality on a device.
- Attributes: Represent a stored value on a device.

  Attributes are contained within clusters and represent the state of a device on a specific endpoint, for a specific cluster.

The Zigbee PRO protocol contents are shown in the following figure.



Zigbee PRO contains:

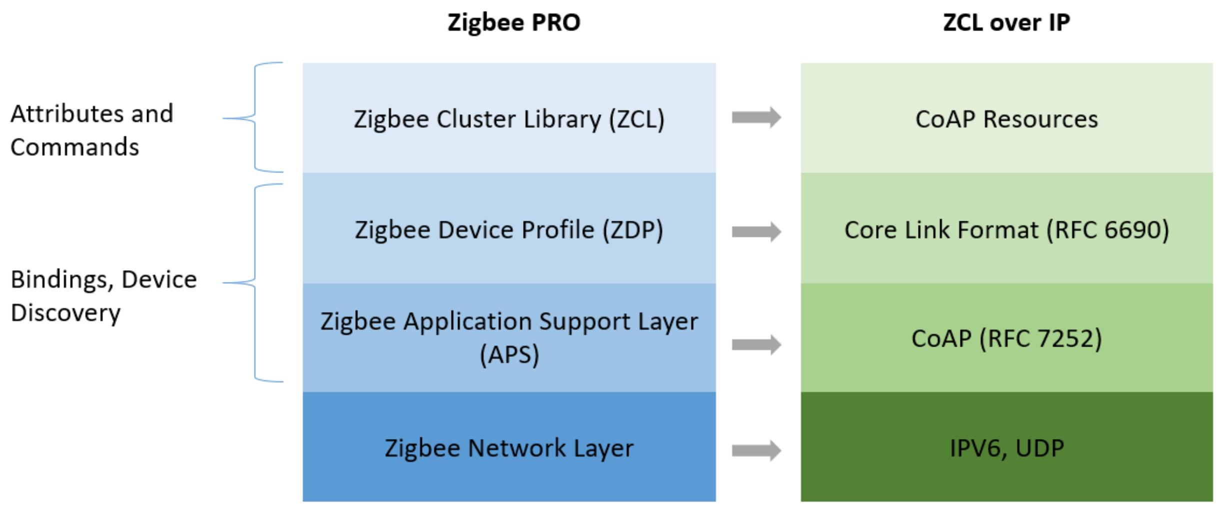
- Zigbee Device Objects (ZDO): Used to access general information about a device, how it is configured and what services it offers.
- ZDP Commands: Used to create and manage bindings on a device. Bindings determine how a device is provisioned on a network.
- ZCL General Commands: Used to access resources on a device including attribute and reporting configuration read and write.
- Cluster functionality: Used to take action on and store the specific state of a device.
- Cluster commands: Expose functions on a device for a given cluster (example: On command in the On/Off cluster).
- Cluster attributes: Expose state on a device for a given cluster (example: OnOff attribute in the On/Off cluster).

11.2 About ZCL/IP

ZCL/IP uses several Internet Engineering Task Force (IETF) documents to map Zigbee into the world of IP and a RESTful interface.

- Constrained RESTful Environments (CoRE) Link Format (RFC 6690)
- Constrained Application Protocol (CoAP) (RFC 7252)
- Concise Binary Object Representation (CBOR) (RFC 7049)

The mapping is reflected in the following figure:



- ZDO information is available through queries using the CoRE Link Format
- ZDP commands are available through CoAP methods GET, PUT, POST, and DELETE
- ZCL General Commands and Cluster commands are accessible through CoAP methods GET, PUT, POST and DELETE
- ZCL General and Cluster response commands are returned in CoAP responses
- ZCL payloads are encoded in CBOR which makes them small and scalable

ZCL/IP follows a RESTful design in which each transaction consists of an originating CoAP Method (GET, PUT, POST, DELETE) and a corresponding CoAP response such as 2.05 Content or, in an error case, 4.05 method not allowed.

Note: Zigbee Command IDs are sometimes included in the originating URI but are excluded from the CoAP response.

11.2.1 The CoRE Link Format

Discovery of a device's exposed functionality, which in Zigbee is accessible through ZDP discovery commands, is available through CoAP `GET` to `.well-known/core`.

Example: Multicast query used to discover Zigbee endpoints implementing the client side of the on/off cluster (ClusterID 0x0006).

```
GET COAP://[FF05::FD]/.well-known/core?rt=urn:zcl:c:6.c
```

Returns a CoAP response code 2.05 (content) with the information about which endpoint implements this cluster

```
2.05 Content (Content-Format: application/link-format (40))
<coap://[2002:8290:4eed::8290:4eed]/zcl/e/1/c6>;rt=urn:zcl:c:6.c;ze=urn:z:cl:d.103.1
```

11.2.2 CoAP

ZCL/IP Resources are summarized in the following table:

Resource	Methods	URI
Resource discovery	GET	/zcl
Endpoints	GET	/e
Attributes	GET, PUT, POST	/a
Commands	GET, POST	/c
Bindings	GET, PUT, POST, DELETE	/b
Report Configuration	GET, PUT, POST, DELETE	/r
Report Notification	POST	/n
Group Notification	POST	/g
EZ-Mode Commissioning	GET, POST	/m

CoAP methods such as GET, PUT, POST, and DELETE to /b provide functionality equivalent to ZDP commands such as those involved in creating and managing bindings:

Example: To retrieve the binding located at index 0 the device would send:

```
GET  coap://[2002:8290:4eed::8290:4eed]/zcl/e/1/s6/b/0
```

These CoAP methods provide functionality equivalent to ZCL General commands.

```
GET to /a/<aid> = ReadAttributes
PUT, POST to /a/<aid> = WriteAttributes
GET to /a = DiscoverAttributes
PUT, POST, DELETE to /r/<rid> = ConfigureReporting
GET to /r/<rid> = ReadReportingConfiguration
POST to /n = ReportAttributes
GET to /c = DiscoverCommandsReceived
```

For example:

ReadAttribute on the OnOff attribute on the On/Off cluster (0x0006) on Endpoint 1 becomes:

```
GET coap://[2002:8290:4eed::8290:4eed]/zcl/e/1/s6/a/0
```

ReadAttributesResponse on the OnOff attribute on the On/Off cluster (0x0006) on endpoint 1 becomes:

```
CoAP Response 2.05 Content with a CBOR map {0:0}
indicating that the OnOff attribute is currently in the Off state.
```

Finally the CoAP method POST to /c/<cid> is used for ZCL Cluster command functionality. ZCL Cluster command responses map to the CoAP responses.

For example: On Command sent to endpoint 1 becomes:

```
POST coap://[2002:8290:4eed::8290:4eed]/zcl/e/1/s6/c/1
```

CoAP response 2.04 Changed with a payload {0:0} indicating a Default Response with status SUCCESS.

11.2.3 CBOR

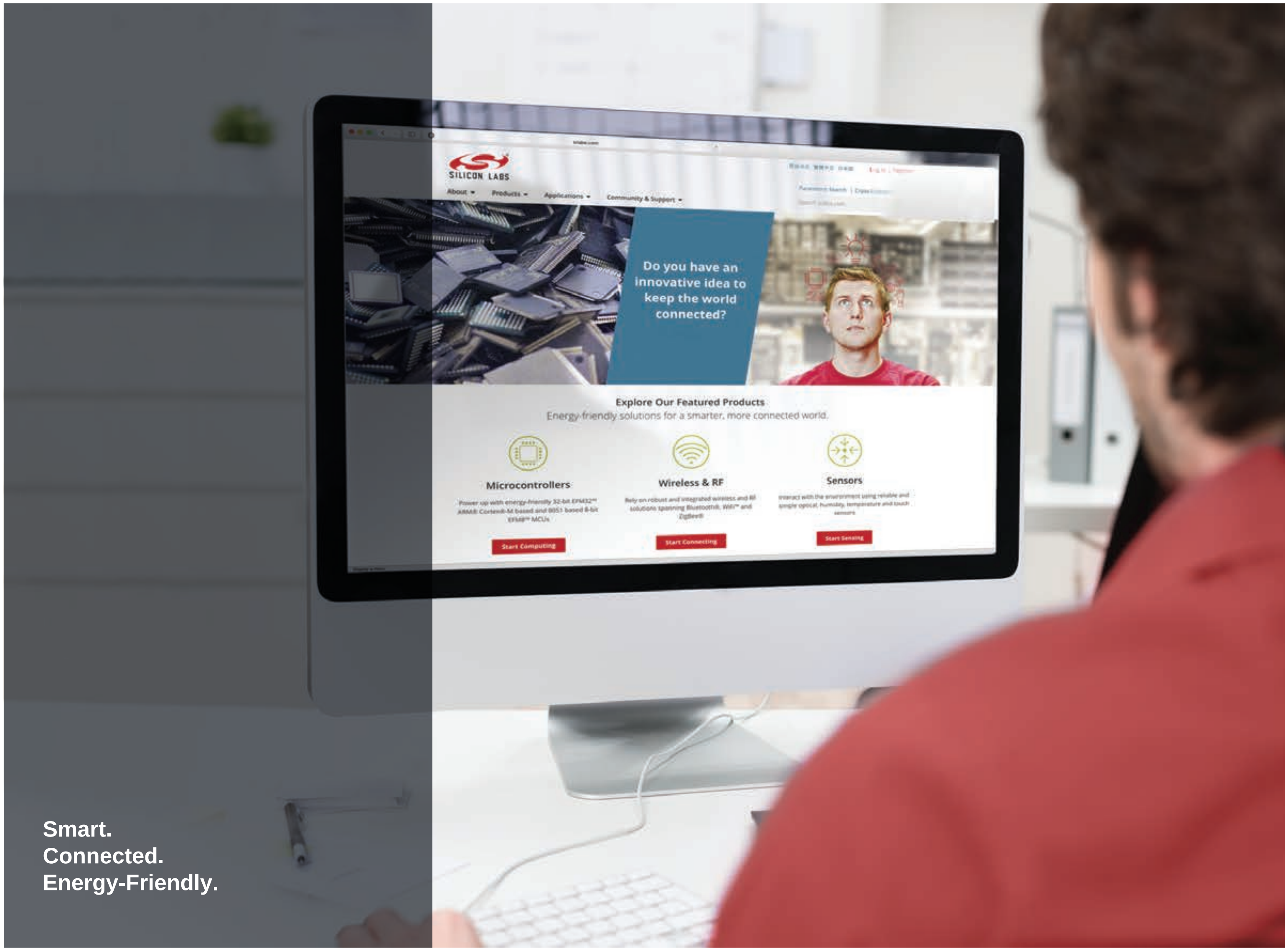
Concise Binary Object Representation (CBOR) is a data format that allows for small code size and reasonably small message sizes and extensibility. CBOR does not require a schema. CBOR uses an extended version of JSON as its underlying data model. The dotdot designers selected CBOR as the encoding scheme because of these characteristics. It provides an efficient representation for the objects needed by dotdot

12. Next Steps

The Thread software includes a certified Thread networking stack and sample applications that demonstrate basic network and application behavior. Customers are encouraged to use the included sample applications to gain familiarity with Thread in general and the Silicon Labs offering in particular. Each of the applications demonstrates how devices form and join networks, as well as how messages are sent and received. The applications are available for use after loading the Thread stack and Simplicity Studio. Simplicity Studio includes support for creating applications (AppBuilder) and decoding the network and application-layer messages (Network Analyzer) in Thread that provide additional insight into the operation of Thread networks. For more information, see *QSG113*: *Getting Started with Silicon Labs Thread*.

For more information about Thread Border Routers see *UG116: Developing Custom Border Router Applications*.

For more information about working with Thread Commercial networks see *AN1198: Using the Thread 1.2 Commercial Support Features*.



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