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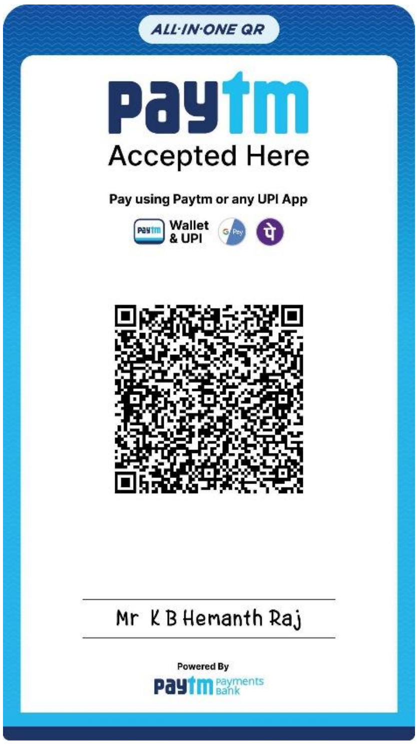

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IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Things

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Chapter 5

IP as the IoT Network Layer

In Chapter 4, "Connecting Smart Objects," you learned about the important considerations in creating an IoT network and common protocols employed by smart objects to access and communicate with a network. Chapter 4 focuses on connectivity at Layer 1 (PHY) and Layer 2 (MAC). In this chapter, we move up the protocol stack and extend the conversation to network layer connectivity, which is commonly referred to as Layer 3. Referring back to the Core IoT Functional Stack introduced in Figure 2-7, this chapter covers the network transport layer sublayer that is part of the communications network layer. Alternatively, you can also align this chapter with the network layer of the oneM2M architecture shown in Figure 2-1 or the connectivity layer of the IoT World Forum architecture detailed in Figure 2-3 if these models are preferable.

This chapter is composed of the following sections:

- **The Business Case for IP:** This section discusses the advantages of IP from an IoT perspective and introduces the concepts of adoption and adaptation.
- **The Need for Optimization:** This section dives into the challenges of constrained nodes and devices when deploying IP. This section also looks at the migration from IPv4 to IPv6 and how it affects IoT networks.
- **Optimizing IP for IoT:** This section explores the common protocols and technologies in IoT networks utilizing IP, including 6LoWPAN, 6TiSCH, and RPL.
- **Profiles and Compliances:** This section provides a summary of some of the most significant organizations and standards bodies involved with IP connectivity and IoT.

This chapter builds on many of the technologies introduced in previous ones. In fact, protocols and technologies from these chapters are often paired together and developed with this pairing in mind. For example, 802.15.4 and 6LoWPAN are a combination that is paired together frequently for many applications.

This chapter has a deliberate focus on IP, which has become the de facto standard in many areas of IoT. With support from numerous standards and industry organizations, IP and its role as the network layer transport for IoT is a foundational element that you should be familiar with.

The Business Case for IP

Data flowing from or to "things" is consumed, controlled, or monitored by data center servers either in the cloud or in locations that may be distributed or centralized. Dedicated applications are then run over virtualized or traditional operating systems or on network edge platforms (for example, fog computing). These lightweight applications communicate with the data center servers. Therefore, the system solutions combining various physical and data link layers call for an architectural approach with a common layer(s) independent from the lower (connectivity) and/or upper (application) layers. This is how and why the Internet Protocol (IP) suite started playing a key architectural role in the early 1990s. IP was not only preferred in the IT markets but also for the OT environment.

The Key Advantages of Internet Protocol

One of the main differences between traditional information technology (IT) and operational technology (OT) is the lifetime of the underlying technologies and products. (For more information on IT and OT, refer to Chapter 1, "What Is IoT?") An entire industrial workflow generally mandates smooth, incremental steps that evolve, with operations itself being the most time- and mission-critical factor for an organization.

One way to guarantee multi-year lifetimes is to define a layered architecture such as the 30-year-old IP architecture. IP has largely demonstrated its ability to integrate small and large evolutions. At the same time, it is able to maintain its operations for large numbers of devices and users, such as the 3 billion Internet users.

Note Using the Internet Protocol suite does not mean that an IoT infrastructure running IP has to be an open or publicly accessible network. Indeed, many existing mission-critical but private and highly secure networks, such as inter-banking networks, military and defense networks, and public-safety and emergency-response networks, use the IP architecture.

Before evaluating the pros and cons of IP adoption versus adaptation, this section provides a quick review of the key advantages of the IP suite for the Internet of Things:

- **Open and standards-based:** Operational technologies have often been delivered as turnkey features by vendors who may have optimized the communications through closed and proprietary networking solutions. The Internet of Things creates a new paradigm in which devices, applications, and users can leverage a large set of devices and functionalities while guaranteeing interchangeability and interoperability, security, and management. This calls for implementation, validation, and deployment of open, standards-based solutions. While many standards development organizations (SDOs) are working on Internet of Things definitions, frameworks, applications, and technologies, none are questioning the role of the Internet Engineering Task Force (IETF) as the foundation for specifying and optimizing the network and transport layers. The IETF is an open standards body that focuses on the development of the Internet Protocol suite and related Internet technologies and protocols.

- **Versatile:** A large spectrum of access technologies is available to offer connectivity of "things" in the last mile. Additional protocols and technologies are also used to transport IoT data through backhaul links and in the data center. Even if physical and data link layers such as Ethernet, Wi-Fi, and cellular are widely adopted, the history of data communications demonstrates that no given wired or wireless technology fits all deployment criteria. Furthermore, communication technologies evolve at a pace faster than the expected 10- to 20-year lifetime of OT solutions. So, the layered IP architecture is well equipped to cope with any type of physical and data link layers. This makes IP ideal as a long-term investment because various protocols at these layers can be used in a deployment now and over time, without requiring changes to the whole solution architecture and data flow.

- **Ubiquitous:** All recent operating system releases, from general-purpose computers and servers to lightweight embedded systems (TinyOS, Contiki, and so on), have an integrated dual (IPv4 and IPv6) IP stack that gets enhanced over time. In addition, IoT application protocols in many industrial OT solutions have been updated in recent years to run over IP. While these updates have mostly consisted of IPv4 to this point, recent standardization efforts in several areas are adding IPv6. In fact, IP is the most pervasive protocol when you look at what is supported across the various IoT solutions and industry verticals.

- **Scalable:** As the common protocol of the Internet, IP has been massively deployed and tested for robust scalability. Millions of private and public IP infrastructure nodes have been operational for years, offering strong foundations for those not familiar with IP network management. Of course, adding huge numbers of "things" to private and public infrastructures may require optimizations and design rules specific to the new devices. However, you should realize that this is not very different from the recent evolution of voice and video endpoints integrated over IP. IP has proven before that scalability is one of its strengths.

- **Manageable and highly secure:** Communications infrastructure requires appropriate management and security capabilities for proper operations. One of the benefits that comes from 30 years of operational IP networks is the well-understood network management and security protocols, mechanisms, and toolsets that are widely available. Adopting IP network management also brings an operational business application to OT. Well-known network and security management tools are easily leveraged with an IP network layer. However, you should be aware that despite the secure nature of IP, real challenges exist in this area. Specifically, the industry is challenged in securing constrained nodes, handling legacy OT protocols, and scaling operations.

- **Stable and resilient:** IP has been around for 30 years, and it is clear that IP is a workable solution. IP has a large and well-established knowledge base and, more importantly, it has been used for years in critical infrastructures, such as financial and defense networks. In addition, IP has been deployed for critical services, such as voice and video, which have already transitioned from closed environments to open IP standards. Finally, its stability and resiliency benefit from the large ecosystem of IT professionals who can help design, deploy, and operate IP-based solutions.
- **Consumers' market adoption:** When developing IoT solutions and products targeting the consumer market, vendors know that consumers' access to applications and devices will occur predominantly over broadband and mobile wireless infrastructure. The main consumer devices range from smart phones to tablets and PCs. The common protocol that links IoT in the consumer space to these devices is IP.
- **The innovation factor:** The past two decades have largely established the adoption of IP as a factor for increased innovation. IP is the underlying protocol for applications ranging from file transfer and e-mail to the World Wide Web, e-commerce, social networking, mobility, and more. Even the recent computing evolution from PC to mobile and mainframes to cloud services are perfect demonstrations of the innovative ground enabled by IP. Innovations in IoT can also leverage an IP underpinning.

In summary, the adoption of IP provides a solid foundation for the Internet of Things by allowing secured and manageable bidirectional data communication capabilities between all devices in a network. IP is a standards-based protocol that is ubiquitous, scalable, versatile, and stable. Network services such as naming, time distribution, traffic prioritization, isolation, and so on are well-known and developed techniques that can be leveraged with IP. From cloud, centralized, or distributed architectures, IP data flow can be developed and implemented according to business requirements. However, you may wonder if IP is an end-to-end requirement; this is covered in the next section.

Adoption or Adaptation of the Internet Protocol

How to implement IP in data center, cloud services, and operation centers hosting IoT applications may seem obvious, but the adoption of IP in the last mile is more complicated and often makes running IP end-to-end more difficult.

If we look at the historical trend of IP adoption by IT in general, we can glean some insight into how IP adoption in the last mile should unfold. Before IPv4 was widely accepted and deployed in IT networks, many different protocol stacks overlapped with IP. For example, X.25/X.75 was standardized and promoted by service providers, while computer manufacturers implemented their own proprietary protocols, such as SNA, DECnet, IPX, and AppleTalk. Multiprotocol routers were needed to handle this proliferation of network layer protocols.

The use of numerous network layer protocols in addition to IP is often a point of contention between computer networking experts. Typically, one of two models, adaptation or adoption, is proposed:

- *Adaptation* means application layered gateways (ALGs) must be implemented to ensure the translation between non-IP and IP layers.
- *Adoption* involves replacing all non-IP layers with their IP layer counterparts, simplifying the deployment model and operations.

A similar transition is now occurring with IoT and its use of IP connectivity in the last mile. While IP is slowly becoming more prevalent, alternative protocol stacks are still often used. Let's look at a few examples in various industries to see how IP adaptation and adoption are currently applied to IoT last-mile connectivity.

In the industrial and manufacturing sector, there has been a move toward IP adoption. Solutions and product lifecycles in this space are spread over 10+ years, and many protocols have been developed for serial communications. While IP and Ethernet support were not specified in the initial versions, more recent specifications for these serial communications protocols integrate Ethernet and IPv4.

Supervisory control and data acquisition (SCADA) applications are typical examples of vertical market deployments that operate both the IP adaptation model and the adoption model. Found at the core of many modern industries, SCADA is an automation control system for remote monitoring and control of equipment. Implementations that make use of IP adaptation have SCADA devices attached through serial interfaces to a gateway tunneling or translating the traffic. With the IP adoption model, SCADA devices are attached via Ethernet to switches and routers forwarding their IPv4 traffic. (For more information on SCADA, see Chapter 6, "Application Protocols for IoT.")

Another example is a ZigBee solution that runs a non-IP stack between devices and a ZigBee gateway that forwards traffic to an application server. (For more information on ZigBee, see Chapter 4.) A ZigBee gateway often acts as a translator between the ZigBee and IP protocol stacks.

As highlighted by these examples, the IP adaptation versus adoption model still requires investigation for particular last-mile technologies used by IoT. You should consider the following factors when trying to determine which model is best suited for last-mile connectivity:

- **Bidirectional versus unidirectional data flow:** While bidirectional communications are generally expected, some last-mile technologies offer optimization for unidirectional communication. For example, as introduced in Chapter 4, different classes of IoT devices, as defined in RFC 7228, may only infrequently need to report a few bytes of data to an application. These sorts of devices, particularly ones that communicate through LPWA technologies, include fire alarms sending alerts or daily test reports, electrical switches being pushed on or off, and water or gas meters sending weekly indexes. LPWA is further discussed in Chapter 4. For these cases, it is not necessarily worth implementing a full IP stack. However, it requires the overall end-to-end architecture to solve potential drawbacks; for example, if there is only one-way communication to upload data to an application, then it is not possible to download new software or firmware to the devices. This makes integrating new features and bug and security fixes more difficult.

- **Overhead for last-mile communications paths:** IP adoption implies a layered architecture with a per-packet overhead that varies depending on the IP version. IPv4 has 20 bytes of header at a minimum, and IPv6 has 40 bytes at the IP network layer. For the IP transport layer, UDP has 8 bytes of header overhead, while TCP has a minimum of 20 bytes. If the data to be forwarded by a device is infrequent and only a few bytes, you can potentially have more header overhead than device data—again, particularly in the case of LPWA technologies. Consequently, you need to decide whether the IP adoption model is necessary and, if it is, how it can be optimized. This same consideration applies to control plane traffic that is run over IP for low-bandwidth, last-mile links. Routing protocol and other verbose network services may either not be required or call for optimization.
- **Data flow model:** One benefit of the IP adoption model is the end-to-end nature of communications. Any node can easily exchange data with any other node in a network, although security, privacy, and other factors may put controls and limits on the "end-to-end" concept. However, in many IoT solutions, a device's data flow is limited to one or two applications. In this case, the adaptation model can work because translation of traffic needs to occur only between the end device and one or two application servers. Depending on the network topology and the data flow needed, both IP adaptation and adoption models have roles to play in last-mile connectivity.
- **Network diversity:** One of the drawbacks of the adaptation model is a general dependency on single PHY and MAC layers. For example, ZigBee devices must only be deployed in ZigBee network islands. This same restriction holds for ITU G.9903 G3-PLC nodes. Therefore, a deployment must consider which applications have to run on the gateway connecting these islands and the rest of the world. Integration and coexistence of new physical and MAC layers or new applications impact how deployment and operations have to be planned. This is not a relevant consideration for the adoption model.

The Need for Optimization

As discussed in the previous section, the Internet of Things will largely be built on the Internet Protocol suite. However, challenges still exist for IP in IoT solutions. In addition to coping with the integration of non-IP devices, you may need to deal with the limits at the device and network levels that IoT often imposes. Therefore, optimizations are needed at various layers of the IP stack to handle the restrictions that are present in IoT networks.

The following sections take a detailed look at why optimization is necessary for IP. Both the nodes and the network itself can often be constrained in IoT solutions. Also, IP is transitioning from version 4 to version 6, which can add further confinements in the IoT space.

Constrained Nodes

As documented in Table 4-1 in Chapter 4, in IoT solutions, different classes of devices coexist. Depending on its functions in a network, a "thing" architecture may or may not offer similar characteristics compared to a generic PC or server in an IT environment.

Another limit is that this network protocol stack on an IoT node may be required to communicate through an unreliable path. Even if a full IP stack is available on the node, this causes problems such as limited or unpredictable throughput and low convergence when a topology change occurs.

Finally, power consumption is a key characteristic of constrained nodes. Many IoT devices are battery powered, with lifetime battery requirements varying from a few months to 10+ years. This drives the selection of networking technologies since high-speed ones, such as Ethernet, Wi-Fi, and cellular, are not (yet) capable of multi-year battery life. Current capabilities practically allow less than a year for these technologies on battery-powered nodes. Of course, power consumption is much less of a concern on nodes that do not require batteries as an energy source.

You should also be aware that power consumption requirements on battery-powered nodes impact communication intervals. To help extend battery life, you could enable a "low-power" mode instead of one that is "always on." Another option is "always off," which means communications are enabled only when needed to send data.

While it has been largely demonstrated that production IP stacks perform well in constrained nodes, classification of these nodes helps when evaluating the IP adoption versus adaptation model selection. IoT constrained nodes can be classified as follows:

- **Devices that are very constrained in resources, may communicate infrequently to transmit a few bytes, and may have limited security and management capabilities:** This drives the need for the IP adaptation model, where nodes communicate through gateways and proxies.
- **Devices with enough power and capacities to implement a stripped-down IP stack or non-IP stack:** In this case, you may implement either an optimized IP stack and directly communicate with application servers (adoption model) or go for an IP or non-IP stack and communicate through gateways and proxies (adaptation model).
- **Devices that are similar to generic PCs in terms of computing and power resources but have constrained networking capacities, such as bandwidth:** These nodes usually implement a full IP stack (adoption model), but network design and application behaviors must cope with the bandwidth constraints.

You probably already realize that the definition of constrained nodes is evolving. The costs of computing power, memory, storage resources, and power consumption are generally decreasing. At the same time, networking technologies continue to improve and offer more bandwidth and reliability. In the future, the push to optimize IP for constrained nodes will lessen as technology improvements and cost decreases address many of these challenges.

Constrained Networks

In the early years of the Internet, network bandwidth capacity was restrained due to technical limitations. Connections often depended on low-speed modems for transferring data. However, these low-speed connections demonstrated that IP could run over low-bandwidth networks.

Fast forward to today, and the evolution of networking has seen the emergence of high-speed infrastructures. However, high-speed connections are not usable by some IoT devices in the last mile. The reasons include the implementation of technologies with low bandwidth, limited distance and bandwidth due to regulated transmit power, and lack of or limited network services. When link layer characteristics that we take for granted are not present, the network is constrained. A constrained network can have high latency and a high potential for packet loss.

Note Constrained networks are often referred to as low-power and lossy networks (LLNs). *Lossy* in this context refers to network unreliability that is caused by disruptions in the data flow or packet loss. LLNs were defined by the IETF's Routing over Low-Power and Lossy Networks (RoLL) working group when developing the IPv6 RPL protocol. An IETF working group is an open discussion group of individuals in a particular technology area. They have a charter that defines their focus and what they are expected to produce. If you are interested in the work of the RoLL working group, see https://datatracker.ietf.org/wg/roll/documents/. (RPL is discussed in more detail later in this chapter.)

Constrained networks have unique characteristics and requirements. In contrast with typical IP networks, where highly stable and fast links are available, constrained networks are limited by low-power, low-bandwidth links (wireless and wired). They operate between a few kbps and a few hundred kbps and may utilize a star, mesh, or combined network topologies, ensuring proper operations.

With a constrained network, in addition to limited bandwidth, it is not unusual for the packet delivery rate (PDR) to oscillate between low and high percentages. Large bursts of unpredictable errors and even loss of connectivity at times may occur. These behaviors can be observed on both wireless and narrowband power-line communication links, where packet delivery variation may fluctuate greatly during the course of a day.

Unstable link layer environments create other challenges in terms of latency and control plane reactivity. One of the golden rules in a constrained network is to "underreact to failure." Due to the low bandwidth, a constrained network that overreacts can lead to a network collapse—which makes the existing problem worse.

Control plane traffic must also be kept at a minimum; otherwise, it consumes the bandwidth that is needed by the data traffic. Finally, you have to consider the power consumption in battery-powered nodes. Any failure or verbose control plane protocol may reduce the lifetime of the batteries.

In summary, constrained nodes and networks pose major challenges for IoT connectivity in the last mile. This in turn has led various standards organizations to work on optimizing protocols for IoT. This optimization for IP is discussed in more detail later in this chapter.

Note In addition to optimizing protocols for IoT, the IETF is publishing guidelines for IoT implementation. Much of this work is occurring in the IETF Light-Weight Implementation Guidance (LWIG) working group. For more information on the work of this working group, see https://datatracker.ietf.org/wg/lwig/documents/.

IP Versions

For 20+ years, the IETF has been working on transitioning the Internet from IP version 4 to IP version 6. The main driving force has been the lack of address space in IPv4 as the Internet has grown. IPv6 has a much larger range of addresses that should not be exhausted for the foreseeable future. Today, both versions of IP run over the Internet, but most traffic is still IPv4 based.

Note A full discussion of the benefits and characteristics of IPv6 is beyond the scope of this book. For a more detailed look at IPv6, please refer to the Cisco Press book *IPv6 Fundamentals: A Straightforward Approach to Understanding IPv6.*

While it may seem natural to base all IoT deployments on IPv6, you must take into account current infrastructures and their associated lifecycle of solutions, protocols, and products. IPv4 is entrenched in these current infrastructures, and so support for it is required in most cases. Therefore, the Internet of Things has to follow a similar path as the Internet itself and support both IPv4 and IPv6 versions concurrently. Techniques such as tunneling and translation need to be employed in IoT solutions to ensure interoperability between IPv4 and IPv6.

A variety of factors dictate whether IPv4, IPv6, or both can be used in an IoT solution. Most often these factors include a legacy protocol or technology that supports only IPv4. Newer technologies and protocols almost always support both IP versions. The following are some of the main factors applicable to IPv4 and IPv6 support in an IoT solution:

- **Application Protocol:** IoT devices implementing Ethernet or Wi-Fi interfaces can communicate over both IPv4 and IPv6, but the application protocol may dictate the choice of the IP version. For example, SCADA protocols such as DNP3/IP (IEEE 1815), Modbus TCP, or the IEC 60870-5-104 standards are specified only for IPv4, as discussed in Chapter 6. So, there are no known production implementations by vendors of these protocols over IPv6 today. For IoT devices with application protocols defined by the IETF, such as HTTP/HTTPS, CoAP, MQTT, and XMPP, both IP versions are supported. (For more information on these IoT application layer protocols, see Chapter 6.) The selection of the IP version is only dependent on the implementation.

- **Cellular Provider and Technology:** IoT devices with cellular modems are dependent on the generation of the cellular technology as well as the data services offered by the provider. For the first three generations of data services—GPRS, Edge, and 3G—IPv4 is the base protocol version. Consequently, if IPv6 is used with these generations, it must be tunneled over IPv4. On 4G/LTE networks, data services can use IPv4 or IPv6 as a base protocol, depending on the provider.

- **Serial Communications:** Many legacy devices in certain industries, such as manufacturing and utilities, communicate through serial lines. Data is transferred using either proprietary or standards-based protocols, such as DNP3, Modbus, or IEC 60870-5-101. In the past, communicating this serial data over any sort of distance could be handled by an analog modem connection. However, as service provider support for analog line services has declined, the solution for communicating with these legacy devices has been to use local connections. To make this work, you connect the serial port of the legacy device to a nearby serial port on a piece of communications equipment, typically a router. This local router then forwards the serial traffic over IP to the central server for processing. Encapsulation of serial protocols over IP leverages mechanisms such as raw socket TCP or UDP. While raw socket sessions can run over both IPv4 and IPv6, current implementations are mostly available for IPv4 only.

- **IPv6 Adaptation Layer:** IPv6-only adaptation layers for some physical and data link layers for recently standardized IoT protocols support only IPv6. While the most common physical and data link layers (Ethernet, Wi-Fi, and so on) stipulate adaptation layers for both versions, newer technologies, such as IEEE 802.15.4 (Wireless Personal Area Network), IEEE 1901.2, and ITU G.9903 (Narrowband Power Line Communications) only have an IPv6 adaptation layer specified. (For more information on these physical and data link layers, see Chapter 4.) This means that any device implementing a technology that requires an IPv6 adaptation layer must communicate over an IPv6-only subnetwork. This is reinforced by the IETF routing protocol for LLNs, RPL, which is IPv6 only. The RPL routing protocol is discussed in more detail later in this chapter.

Note Transition mechanisms such as Mapping of Address and Port using Translation (MAP-T) allow IPv4 traffic to be forwarded over an IPv6 network. Such techniques enable older, industrial end devices and applications to continue running IPv4 even though the network providing connectivity is IPv6. Often these legacy devices and applications do not even have the ability to be upgraded to support IPv6. Please see Chapter 6 to learn more about MAP-T. For even more detailed information on MAP-T, see IETF RFC 7599, at https://tools.ietf.org/html/rfc7599.

Optimizing IP for IoT

While the Internet Protocol is key for a successful Internet of Things, constrained nodes and constrained networks mandate optimization at various layers and on multiple protocols of the IP architecture. The following sections introduce some of these optimizations already available from the market or under development by the IETF. Figure 5-1 highlights the TCP/IP layers where optimization is applied.

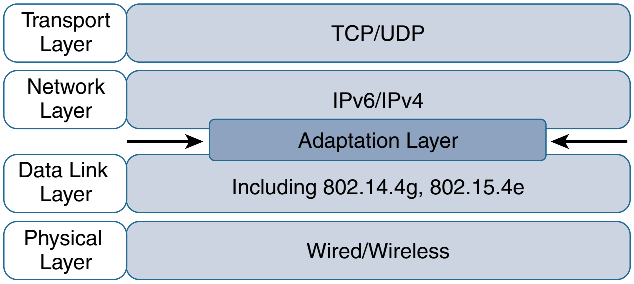

Figure 5-1 *Optimizing IP for IoT Using an Adaptation Layer*

From 6LoWPAN to 6Lo

In the IP architecture, the transport of IP packets over any given Layer 1 (PHY) and Layer 2 (MAC) protocol must be defined and documented. The model for packaging IP into lower-layer protocols is often referred to as an *adaptation layer*.

Unless the technology is proprietary, IP adaptation layers are typically defined by an IETF working group and released as a Request for Comments (RFC). An RFC is a publication from the IETF that officially documents Internet standards, specifications, protocols, procedures, and events. For example, RFC 864 describes how an IPv4 packet gets encapsulated over an Ethernet frame, and RFC 2464 describes how the same function is performed for an IPv6 packet.

IoT-related protocols follow a similar process. The main difference is that an adaptation layer designed for IoT may include some optimizations to deal with constrained nodes and networks. (See the sections "Constrained Nodes" and "Constrained Networks," earlier in this chapter.)

The main examples of adaptation layers optimized for constrained nodes or "things" are the ones under the 6LoWPAN working group and its successor, the 6Lo working group. The initial focus of the 6LoWPAN working group was to optimize the transmission of IPv6 packets over constrained networks such as IEEE 802.15.4. (For more information on IEEE 802.15.4, see Chapter 4.) Figure 5-2 shows an example of an IoT protocol stack using the 6LoWPAN adaptation layer beside the well-known IP protocol stack for reference.

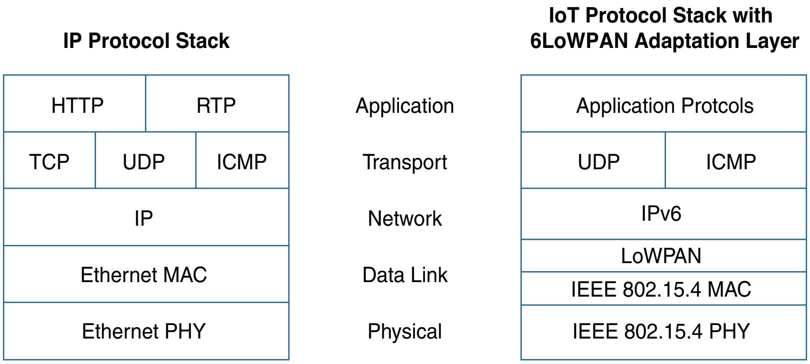

Figure 5-2 *Comparison of an IoT Protocol Stack Utilizing 6LoWPAN and an IP Protocol Stack*

The 6LoWPAN working group published several RFCs, but RFC 4994 is foundational because it defines frame headers for the capabilities of header compression, fragmentation, and mesh addressing. These headers can be stacked in the adaptation layer to keep these concepts separate while enforcing a structured method for expressing each capability. Depending on the implementation, all, none, or any combination of these capabilities and their corresponding headers can be enabled. Figure 5-3 shows some examples of typical 6LoWPAN header stacks.

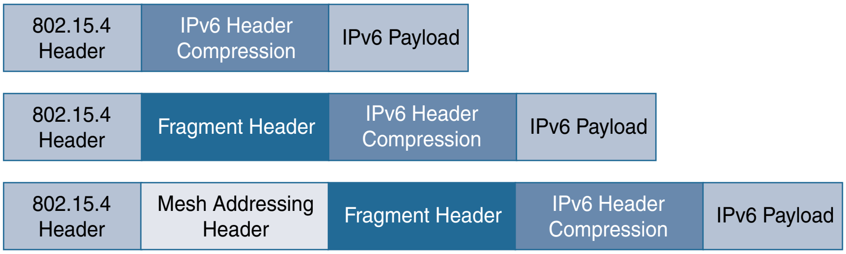

Figure 5-3 *6LoWPAN Header Stacks*

Figure 5-3 shows the subheaders related to compression, fragmentation, and mesh addressing. You'll learn more about these capabilities in the following subsections.

Note The 6LoWPAN working group also published RFC 6775. This document defines neighbor discovery and autoconfiguration, and you are encouraged to refer directly to RFC 6775 for more information on this part of 6LoWPAN. For a full listing of all the documents produced by the 6LoWPAN working group, see https://datatracker.ietf.org/wg/6lowpan/documents/.

Header Compression

IPv6 header compression for 6LoWPAN was defined initially in RFC 4944 and subsequently updated by RFC 6282. This capability shrinks the size of IPv6's 40-byte headers and User Datagram Protocol's (UDP's) 8-byte headers down as low as 6 bytes combined in some cases.

Note that header compression for 6LoWPAN is only defined for an IPv6 header and not IPv4. The 6LoWPAN protocol does not support IPv4, and, in fact, there is no standardized IPv4 adaptation layer for IEEE 802.15.4.

6LoWPAN header compression is stateless, and conceptually it is not too complicated. However, a number of factors affect the amount of compression, such as implementation of RFC 4944 versus RFC 6922, whether UDP is included, and various IPv6 addressing scenarios. It is beyond the scope of this book to cover every use case and how the header fields change for each. However, this chapter provides an example that shows the impact of 6LoWPAN header compression.

At a high level, 6LoWPAN works by taking advantage of shared information known by all nodes from their participation in the local network. In addition, it omits some standard header fields by assuming commonly used values. Figure 5-4 highlights an example that shows the amount of reduction that is possible with 6LoWPAN header compression.

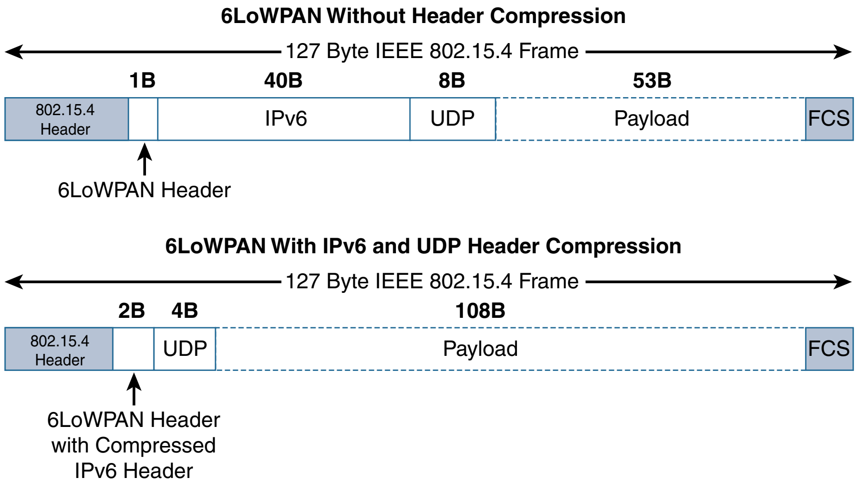

Figure 5-4 *6LoWPAN Header Compression*

At the top of Figure 5-4, you see a 6LoWPAN frame without any header compression enabled: The full 40-byte IPv6 header and 8-byte UDP header are visible. The 6LoWPAN header is only a single byte in this case. Notice that uncompressed IPv6 and UDP headers leave only 53 bytes of data payload out of the 127-byte maximum frame size in the case of IEEE 802.15.4.

The bottom half of Figure 5-4 shows a frame where header compression has been enabled for a best-case scenario. The 6LoWPAN header increases to 2 bytes to accommodate the compressed IPv6 header, and UDP has been reduced in half, to 4 bytes from 8. Most importantly, the header compression has allowed the payload to more than double, from 53 bytes to 108 bytes, which is obviously much more efficient. Note that the 2-byte header compression applies to intra-cell communications, while communications external to the cell may require some field of the header to not be compressed.

Note While nothing precludes running TCP over IPv6/6LoWPAN, no TCP header compression is defined. The main reason is because TCP's congestion-avoidance algorithms could overreact to LLN's packet drops and/or round-trip delay variance.

Fragmentation

The maximum transmission unit (MTU) for an IPv6 network must be at least 1280 bytes. The term *MTU* defines the size of the largest protocol data unit that can be passed. For IEEE 802.15.4, 127 bytes is the MTU. You can see that this is a problem because IPv6, with a much larger MTU, is carried inside the 802.15.4 frame with a much smaller one. To remedy this situation, large IPv6 packets must be fragmented across multiple 802.15.4 frames at Layer 2.

Note You may recall from Chapter 4 that the IEEE 802.15.4g standard specifically is not bounded by the short 127-byte MTU limitation while using the 6LoWPAN adaptation layer. Our discussion on fragmentation and its necessity in this section obviously excludes this variant of 802.15.4.

The fragment header utilized by 6LoWPAN is composed of three primary fields: Datagram Size, Datagram Tag, and Datagram Offset. The 1-byte Datagram Size field specifies the total size of the unfragmented payload. Datagram Tag identifies the set of fragments for a payload. Finally, the Datagram Offset field delineates how far into a payload a particular fragment occurs. Figure 5-5 provides an overview of a 6LoWPAN fragmentation header.

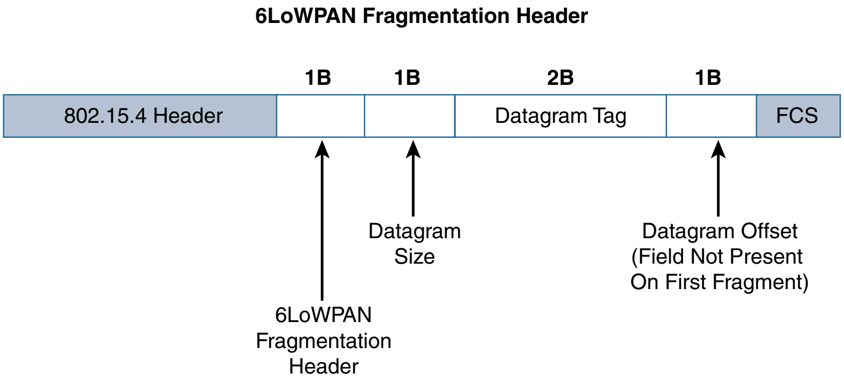

Figure 5-5 *6LoWPAN Fragmentation Header*

In Figure 5-5, the 6LoWPAN fragmentation header field itself uses a unique bit value to identify that the subsequent fields behind it are fragment fields as opposed to another capability, such as header compression. Also, in the first fragment, the Datagram Offset field is not present because it would simply be set to 0. This results in the first fragmentation header for an IPv6 payload being only 4 bytes long. The remainder of the fragments have a 5-byte header field so that the appropriate offset can be specified.

Mesh Addressing

The purpose of the 6LoWPAN mesh addressing function is to forward packets over multiple hops. Three fields are defined for this header: Hop Limit, Source Address, and Destination Address. Analogous to the IPv6 hop limit field, the hop limit for mesh addressing also provides an upper limit on how many times the frame can be forwarded. Each hop decrements this value by 1 as it is forwarded. Once the value hits 0, it is dropped and no longer forwarded.

The Source Address and Destination Address fields for mesh addressing are IEEE 802.15.4 addresses indicating the endpoints of an IP hop. Figure 5-6 details the 6LoWPAN mesh addressing header fields.

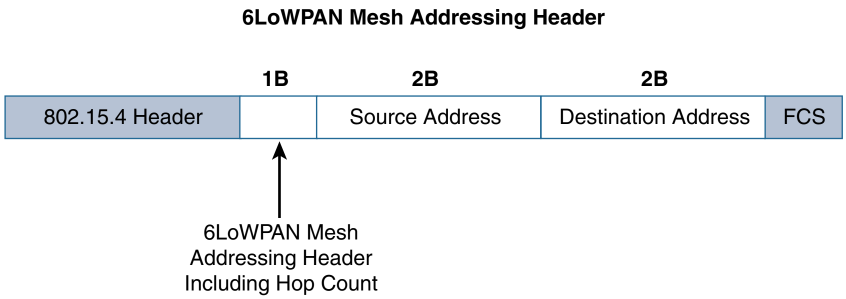

Figure 5-6 *6LoWPAN Mesh Addressing Header*

Note that the mesh addressing header is used in a single IP subnet and is a Layer 2 type of routing known as mesh-under. The concept of mesh-under is discussed in the next section. Keep in mind that RFC 4944 only provisions the function in this case as the definition of Layer 2 mesh routing specifications was outside the scope of the 6LoWPAN working group, and the IETF doesn't define "Layer 2 routing." An implementation performing Layer 3 IP routing does not need to implement a mesh addressing header unless required by a given technology profile.

Mesh-Under Versus Mesh-Over Routing

For network technologies such as IEEE 802.15.4, IEEE 802.15.4g, and IEEE 1901.2a that support mesh topologies and operate at the physical and data link layers, two main options exist for establishing reachability and forwarding packets. With the first option, mesh-under, the routing of packets is handled at the 6LoWPAN adaptation layer.

The other option, known as “mesh-over” or “route-over,” utilizes IP routing for getting packets to their destination.

With mesh-under routing, the routing of IP packets leverages the 6LoWPAN mesh addressing header discussed in the previous section to route and forward packets at the link layer. The term *mesh-under* is used because multiple link layer hops can be used to complete a single IP hop. Nodes have a Layer 2 forwarding table that they consult to route the packets to their final destination within the mesh. An edge gateway terminates the mesh-under domain. The edge gateway must also implement a mechanism to translate between the configured Layer 2 protocol and any IP routing mechanism implemented on other Layer 3 IP interfaces.

In mesh-over or route-over scenarios, IP Layer 33 routing is utilized for computing reachability and then getting packets forwarded to their destination, either inside or outside the mesh domain. Each full-functioning node acts as an IP router, so each link layer hop is an IP hop. When a LoWPAN has been implemented using different link layer technologies, a mesh-over routing setup is useful. While traditional IP routing protocols can be used, a specialized routing protocol for smart objects, such as RPL, is recommended. RPL is discussed in more detail later in this chapter.

6Lo Working Group

With the work of the 6LoWPAN working group completed, the 6Lo working group seeks to expand on this completed work with a focus on IPv6 connectivity over constrained-node networks. While the 6LoWPAN working group initially focused its optimizations on IEEE 802.15.4 LLNs, standardizing IPv6 over other link layer technologies is still needed.

Therefore, the charter of the 6Lo working group, now called the IPv6 over Networks of Resource-Constrained Nodes, is to facilitate the IPv6 connectivity over constrained-node networks. In particular, this working group is focused on the following:

- **IPv6-over-foo adaptation layer specifications using 6LoWPAN technologies (RFC4944, RFC6282, RFC6775) for link layer technologies:** For example, this includes:
  - IPv6 over Bluetooth Low Energy
  - Transmission of IPv6 packets over near-field communication
  - IPv6 over 802.11ah
  - Transmission of IPv6 packets over DECT Ultra Low Energy
  - Transmission of IPv6 packets on WIA-PA (Wireless Networks for Industrial Automation–Process Automation)
  - Transmission of IPv6 over Master Slave/Token Passing (MS/TP)

- **Information and data models such as MIB modules:** One example is RFC 7388, "Definition of Managed Objects for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)."
- **Optimizations that are applicable to more than one adaptation layer specification:** For example, this includes RFC 7400, "6LoWPAN-GHC: Generic Header Compression for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)."
- **Informational and maintenance publications needed for the IETF specifications in this area**

In summary, the 6Lo working group is standardizing the 6LoWPAN adaptation layer that initially focused on the IEEE 802.15.4 Layer 2 protocol to others that are commonly found with constrained nodes. In fact, based on the work of the 6LoWPAN working group and now the 6Lo working group, the 6LoWPAN adaptation layer is becoming the de factor standard for connecting constrained nodes in IoT networks.

6TiSCH

Many proprietary wireless technologies have been developed and deployed in various industry verticals over the years. However, the publication of the IEEE 802.15.4 physical and data link layer specifications, followed by IEEE 802.15.4e amendments, has opened the path to standardized, deterministic communications over wireless networks.

IEEE 802.15.4e, Time-Slotted Channel Hopping (TSCH), is an add-on to the Media Access Control (MAC) portion of the IEEE 802.15.4 standard, with direct inheritance from other standards, such as WirelessHART and ISA100.11a.

Devices implementing IEEE 802.15.4e TSCH communicate by following a Time Division Multiple Access (TDMA) schedule. An allocation of a unit of bandwidth or time slot is scheduled between neighbor nodes. This allows the programming of predictable transmissions and enables deterministic, industrial-type applications. In comparison, other 802.15.4 implementations do not allocate slices of bandwidth, so communication, especially during times of contention, may be delayed or lost because it is always best effort.

To standardize IPv6 over the TSCH mode of IEEE 802.15.4e (known as 6TiSCH), the IETF formed the 6TiSCH working group. This working group works on the architecture, information model, and minimal 6TiSCH configuration, leveraging and enhancing work done by the 6LoWPAN working group, RoLL working group, and CoRE working group. The RoLL working group focuses on Layer 3 routing for constrained networks. The work of the RoLL working group is discussed in more detail in the upcoming section "RPL." The CoRE working group is covered in Chapter 6.

An important element specified by the 6TiSCH working group is 6top, a sublayer that glues together the MAC layer and 6LoWPAN adaptation layer. This sublayer provides commands to the upper network layers, such as RPL. In return, these commands enable functionalities including network layer routing decisions, configuration, and control procedures for 6TiSCH schedule management.

The IEEE 802.15.4e standard defines a time slot structure, but it does not mandate a scheduling algorithm for how the time slots are utilized. This is left to higher-level protocols like 6TiSCH. Scheduling is critical because it can affect throughput, latency, and power consumption. Figure 5-7 shows where 6top resides in relation to IEEE 802.15.4e, 6LoWPAN HC, and IPv6. 6LoWPAN HC is covered earlier in this chapter, in the section "Header Compression."

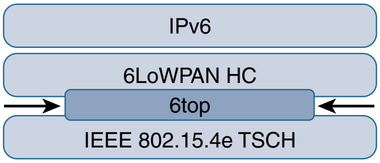

Figure 5-7 *Location of 6TiSCH's 6top Sublayer*

Schedules in 6TiSCH are broken down into cells. A cell is simply a single element in the TSCH schedule that can be allocated for unidirectional or bidirectional communications between specific nodes. Nodes only transmit when the schedule dictates that their cell is open for communication. The 6TiSCH architecture defines four schedule management mechanisms:

- **Static scheduling:** All nodes in the constrained network share a fixed schedule. Cells are shared, and nodes contend for slot access in a slotted aloha manner. Slotted aloha is a basic protocol for sending data using time slot boundaries when communicating over a shared medium. Static scheduling is a simple scheduling mechanism that can be used upon initial implementation or as a fallback in the case of network malfunction. The drawback with static scheduling is that nodes may expect a packet at any cell in the schedule. Therefore, energy is wasted idly listening across all cells.
- **Neighbor-to-neighbor scheduling:** A schedule is established that correlates with the observed number of transmissions between nodes. Cells in this schedule can be added or deleted as traffic requirements and bandwidth needs change.
- **Remote monitoring and scheduling management:** Time slots and other resource allocation are handled by a management entity that can be multiple hops away. The scheduling mechanism leverages 6top and even CoAP in some scenarios. For more information on the application layer protocol CoAP, see Chapter 6. This scheduling mechanism provides quite a bit of flexibility and control in allocating cells for communication between nodes.
- **Hop-by-hop scheduling:** A node reserves a path to a destination node multiple hops away by requesting the allocation of cells in a schedule at each intermediate node hop in the path. The protocol that is used by a node to trigger this scheduling mechanism is not defined at this point.

In addition to schedule management functions, the 6TiSCH architecture also defines three different forwarding models. Forwarding is the operation performed on each packet by a node that allows it to be delivered to a next hop or an upper-layer protocol. The forwarding decision is based on a preexisting state that was learned from a routing computation. There are three 6TiSCH forwarding models:

- **Track Forwarding (TF):** This is the simplest and fastest forwarding model. A "track" in this model is a unidirectional path between a source and a destination. This track is constructed by pairing bundles of receive cells in a schedule with a bundle of receive cells set to transmit. So, a frame received within a particular cell or cell bundle is switched to another cell or cell bundle. This forwarding occurs regardless of the network layer protocol.
- **Fragment forwarding (FF):** This model takes advantage of 6LoWPAN fragmentation to build a Layer 2 forwarding table. Fragmentation within the 6LoWPAN protocol is covered earlier in this chapter, in the section "Fragmentation." As you may recall, IPv6 packets can get fragmented at the 6LoWPAN sublayer to handle the differences between IEEE 802.15.4 payload size and IPv6 MTU. Additional headers for RPL source route information can further contribute to the need for fragmentation. However, with FF, a mechanism is defined where the first fragment is routed based on the IPv6 header present. The 6LoWPAN sublayer learns the next-hop selection of this first fragment, which is then applied to all subsequent fragments of that packet. Otherwise, IPv6 packets undergo hop-by-hop reassembly. This increases latency and can be power- and CPU-intensive for a constrained node.
- **IPv6 Forwarding (6F):** This model forwards traffic based on its IPv6 routing table. Flows of packets should be prioritized by traditional QoS (quality of service) and RED (random early detection) operations. QoS is a classification scheme for flows based on their priority, and RED is a common congestion avoidance mechanism.

For many IoT wireless networks, it is not necessary to be able to control the latency and throughput for sensor data. However, when some sort of determinism is needed, 6TiSCH provides an open, IPv6-based standard solution for ensuring predictable communications over wireless sensor networks. However, its adoption by the industry is still an ongoing effort.

RPL

The IETF chartered the RoLL (Routing over Low-Power and Lossy Networks) working group to evaluate all Layer 3 IP routing protocols and determine the needs and requirements for developing a routing solution for IP smart objects. After study of various use cases and a survey of existing protocols, the consensus was that a new routing protocol should be developed for use by IP smart objects, given the characteristics and requirements of constrained networks. This new distance-vector routing protocol was named the IPv6 Routing Protocol for Low Power and Lossy Networks (RPL). The RPL specification was published as RFC 6550 by the RoLL working group.

Note In addition to the main RPL standard (RFC 6550), RPL is also addressed across a number of other RFCs published by the RoLL working group. These RFCs include RPL use cases, RPL-specific terms with definitions, and other enhancements or clarifications to the protocol. This section provides a high-level overview of RPL and how it works, but you should refer to the RFCs listed here for a more in-depth study of RPL: https://datatracker.ietf.org/wg/roll/documents/.

In an RPL network, each node acts as a router and becomes part of a mesh network. Routing is performed at the IP layer. Each node examines every received IPv6 packet and determines the next-hop destination based on the information contained in the IPv6 header. No information from the MAC-layer header is needed to perform next-hop determination. Remember from earlier in this chapter that this is referred to as mesh-over routing.

To cope with the constraints of computing and memory that are common characteristics of constrained nodes, the protocol defines two modes:

- **Storing mode:** All nodes contain the full routing table of the RPL domain. Every node knows how to directly reach every other node.
- **Non-storing mode:** Only the border router(s) of the RPL domain contain(s) the full routing table. All other nodes in the domain only maintain their list of parents and use this as a list of default routes toward the border router. This abbreviated routing table saves memory space and CPU. When communicating in non-storing mode, a node always forwards its packets to the border router, which knows how to ultimately reach the final destination.

RPL is based on the concept of a directed acyclic graph (DAG). A DAG is a directed graph where no cycles exist. This means that from any vertex or point in the graph, you cannot follow an edge or a line back to this same point. All of the edges are arranged in paths oriented toward and terminating at one or more root nodes. Figure 5-8 shows a basic DAG.

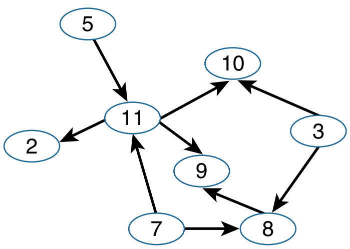

Figure 5-8 *Example of a Directed Acyclic Graph (DAG)*

A basic RPL process involves building a destination-oriented directed acyclic graph (DODAG). A DODAG is a DAG rooted to one destination. In RPL, this destination occurs at a border router known as the DODAG root. Figure 5-9 compares a DAG and a DODAG. You can see that that a DAG has multiple roots, whereas the DODAG has just one.

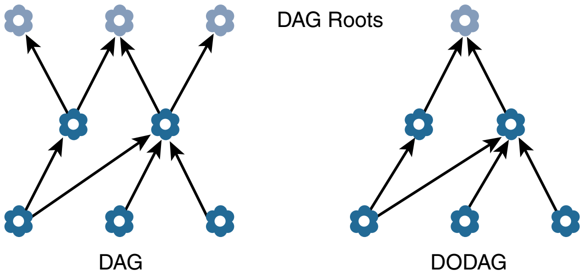

Figure 5-9 *DAG and DODAG Comparison*

In a DODAG, each node maintains up to three parents that provide a path to the root. Typically, one of these parents is the preferred parent, which means it is the preferred next hop for upward routes toward the root.

The routing graph created by the set of DODAG parents across all nodes defines the full set of upward routes. RPL protocol implementation should ensure that routes are loop free by disallowing nodes from selected DODAG parents that are positioned further away from the border router.

Upward routes in RPL are discovered and configured using DAG Information Object (DIO) messages. Nodes listen to DIOs to handle changes in the topology that can affect routing. The information in DIO messages determines parents and the best path to the DODAG root.

Nodes establish downward routes by advertising their parent set toward the DODAG root using a Destination Advertisement Object (DAO) message. DAO messages allow nodes to inform their parents of their presence and reachability to descendants.

In the case of the non-storing mode of RPL, nodes sending DAO messages report their parent sets directly to the DODAG root (border router), and only the root stores the routing information. The root uses the information to then determine source routes needed for delivering IPv6 datagrams to individual nodes downstream in the mesh.

For storing mode, each node keeps track of the routing information that is advertised in the DAO messages. While this is more power- and CPU-intensive for each node, the benefit is that packets can take shorter paths between destinations in the mesh. The nodes can make their own routing decisions; in non-storing mode, on the other hand, all packets must go up to the root to get a route for moving downstream.

RPL messages, such as DIO and DAO, run on top of IPv6. These messages exchange and advertise downstream and upstream routing information between a border router and the nodes under it. As illustrated in Figure 5-10, DAO and DIO messages move both up and down the DODAG, depending on the exact message type.

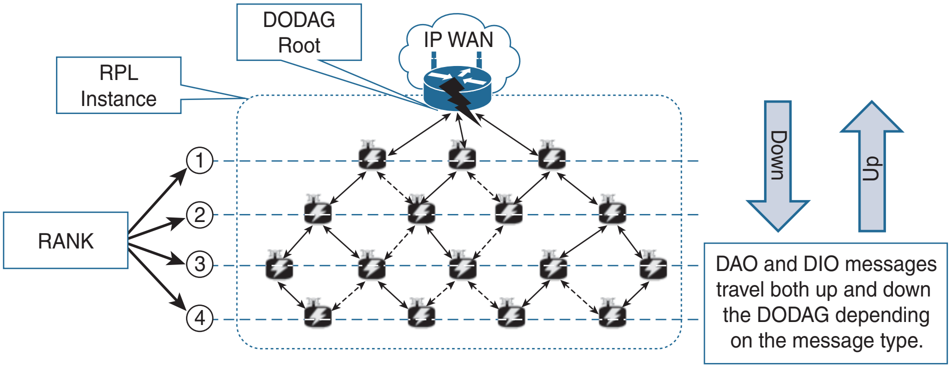

Figure 5-10 *RPL Overview*

Objective Function (OF)

An objective function (OF) defines how metrics are used to select routes and establish a node's rank. Standards such as RFC 6552 and 6719 have been published to document OFs specific to certain use cases and node types.

For example, nodes implementing an OF based on RFC 6719's Minimum Expected Number of Transmissions (METX) advertise the METX among their parents in DIO messages. Whenever a node establishes its rank, it simply sets the rank to the current minimum METX among its parents.

Rank

The rank is a rough approximation of how "close" a node is to the root and helps avoid routing loops and the count-to-infinity problem. Nodes can only increase their rank when receiving a DIO message with a larger version number. However, nodes may decrease their rank whenever they have established lower-cost routes. While the rank and routing metrics are closely related, the rank differs from routing metrics in that it is used as a constraint to prevent routing loops.

RPL Headers

Specific network layer headers are defined for datagrams being forwarded within an RPL domain. One of the headers is standardized in RFC 6553, "The Routing Protocol for Low-Power and Lossy Networks (RPL) Option for Carrying RPL Information in Data-Plane Datagrams," and the other is discussed in RFC 6554, "An IPv6 Routing Header for Source Routes with the Routing Protocol for Low-Power and Lossy Networks (RPL)."

RFC 6553 defines a new IPv6 option, known as the RPL option. The RPL option is carried in the IPv6 Hop-by-Hop header. The purpose of this header is to leverage data-plane packets for loop detection in a RPL instance. As discussed earlier, DODAGs only have single paths and should be loop free.

RFC 6554 specifies the Source Routing Header (SRH) for use between RPL routers. A border router or DODAG root inserts the SRH when specifying a source route to deliver datagrams to nodes downstream in the mesh network.

Metrics

RPL defines a large and flexible set of new metrics and constraints for routing in RFC 6551. Developed to support powered and battery-powered nodes, RPL offers a far more complete set than any other routing protocol. Some of the RPL routing metrics and constraints defined in RFC 6551 include the following:

- **Expected Transmission Count (ETX):** Assigns a discrete value to the number of transmissions a node expects to make to deliver a packet.
- **Hop Count:** Tracks the number of nodes traversed in a path. Typically, a path with a lower hop count is chosen over a path with a higher hop count.
- **Latency:** Varies depending on power conservation. Paths with a lower latency are preferred.
- **Link Quality Level:** Measures the reliability of a link by taking into account packet error rates caused by factors such as signal attenuation and interference.
- **Link Color:** Allows manual influence of routing by administratively setting values to make a link more or less desirable. These values can be either statically or dynamically adjusted for specific traffic types.
- **Node State and Attribute:** Identifies nodes that function as traffic aggregators and nodes that are being impacted by high workloads. High workloads could be indicative of nodes that have incurred high CPU or low memory states. Naturally, nodes that are aggregators are preferred over nodes experiencing high workloads.
- **Node Energy:** Avoids nodes with low power, so a battery-powered node that is running out of energy can be avoided and the life of that node and the network can be prolonged.
- **Throughput:** Provides the amount of throughput for a node link. Often, nodes conserving power use lower throughput. This metric allows the prioritization of paths with higher throughput.

In addition to the metrics and constraints listed in RFC 6551, others can also be implemented. For example, let's look at a scenario in which two constraints are used as a filter for pruning links that do not satisfy the specified conditions.

One of the constraints is ETX. ETX, which is described in RFC 6551, is defined earlier in this chapter. The other constraint, Relative Signal Strength Indicator (RSSI), specifies the power present in a received radio signal. Signals with low strength are generally less reliable and more susceptible to interference, resulting in packet loss.

In this scenario, a DODAG root and nodes form an IEEE 802.15.4 mesh. When a node finds a potential parent, it enters the neighbor into its routing table. However, it does not yet use the new neighbor for routing. Instead, the node must first establish that the link quality to its neighbor is sufficient for forwarding datagrams.

The node determines whether the link quality to a potential parent is sufficient by looking at its programmed constraints. In this example, the configured constraints are ETX and RSSI. If the RSSI in both directions exceeds a threshold and the ETX falls below a threshold, then the node confirms that the link quality to the potential parent is sufficient.

Once a node has determined that the link quality to a potential parent is sufficient, it adds the appropriate default route entry to its forwarding table. Maintaining RSSI and ETX for neighboring nodes is done at the link layer and stored in the link layer neighbor table.

The results from all link layer unicast traffic are fed into the RSSI and ETX computation for neighboring devices. If the link quality is not sufficient, then the link is not added to the forwarding table and is therefore not used for routing packets.

To illustrate, Example 5-1 displays a simple RPL routing tree on a Cisco CGR-1000 router connecting an IEEE 802.15.4g mesh 6LoWPAN-based subnetwork. The first IPv6 address in this example, which ends in **1CC5**, identifies the DODAG root for the RPL tree. This DODAG root has branches to two nodes, indicated by the two IPv6 addresses ending in **924D** and **6C35**.

Example 5-1 **show wpan <interface> rpl tree** *Command from a Cisco CGR-1000*

```
pat1# show wpan 3/1 rpl tree

---------------------------- WPAN RPL TREE FIGURE [3] --------------------------
[2013:DB8:9999:8888:207:8108:B8:1CC5] (2)
\--- 2013:DB8:9999:8888:89C6:F7C9:D551:924D
\--- 2013:DB8:9999:8888:95DF:2AD4:C1B1:6C35
RPL TREE: Num.DataEntries 2, Num.GraphNodes 3
```

RPL integration in a routing domain follows the same rules as more traditional IP routing protocols. Route redistribution, filtering, load balancing, and dynamic rerouting can be implemented the same way as other well-known protocols. For example, in IoT routers, you could see routes learned via RPL being redistributed into more well-known routing protocols, such as BGP and EIGRP.

In summary, RPL is a new routing protocol that enables an IPv6 standards-based solution to be deployed on a large scale while being operated in a similar way to today's IP infrastructures. RPL was designed to meet the requirements of constrained nodes and networks, and this has led to it becoming one of the main network layer IPv6-based routing protocols in IoT sensor networks.

Authentication and Encryption on Constrained Nodes

IoT security is a complex topic that often spawns discussions and debates across the industry. While IoT security is the focus of Chapter 8, "Securing IoT," we have discussed constrained nodes and networks extensively in this chapter. So it is worth mentioning here the IETF working groups that are focused on their security: ACE and DICE.

ACE

Much like the RoLL working group, the Authentication and Authorization for Constrained Environments (ACE) working group is tasked with evaluating the applicability of existing authentication and authorization protocols and documenting their suitability for certain constrained-environment use cases. Once the candidate solutions are validated, the ACE working group will focus its work on CoAP with the Datagram Transport Layer Security (DTLS) protocol. (The CoAP protocol is covered in Chapter 6, and RFC 6437 defines the DTLS security protocol.) The ACE working group may investigate other security protocols later, with a particular focus on adapting whatever solution is chosen to HTTP and TLS.

The ACE working group expects to produce a standardized solution for authentication and authorization that enables authorized access (Get, Put, Post, Delete) to resources identified by a URI and hosted on a resource server in constrained environments. An unconstrained authorization server performs mediation of the access. Aligned with the initial focus, access to resources at a resource server by a client device occurs using CoAP and is protected by DTLS.

DICE

New generations of constrained nodes implementing an IP stack over constrained access networks are expected to run an optimized IP protocol stack. For example, when implementing UDP at the transport layer, the IETF Constrained Application Protocol (CoAP) should be used at the application layer. (See Chapter 6 for more details on CoAP.)

In constrained environments secured by DTLS, CoAP can be used to control resources on a device. (Constrained environments are network situations where constrained nodes and/or constrained networks are present. Constrained networks and constrained nodes are discussed earlier in this chapter, in the sections "Constrained Nodes" and "Constrained Networks.")

The DTLS in Constrained Environments (DICE) working group focuses on implementing the DTLS transport layer security protocol in these environments. The first task of the DICE working group is to define an optimized DTLS profile for constrained nodes. In addition, the DICE working group is considering the applicability of the DTLS record layer to secure multicast messages and investigating how the DTLS handshake in constrained environments can get optimized.

Profiles and Compliances

As discussed throughout this chapter, leveraging the Internet Protocol suite for smart objects involves a collection of protocols and options that must work in coordination with lower and upper layers. Therefore, profile definitions, certifications, and promotion by alliances can help implementers develop solutions that guarantee interoperability and/or interchangeability of devices.

This section introduces some of the main industry organizations working on profile definitions and certifications for IoT constrained nodes and networks. You can find various documents and promotions from these organizations in the IoT space, so it is worth being familiar with them and their goals.

Internet Protocol for Smart Objects (IPSO) Alliance

Established in 2008, the Internet Protocol for Smart Objects (IPSO) Alliance has had its objective evolve over years. The alliance initially focused on promoting IP as the premier solution for smart objects communications. Today, it is more focused on how to use IP, with the IPSO Alliance organizing interoperability tests between alliance members to validate that IP for smart objects can work together and properly implement industry standards. The IPSO Alliance does not define technologies, as that is the role of the IETF and other standard organizations, but it documents the use of IP-based technologies for various IoT use cases and participates in educating the industry. As the IPSO Alliance declares in its value and mission statement, it wants to ensure that "engineers and product builders will have access to the necessary tools for 'how to build the IoT RIGHT.'" For more information on the IPSO Alliance, visit www.ipso-alliance.org.

Wi-SUN Alliance

The Wi-SUN Alliance is an example of efforts from the industry to define a communication profile that applies to specific physical and data link layer protocols. Currently, Wi-SUN's main focus is on the IEEE 802.15.4g protocol and its support for multiservice and secure IPv6 communications with applications running over the UDP transport layer.

The utilities industry is the main area of focus for the Wi-SUN Alliance. The Wi-SUN field area network (FAN) profile enables smart utility networks to provide resilient, secure, and cost-effective connectivity with extremely good coverage in a range of topographic environments, from dense urban neighborhoods to rural areas. (FANs are described in more detail in Chapter 11, "Utilities."). You can read more about the Wi-SUN Alliance and its certification programs at the Wi-SUN Alliance website, www.wi-sun.org.

Thread

A group of companies involved with smart object solutions for consumers created the Thread Group. This group has defined an IPv6-based wireless profile that provides the best way to connect more than 250 devices into a low-power, wireless mesh network.

The wireless technology used by Thread is IEEE 802.15.4, which is different from Wi-SUN's IEEE 802.15.4g. Please see Chapter 4 for more information on 802.15.4 and 802.15.4g and their differences. For additional information on Thread and its specifications, visit http://threadgroup.org.

IPv6 Ready Logo

Initially, the IPv6 Forum ensured the promotion of IPv6 around the world. Once IPv6 implementations became widely available, the need for interoperability and certification led to the creation of the IPv6 Ready Logo program.

The IPv6 Ready Logo program has established conformance and interoperability testing programs with the intent of increasing user confidence when implementing IPv6. The IPv6 Core and specific IPv6 components, such as DHCP, IPsec, and customer edge router certifications, are in place. These certifications have industry-wide recognition, and many products are already certified. An IPv6 certification effort specific to IoT is currently under definition for the program.

Summary

The IP protocol suite has been deployed in private and public networks over the past three decades, interconnecting billions of IP devices and users. The architecture has proven to be highly flexible, and it has protected investments in many ways. For example, new link types have been adapted, new routing and transport protocols have been specified and deployed, and the number of supported applications has exceeded all expectations by an order of magnitude.

The vast majority of the IP protocols and technologies, including addressing, address provisioning, QoS, transport, reliability, and so on, can be reused as is by IoT solutions. Where IP may fall short is in scenarios where IoT devices are constrained nodes and/or connect to constrained networks. This is especially the case for some highly constrained devices that use LPWA technologies for last-mile communications.

To remedy these scenarios, the IETF, the main standards organization in charge of the TCP/IP architecture, is now engaged through several working groups to optimize IP for IoT and smart objects communications. These working groups have often had to develop new protocols, such as RPL, or adaptation layers, such as 6LoWPAN, to handle the constrained environments where IoT sensor networks are often deployed.

As highlighted in this chapter, the foundation for the network layer in IoT implementations is firmly in place. The IETF and other standards bodies continue to work on defining the networks, protocols, and use cases that are necessary for advancing the Internet of Things.

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Chapter 6

Application Protocols for IoT

As with the wired and wireless access technologies discussed in Chapter 5, "IP as the IoT Network Layer," the IoT application protocols you select should be contingent on the use cases and vertical industries they apply to. In addition, IoT application protocols are dependent on the characteristics of the lower layers themselves. For example, application protocols that are sufficient for generic nodes and traditional networks often are not well suited for constrained nodes and networks.

This chapter focuses on how higher-layer IoT protocols are transported. Specifically, this chapter includes the following sections:

- **The Transport Layer:** IP-based networks use either TCP or UDP. However, the constrained nature of IoT networks requires a closer look at the use of these traditional transport mechanisms.
- **IoT Application Transport Methods:** This section explores the various types of IoT application data and the ways this data can be carried across a network.

As in traditional networks, TCP or UDP are utilized in most cases when transporting IoT application data. The transport methods are covered in depth and form the bulk of the material in this chapter. You will notice that, as with the lower-layer IoT protocols, there are typically multiple options and solutions presented for transporting IoT application data. This is because IoT is still developing and maturing and has to account for the transport of not only new application protocols and technologies but legacy ones as well.

The Transport Layer

This section reviews the selection of a protocol for the transport layer as supported by the TCP/IP architecture in the context of IoT networks. With the TCP/IP protocol, two main protocols are specified for the transport layer:

- **Transmission Control Protocol (TCP):** This connection-oriented protocol requires a session to get established between the source and destination before exchanging data. You can view it as an equivalent to a traditional telephone conversation, in which two phones must be connected and the communication link established before the parties can talk.
- **User Datagram Protocol (UDP):** With this connectionless protocol, data can be quickly sent between source and destination—but with no guarantee of delivery. This is analogous to the traditional mail delivery system, in which a letter is mailed to a destination. Confirmation of the reception of this letter does not happen until another letter is sent in response.

With the predominance of human interactions over the Internet, TCP is the main protocol used at the transport layer. This is largely due to its inherent characteristics, such as its ability to transport large volumes of data into smaller sets of packets. In addition, it ensures reassembly in a correct sequence, flow control and window adjustment, and retransmission of lost packets. These benefits occur with the cost of overhead per packet and per session, potentially impacting overall packet per second performances and latency.

In contrast, UDP is most often used in the context of network services, such as Domain Name System (DNS), Network Time Protocol (NTP), Simple Network Management Protocol (SNMP), and Dynamic Host Control Protocol (DHCP), or for real-time data traffic, including voice and video over IP. In these cases, performance and latency are more important than packet retransmissions because re-sending a lost voice or video packet does not add value. When the reception of packets must be guaranteed error free, the application layer protocol takes care of that function.

When considering the choice of a transport layer by a given IoT application layer protocol, it is recommended to evaluate the impact of this choice on both the lower and upper layers of the stack. For example, most of the industrial application layer protocols, as discussed later in this chapter, are implemented over TCP, while their specifications may offer support for both transport models. The reason for this is that often these industrial application layer protocols are older and were deployed when data link layers were often unreliable and called for error protection.

While the use of TCP may not strain generic compute platforms and high-data-rate networks, it can be challenging and is often overkill on constrained IoT devices and networks. This is particularly true when an IoT device needs to send only a few bytes of data per transaction. When using TCP, each packet needs to add a minimum of 20 bytes of TCP overhead, while UDP adds only 8 bytes. TCP also requires the establishment and potential maintenance of an open logical channel.

IoT nodes may also be limited by the intrinsic characteristics of the data link layers. For example, low-power and lossy networks (LLNs), as discussed in Chapter 5, may not cope well with supporting large numbers of TCP sessions.

This may explain why a new IoT application protocol, such as Constrained Application Protocol (CoAP), almost always uses UDP and why implementations of industrial application layer protocols may call for the optimization and adoption of the UDP transport layer if run over LLNs. For example, the Device Language Message Specification/Companion Specification for Energy Metering (DLMS/COSEM) application layer protocol, a popular protocol for reading smart meters in the utilities space, is the de facto standard in Europe. Adjustments or optimizations to this protocol should be made depending on the IoT transport protocols that are present in the lower layers. For example, if you compare the transport of DLMS/COSEM over a cellular network versus an LLN deployment, you should consider the following:

- Select TCP for cellular networks because these networks are typically more robust and can handle the overhead. For LLNs, where both the devices and network itself are usually constrained, UDP is a better choice and often mandatory.
- DLMS/COSEM can reduce the overhead associated with session establishment by offering a "long association" over LLNs. *Long association* means that sessions stay up once in place because the communications overhead necessary to keep a session established is much less than is involved in opening and closing many separate sessions over the same time period. Conversely, for cellular networks, a short association better controls the costs by tearing down the open associations after transmitting.
- When transferring large amounts of DLMS/COSEM data, cellular links are preferred to optimize each open association. Smaller amounts of data can be handled efficiently over LLNs. Because packet loss ratios are generally higher on LLNs than on cellular networks, keeping the data transmission amounts small over LLNs limits the retransmission of large numbers of bytes.

Multicast requirements are also impacted by the protocol selected for the transport layer. With multicast, a single message can be sent to multiple IoT devices. This is useful in the IoT context for upgrading the firmware of many IoT devices at once. Also, keep in mind that multicast utilizes UDP exclusively.

To guarantee interoperability, certification and compliance profiles, such as Wi-SUN, need to specify the stack from Layer 1 to Layer 4. This enables the chosen technology to be compatible with the different options of the stack while also being compatible with IP. (Chapter 4, "Connecting Smart Objects," provides more information on Wi-SUN.)

In summary, TCP and UDP are the two main choices at the transport layer for the TCP/IP protocol. The performance and scalability of IoT constrained devices and networks is impacted by which one of these is selected.

IoT Application Transport Methods

Because of the diverse types of IoT application protocols, there are various means for transporting these protocols across a network. Sometimes you may be dealing with legacy utility and industrial IoT protocols that have certain requirements, while other times you might need to consider the transport requirements of more modern application layer protocols. To make these decisions easier, it makes sense to categorize the common IoT application protocols and then focus on the transport methods available for each category. The following categories of IoT application protocols and their transport methods are explored in the following sections:

- **Application layer protocol not present:** In this case, the data payload is directly transported on top of the lower layers. No application layer protocol is used.
- **Supervisory control and data acquisition (SCADA):** SCADA is one of the most common industrial protocols in the world, but it was developed long before the days of IP, and it has been adapted for IP networks.
- **Generic web-based protocols:** Generic protocols, such as Ethernet, Wi-Fi, and 4G/LTE, are found on many consumer- and enterprise-class IoT devices that communicate over non-constrained networks.
- **IoT application layer protocols:** IoT application layer protocols are devised to run on constrained nodes with a small compute footprint and are well adapted to the network bandwidth constraints on cellular or satellite links or constrained 6LoWPAN networks. Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP), covered later in this chapter, are two well-known examples of IoT application layer protocols.

Application Layer Protocol Not Present

As introduced in Chapter 4, IETF RFC 7228 devices defined as class 0 send or receive only a few bytes of data. For myriad reasons, such as processing capability, power constraints, and cost, these devices do not implement a fully structured network protocol stack, such as IP, TCP, or UDP, or even an application layer protocol. Class 0 devices are usually simple smart objects that are severely constrained. Implementing a robust protocol stack is usually not useful and sometimes not even possible with the limited available resources.

For example, consider low-cost temperature and relative humidity (RH) sensors sending data over an LPWA LoRaWAN infrastructure. (LPWA and LoRaWAN are discussed in Chapter 4.) Temperature is represented as 2 bytes and RH as another 2 bytes of data. Therefore, this small data payload is directly transported on top of the LoRaWAN MAC layer, without the use of TCP/IP. Example 6-1 shows the raw data for temperature and relative humidity and how it can be decoded by the application.

Example 6-1 *Decoding Temperature and Relative Humidity Sensor Data*

```
Temperature data payload over the network: Tx = 0x090c
Temperature conversion required by the application
T = Tx/32 - 50  to  T = 0x090c/32 - 50  to  T = 2316/32 - 50 = 22.4°
RH data payload over the network: RHx = 0x062e
RH conversion required by the application:
100RH = RHx/16-24  to 100RH = 0x062e/16-24 = 74.9  to RH = 74.9%
```

While many constrained devices, such as sensors and actuators, have adopted deployments that have no application layer, this transportation method has not been standardized. This lack of standardization makes it difficult for generic implementations of this transport method to be successful from an interoperability perspective.

Imagine expanding Example 6-1 to different kinds of temperature sensors from different manufacturers. These sensors will report temperature data in varying formats. A temperature value will always be present in the data transmitted by each sensor, but decoding this data will be vendor specific. If you scale this scenario out across hundreds or thousands of sensors, the problem of allowing various applications to receive and interpret temperature values delivered in different formats becomes increasingly complex. The solution to this problem is to use an IoT data broker, as detailed in Figure 6-1. An IoT data broker is a piece of middleware that standardizes sensor output into a common format that can then be retrieved by authorized applications. (The concept of the IoT data broker is introduced in Chapter 1, "What Is IoT?")

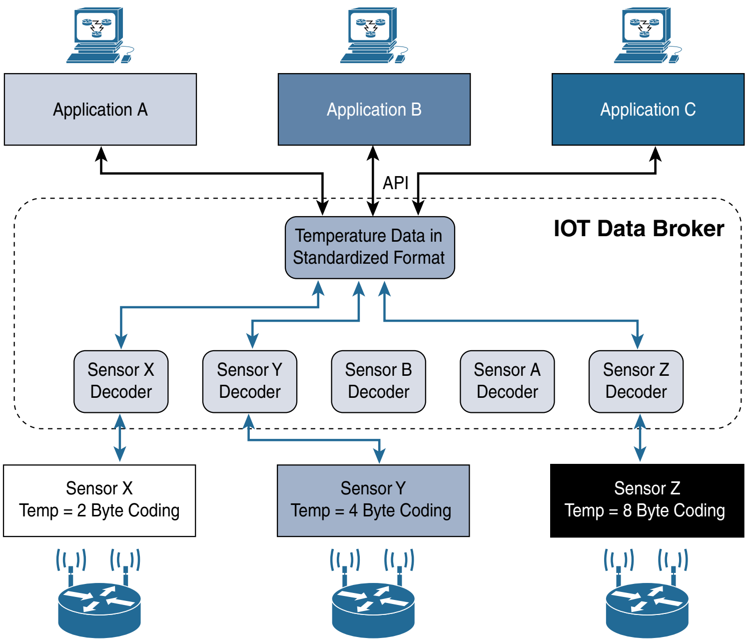

Figure 6-1 *IoT Data Broker*

In Figure 6-1, Sensors X, Y, and Z are all temperature sensors, but their output is encoded differently. The IoT data broker understands the different formats in which the temperature is encoded and is therefore able to decode this data into a common, standardized format. Applications A, B, and C in Figure 6-1 can access this temperature data without having to deal with decoding multiple temperature data formats.

You should note that IoT data brokers are also utilized from a commercial perspective to distribute and sell IoT data to third parties. Companies can provide access to their data broker from another company's application for a fee. This makes an IoT data broker a possible revenue stream, depending on the value of the data it contains.

In summary, while directly transporting data payload without a structured network stack clearly optimizes data transmission over low-data-rate networks, the lack of a data model implies that each application needs to know how to interpret the data-specific format. This becomes increasingly complex for larger networks of devices with different data payload formats. Furthermore, it makes the IoT application environment challenging in terms of evolution, development, interoperability, and so on, and often calls for structured data models and data broker applications.

SCADA

In the world of networking technologies and protocols, IoT is relatively new. Combined with the fact that IP is the de facto standard for computer networking in general, older protocols that connected sensors and actuators have evolved and adapted themselves to utilize IP.

A prime example of this evolution is supervisory control and data acquisition (SCADA). Designed decades ago, SCADA is an automation control system that was initially implemented without IP over serial links, before being adapted to Ethernet and IPv4.

A Little Background on SCADA

For many years, vertical industries have developed communication protocols that fit their specific requirements. Many of them were defined and implemented when the most common networking technologies were serial link-based, such as RS-232 and RS-485. This led to SCADA networking protocols, which were well structured compared to the protocols described in the previous section, running directly over serial physical and data link layers.

At a high level, SCADA systems collect sensor data and telemetry from remote devices, while also providing the ability to control them. Used in today's networks, SCADA systems allow global, real-time, data-driven decisions to be made about how to improve business processes.

SCADA networks can be found across various industries, but you find SCADA mainly concentrated in the utilities and manufacturing/industrial verticals. Within these specific industries, SCADA commonly uses certain protocols for communications between devices and applications. For example, Modbus and its variants are industrial protocols used to monitor and program remote devices via a master/slave relationship. Modbus is also found in building management, transportation, and energy applications. The DNP3 and International Electrotechnical Commission (IEC) 60870-5-101 protocols are found mainly in the utilities industry, along with DLMS/COSEM and ANSI C12 for advanced meter reading (AMR). Both DNP3 and IEC 60870-5-101 are discussed in more detail later in this chapter.

As mentioned previously, these protocols go back decades and are serial based. So, transporting them over current IoT and traditional networks requires that certain accommodations be made from both protocol and implementation perspectives. These accommodations and other adjustments form various SCADA transport methods that are the focus of upcoming sections.

Adapting SCADA for IP

In the 1990s, the rapid adoption of Ethernet networks in the industrial world drove the evolution of SCADA application layer protocols. For example, the IEC adopted the Open System Interconnection (OSI) layer model to define its protocol framework. Other protocol user groups also slightly modified their protocols to run over an IP infrastructure. Benefits of this move to Ethernet and IP include the ability to leverage existing equipment and standards while integrating seamlessly the SCADA subnetworks to the corporate WAN infrastructures.

To further facilitate the support of legacy industrial protocols over IP networks, protocol specifications were updated and published, documenting the use of IP for each protocol. This included assigning TCP/UDP port numbers to the protocols, such as the following:

- DNP3 (adopted by IEEE 1815-2012) specifies the use of TCP or UDP on port 20000 for transporting DNP3 messages over IP.
- The Modbus messaging service utilizes TCP port 502.
- IEC 60870-5-104 is the evolution of IEC 60870-5-101 serial for running over Ethernet and IPv4 using port 2404.
- DLMS User Association specified a communication profile based on TCP/IP in the DLMS/COSEM Green Book (Edition 5 or higher), or in the IEC 62056-53 and IEC 62056-47 standards, allowing data exchange via IP and port 4059.

> **Note** The DNP3 protocol is based on the IEC 60870-5 standard. So, while DNP3 is not interoperable with IEC 60870-5, it is very similar in its operation and functionality. Both are associated with SCADA networks, with DNP3 found predominantly in the United States and Canada and IEC 60870-5 in Europe. See Chapter 11, "Utilities," for a discussion of how these SCADA protocols are used in utilities networks.

These legacy serial protocols have adapted and evolved to utilize IP and TCP/UDP as both networking and transport mechanisms. This has allowed utilities and other companies to continue leveraging their investment in equipment and infrastructure, supporting these legacy protocols with modern IP networks. Let's dig deeper into how these legacy serial protocols have evolved to use IP by looking specifically at DNP3 as a representative use case.

Like many of the other SCADA protocols, DNP3 is based on a master/slave relationship. The term *master* in this case refers to what is typically a powerful computer located in the control center of a utility, and a *slave* is a remote device with computing resources found in a location such as a substation. DNP3 refers to slaves specifically as *outstations*.

Outstations monitor and collect data from devices that indicate their state, such as whether a circuit breaker is on or off, and take measurements, including voltage, current, temperature, and so on. This data is then transmitted to the master when it is requested, or events and alarms can be sent in an asynchronous manner. The master also issues control commands, such as to start a motor or reset a circuit breaker, and logs the incoming data.

The IEEE 1815-2012 specification describes how the DNP3 protocol implementation must be adapted to run either over TCP (recommended) or UDP. This specification defines connection management between the DNP3 protocol and the IP layers, as shown in Figure 6-2. Connection management links the DNP3 layers with the IP layers in addition to the configuration parameters and methods necessary for implementing the network connection. The IP layers appear transparent to the DNP3 layers as each piece of the protocol stack in one station logically communicates with the respective part in the other. This means that the DNP3 endpoints or devices are not aware of the underlying IP transport that is occurring.

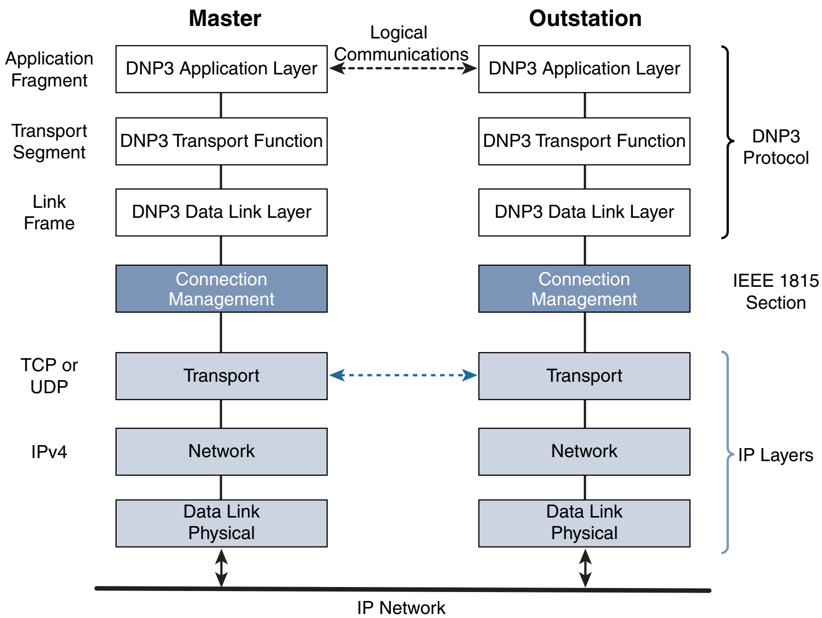

Figure 6-2 *Protocol Stack for Transporting Serial DNP3 SCADA over IP*

In Figure 6-2, the master side initiates connections by performing a TCP active open. The outstation listens for a connection request by performing a TCP passive open. *Dual endpoint* is defined as a process that can both listen for connection requests and perform an active open on the channel if required.

Master stations may parse multiple DNP3 data link layer frames from a single UDP datagram, while DNP3 data link layer frames cannot span multiple UDP datagrams. Single or multiple connections to the master may get established while a TCP keepalive timer monitors the status of the connection. Keepalive messages are implemented as DNP3 data link layer status requests. If a response is not received to a keepalive message, the connection is deemed broken, and the appropriate action is taken.

Tunneling Legacy SCADA over IP Networks

Deployments of legacy industrial protocols, such as DNP3 and other SCADA protocols, in modern IP networks call for flexibility when integrating several generations of devices or operations that are tied to various releases and versions of application servers. Native support for IP can vary and may require different solutions. Ideally, end-to-end native IP support is preferred, using a solution like IEEE 1815-2012 in the case of DNP3. Otherwise, transport of the original serial protocol over IP can be achieved either by tunneling using raw sockets over TCP or UDP or by installing an intermediate device that performs protocol translation between the serial protocol version and its IP implementation.

A raw socket connection simply denotes that the serial data is being packaged directly into a TCP or UDP transport. A socket in this instance is a standard application programming interface (API) composed of an IP address and a TCP or UDP port that is used to access network devices over an IP network. More modern industrial application servers may support this capability, while older versions typically require another device or piece of software to handle the transition from pure serial data to serial over IP using a raw socket. Figure 6-3 details raw socket scenarios for a legacy SCADA server trying to communicate with remote serial devices.

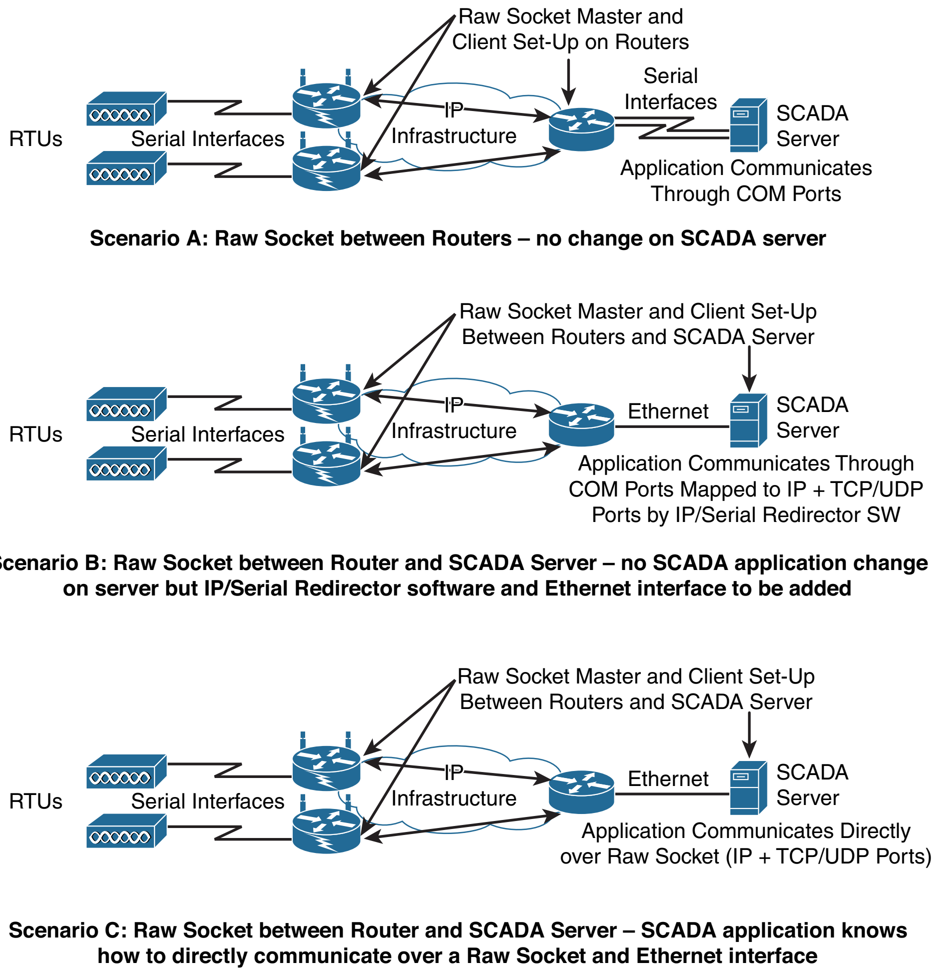

Figure 6-3 *Raw Socket TCP or UDP Scenarios for Legacy Industrial Serial Protocols*

In all the scenarios in Figure 6-3, notice that routers connect via serial interfaces to the remote terminal units (RTUs), which are often associated with SCADA networks. An RTU is a multipurpose device used to monitor and control various systems, applications, and devices managing automation. From the master/slave perspective, the RTUs are the slaves. Opposite the RTUs in each Figure 6-3 scenario is a SCADA server, or master, that varies its connection type. In reality, other legacy industrial application servers could be shown here as well.

In Scenario A in Figure 6-3, both the SCADA server and the RTUs have a direct serial connection to their respective routers. The routers terminate the serial connections at both ends of the link and use raw socket encapsulation to transport the serial payload over the IP network.

Scenario B has a small change on the SCADA server side. A piece of software is installed on the SCADA server that maps the serial COM ports to IP ports. This software is commonly referred to as an IP/serial redirector. The IP/serial redirector in essence terminates the serial connection of the SCADA server and converts it to a TCP/IP port using a raw socket connection.

In Scenario C in Figure 6-3, the SCADA server supports native raw socket capability. Unlike in Scenarios A and B, where a router or IP/serial redirector software has to map the SCADA server's serial ports to IP ports, in Scenario C the SCADA server has full IP support for raw socket connections.

Note While the examples shown here highlight tunneling of older serial-based SCADA protocols over IP using raw sockets, this mechanism can also be used to tunnel other legacy serial communication protocols that are not part of SCADA.

SCADA Protocol Translation

As mentioned earlier, an alternative to a raw socket connection for transporting legacy serial data across an IP network is protocol translation. With protocol translation, the legacy serial protocol is translated to a corresponding IP version. For example, Figure 6-4 shows two serially connected DNP3 RTUs and two master applications supporting DNP3 over IP that control and pull data from the RTUs. The IoT gateway in this figure performs a protocol translation function that enables communication between the RTUs and servers, despite the fact that a serial connection is present on one side and an IP connection is used on the other.

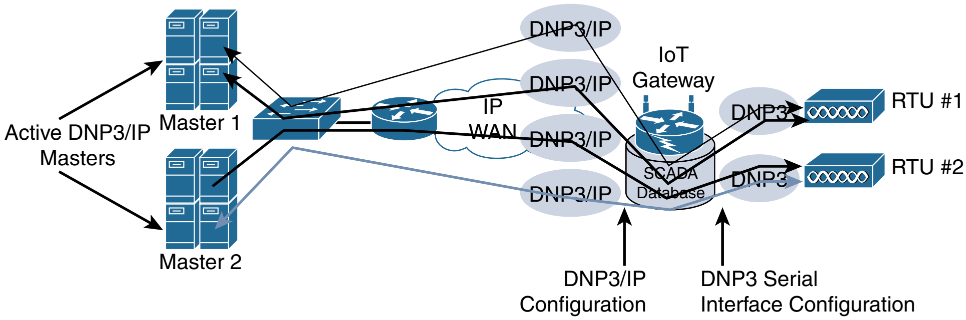

Figure 6-4 *DNP3 Protocol Translation*

By running protocol translation, the IoT gateway connected to the RTUs in Figure 6-4 is implementing a computing function close to the edge of the network. Adding computing functions close to the edge helps scale distributed intelligence in IoT networks. This can be accomplished by offering computing resources on IoT gateways or routers, as shown in this protocol translation example. Alternatively, this can also be performed directly on a node connecting multiple sensors. In either case, this is referred to as fog computing. (For more information on fog computing, see Chapter 2, "IoT Network Architecture and Design.")

Note In Figure 6-4, DNP3 is shown as the protocol being translated. However, the scenario in this figure is just as applicable to IEC 60870-5. For example, instead of the RTU using DNP3 to connect to the IoT gateway, IEC 60870-5-101 or T101 could be used. On the opposite side, IEC 60870-5-104 or T104 would replace DNP3/IP.

SCADA Transport over LLNs with MAP-T

Due to the constrained nature of LLNs, the implementation of industrial protocols should at a minimum be done over UDP. This in turn requires that both the application servers and devices support and implement UDP. While the long-term evolution of SCADA and other legacy industrial protocols is to natively support IPv6, it must be highlighted that most, if not all, of the industrial devices supporting IP today support IPv4 only. When deployed over LLN subnetworks that are IPv6 only, a transition mechanism, such as MAP-T (Mapping of Address and Port using Translation, RFC 7599), needs to be implemented. This allows the deployment to take advantage of native IPv6 transport transparently to the application and devices.

Figure 6-5 depicts a scenario in which a legacy endpoint is connected across an LLN running 6LoWPAN to an IP-capable SCADA server. The legacy endpoint could be running various industrial and SCADA protocols, including DNP3/IP, Modbus/TCP, or IEC 60870-5-104. In this scenario, the legacy devices and the SCADA server support only IPv4 (typical in the industry today). However, IPv6 (with 6LoWPAN and RPL) is being used for connectivity to the endpoint. As discussed in Chapter 5, 6LoWPAN is a standardized protocol designed for constrained networks, but it only supports IPv6. In this situation, the end devices, the endpoints, and the SCADA server support only IPv4, but the network in the middle supports only IPv6.

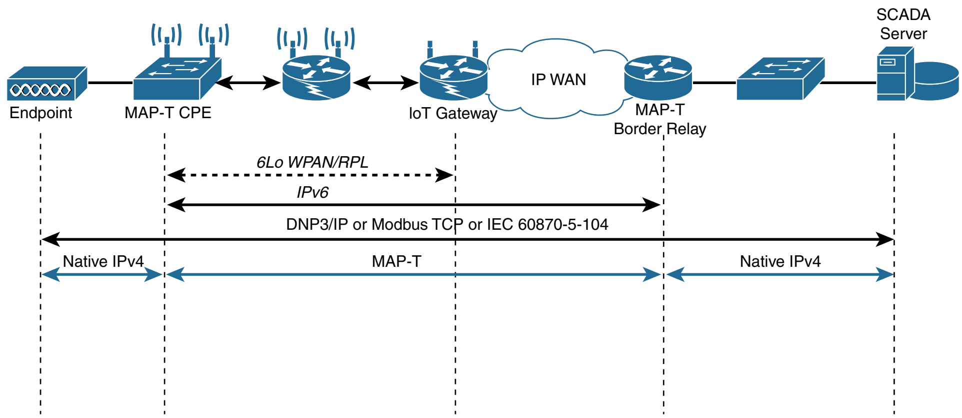

Figure 6-5 *DNP3 Protocol over 6LoWPAN Networks with MAP-T*

The solution to this problem is to use the protocol known as MAP-T, introduced in Chapter 5. MAP-T makes the appropriate mappings between IPv4 and the IPv6 protocols. This allows legacy IPv4 traffic to be forwarded across IPv6 networks. In other words, older devices and protocols can continue running IPv4 even though the network is requiring IPv6.

In Figure 6-5 the IPv4 endpoint on the left side is connected to a Customer Premise Equipment (CPE) device. The MAP-T CPE device has an IPv6 connection to the RPL mesh. On the right side, a SCADA server with native IPv4 support connects to a MAP-T border gateway. The MAP-T CPE device and MAP-T border gateway are thus responsible for the MAP-T conversion from IPv4 to IPv6.

Legacy implementations of SCADA and other industrial protocols are still widely deployed across many industries. While legacy SCADA has evolved from older serial connections to support IP, we can still expect to see mixed deployments for many years. To address this challenge, OT networks require mechanisms such as raw sockets and protocol translation to transport legacy versions over modern IP networks. Even when the legacy devices have IPv4 capability, the constrained portions of the network often require IPv6, not IPv4. In these cases, a MAP-T solution can be put in place to enable IPv4 data to be carried across an IPv6 network.

Generic Web-Based Protocols

Over the years, web-based protocols have become common in consumer and enterprise applications and services. Therefore, it makes sense to try to leverage these protocols when developing IoT applications, services, and devices in order to ease the integration of data and devices from prototyping to production.

The level of familiarity with generic web-based protocols is high. Therefore, programmers with basic web programming skills can work on IoT applications, and this may lead to innovative ways to deliver and handle real-time IoT data. For example, an IoT device generating an event can have the result of launching a video capture, while at the same time a notification is sent to a collaboration tool, such as a Cisco Spark room. This notification allows technicians and engineers to immediately start working on this alert. In addition to a generally high level of familiarity with web-based protocols, scaling methods for web environments are also well understood—and this is crucial when developing consumer applications for potentially large numbers of IoT devices.

Once again, the definition of constrained nodes and networks must be analyzed to select the most appropriate protocol. (Constrained nodes and networks are discussed in Chapter 5.) On non-constrained networks, such as Ethernet, Wi-Fi, or 3G/4G cellular, where bandwidth is not perceived as a potential issue, data payloads based on a verbose data model representation, including XML or JavaScript Object Notation (JSON), can be transported over HTTP/HTTPS or WebSocket. This allows implementers to develop their IoT applications in contexts similar to web applications.

The HTTP/HTTPS client/server model serves as the foundation for the World Wide Web. Recent evolutions of embedded web server software with advanced features are now implemented with very little memory (in the range of tens of kilobytes in some cases). This enables the use of embedded web services software on some constrained devices.

When considering web services implementation on an IoT device, the choice between supporting the client or server side of the connection must be carefully weighed. IoT devices that only push data to an application (for example, an Ethernet- or Wi-Fi-based weather station reporting data to a weather map application or a Wi-Fi–enabled body weight scale that sends data to a health application) may need to implement web services on the client side. The HTTP client side only initiates connections and does not accept incoming ones.

On the other hand, some IoT devices, such as a video surveillance camera, may have web services implemented on the server side. However, because these devices often have limited resources, the number of incoming connections must be kept low. In addition, advanced development in data modeling should be considered as a way to shift the workload from devices to clients, including web browsers on PCs, mobile phones, tablets, and cloud applications.

Interactions between real-time communication tools powering collaborative applications, such as voice and video, instant messaging, chat rooms, and IoT devices, are also emerging. This is driving the need for simpler communication systems between people and IoT devices. One protocol that addresses this need is Extensible Messaging and Presence Protocol (XMPP). (For more information on XMPP-IoT, see www.xmpp-iot.org.)

Note In IoT networks, it is common to see both Simple Object Access Protocol (SOAP) and representational state transfer (REST) utilized as web services access protocols. Based on Extensible Markup Language (XML), SOAP is verbose and complex from a coding perspective, with a slow parsing speed, but it is versatile and has built-in error handling that can make resolving issues easier. XML is a specification that details a set of rules for encoding documents and other data structures in a way that is readable by both humans and computers.

As a simple, lightweight alternative to SOAP, REST often implements a simple URI or JSON instead of XML for requests. JSON is easier to read and understand than XML. Also, REST itself is not a standard-based protocol like SOAP but an architectural style.

A detailed discussion of the intricacies of SOAP and REST is beyond the scope of this book, but each of them has a place in performing web services in IoT networks. From a high-level perspective, the simplicity of REST makes it suited more for applications on lightweight clients, such as mobile and embedded devices. SOAP, on the other hand, has better adherence to enterprise and business applications and has stronger security requirements. Many coders have the opinion that REST is the future, but at the same time you will find that SOAP is still quite prevalent in certain applications.

In summary, the Internet of Things greatly benefits from the existing web-based protocols. These protocols, including HTTP/HTTPS and XMPP, ease the integration of IoT devices in the Internet world through well-known and scalable programming techniques.

However, to fully address constrained devices and networks, optimized IoT protocols are required. These protocols are discussed in the next sections.

IoT Application Layer Protocols

When considering constrained networks and/or a large-scale deployment of constrained nodes, verbose web-based and data model protocols, as discussed in the previous section, may be too heavy for IoT applications. To address this problem, the IoT industry is working on new lightweight protocols that are better suited to large numbers of constrained nodes and networks. Two of the most popular protocols are CoAP and MQTT. Figure 6-6 highlights their position in a common IoT protocol stack.

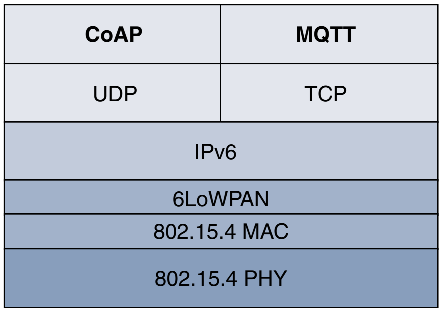

Figure 6-6 *Example of a High-Level IoT Protocol Stack for CoAP and MQTT*

In Figure 6-6, CoAP and MQTT are naturally at the top of this sample IoT stack, based on an IEEE 802.15.4 mesh network. While there are a few exceptions, you will almost always find CoAP deployed over UDP and MQTT running over TCP. The following sections take a deeper look at CoAP and MQTT.

CoAP

Constrained Application Protocol (CoAP) resulted from the IETF Constrained RESTful Environments (CoRE) working group's efforts to develop a generic framework for resource-oriented applications targeting constrained nodes and networks. (For more information on the IETF CoRE working group, see https://datatracker.ietf.org/wg/core/charter/.) Constrained nodes and networks are discussed in Chapter 5.

The CoAP framework defines simple and flexible ways to manipulate sensors and actuators for data or device management. The IETF CoRE working group has published multiple standards-track specifications for CoAP, including the following:

- **RFC 6690:** Constrained RESTful Environments (CoRE) Link Format
- **RFC 7252:** The Constrained Application Protocol (CoAP)

- **RFC 7641:** Observing Resources in the Constrained Application Protocol (CoAP)
- **RFC 7959:** Block-Wise Transfers in the Constrained Application Protocol (CoAP)
- **RFC 8075:** Guidelines for Mapping Implementations: HTTP to the Constrained Application Protocol (CoAP)

The CoAP messaging model is primarily designed to facilitate the exchange of messages over UDP between endpoints, including the secure transport protocol Datagram Transport Layer Security (DTLS). (UDP is discussed earlier in this chapter.) The IETF CoRE working group is studying alternate transport mechanisms, including TCP, secure TLS, and WebSocket. CoAP over Short Message Service (SMS) as defined in Open Mobile Alliance for Lightweight Machine-to-Machine (LWM2M) for IoT device management is also being considered. (For more information on the Open Mobile Alliance, see http://openmobilealliance.org.)

RFC 7252 provides more details on securing CoAP with DTLS. It specifies how a CoAP endpoint is provisioned with keys and a filtering list. Four security modes are defined: NoSec, PreSharedKey, RawPublicKey, and Certificate. The NoSec and RawPublicKey implementations are mandatory. (For more information about these security modes, see https://tools.ietf.org/html/rfc7252.)

From a formatting perspective, a CoAP message is composed of a short fixed-length Header field (4 bytes), a variable-length but mandatory Token field (0–8 bytes), Options fields if necessary, and the Payload field. Figure 6-7 details the CoAP message format, which delivers low overhead while decreasing parsing complexity.

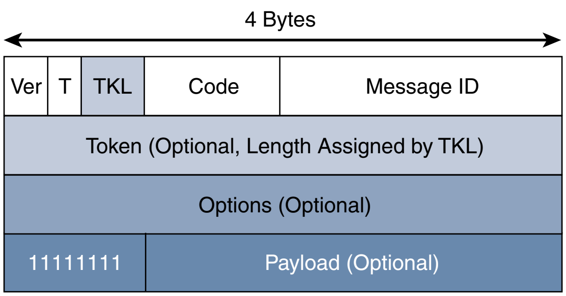

Figure 6-7 *CoAP Message Format*

As you can see in Figure 6-7, the CoAP message format is relatively simple and flexible. It allows CoAP to deliver low overhead, which is critical for constrained networks, while also being easy to parse and process for constrained devices. Table 6-1 provides an overview of the various fields of a CoAP message. (For more details on these fields, see https://tools.ietf.org/html/rfc7252.)

Table 6-1 *CoAP Message Fields*

CoAP Message Field	Description
Ver (Version)	Identifies the CoAP version.
T (Type)	Defines one of the following four message types: Confirmable (CON), Non-confirmable (NON), Acknowledgement (ACK), or Reset (RST). CON and ACK are highlighted in more detail in Figure 6-9.
TKL (Token Length)	Specifies the size (0–8 Bytes) of the Token field.
Code	Indicates the request method for a request message and a response code for a response message. For example, in Figure 6-9, GET is the request method, and 2.05 is the response code. For a complete list of values for this field, refer to RFC 7252.
Message ID	Detects message duplication and used to match ACK and RST message types to Con and NON message types.
Token	With a length specified by TKL, correlates requests and responses.
Options	Specifies option number, length, and option value. Capabilities provided by the Options field include specifying the target resource of a request and proxy functions.
Payload	Carries the CoAP application data. This field is optional, but when it is present, a single byte of all 1s (0xFF) precedes the payload. The purpose of this byte is to delineate the end of the Options field and the beginning of Payload.

CoAP can run over IPv4 or IPv6. However, it is recommended that the message fit within a single IP packet and UDP payload to avoid fragmentation. For IPv6, with the default MTU size being 1280 bytes and allowing for no fragmentation across nodes, the maximum CoAP message size could be up to 1152 bytes, including 1024 bytes for the payload. In the case of IPv4, as IP fragmentation may exist across the network, implementations should limit themselves to more conservative values and set the IPv4 Don't Fragment (DF) bit.

While most sensor and actuator traffic utilizes small-packet payloads, some use cases, such as firmware upgrades, require the capability to send larger payloads. CoAP doesn't rely on IP fragmentation but defines (in RFC 7959) a pair of Block options for transferring multiple blocks of information from a resource representation in multiple request/response pairs.

As illustrated in Figure 6-8, CoAP communications across an IoT infrastructure can take various paths. Connections can be between devices located on the same or different constrained networks or between devices and generic Internet or cloud servers, all operating over IP. Proxy mechanisms are also defined, and RFC 7252 details a basic HTTP mapping for CoAP. As both HTTP and CoAP are IP-based protocols, the proxy function can be located practically anywhere in the network, not necessarily at the border between constrained and non-constrained networks.

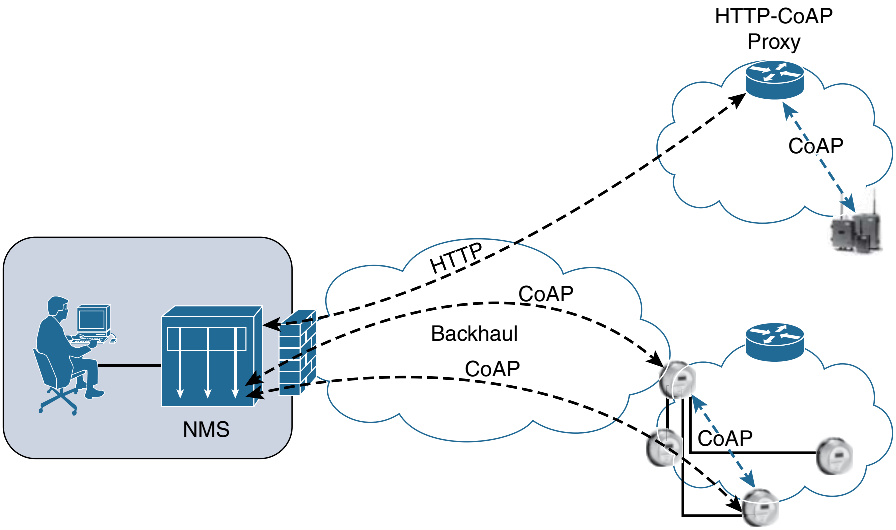

Figure 6-8 *CoAP Communications in IoT Infrastructures*

Just like HTTP, CoAP is based on the REST architecture, but with a "thing" acting as both the client and the server. Through the exchange of asynchronous messages, a client requests an action via a method code on a server resource. A uniform resource identifier (URI) localized on the server identifies this resource. The server responds with a response code that may include a resource representation. The CoAP request/response semantics include the methods GET, POST, PUT, and DELETE.

Example 6-2 shows the CoAP URI format. You may notice that the CoAP URI format is similar to HTTP/HTTPS. The **coap/coaps** URI scheme identifies a resource, including host information and optional UDP port, as indicated by the **host** and **port** parameters in the URI.

Example 6-2 *CoAP URI format*

```
coap-URI = "coap:" "//" host [":" port] path-abempty ["?" query]
coaps-URI = "coaps:" "//" host [":" port] path-abempty  ["?" query]
```

CoAP defines four types of messages: confirmable, non-confirmable, acknowledgement, and reset. Method codes and response codes included in some of these messages make them carry requests or responses. CoAP code, method and response codes, option numbers, and content format have been assigned by IANA as Constrained RESTful Environments (CoRE) parameters. (For more information on these parameters, see www.iana.org/assignments/core-parameters/core-parameters.xhtml.)

While running over UDP, CoAP offers a reliable transmission of messages when a CoAP header is marked as “confirmable.” In addition, CoAP supports basic congestion control with a default time-out, simple stop and wait retransmission with exponential back-off mechanism, and detection of duplicate messages through a message ID. If a request or response is tagged as confirmable, the recipient must explicitly either acknowledge or reject the message, using the same message ID, as shown in Figure 6-9. If a recipient can’t process a non-confirmable message, a reset message is sent.

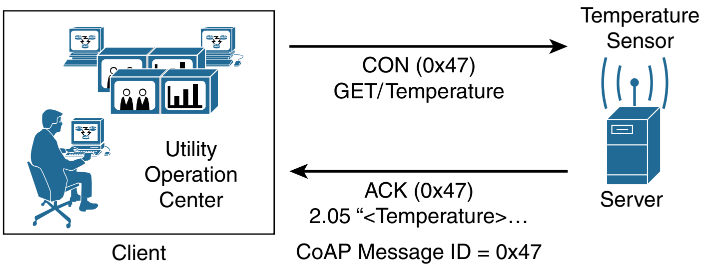

Figure 6-9 *CoAP Reliable Transmission Example*

Figure 6-9 shows a utility operations center on the left, acting as the CoAP client, with the CoAP server being a temperature sensor on the right of the figure. The communication between the client and server uses a CoAP message ID of 0x47. The CoAP Message ID ensures reliability and is used to detect duplicate messages.

The client in Figure 6-9 sends a GET message to get the temperature from the sensor. Notice that the 0x47 message ID is present for this GET message and that the message is also marked with CON. A CON, or confirmable, marking in a CoAP message means the message will be retransmitted until the recipient sends an acknowledgement (or ACK) with the same message ID.

In Figure 6-9, the temperature sensor does reply with an ACK message referencing the correct message ID of 0x47. In addition, this ACK message piggybacks a successful response to the GET request itself. This is indicated by the 2.05 response code followed by the requested data.

CoAP supports data requests sent to a group of devices by leveraging the use of IP Multicast. Implementing IP Multicast with CoAP requires the use of all-CoAP-node multicast addresses. For IPv4 this address is 224.0.1.187, and for IPv6 it is FF0X::FD. These multicast addresses are joined by CoAP nodes offering services to other endpoints while listening on the default CoAP port, 5683. Therefore, endpoints can find available CoAP services through multicast service discovery. A typical use case for multicasting is deploying a firmware upgrade for a group of IoT devices, such as smart meters.

With often no affordable manual configuration on the IoT endpoints, a CoAP server offering services and resources needs to be discovered by the CoAP clients. Services from a CoAP server can either be discovered by learning a URI in a namespace or through the "All CoAP nodes" multicast address. When utilizing the URI scheme for discovering services, the default port 5683 is used for non-secured CoAP, or **coap**, while port 5684 is utilized for DTLS-secured CoAP, or **coaps**. The CoAP server must be in listening state on these ports, unless a different port number is associated with the URI in a namespace.

Much as with accessing web server resources, CoAP specifications provide a description of the relationships between resources in RFC 6690, "Constrained RESTful Environments (CoRE) Link Format." This standard defines the CoRE Link format carried as a payload with an assigned Internet media type. A default entry point for listing to a CoAP server's resource links is to set a well-known relative URI, such as **/.well-known/core**.

To improve the response time and reduce bandwidth consumption, CoAP supports caching capabilities based on the response code. To use a cache entry, a CoAP endpoint must validate the presented request and stored response matches, including all options (unless marked as NoCacheKey). This confirms that the stored response is fresh or valid.

A wide range of CoAP implementations are available. Some are published with open source licenses, and others are part of vendor solutions. A good resource for CoAP implementations is http://coap.technology/impls.html.

In summary, CoAP is a key application protocol adapted to the IoT framework. Because its standardization is led by the IETF CoRE working group, it closely coordinates with other IETF working groups, in particular those looking at constrained nodes and networks, such as 6Lo, 6TiSCH, LWIG, RoLL, ACE, and COSE. Therefore, CoAP is fully optimized for IoT constrained nodes and networks, while leveraging traditional web programming techniques to make it easily understandable by the development community. (For more information on CoAP resources, see http://coap.technology/.)

Message Queuing Telemetry Transport (MQTT)

At the end of the 1990s, engineers from IBM and Arcom (acquired in 2006 by Eurotech) were looking for a reliable, lightweight, and cost-effective protocol to monitor and control a large number of sensors and their data from a central server location, as typically used by the oil and gas industries. Their research resulted in the development and implementation of the Message Queuing Telemetry Transport (MQTT) protocol that is now standardized by the Organization for the Advancement of Structured Information Standards (OASIS). (For more information on OASIS, see www.oasis-open.org.)

Considering the harsh environments in the oil and gas industries, an extremely simple protocol with only a few options was designed, with considerations for constrained nodes, unreliable WAN backhaul communications, and bandwidth constraints with variable latencies. These were some of the rationales for the selection of a client/server and publish/subscribe framework based on the TCP/IP architecture, as shown in Figure 6-10.

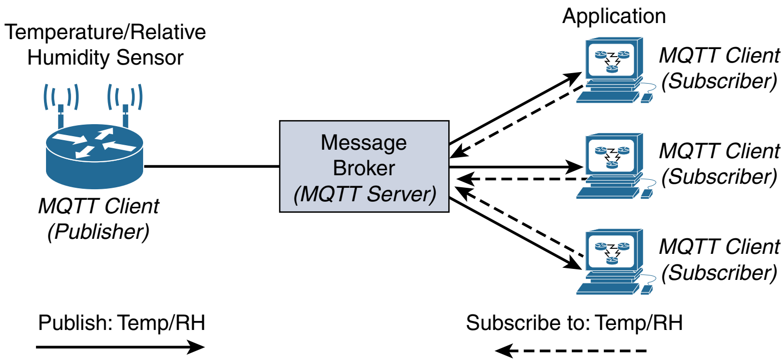

Figure 6-10 *MQTT Publish/Subscribe Framework*

An MQTT client can act as a publisher to send data (or resource information) to an MQTT server acting as an MQTT message broker. In the example illustrated in Figure 6-10, the MQTT client on the left side is a temperature (Temp) and relative humidity (RH) sensor that publishes its Temp/RH data. The MQTT server (or message broker) accepts the network connection along with application messages, such as Temp/RH data, from the publishers. It also handles the subscription and unsubscription process and pushes the application data to MQTT clients acting as subscribers.

The application on the right side of Figure 6-10 is an MQTT client that is a subscriber to the Temp/RH data being generated by the publisher or sensor on the left. This model, where subscribers express a desire to receive information from publishers, is well known. A great example is the collaboration and social networking application Twitter.

With MQTT, clients can subscribe to all data (using a wildcard character) or specific data from the information tree of a publisher. In addition, the presence of a message broker in MQTT decouples the data transmission between clients acting as publishers and subscribers. In fact, publishers and subscribers do not even know (or need to know) about each other. A benefit of having this decoupling is that the MQTT message broker ensures that information can be buffered and cached in case of network failures. This also means that publishers and subscribers do not have to be online at the same time.

MQTT control packets run over a TCP transport using port 1883. TCP ensures an ordered, lossless stream of bytes between the MQTT client and the MQTT server. Optionally, MQTT can be secured using TLS on port 8883, and WebSocket (defined in RFC 6455) can also be used.

MQTT is a lightweight protocol because each control packet consists of a 2-byte fixed header with optional variable header fields and optional payload. You should note that a control packet can contain a payload up to 256 MB. Figure 6-11 provides an overview of the MQTT message format.

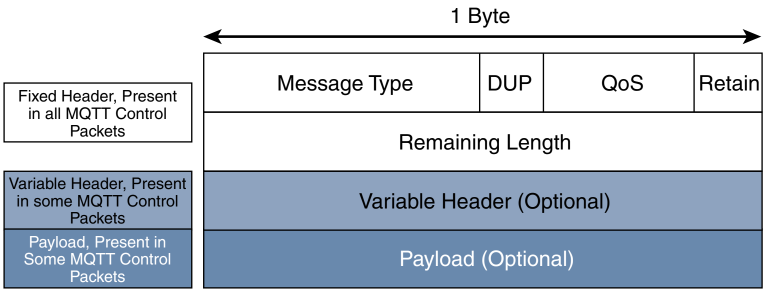

Figure 6-11 *MQTT Message Format*

Compared to the CoAP message format in Figure 6-7, you can see that MQTT contains a smaller header of 2 bytes compared to 4 bytes for CoAP. The first MQTT field in the header is Message Type, which identifies the kind of MQTT packet within a message. Fourteen different types of control packets are specified in MQTT version 3.1.1. Each of them has a unique value that is coded into the Message Type field. Note that values 0 and 15 are reserved. MQTT message types are summarized in Table 6-2.

Table 6-2 *MQTT Message Types*

Message Type	Value	Flow	Description
CONNECT	1	Client to server	Request to connect
CONNACK	2	Server to client	Connect acknowledgement
PUBLISH	3	Client to server Server to client	Publish message
PUBACK	4	Client to server Server to client	Publish acknowledgement
PUBREC	5	Client to server Server to client	Publish received
PUBREL	6	Client to server Server to client	Publish release
PUBCOMP	7	Client to server Server to client	Publish complete
SUBSCRIBE	8	Client to server	Subscribe request
SUBACK	9	Server to client	Subscribe acknowledgement
UNSUBSCRIBE	10	Client to server	Unsubscribe request

Message Type	Value	Flow	Description
UNSUBACK	11	Server to client	Unsubscribe acknowledgement
PINGREQ	12	Client to server	Ping request
PINGRESP	13	Server to client	Ping response
DISCONNECT	14	Client to server	Client disconnecting

The next field in the MQTT header is DUP (Duplication Flag). This flag, when set, allows the client to notate that the packet has been sent previously, but an acknowledgement was not received.

The QoS header field allows for the selection of three different QoS levels. These are discussed in more detail later in this chapter.

The next field is the Retain flag. Only found in a PUBLISH message (refer to Table 6-2), the Retain flag notifies the server to hold onto the message data. This allows new subscribers to instantly receive the last known value without having to wait for the next update from the publisher.

The last mandatory field in the MQTT message header is Remaining Length. This field specifies the number of bytes in the MQTT packet following this field.

MQTT sessions between each client and server consist of four phases: session establishment, authentication, data exchange, and session termination. Each client connecting to a server has a unique client ID, which allows the identification of the MQTT session between both parties. When the server is delivering an application message to more than one client, each client is treated independently.

Subscriptions to resources generate SUBSCRIBE/SUBACK control packets, while unsubscription is performed through the exchange of UNSUBSCRIBE/UNSUBACK control packets. Graceful termination of a connection is done through a DISCONNECT control packet, which also offers the capability for a client to reconnect by re-sending its client ID to resume the operations.

A message broker uses a topic string or topic name to filter messages for its subscribers. When subscribing to a resource, the subscriber indicates the one or more topic levels that are used to structure the topic name. The forward slash (/) in an MQTT topic name is used to separate each level within the topic tree and provide a hierarchical structure to the topic names. Figure 6-12 illustrates these concepts with **adt/lora.adeunis** being a topic level and **adt/lora/adeunis/0018B2000000023A** being an example of a topic name.

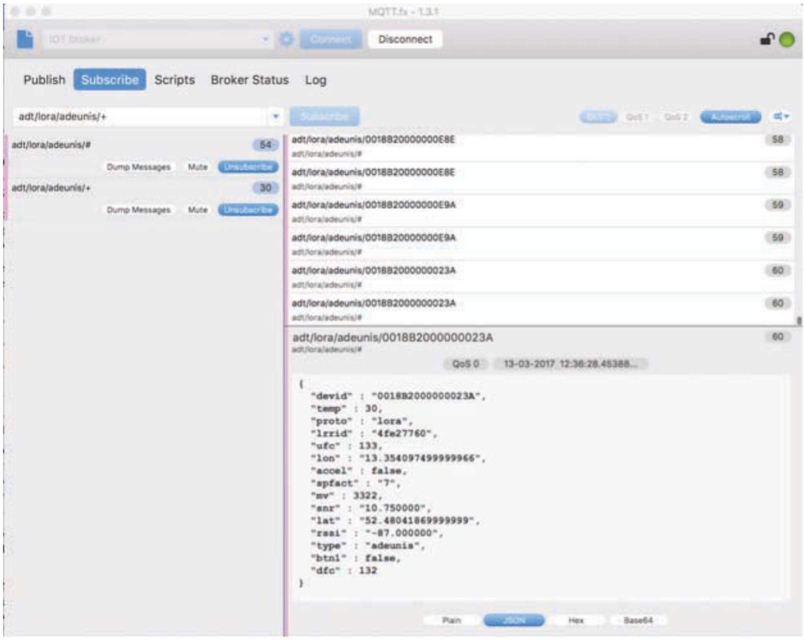

Figure 6-12 *MQTT Subscription Example*

Wide flexibility is available to clients subscribing to a topic name. An exact topic can be subscribed to, or multiple topics can be subscribed to at once, through the use of wildcard characters. A subscription can contain one of the wildcard characters to allow subscription to multiple topics at once.

The pound sign (#) is a wildcard character that matches any number of levels within a topic. The multilevel wildcard represents the parent and any number of child levels. For example, subscribing to **adt/lora/adeunis/#** enables the reception of the whole subtree, which could include topic names such as the following:

- **adt/lora/adeunis/0018B20000000E9E**
- **adt/lora/adeunis/0018B20000000E8E**
- **adt/lora/adeunis/0018B20000000E9A**

The plus sign (+) is a wildcard character that matches only one topic level. For example, **adt/lora/+** allows access to **adt/lora/adeunis/** and **adt/lora/abeeway** but not to **adt/lora/adeunis/0018B20000000E9E**.

Topic names beginning with the dollar sign ($) must be excluded by the server when subscriptions start with wildcard characters (# or +). Often, these types of topic names are utilized for message broker internal statistics. So messages cannot be published to these topics by clients. For example, a subscription to **+/monitor/Temp** does not receive any messages published to **$SYS/monitor/Temp**. This topic could be the control channel for this temperature sensor.

PINGREQ/PINGRESP control packets are used to validate the connections between the client and server. Similar to ICMP pings that are part of IP, they are a sort of keepalive that helps to maintain and check the TCP session.

Securing MQTT connections through TLS is considered optional because it calls for more resources on constrained nodes. When TLS is not used, the client sends a clear-text username and password during the connection initiation. MQTT server implementations may also accept anonymous client connections (with the username/password being “blank”). When TLS is implemented, a client must validate the server certificate for proper authentication. Client authentication can also be performed through certificate exchanges with the server, depending on the server configuration.

The MQTT protocol offers three levels of quality of service (QoS). QoS for MQTT is implemented when exchanging application messages with publishers or subscribers, and it is different from the IP QoS that most people are familiar with. The delivery protocol is symmetric. This means the client and server can each take the role of either sender or receiver. The delivery protocol is concerned solely with the delivery of an application message from a single sender to a single receiver. These are the three levels of MQTT QoS:

- **QoS 0:** This is a best-effort and unacknowledged data service referred to as “at most once” delivery. The publisher sends its message one time to a server, which transmits it once to the subscribers. No response is sent by the receiver, and no retry is performed by the sender. The message arrives at the receiver either once or not at all.
- **QoS 1:** This QoS level ensures that the message delivery between the publisher and server and then between the server and subscribers occurs at least once. In PUBLISH and PUBACK packets, a packet identifier is included in the variable header. If the message is not acknowledged by a PUBACK packet, it is sent again. This level guarantees “at least once” delivery.
- **QoS 2:** This is the highest QoS level, used when neither loss nor duplication of messages is acceptable. There is an increased overhead associated with this QoS level because each packet contains an optional variable header with a packet identifier. Confirming the receipt of a PUBLISH message requires a two-step acknowledgement process. The first step is done through the PUBLISH/PUBREC packet pair, and the second is achieved with the PUBREL/PUBCOMP packet pair. This level provides a “guaranteed service” known as “exactly once” delivery, with no consideration for the number of retries as long as the message is delivered once.

As mentioned earlier, the QoS process is symmetric in regard to the roles of sender and receiver, but two separate transactions exist. One transaction occurs between the publishing client and the MQTT server, and the other transaction happens between the MQTT server and the subscribing client. Figure 6-13 provides an overview of the MQTT QoS flows for the three different levels.

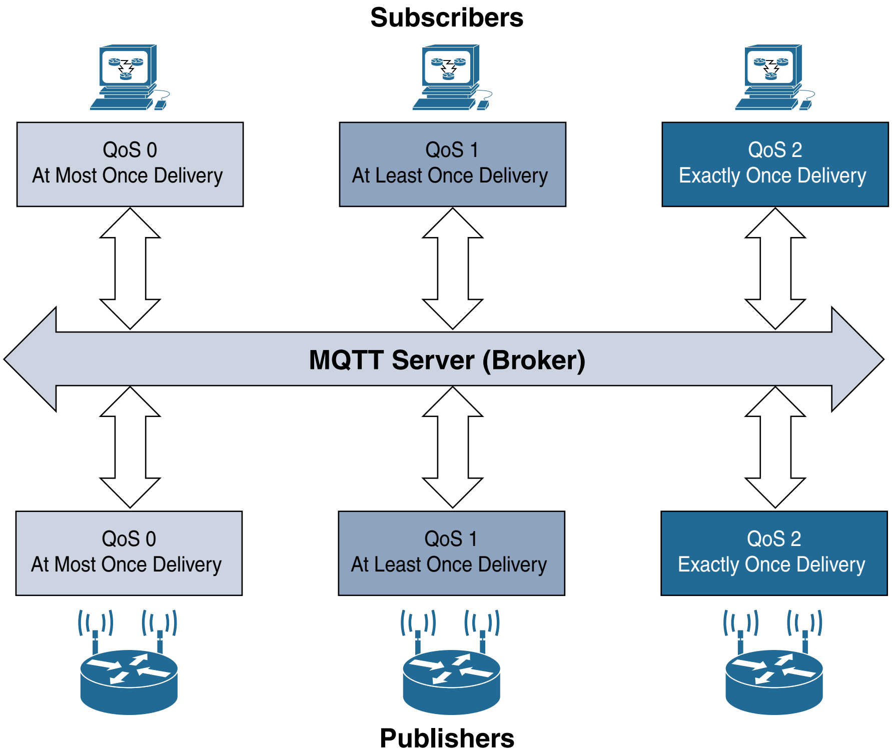

Figure 6-13 *MQTT QoS Flows*

> **Note** The client on each side of the MQTT flow sets the QoS level. The publishing client side sets the QoS level for communications to the MQTT server. On the other side, the client subscriber sets the QoS level through the subscription with the MQTT server. As illustrated in Figure 6-13, in most cases, QoS remains the same between clients and broker end to end. However, you should be aware that in some scenarios, QoS levels change and are not the same end to end.

As with CoAP, a wide range of MQTT implementations are now available. They are either published as open source licenses or integrated into vendors' solutions, such as Facebook Messenger. For more information on MQTT implementations, see either the older MQTT.org site, at http://mqtt.org, or check out the MQTT community wiki, at https://github.com/mqtt/mqtt.github.io/wiki.

> **Note** A free tool for working and experimenting with MQTT is MQTT.fx (shown in Figure 6-12). For more information on MQTT.fx, see www.mqttfx.org.

Now that both CoAP and MQTT have been discussed in detail, you can face questions like “Which protocol is better for a given use case?” and “Which one should I used in my IoT network?” Unfortunately, the answer is not always clear, and both MQTT and CoAP have their place. Table 6-3 provides an overview of the differences between MQTT and CoAP, along with their strengths and weaknesses from an IoT perspective.

Table 6-3 *Comparison Between CoAP and MQTT*

Factor	CoAP	MQTT
Main transport protocol	UDP	TCP
Typical messaging	Request/response	Publish/subscribe
Effectiveness in LLNs	Excellent	Low/fair (Implementations pairing UDP with MQTT are better for LLNs.)
Security	DTLS	SSL/TLS
Communication model	One-to-one	many-to-many
Strengths	Lightweight and fast, with low overhead, and suitable for constrained networks; uses a RESTful model that is easy to code to; easy to parse and process for constrained devices; support for multicasting; asynchronous and synchronous messages	TCP and multiple QoS options provide robust communications; simple management and scalability using a broker architecture
Weaknesses	Not as reliable as TCP-based MQTT, so the application must ensure reliability.	Higher overhead for constrained devices and networks; TCP connections can drain low-power devices; no multicasting support

In summary, MQTT is different from the “one-to-one” CoAP model in its “many-to-many” subscription framework, which can make it a better option for some deployments. MQTT is TCP-based, and it ensures an ordered and lossless connection. It has a low overhead when optionally paired with UDP and flexible message format, supports TLS for security, and provides for three levels of QoS. This makes MQTT a key application layer protocol for the successful adoption and growth of the Internet of Things.

Summary

This chapter completes the discussion of the IoT protocol stack. Chapter 4 covers the IoT options for the PHY and MAC layers, and Chapter 5 details the options at the network layer. This chapter focuses on the transport of application protocols in IoT networks.

This chapter begins with a discussion of TCP and UDP. Both of these protocols have their place in IoT networks, depending on the application.

The rest of this chapter focuses on the various methods for transporting IoT application data. The first method discussed is application layer protocol not present, in which the data payload is directly transported on top of the lower layers. An IoT data broker is needed to scale this method of transporting application data.

The second method discussed is IP-adapted application layer. This technique utilizes an IP adaptation layer to transport application data that comes from a non-IP stack. Legacy industrial protocols, such as DNP3, fall in this category and require capabilities like raw sockets and protocol translation to successfully communicate across an IP network.

The next method discussed is generic web-based protocols (such as HTTP), which can be used with non-constrained networks, such as Ethernet and Wi-Fi.

The last approach discussed for handling IoT application data at the upper layers is IoT application layer protocols. This method handles constrained nodes and networks and is recommended for most IoT networks. Special protocols, like CoAP and MQTT, handle the IoT application data requirements and are quite efficient for smart objects with a small compute footprint that need to communicate over a low-bandwidth network.