

# IOT 18CS81 MOD 2 SHORT NOTES

VTU short notes by YouTuber **Afnan Marquee**. The notes are in simple format for quick learning. For video explanation, check out my YouTube Channel!

Module 2	Smart Objects: The “Things” in IoT, Sensors, Actuators, and Smart Objects, Sensor Networks, Connecting Smart Objects, Communications Criteria, IoT Access Technologies.	08
<b>Textbook 1: Ch.3, 4</b>		
<b>RBT: L1, L2, L3</b>		

## Smart Objects: The “Things” in IoT

Sensors are fundamental building blocks of IoT networks, they are the foundational elements found in smart objects—the “things” in the Internet of Things. Smart objects are any physical objects that contain embedded technology to sense and/or interact with their environment in a meaningful way by being interconnected and enabling communication among themselves or an external agent.

### 2.1 Sensors

A sensor does exactly as its name indicates: It senses. More specifically, a sensor measures some physical quantity and converts that measurement reading into a digital representation. That digital representation is typically passed to another device for transformation into useful data that can be consumed by intelligent devices or humans.

There are different types of sensors available to measure virtually everything in the physical world and they are categorized as following:

- **Active or passive:** Sensors can be categorized based on whether they produce an energy output and typically require an external power supply (active) or whether they simply receive energy and typically require no external power supply (passive).
- **Invasive or non-invasive:** Sensors can be categorized based on whether a sensor is part of the environment it is measuring (invasive) or external to it (non-invasive).
- **Contact or no-contact:** Sensors can be categorized based on whether they require physical contact with what they are measuring (contact) or not (no-contact).
- **Absolute or relative:** Sensors can be categorized based on whether they measure on an absolute scale (absolute) or based on a difference with a fixed or variable reference value (relative).
- **Area of application:** Sensors can be categorized based on the specific industry or vertical where they are being used.
- **How sensors measure:** Sensors can be categorized based on the physical mechanism used to measure sensory input (for example, thermoelectric, electrochemical, piezoresistive, optic, electric, fluid mechanic, photoelastic).
- **What sensors measure:** Sensors can be categorized based on their applications or what physical variables they measure.

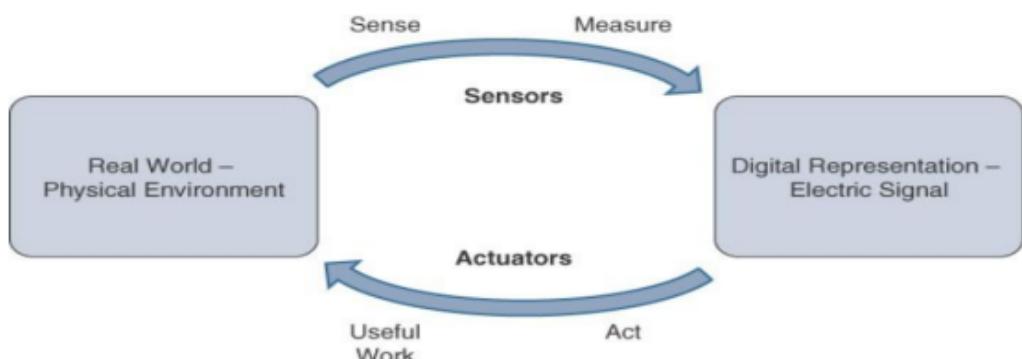
Sensors can measure position, occupancy and motion, velocity and acceleration and force, force, pressure, flow, acoustic, humidity, biosensors, light, radiation, temperature and chemical.



**Figure 3-2 Sensors in a Smart Phone**

## 2.2 Actuators

Actuators are natural complements to sensors. Figure 3-4 demonstrates the symmetry and complementary nature of these two types of devices. Actuators receive some type of control signal (commonly an electric signal or digital command) that triggers a physical effect, usually some type of motion, force, and so on.



**Figure 3-4 How Sensors and Actuators Interact with the Physical World**

Actuators vary greatly in function, size, design, and so on. Some common ways that they can be classified include the following:

- **Type of motion:** Actuators can be classified based on the type of motion they produce (for example, linear, rotary, one/two/three-axes).
- **Power:** Actuators can be classified based on their power output (for example, high power, low power, micro power)
- **Binary or continuous:** Actuators can be classified based on the number of stable-state outputs.
- **Area of application:** Actuators can be classified based on the specific industry or vertical where they are used.
- **Type of energy:** Actuators can be classified based on their energy type.

Categorizing actuators is quite complex, given their variety, so this is by no means an exhaustive list of classification schemes. The most commonly used classification is based on energy type. Table 3-2 shows actuators classified by energy type and some examples for each type.

Type	Examples
Mechanical actuators	Lever, screw jack, hand crank
Electrical actuators	Thyristor, bipolar transistor, diode
Electromechanical actuators	AC motor, DC motor, step motor
Electromagnetic actuators	Electromagnet, linear solenoid
Hydraulic and pneumatic actuators	Hydraulic cylinder, pneumatic cylinder, piston, pressure control valves, air motors
Smart material actuators (includes thermal and magnetic actuators)	Shape memory alloy (SMA), ion exchange fluid, magnetoresistive material, bimetallic strip, piezoelectric bimorph
Micro- and nanoactuators	Electrostatic motor, microvalve, comb drive

**Table 3-2** Actuator Classification by Energy Type

Whereas sensors provide the information, actuators provide the action. The most interesting use cases for IoT are those where sensors and actuators work together in an intelligent, strategic, and complementary fashion. This powerful combination can be used to solve everyday problems by simply elevating the data that sensors provide to actionable insight that can be acted on by work-producing actuators.

The precision agriculture example can demonstrate how actuators can be complement and enhance a sensor-only solution. For example, the smart sensors used to evaluate soil quality (by measuring a variety of soil, temperature, and plant characteristics) can be connected with electrically or pneumatically controlled valve actuators that control water, pesticides, fertilizers, herbicides, and so on. Intelligently triggering a high-precision actuator based on well-defined sensor readings of temperature, pH, soil/air humidity, nutrient levels, and so on to deliver a highly optimized and custom environment-specific solution is truly smart farming.

### 3.3 Smart Objects

Smart objects are, quite simply, the building blocks of IoT. They are what transform everyday objects into a network of intelligent objects that are able to learn from and interact with their environment in a meaningful way. It can't be stressed enough that the real power of smart objects in IoT comes from being networked together rather than being isolated as standalone objects. This ability to communicate over a network has a multiplicative effect and allows for very sophisticated correlation and interaction between disparate smart objects. For instance, recall the smart farming sensors described previously. If a sensor is a standalone device that simply measures the humidity of the soil, it is interesting and useful, but it isn't revolutionary. If that same sensor is connected as part of an intelligent network that is able to coordinate intelligently with actuators to trigger irrigation systems as needed based on those sensor readings. Extending that even further, imagine that the coordinated sensor/actuator set is intelligently interconnected with other sensor/actuator sets to further coordinate fertilization, pest control, and so on—and even communicate with an intelligent backend to calculate crop yield potential. This now starts to look like a complete system that begins to unlock the power of IoT and provides the intelligent automation to expect from such a revolutionary technology.

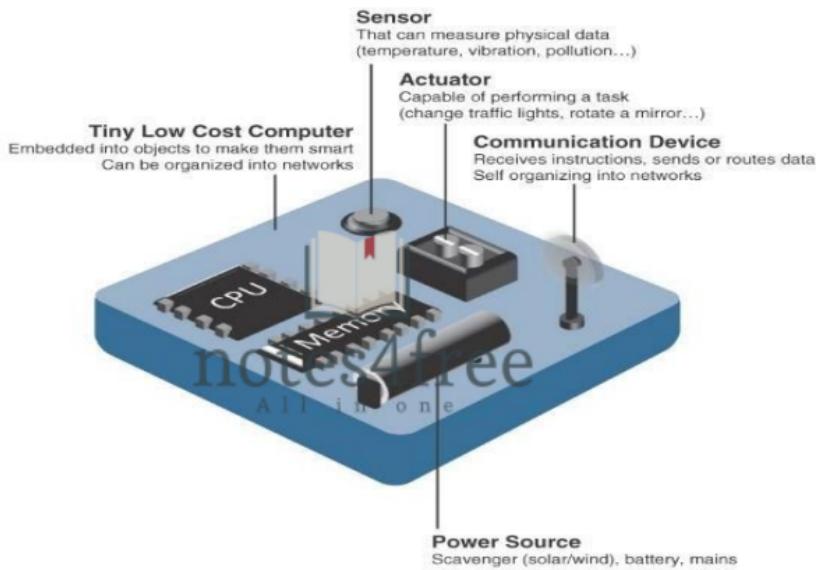


Figure 3-7 Characteristics of a Smart Object

## Trends in IOT

- **Size is decreasing:** As discussed earlier, in reference to MEMS, there is a clear trend of ever-decreasing size. Some smart objects are so small they are not even visible to the naked eye. This reduced size makes smart objects easier to embed in everyday objects.
- **Power consumption is decreasing:** The different hardware components of a smart object continually consume less power. This is especially true for sensors, many of which are completely passive. Some battery-powered sensors last 10 or more years without battery replacement.
- **Processing power is increasing:** Processors are continually getting more powerful and smaller. This is a key advancement for smart objects, as they become increasingly complex and connected.
- **Communication capabilities are improving:** It's no big surprise that wireless speeds are continually increasing, but they are also increasing in range. IoT is driving the development of more and more specialized communication protocols covering a greater diversity of use cases and environments.
- **Communication is being increasingly standardized:** There is a strong push in the industry to develop open standards for IoT communication protocols. In addition, there are more and more open source efforts to advance IoT.

These trends in smart objects begin to paint a picture of increasingly sophisticated devices that are able to perform increasingly complex tasks with greater efficiency. The power of IoT is truly unlocked when smart objects are networked together in sensor/actuator networks.

## 3.4 Sensor Networks

A sensor/actuator network (SANET), as the name suggests, is a network of sensors that sense and measure their environment and/or actuators that act on their environment. The sensors and/or actuators in a SANET are capable of communicating and cooperating in a productive manner. Effective and well-coordinated communication and cooperation is a prominent challenge, primarily because the sensors and actuators in SANETs are diverse, heterogeneous, and resource-constrained.

The following are some advantages and disadvantages that a wireless-based solution offers:

### Advantages:

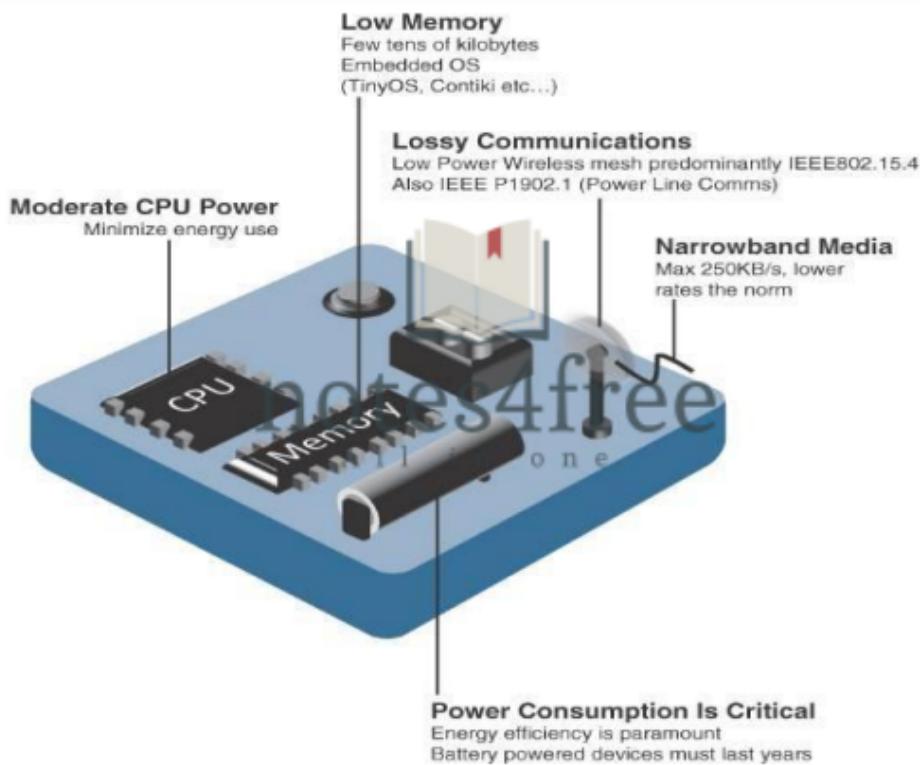
- Greater deployment flexibility (especially in extreme environments or hard-to-reach places)
- Simpler scaling to a large number of nodes
- Lower implementation costs
- Easier long-term maintenance
- Effortless introduction of new sensor/actuator nodes
- Better equipped to handle dynamic/rapid topology changes

### **Disadvantages:**

- Potentially less secure (for example, hijacked access points)
- Typically lower transmission speeds
- Greater level of impact/influence by environment

#### **3.4.2 Wireless Sensor Networks (WSNs)**

Wireless sensor networks are made up of wirelessly connected smart objects, which are sometimes referred to as motes. The fact that there is no infrastructure to consider with WSNs is surely a powerful advantage for flexible deployments, but there are a variety of design constraints to consider with these wirelessly connected smart objects. Figure 3-8 illustrates some of these assumptions and constraints usually involved in WSNs.



*Figure 3-8 Design Constraints for Wireless Smart Objects*

The following are some of the most significant limitations of the smart objects in WSNs:

- Limited processing power
- Limited memory
- Lossy communication
- Limited transmission speeds
- Limited power

Wireless sensor networks interact with their environment. Sensors often produce large amounts of sensing and measurement data that needs to be processed. This data can be processed locally by the nodes of a WSN or across zero or more hierarchical levels in IoT networks. Communication protocols need to facilitate routing and message handling for this data flow between sensor nodes as well as from sensor nodes to optional gateways, edge compute, or centralized cloud compute. IoT communication protocols for WSNs thus straddle the entire protocol stack. Ultimately, they are used to provide a platform for a variety of IoT smart services.

## 3.5 Connecting Smart Objects

IoT devices and sensors must be connected to the network for their data to be utilized. In addition to the wide range of sensors, actuators, and smart objects that make up IoT, there are also a number of different protocols used to connect them. Here the characteristics and communications criteria that are important for the technologies that smart objects employ for their connectivity, along with a deeper dive into some of the major technologies being deployed today.

### 3.5.1 Communications Criteria

In the world of connecting “things,” a large number of wired and wireless access technologies are available or under development. Before reviewing some of these access technologies, it is important to talk about the criteria to use in evaluating them for various use cases and system solutions.

Wireless communication is prevalent in the world of smart object connectivity, mainly because it eases deployment and allows smart objects to be mobile, changing location without losing connectivity. The following sections take this into account as they discuss various criteria. In addition, wired connectivity considerations are mentioned when applicable.

#### 3.5.1.1 Range

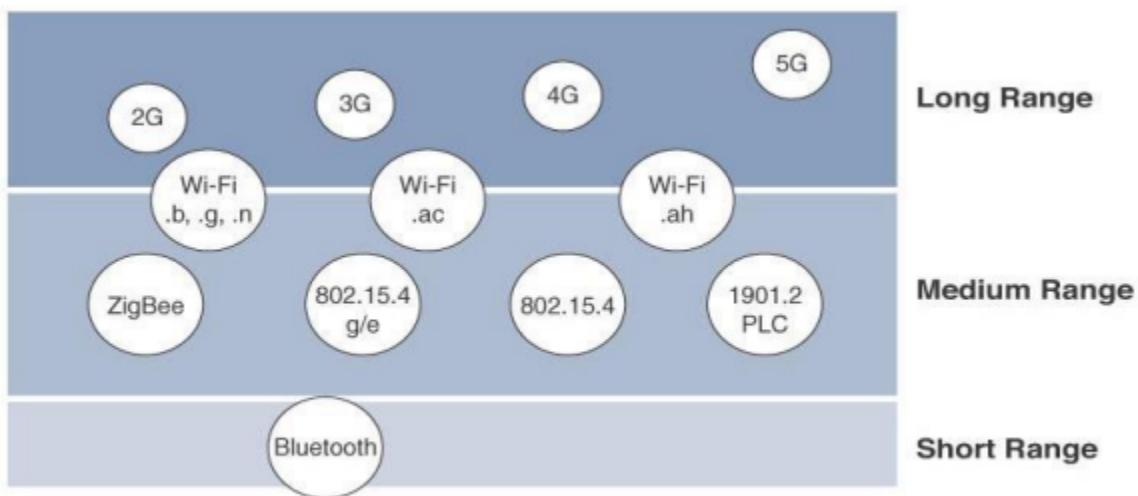


Figure 4-1 Wireless Access Landscape

### **3.5.1.2 Frequency Bands**

Radio spectrum is regulated by countries and/or organizations, such as the International Telecommunication Union (ITU) and the Federal Communications Commission (FCC). These groups define the regulations and transmission requirements for various frequency bands. For example, portions of the spectrum are allocated to types of telecommunications such as radio, television, military, and so on.

An important consideration for IoT access infrastructures that wish to utilize licensed spectrum is that users must subscribe to services when connecting their IoT devices. This adds more complexity to a deployment involving large numbers of sensors and other IoT devices, but in exchange for the subscription fee, the network operator can guarantee the exclusivity of the frequency usage over the target area and can therefore sell a better guarantee of service.

The ITU has also defined unlicensed spectrum for the industrial, scientific, and medical (ISM) portions of the radio bands. These frequencies are used in many communications technologies for short-range devices (SRDs). Unlicensed means that no guarantees or protections are offered in the ISM bands for device communications. For IoT access, these are the most well-known ISM bands:

- 2.4 GHz band as used by IEEE 802.11b/g/n Wi-Fi
- IEEE 802.15.1 Bluetooth
- IEEE 802.15.4 WPAN

### **3.5.1.3 Power Consumption**

While the definition of IoT device is very broad, there is a clear delineation between powered nodes and battery-powered nodes. A powered node has a direct connection to a power source, and communications are usually not limited by power consumption criteria. However, ease of deployment of powered nodes is limited by the availability of a power source, which makes mobility more complex.

Battery-powered nodes bring much more flexibility to IoT devices. These nodes are often classified by the required lifetimes of their batteries. Does a node need 10 to 15 years of battery life, such as on water or gas meters? Or is a 5- to 7-year battery life sufficient for devices such as smart parking sensors? Their batteries can be changed or the devices replaced when a street gets resurfaced. For devices under regular maintenance, a battery life of 2 to 3 years is an option.

Wired IoT access technologies consisting of powered nodes are not exempt from power optimization. In the case of deployment of smart meters over PLC, the radio interface on meters can't consume 5 to 10 watts of power, or this will add up to a 20-million-meter deployment consuming 100 to 200 megawatts of energy for communications.

### 3.5.1.4 Topology

Among the access technologies available for connecting IoT devices, three main topology schemes are dominant: star, mesh, and peer-to-peer. For long-range and short-range technologies, a star topology is prevalent, as seen with cellular, LPWA, and Bluetooth networks. Star topologies utilize a single central base station or controller to allow communications with endpoints.

For medium-range technologies, a star, peer-to-peer, or mesh topology is common, as shown in Figure 4-2. Peer-to-peer topologies allow any device to communicate with any other device as long as they are in range of each other. Obviously, peer-to-peer topologies rely on multiple full-function devices. Peer-to-peer topologies enable more complex formations, such as a mesh networking topology.

A mesh topology helps cope with low transmit power, searching to reach a greater overall distance, and coverage by having intermediate nodes relaying traffic for other nodes. Mesh topology requires the implementation of a Layer 2 forwarding protocol known as mesh-under or a Layer 3 forwarding protocol referred to as mesh-over on each intermediate node. An intermediate node or full-function device (FFD) is simply a node that interconnects other nodes. A node that doesn't interconnect or relay the traffic of other nodes is known as a leaf node, or reduced-function device (RFD).

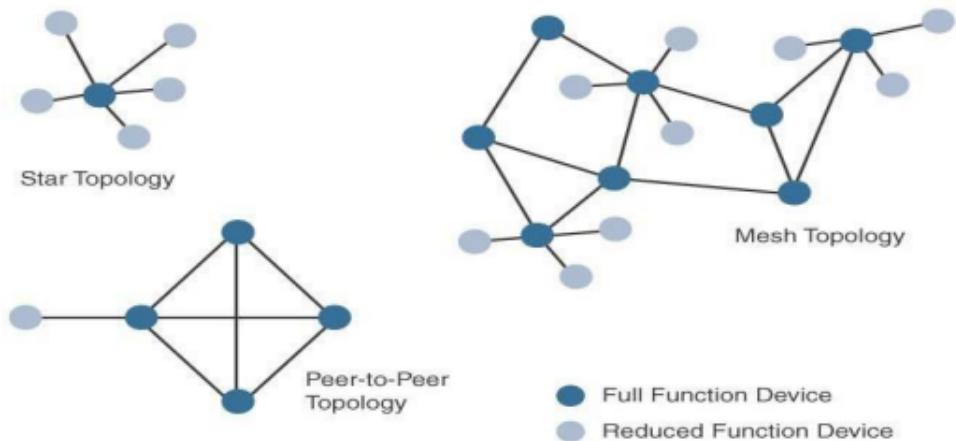


Figure 4-2 Star, Peer-to-Peer, and Mesh Topologies

## 3.5 Constrained Devices

The Internet Engineering Task Force (IETF) acknowledges in RFC 7228 that different categories of IoT devices are deployed. While categorizing the class of IoT nodes is a perilous exercise, with computing, memory, storage, power, and networking continuously evolving and improving, RFC 7228 gives some definitions of constrained nodes. These definitions help differentiate constrained nodes from unconstrained nodes, such as servers, desktop or laptop computers, and powerful mobile devices such as smart phones. According to RFC 7228, constrained nodes can be broken down into the classes defined in Table 4-1.

Class	Definition
Class 0	This class of nodes is severely constrained, with less than 10 KB of memory and less than 100 KB of Flash processing and storage capability. These nodes are typically battery powered. They do not have the resources required to directly implement an IP stack and associated security mechanisms. An example of a Class 0 node is a push button that sends 1 byte of information when changing its status. This class is particularly well suited to leveraging new unlicensed LPWA wireless technology.
Class 1	While greater than Class 0, the processing and code space characteristics (approximately 10 KB RAM and approximately 100 KB Flash) of Class 1 are still lower than expected for a complete IP stack implementation. They cannot easily communicate with nodes employing a full IP stack. However, these nodes can implement an optimized stack specifically designed for constrained nodes, such as Constrained Application Protocol (CoAP). This allows Class 1 nodes to engage in meaningful conversations with the network without the help of a gateway, and provides support for the necessary security functions. Environmental sensors are an example of Class 1 nodes.
Class 2	Class 2 nodes are characterized by running full implementations of an IP stack on embedded devices. They contain more than 50 KB of memory and 250 KB of Flash, so they can be fully integrated in IP networks. A smart power meter is an example of a Class 2 node.

**Table 4-1** Classes of Constrained Nodes, as Defined by RFC 7228

### 3.6.1 Constrained-Node Networks

While several of the IoT access technologies, such as Wi-Fi and cellular, are applicable to laptops, smart phones, and some IoT devices, some IoT access technologies are more suited to specifically connect constrained nodes. Typical examples are IEEE 802.15.4 and 802.15.4g RF, IEEE 1901.2a PLC, LPWA, and IEEE 802.11ah access technologies.

Constrained-node networks are often referred to as **Low-power and Lossy Networks (LLNs)**. Low-power in the context of LLNs refers to the fact that nodes must cope with the requirements from powered and battery-powered constrained nodes. Lossy networks indicates that network performance may suffer from interference and variability due to harsh radio environments. Layer 1 and Layer 2 protocols that can be used for constrained-node networks must be evaluated in the context of the following characteristics for use-case applicability: data rate and throughput, latency and determinism, and overhead and payload.

### **1. Data Rate and Throughput**

The data rates available from IoT access technologies range from 100 bps with protocols such as Sigfox to tens of megabits per second with technologies such as LTE and IEEE 802.11ac. However, the actual throughput is less—sometimes much less—than the data rate. Therefore, understanding the bandwidth requirements of a particular technology, its applicability to given use cases, the capacity

planning rules, and the expected real throughput are important for proper network design and successful production deployment.

Short-range technologies can also provide medium to high data rates that have enough throughput to connect a few endpoints. For example, Bluetooth sensors that are now appearing on connected wearables fall into this category. The IoT access technologies developed for constrained nodes are optimized for low power consumption, but they are also limited in terms of data rate, which depends on the selected frequency band, and throughput.

### **Latency and Determinism**

On constrained networks, latency may range from a few milliseconds to seconds, and applications and protocol stacks must cope with these wide-ranging values. For example, UDP at the transport layer is strongly recommended for IP endpoints communicating over LLNs. In the case of mesh topologies, if communications are needed between two devices inside the mesh, the forwarding path may call for some routing optimization, which is available using the IPv6 RPL protocol.

### **Overhead and Payload**

When considering constrained access network technologies, it is important to review the MAC payload size characteristics required by applications. The minimum IPv6 MTU size is expected to be

1280 bytes. Therefore, the fragmentation of the IPv6 payload has to be taken into account by link layer access protocols with smaller MTUs.

For example, the payload size for IEEE 802.15.4 is 127 bytes and requires an IPv6 payload with a minimum MTU of 1280 bytes to be fragmented. On the other hand, IEEE 802.15.4g enables payloads up to 2048 bytes, easing the support of the IPv6 minimum MTU of 1280 bytes.

## **3.6 IoT Access Technologies**

The following are the important **IoT Access Technologies**:

### **3.6.1 IEEE 802.15.4**

### **3.6.2 IEEE 802.15.4g and 802.15.4e**

### **3.6.3 IEEE 1901.2a**

### **3.6.4 IEEE 802.11ah**

### **3.6.5 LoRaWAN**

### 3.6.6 NB-IoT and Other LTE Variations

The technologies highlighted here are the ones that are seen as having market and/or mind share. Therefore, it is necessary to have a basic familiarity with them as they are fundamental to many IoT conversations. For each of the IoT access technologies discussed here, a common information set is being provided. Particularly, the following topics are addressed for each IoT access technology:

- **Standardization and alliances:** The standards bodies that maintain the protocols for a technology
- **Physical layer:** The wired or wireless methods and relevant frequencies
- **MAC layer:** Considerations at the Media Access Control (MAC) layer, which bridges the physical layer with data link control
- **Topology:** The topologies supported by the technology
- **Security:** Security aspects of the technology
- **Competitive technologies:** Other technologies that are similar and may be suitable alternatives to the given technology

#### 3.6.1 IEEE 802.15.4

IEEE 802.15.4 is a wireless access technology for low-cost and low-data-rate devices that are powered or run on batteries. In addition to being low cost and offering a reasonable battery life, this access technology enables easy installation using a compact protocol stack while remaining both simple and flexible. Several network communication stacks, including deterministic ones, and profiles leverage this technology to address a wide range of IoT use cases in both the consumer and business markets. IEEE 802.15.4 is commonly found in the following types of deployments:

- Home and building automation
- Automotive networks
- Industrial wireless sensor networks
- Interactive toys and remote controls

##### Standardization and Alliances

IEEE 802.15.4 or IEEE 802.15 Task Group 4 defines low-data-rate PHY and MAC layer specifications for wireless personal area networks (WPAN). This standard has evolved over the years and is a well-known solution for low-complexity wireless devices with low data rates that need many months or even years of battery life.

While there is **no alliance** or promotion body for IEEE 802.15.4 per se, the IEEE 802.15.4 PHY and MAC layers are the foundations for several networking protocol stacks. These protocol stacks make use of 802.15.4 at the physical and link layer levels, but the upper layers are different.

Few of the **promotion stacks** used are:

ZigBee, 6LoWPAN, ZigBee IP, ISA100.11a, WirelessHART, thread

## Physical Layer

The 802.15.4 standard supports an extensive number of PHY options that range from 2.4 GHz to sub-GHz frequencies in ISM bands. original IEEE 802.15.4-2003 standard specified only three PHY options based on **Direct Sequence Spread Spectrum (DSSS)** modulation. DSSS is a modulation technique in which a signal is intentionally spread in the frequency domain, resulting in greater bandwidth. The original physical layer transmission options were as follows:

- 2.4 GHz, 16 channels, with a data rate of 250 kbps
- 915 MHz, 10 channels, with a data rate of 40 kbps
- 868 MHz, 1 channel, with a data rate of 20 kbps

## MAC Layer

The IEEE 802.15.4 MAC layer manages access to the PHY channel by defining how devices in the same area will share the frequencies allocated. At this layer, the scheduling and routing of data frames are also coordinated. The 802.15.4 MAC layer performs the following tasks:

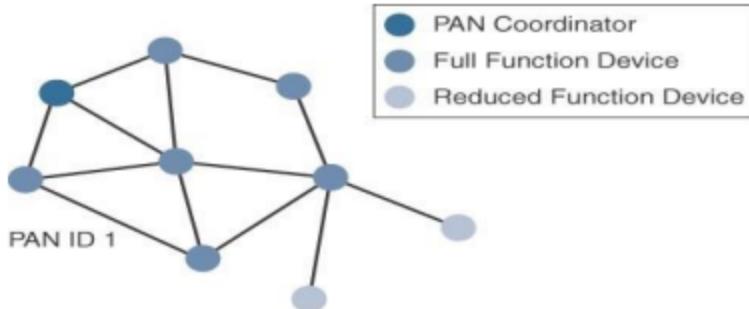
- Network beaconing for devices acting as coordinators (New devices use beacons to join an 802.15.4 network)
- PAN association and disassociation by a device
- Device security
- Reliable link communications between two peer MAC entities

The MAC layer achieves these tasks by using various predefined frame types. In fact, four types of MAC frames are specified in 802.15.4:

- **Data frame:** Handles all transfers of data
- **Beacon frame:** Used in the transmission of beacons from a PAN coordinator
- **Acknowledgement frame:** Confirms the successful reception of a frame
- **MAC command frame:** Responsible for control communication between devices

## Topology

IEEE 802.15.4-based networks can be built as star, peer-to-peer, or mesh topologies. Mesh networks tie together many nodes. This allows nodes that would be out of range if trying to communicate directly to leverage intermediary nodes to transfer communications. Please note that every 802.15.4 PAN should be set up with a unique ID. All the nodes in the same 802.15.4 network should use the same PAN ID. Figure 4-7 shows an example of an 802.15.4 mesh network with a PAN ID of 1.



**Figure 4-7 802.15.4 Sample Mesh Network Topology**

## Security

The IEEE 802.15.4 specification uses Advanced Encryption Standard (AES) with a 128-bit key length as the base encryption algorithm for securing its data. Established by the US National Institute of Standards and Technology in 2001, AES is a block cipher, which means it operates on fixed-size blocks of data. The use of AES by the US government and its widespread adoption in the private sector has helped it become one of the most popular algorithms used in symmetric key cryptography. (A symmetric key means that the same key is used for both the encryption and decryption of the data.) In addition to encrypting the data, AES in 802.15.4 also validates the data that is sent. This is accomplished by a message integrity code (MIC), which is calculated for the entire frame using the same AES key that is used for encryption.

## Competitive Technologies

A competitive radio technology that is different in its PHY and MAC layers is DASH7. DASH7 was originally based on the ISO18000-7 standard and positioned for industrial communications, whereas IEEE 802.15.4 is more generic. Commonly employed in active radio frequency identification (RFID) implementations, DASH7 was used by US military forces for many years, mainly for logistics purposes. Active RFID utilizes radio waves generated by a battery-powered tag on an object to enable continuous tracking.

### 3.6.2 IEEE 802.15.4g and 802.15.4e

The IEEE frequently makes amendments to the core 802.15.4 specification, before integrating them into the next revision of the core specification. When these amendments are made, a lowercase letter is appended. Two such examples of this are 802.15.4e-2012 and 802.15.4g-2012, both of which are especially relevant to the subject of IoT. Both of these amendments were integrated in IEEE 802.15.4-2015 but are often still referred to by their amendment names.

## Standardization and Alliances

Because 802.15.4g-2012 and 802.15.4e-2012 are simply amendments to IEEE 802.15.4-2011, the same IEEE 802.15 Task Group 4 standards body authors, maintains, and integrates them into the next release of the core specification. However, the additional capabilities and options provided by 802.15.4g-2012 and 802.15.4e-2012 led to additional difficulty in achieving the interoperability between devices and mixed vendors that users requested.

## Physical Layer

In IEEE 802.15.4g-2012, the original IEEE 802.15.4 maximum PSDU or payload size of 127 bytes was increased for the SUN PHY to 2047 bytes. This provides a better match for the greater packet sizes found in many upper-layer protocols. For example, the default IPv6 MTU setting is 1280 bytes. Fragmentation is no longer necessary at Layer 2 when IPv6 packets are transmitted over IEEE 802.15.4g MAC frames. Also, the error protection was improved in IEEE 802.15.4g by evolving the CRC from 16 to 32 bits.

## MAC Layer

While the IEEE 802.15.4e-2012 amendment is not applicable to the PHY layer, it is pertinent to the MAC layer. This amendment enhances the MAC layer through various functions, which may be selectively enabled based on various implementations of the standard. In fact, if interoperability is a “must have,” then using profiles defined by organizations such as Wi-SUN is necessary. The following are some of the main enhancements to the MAC layer proposed by IEEE 802.15.4e-2012:

- Time-slotted channel hopping
- Information elements
- Enhanced beacons
- Enhanced beacons requests
- Enhanced acknowledgement

## Topology

Deployments of IEEE 802.15.4g-2012 are mostly based on a mesh topology. This is because a mesh topology is typically the best choice for use cases in the industrial and smart cities areas where 802.15.4g-2012 is applied. A mesh topology allows deployments to be done in urban or rural areas, expanding the distance between nodes that can relay the traffic of other nodes. Considering the use cases addressed by this technology, powered nodes have been the primary targets of implementations.

## Security

Both IEEE 802.15.4g and 802.15.4e inherit their security attributes from the IEEE 802.15.4-2006 specification. Therefore, encryption is provided by AES, with a 128-bit key. In addition to the Auxiliary Security Header field initially defined in 802.15.4-2006, a secure acknowledgement and a secure Enhanced Beacon field complete the MAC layer security. Figure 4-10 shows a high-level overview of the security associated with an IEEE 802.15.4e MAC frame.

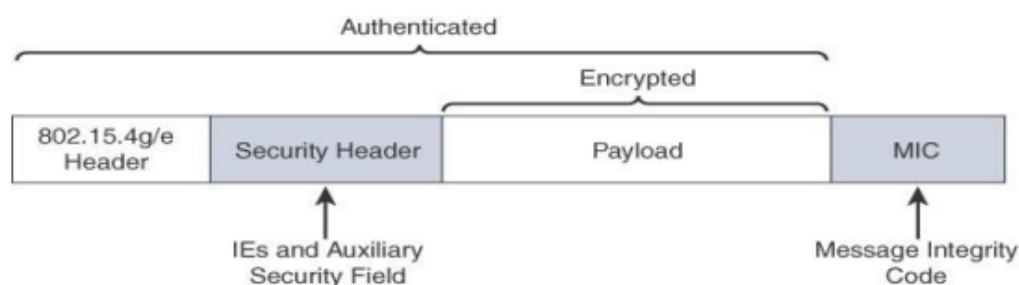


Figure 4-10 IEEE 802.15.4g/e MAC Layer Security

## **Competitive Technologies**

Competitive technologies to IEEE 802.15.4g and 802.15.4e parallel the technologies that also compete with IEEE 802.15.4, such as DASH7. In many ways, 802.15.4 and its various flavors of upper-layer protocols, as shown in Table 4-2, can be seen as competitors as well. IEEE 802.15.4 is well established and already deployed in many scenarios, mostly indoors.

### **3.6.3 IEEE 1901.2a**

While most of the constrained network technologies relate to wireless, IEEE 1901.2a-2013 is a wired technology that is an update to the original IEEE 1901.2 specification. This is a standard for Narrowband Power Line Communication (NB-PLC). NB-PLC is a narrowband spectrum for low power, long range, and resistance to interference over the same wires that carry electric power. NB-PLC is often found in use cases such as the following

- **Smart metering:** NB-PLC can be used to automate the reading of utility meters, such as electric, gas, and water meters. This is true particularly in Europe, where PLC is the preferred technology for utilities deploying smart meter solutions.
- **Distribution automation:** NB-PLC can be used for distribution automation, which involves monitoring and controlling all the devices in the power grid.
- **Public lighting:** A common use for NB-PLC is with public lighting—the lights found in cities and along streets, highways, and public areas such as parks.
- **Electric vehicle charging stations:** NB-PLC can be used for electric vehicle charging stations, where the batteries of electric vehicles can be recharged.
- **Microgrids:** NB-PLC can be used for microgrids, local energy grids that can disconnect from the traditional grid and operate independently.
- **Renewable energy:** NB-PLC can be used in renewable energy applications, such as solar, wind power, hydroelectric, and geothermal heat.

All these use cases require a direct connection to the power grid. So it makes sense to transport IoT data across power grid connections that are already in place.

## **Standardization and Alliances**

The first generations of NB-PLC implementations have generated a lot of interest from utilities in Europe but have often suffered from poor reliability, low throughput (in the range of a few hundred bits per second to a maximum of 2 kbps), lack of manageability, and poor interoperability. This has led several organizations (including standards bodies and alliance consortiums) to develop their own specifications for new generations of NB-PLC technologies. Most recent NB-PLC standards are based on orthogonal frequency-division multiplexing (OFDM). However, different standards from various vendors competing with one another have created a fragmented market. OFDM encodes digital data on multiple carrier frequencies. This provides several parallel streams that suffer less from high frequency attenuation in copper wire and narrowband interference.

## Physical Layer

NB-PLC is defined for frequency bands from 3 to 500 kHz. Much as with wireless sub-GHz frequency bands, regional regulations and definitions apply to NB-PLC. The IEEE 1901.2 working group has integrated support for all world regions in order to develop a worldwide standard. Specifications include support for CENELEC A and B bands, US FCC-Low and FCC-above- CENELEC, and Japan ARIB bands. CENELEC is the French Comité Européen de Normalisation Électrotechnique, which in English translates to European Committee for Electrotechnical Standardization. This organization is responsible for standardization in the area of electrical engineering for Europe. The CENELEC A and B bands refer to 9–95 kHz and 95–125 kHz, respectively.

## MAC Layer

The MAC frame format of IEEE 1901.2a is based on the IEEE 802.15.4 MAC frame but integrates the latest IEEE 802.15.4e-2012 amendment, which enables key features to be supported. (For more information on the 802.15.4 MAC frame format, refer to Figure 4-6. For the 802.15.4e MAC frame format, see Figure 4-9.) One of the key components brought from 802.15.4e to IEEE 1901.2a is information elements. With IE support, additional capabilities, such as IEEE 802.15.9 Key Management Protocol and SSID, are supported. Figure 4-12 provides an overview of the general MAC frame format for IEEE 1901.2. Note that the numeric value above each field in the frame shows the size of the field, in bytes.

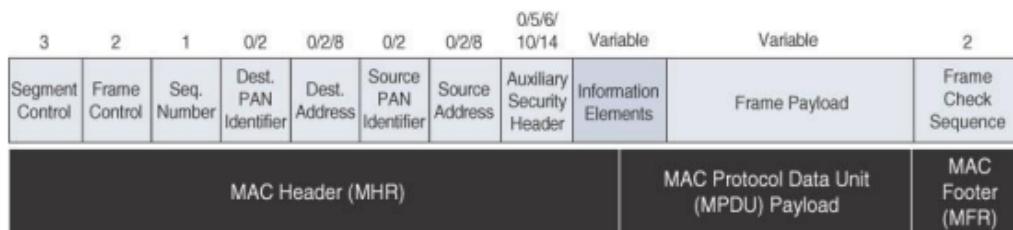


Figure 4-12 General MAC Frame Format for IEEE 1901.2

## Topology

Use cases and deployment topologies for IEEE 1901.2a are tied to the physical power lines. As with wireless technologies, signal propagation is limited by factors such as noise, interference, distortion, and attenuation. These factors become more prevalent with distance, so most NB-PLC deployments use some sort of mesh topology. Mesh networks offer the advantage of devices relaying the traffic of other devices so longer distances can be segmented. The IEEE 1901.2a standard offers the flexibility to run any upper-layer protocol. So, implementations of IPv6 6LoWPAN and RPL IPv6 protocols are supported.

## **Security**

IEEE 1901.2a security offers similar features to IEEE 802.15.4g. Encryption and authentication are performed using AES. In addition, IEEE 1901.2a aligns with 802.15.4g in its ability to support the IEEE 802.15.9 Key Management Protocol. However, some differences exist. These differences are mostly tied to the PHY layer fragmentation capabilities of IEEE 1901.2a and include the following:

- The Security Enabled bit in the Frame Control field should be set in all MAC frames carrying segments of an encrypted frame.
- If data encryption is required, it should be done before packet segmentation. During packet encryption, the Segment Control field should not be included in the input to the encryption algorithm.
- On the receiver side, the data decryption is done after packet reassembly.
- When security is enabled, the MAC payload is composed of the ciphered payload and the message integrity code (MIC) authentication tag for non-segmented payloads. If the payload is segmented, the MIC is part of the last packet (segment) only. The MIC authentication is computed using only information from the MHR of the frame carrying the first segment.

## **Competitive Technologies**

In the domain of NB-PLC, two technologies compete against IEEE 1901.2a: G3-PLC (now ITU G.9903) and PRIME (now ITU G.9904). Both of these technologies were initially developed to address a single use case: smart metering deployment in Europe over the CENELEC A band. IEEE 1901.2a has portions of G3-PLC and PRIME, and it also competes with them. More specifically, G3- PLC is really close to IEEE 1901.2. The main differences include the fact that G3-PLC mandates data link layer protocol options for bootstrapping and allocating device addresses, and it is incompatible with IEEE 802.15.4g/e and an end-to-end IPv6 model.

### **3.6.4 IEEE 802.11ah**

In unconstrained networks, IEEE 802.11 Wi-Fi is certainly the most successfully deployed wireless technology. This standard is a key IoT wireless access technology, either for connecting endpoints such as fog computing nodes, high-data-rate sensors, and audio or video analytics devices or for deploying Wi-Fi backhaul infrastructures, such as outdoor Wi-Fi mesh in smart cities, oil and mining, or other environments. However, Wi-Fi lacks sub-GHz support for better signal penetration, low power for battery-powered nodes, and the ability to support a large number of devices. For these reasons, the IEEE 802.11 working group launched a task group named IEEE 802.11ah to specify a sub-GHz version of Wi-Fi. Three main use cases are identified for IEEE 802.11ah:

- **Sensors and meters covering a smart grid:** Meter to pole, environmental/agricultural monitoring, industrial process sensors, indoor healthcare system and fitness sensors, home and building automation sensors.

**Backhaul aggregation of industrial sensors and meter data:** Potentially connecting IEEE 802.15.4g subnetworks,

- **Extended range Wi-Fi:** For outdoor extended-range hotspot or cellular traffic offloading when distances already covered by IEEE 802.11a/b/g/n/ac are not good enough.

## **Standardization and Alliances**

For the 802.11ah standard, the Wi-Fi Alliance defined a new brand called Wi-Fi HaLow. This marketing name is based on a play on words between “11ah” in reverse and “low power.” It is similar to the word “hello” but it is pronounced “hay-low.” The HaLow brand exclusively covers IEEE 802.11ah for sub-GHz device certification. Wi-Fi HaLow is a commercial designation for products incorporating IEEE 802.11ah technology.

## **Physical Layer**

IEEE 802.11ah essentially provides an additional 802.11 physical layer operating in unlicensed sub-GHz bands. For example, various countries and regions use the following bands for IEEE 802.11ah: 868–868.6 MHz for EMEAR, 902–928 MHz and associated subsets for North America and Asia-Pacific regions, and 314–316 MHz, 430–434 MHz, 470–510 MHz, and 779–787 MHz for China.

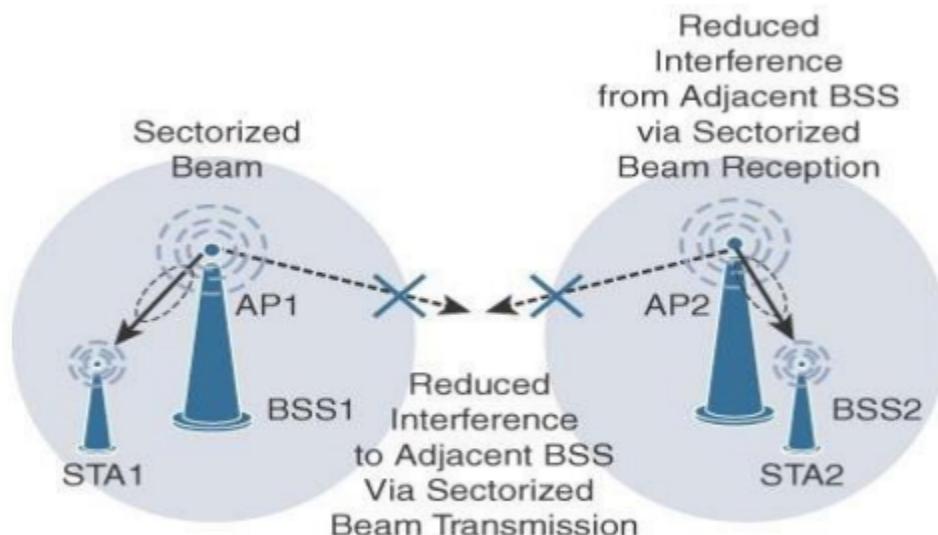
## **MAC Layer**

The IEEE 802.11ah MAC layer is optimized to support the new sub-GHz Wi-Fi PHY while providing low power consumption and the ability to support a larger number of endpoints. Enhancements and features specified by IEEE 802.11ah for the MAC layer include the following:

- **Number of devices:** Has been scaled up to 8192 per access point.
- **MAC header:** Has been shortened to allow more efficient communication.
- **Null data packet (NDP) support:** Is extended to cover several control and management frames. Relevant information is concentrated in the PHY header and the additional overhead associated with decoding the MAC header and data payload is avoided. This change makes the control frame exchanges efficient and less power-consuming for the receiving stations.
- **Grouping and sectorization:** Enables an AP to use sector antennas and also group stations (distributing a group ID). In combination with RAW and TWT, this mechanism reduces contention in large cells with many clients by restricting which group, in which sector, can contend during which time window. (Sectors are described in more detail in the following section.)
- **Restricted access window (RAW):** Is a control algorithm that avoids simultaneous transmissions when many devices are present and provides fair access to the wireless network. By providing more efficient access to the medium, additional power savings for battery-powered devices can be achieved, and collisions are reduced.
- **Target wake time (TWT):** Reduces energy consumption by permitting an access point to define times when a device can access the network. This allows devices to enter a low-power state until their TWT time arrives. It also reduces the probability of collisions in large cells with many clients.
- **Speed frame exchange:** Enables an AP and endpoint to exchange frames during a reserved transmit opportunity (TXOP). This reduces contention on the medium, minimizes the number of frame exchanges to improve channel efficiency, and extends battery life by keeping awake times short.

## Topology

While IEEE 802.11ah is deployed as a star topology, it includes a simple hops relay operation to extend its range. This relay option is not capped, but the IEEE 802.11ah task group worked on the assumption of two hops. It allows one 802.11ah device to act as an intermediary and relay data to another. In some ways, this is similar to a mesh, and it is important to note that the clients and not the access point handle the relay function. This relay operation can be combined with a higher transmission rate or modulation and coding scheme (MCS). This means that a higher transmit rate is used by relay devices talking directly to the access point.



**Figure 4-14 IEEE 802.11ah Sectorization**

## Security

No additional security has been identified for IEEE 802.11ah compared to other IEEE 802.11 specifications. These protocols include IEEE 802.15.4, IEEE 802.15.4e, and IEEE 1901.2a, and the security information for them is also applicable to IEEE 802.11ah.

## Competitive Technologies

Competitive technologies to IEEE 802.11ah are IEEE 802.15.4 and IEEE 802.15.4e, along with the competitive technologies highlighted in each of their sections.

### 3.6.5 LoRaWAN

In recent years, a new set of wireless technologies known as Low-Power Wide-Area (LPWA) has received a lot of attention from the industry and press. Particularly well adapted for long-range and battery-powered endpoints, LPWA technologies open new business opportunities to both services providers and enterprises considering IoT solutions. This section discusses an example of an unlicensed-band LPWA technology, known as LoRaWAN, and the next section, “NB-IoT and Other LTE Variations,” reviews licensed-band alternatives from the 3rd Generation Partnership Project (3GPP).

## **Standardization and Alliances**

Initially, LoRa was a physical layer, or Layer 1, modulation that was developed by a French company named Cycleo. Later, Cycleo was acquired by Semtech. Optimized for long-range, two-way communications and low power consumption, the technology evolved from Layer 1 to a broader scope through the creation of the LoRa Alliance. It quickly achieved industry support and currently has hundreds of members.

## **Physical Layer**

Semtech LoRa modulation is based on chirp spread spectrum modulation, which trades a lower data rate for receiver sensitivity to significantly increase the communication distance. In addition, it allows demodulation below the noise floor, offers robustness to noise and interference, and manages a single channel occupation by different spreading factors. This enables LoRa devices to receive on multiple channels in parallel.

LoRaWAN 1.0.2 regional specifications describe the use of the main unlicensed sub-GHz frequency bands of 433 MHz, 779–787 MHz, 863–870 MHz, and 902–928 MHz, as well as regional profiles for a subset of the 902–928 MHz bandwidth. For example, Australia utilizes 915–928 MHz frequency bands, while South Korea uses 920–923 MHz and Japan uses 920–928 MHz.

## **MAC Layer**

As mentioned previously, the MAC layer is defined in the LoRaWAN specification. This layer takes advantage of the LoRa physical layer and classifies LoRaWAN endpoints to optimize their battery life and ensure downstream communications to the LoRaWAN endpoints. The LoRaWAN specification documents three classes of LoRaWAN devices:

- **Class A:** This class is the default implementation. Optimized for battery-powered nodes, it allows bidirectional communications, where a given node is able to receive downstream traffic after transmitting. Two receive windows are available after each transmission.
- **Class B:** This class was designated “experimental” in LoRaWAN 1.0.1 until it can be better defined. A Class B node or endpoint should get additional receive windows compared to Class A, but gateways must be synchronized through a beaconing process.
- **Class C:** This class is particularly adapted for powered nodes. This classification enables a node to be continuously listening by keeping its receive window open when not transmitting.

## **Topology**

LoRaWAN topology is often described as a “star of stars” topology. As shown in Figure 4-17, the infrastructure consists of endpoints exchanging packets through gateways acting as bridges, with a central LoRaWAN network server. Gateways connect to the backend network using standard IP connections, and endpoints communicate directly with one or more gateways.

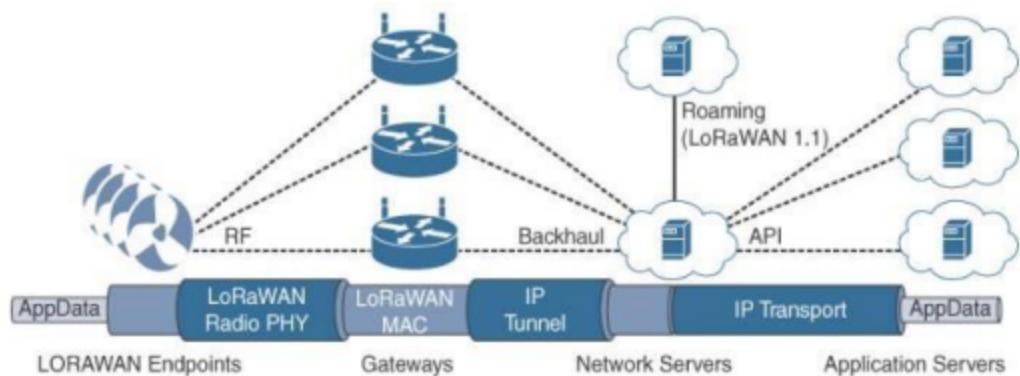


Figure 4-17 LoRaWAN Architecture

## Security

Security in a LoRaWAN deployment applies to different components of the architecture, as detailed in Figure 4-18. LoRaWAN endpoints must implement two layers of security, protecting communications and data privacy across the network.

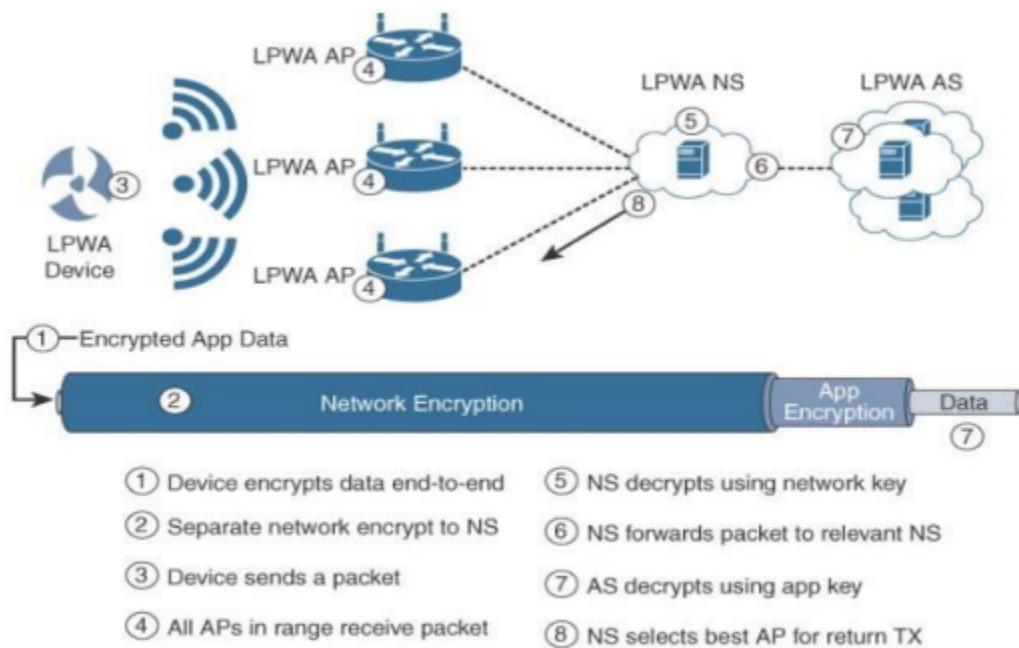


Figure 4-18 LoRaWAN Security

## Competitive Technologies

LPWA solutions and technologies are split between unlicensed and licensed bands. The licensed- band technologies are dedicated to mobile service providers that have acquired spectrum licenses; they are discussed in the next section. In addition, several technologies are targeting the unlicensed- band LPWA market to compete against LoRaWAN. The LPWA market is quickly evolving. Table 4- 5 evaluates two of the best-established vendors known to provide LPWA options.

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Characteristic	LoRaWAN	Sigfox	Ingenu Onramp
Frequency bands	433 MHz, 868 MHz, 902–928 MHz	433 MHz, 868 MHz, 902–928 MHz	2.4 GHz
Modulation	Chirp spread spectrum	Ultra-narrowband	DSSS
Topology	Star of stars	Star	Star; tree supported with an RPMA extender
Data rate	250 bps–50 kbps (868 MHz)  980 bps–21.9 kbps (915 MHz)	100 bps (868 MHz)  600 bps (915 MHz)	6 kbps
Adaptive data rate	Yes	No	No
Payload	59–230 bytes (868 MHz)  19–250 bytes (915 MHz)	12 bytes	6 bytes–10 KB
Two-way communications	Yes	Partial	Yes
Geolocation	Yes (LoRa GW version 2 reference design)	No	No
Roaming	Yes (LoRaWAN 1.1)	No	Yes
Specifications	LoRA Alliance	Proprietary	Proprietary

Table 4-5 Unlicensed LPWA Technology Comparison

### **3.6.6 NB-IoT and Other LTE Variations**

Existing cellular technologies, such as GPRS, Edge, 3G, and 4G/LTE, are not particularly well adapted to battery-powered devices and small objects specifically developed for the Internet of Things. While industry players have been developing unlicensed-band LPWA technologies, 3GPP and associated vendors have been working on evolving cellular technologies to better address IoT requirements. The effort started with the definition of new LTE device categories. The aim was to both align with specific IoT requirements, such as low throughput and low power consumption, and decrease the complexity and cost of the LTE devices. This resulted in the definition of the LTE-M work item.

Because the new LTE-M device category was not sufficiently close to LPWA capabilities, in 2015 3GPP approved a proposal to standardize a new narrowband radio access technology called Narrowband IoT (NB-IoT). NB-IoT specifically addresses the requirements of a massive number of low-throughput devices, low device power consumption, improved indoor coverage, and optimized network architecture. The following sections review the proposed evolution of cellular technologies to better support the IoT opportunities by mobile service providers.

#### **Standardization and Alliances**

The 3GPP organization includes multiple working groups focused on many different aspects of telecommunications (for example, radio, core, terminal, and so on). Many service providers and vendors make up 3GPP, and the results of their collaborative work in these areas are the 3GPP specifications and studies. The workflow within 3GPP involves receiving contributions related to licensed LPWA work from the involved vendors. Then, depending on the access technology that is most closely aligned, such as 3G, LTE, or GSM, the IoT-related contribution is handled by either 3GPP or the GSM EDGE Radio Access Networks (GERAN) group.

#### **3.6.6.1 LTE Cat 0**

The first enhancements to better support IoT devices in 3GPP occurred in LTE Release 12. A new user equipment (UE) category, Category 0, was added, with devices running at a maximum data rate of 1 Mbps. Generally, LTE enhancements target higher bandwidth improvements. Category 0 includes important characteristics to be supported by both the network and end devices. Meanwhile, the UE still can operate in existing LTE systems with bandwidths up to 20 MHz. These Cat 0 characteristics include the following:

- **Power saving mode (PSM):** This new device status minimizes energy consumption. Energy consumption is expected to be lower with PSM than with existing idle mode. PSM is defined as being similar to “powered off” mode, but the device stays registered with the network. By
- **Half-duplex mode:** This mode reduces the cost and complexity of a device’s implementation because a duplex filter is not needed. Most IoT endpoints are sensors that send low amounts of data that do not have a full-duplex communication requirement.

### 3.6.6.2 LTE-M

Following LTE Cat 0, the next step in making the licensed spectrum more supportive of IoT devices was the introduction of the LTE-M category for 3GPP LTE Release 13. These are the main characteristics of the LTE-M category in Release 13:

- **Lower receiver bandwidth:** Bandwidth has been lowered to 1.4 MHz versus the usual 20 MHz. This further simplifies the LTE endpoint.
- **Lower data rate:** Data is around 200 kbps for LTE-M, compared to 1 Mbps for Cat 0.
- **Half-duplex mode:** Just as with Cat 0, LTE-M offers a half-duplex mode that decreases node complexity and cost.
- **Image Enhanced discontinuous reception (eDRX):** This capability increases from seconds to minutes the amount of time an endpoint can “sleep” between paging cycles. A paging cycle is a periodic check-in with the network. This extended “sleep” time between paging cycles extends the battery lifetime for an endpoint significantly.

### 3.6.6.3 NB-IoT

Recognizing that the definition of new LTE device categories was not sufficient to support LPWA IoT requirement, 3GPP specified Narrowband IoT (NB-IoT). The work on NB-IoT started with multiple proposals pushed by the involved vendors, including the following:

- Extended Coverage GSM (EC-GSM), Ericsson proposal
- Narrowband GSM (N-GSM), Nokia proposal
- Narrowband M2M (NB-M2M), Huawei/Neul proposal
- Narrowband OFDMA (orthogonal frequency-division multiple access), Qualcomm proposal
- Narrowband Cellular IoT (NB-CIoT), combined proposal of NB-M2M and NB-OFDMA
- Narrowband LTE (NB-LTE), Alcatel-Lucent, Ericsson, and Nokia proposal