Wireless RF:
The Ins and Outs of LPWAN Technologies

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In this article we discuss radio frequency (RF) fundamentals and build upon these concepts to help the technical architects responsible for designing Internet of Things (IoT) solutions understand the impact of RF on low power wide area networks (LPWANs). The goal of this article is to help technical architects choose from among the different LPWAN options to best meet the needs of their LPWAN solutions.

In the first section, RF fundamentals, we cover the basics of radio frequency and explain how the frequency chosen has a direct relationship with the amount of data that can be transmitted, the range the signal can reach and the power requirements of the device. If you are comfortable with radio frequency basics, skip to the section on RF-based Networks for IoT.

Next, we'll touch on wireless personal area network (WPAN) solutions like Wi-Fi, Bluetooth, Zigbee and Z-Wave, and explain why these are not suitable when building a network that needs to run over a wide area, as these all have a relatively short range.

Finally, we will review some of the most commonly-used LPWAN options with a focus on cellular technologies (NB-IoT and LTE-M), and those using unlicensed bandwidth, LoRa®/LoRaWAN® and Sigfox. We'll also explore the differences among these technologies to help you select the right option for your use case.

RF Fundamentals

RF is a term used to describe the communication of digital or analog data over distances using radio waves, a type of electromagnetic radiation. Data can be transformed (**modulated**) into radio waves and transmitted from one device to one or more receiving devices. The receiving devices then transform the radio waves back into the source data.

Radio waves can be transmitted over cables or in the air. Wireless RF refers to radio waves transmitted over the air.

Frequency

The specific frequency of a radio wave identifies how frequently the radio wave cycles, or **oscillates**, per second.

Figure 1 shows a radio wave with a lower frequency; it does not cycle as many times per second as a higher frequency wave.

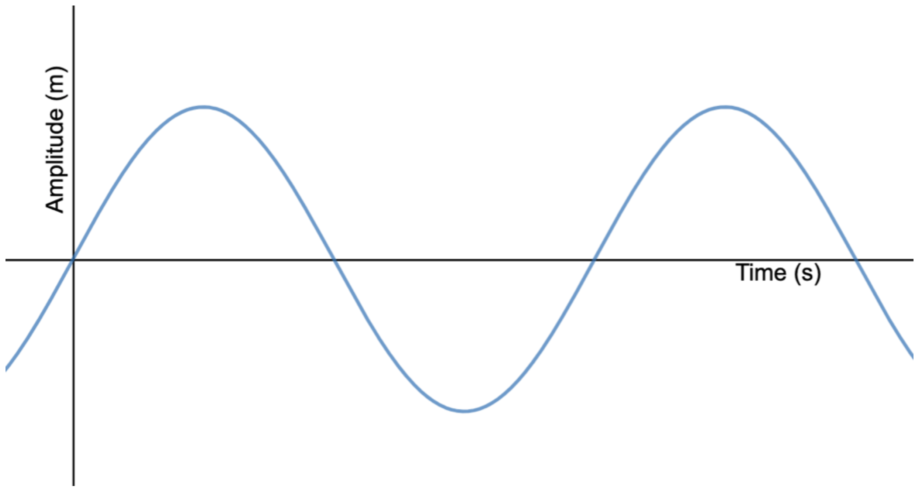

Figure 1: A low-frequency wave cycles a lower number of times in a set period.

Figure 2 shows radio wave that has a higher frequency; it cycles many more times per second than the frequency depicted in Figure 1.

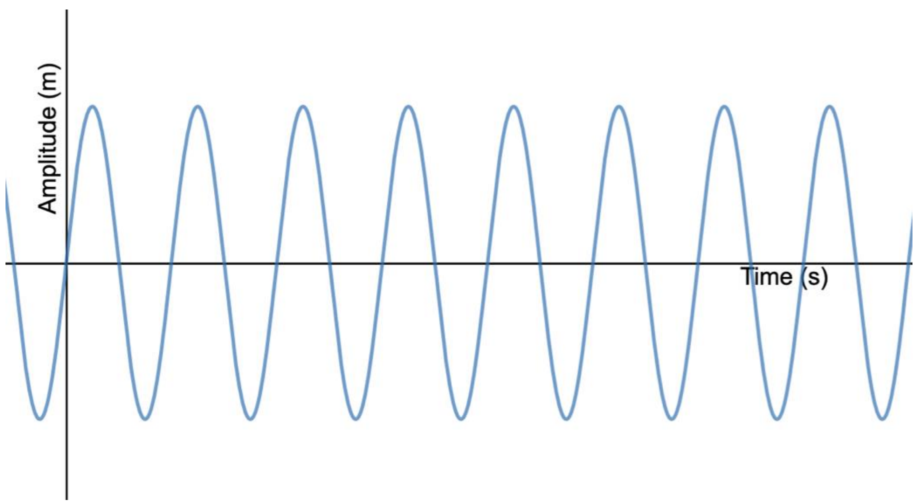

Figure 2: A Higher frequency wave cycles a larger number of times in a set period.

The frequency is measured in **hertz** (notated as **Hz).** A wave with a frequency of 1Hz is a wave which completes one cycle per second.

Table 1: Number of cycles per second for different frequencies.

Frequency	Number of cycles per second
1Hz	1 cycle per second
1MHz	1 million cycles per second
1GHz	1 billion cycles per second

A common frequency in the field of IoT is 2.4GHz (i.e. the wave cycles 2.4 billion times per second). Bluetooth, Wi-Fi 802.11, and microwave ovens, among others, all use the 2.4GHz radio frequency.

Table 2: Common uses of high and low frequency RF

Frequency	Example	Cycles per second	Example Uses
Lower frequency	900MHz	900 million	LoRa, Sigfox
Higher frequency	2.4GHz	2.4 billion	Wi-Fi, Bluetooth

Wavelength and Data Speeds

Wavelength is the length of one complete cycle of the wave measured in meters. In a low frequency the wavelength is longer, and in a high frequency the wavelength is shorter. **Amplitude,** or maximum amplitude, is the maximum height of the wave. This is also measured in meters, and is proportional to the strength or power of the signal.

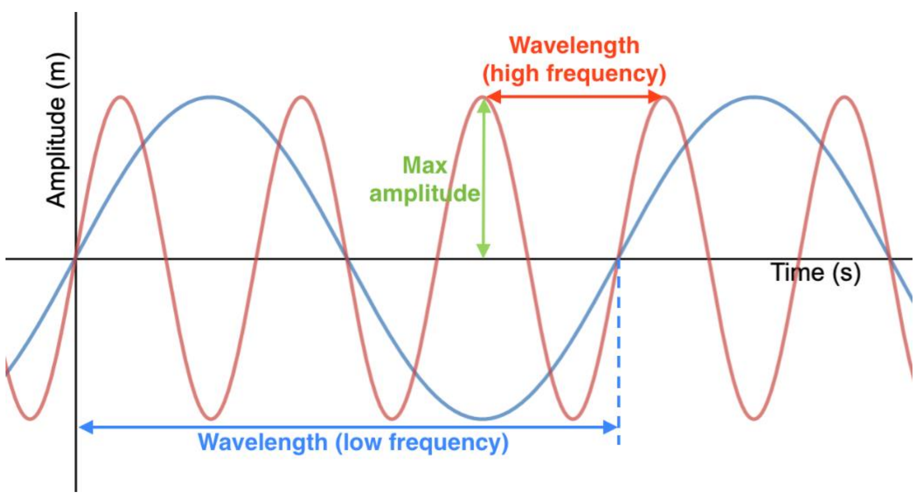

Figure 3: The wavelength of a wave is the distance over which the wave completes an oscillation cycle. The maximum amplitude is the height of the oscillation.

A **bit** is a single binary digit with a value of 0 or 1. A **bitrate** is the number of bits that can be transmitted and then received per second, from transmission to receipt. One kilobit per second (Kbps) is 1,000 bits per second, and one megabit per second (Mbps) is 1000 kilobits per second.

A single wave cycle, or oscillation, carries a **symbol**, which can be considered the shape of the oscillation. **Modulation** is the process of changing the shape of the wave, such as amplitude or frequency, to communicate data. As waves are received, the differences between each wave can be used to determine how the wave has changed and this can be mapped into bits. A **modulation scheme** refers to the rules used to map data to waves. Depending on the complexity of the modulation scheme, a symbol can contain a single bit or multiple bits, increasing the amount of data that can be transmitted per cycle.

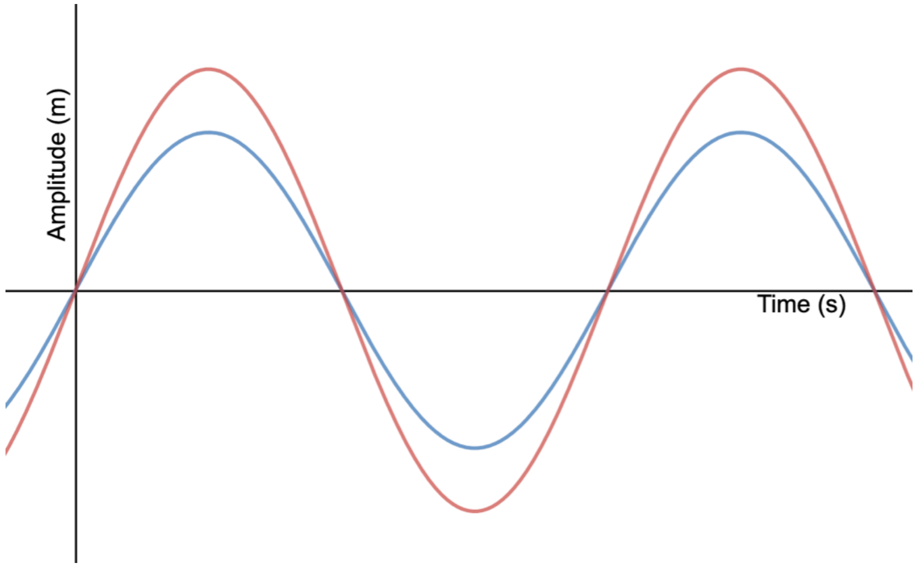

Figure 4: Amplitude-Shift keying. The amplitude of the wave can be varied to represent the symbol to send.

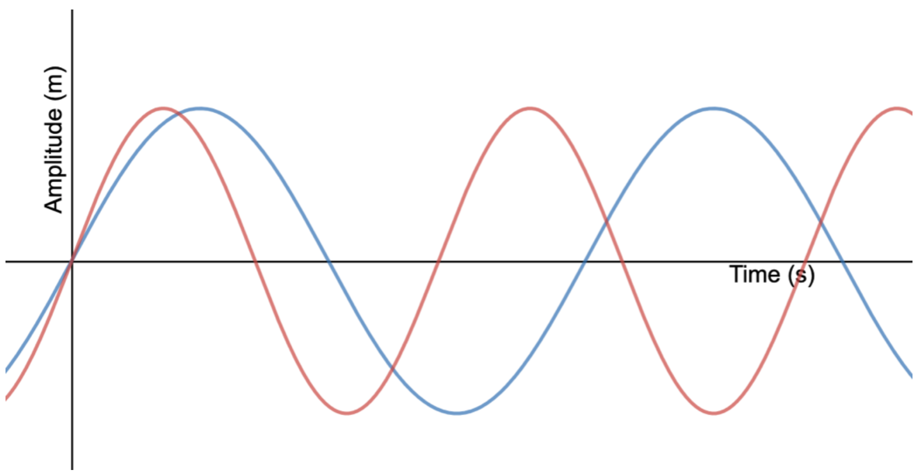

Figure 5: Frequency-Shift keying. The frequency of the wave can be varied to represent the symbol to send.

Naturally, the more waves per second, the higher the frequency and the more symbols that can be transmitted. Thus, a higher frequency can carry more data more quickly than a lower frequency.

Table 3: Frequency dependence on speed/data transfer rate.

Frequency	Example	Cycles per second	Speed/amount of data transfer
Lower frequency	900MHz	900 million	Lower
Higher frequency	2.4GHz	2.4 billion	Higher

Signal Strength Loss and Range

RSSI, or the **received signal strength indicator,** is a number that shows the amount of power a signal or radio wave has at the receiving end of the broadcast. The amount of signal strength that is lost during transmission is called **strength loss**.

When a signal is transmitted, it will always undergo some degree of strength loss as it travels over distance. Key reasons for this strength loss are explained here, including:

- Free space path loss
- Interference from buildings and other objects
- Other RF waves
- Background noise

Free Space Path Loss

In a perfect scenario (one without any obstacles) the degree of loss can be calculated using **free space path loss** (the loss in signal strength as a signal travels through free space). This is a simplified model. Other, more accurate formulas exist which take into account other factors, such as **plane earth loss** and the **Okumura-Hata model**.

These formulas show us that:

- Loss increases with the distance between the transmitter and the receiver
- Loss increases as wavelengths get shorter

When loss increases, the signal becomes more difficult and eventually impossible to receive.

The power loss is proportional to the frequency and is therefore inversely proportional to the wavelength. Low frequency signals have longer wavelengths, so the rate of loss is smaller and they can travel over greater distances.

Power of Waves

The power of the wave is related to the square of the frequency and the square of the amplitude of the wave. Waves with higher frequencies or higher amplitudes therefore contain more power. To produce a wave with a high frequency, more energy is needed. The law of conservation of energy, is *a physical law that states energy cannot be created or destroyed but may be changed from one form to another.*[1] In practical terms, when it comes to radio waves, this means that a wave of lower amplitude or lower frequency will contain, and therefore require, less power.

Interference from Other Objects

In the real world, free space path loss is not the only form of signal loss. There are also several forms of interference caused by other objects such as buildings, materials and other elements, including:

- **Absorption**: Some materials such as walls and wood can absorb signals. Lower frequency signals are less impacted by absorption than higher frequency signals.
- **Scattering**: Occurs when a signal hits an object such as smog and scatters into multiple waves
- **Reflection**: Occurs when a signal changes direction as it hits an object, such as metal
- **Diffraction**: Occurs when a signal hits an object, such as a hill, and moves around it
- **Refraction**: Occurs when a signal bends when it hits a medium such as water, causing it to change direction. Higher frequencies bend more when moving through a refractive medium than lower frequencies.

[1] https://www.thoughtco.com/law-of-conservation-of-energy-605849

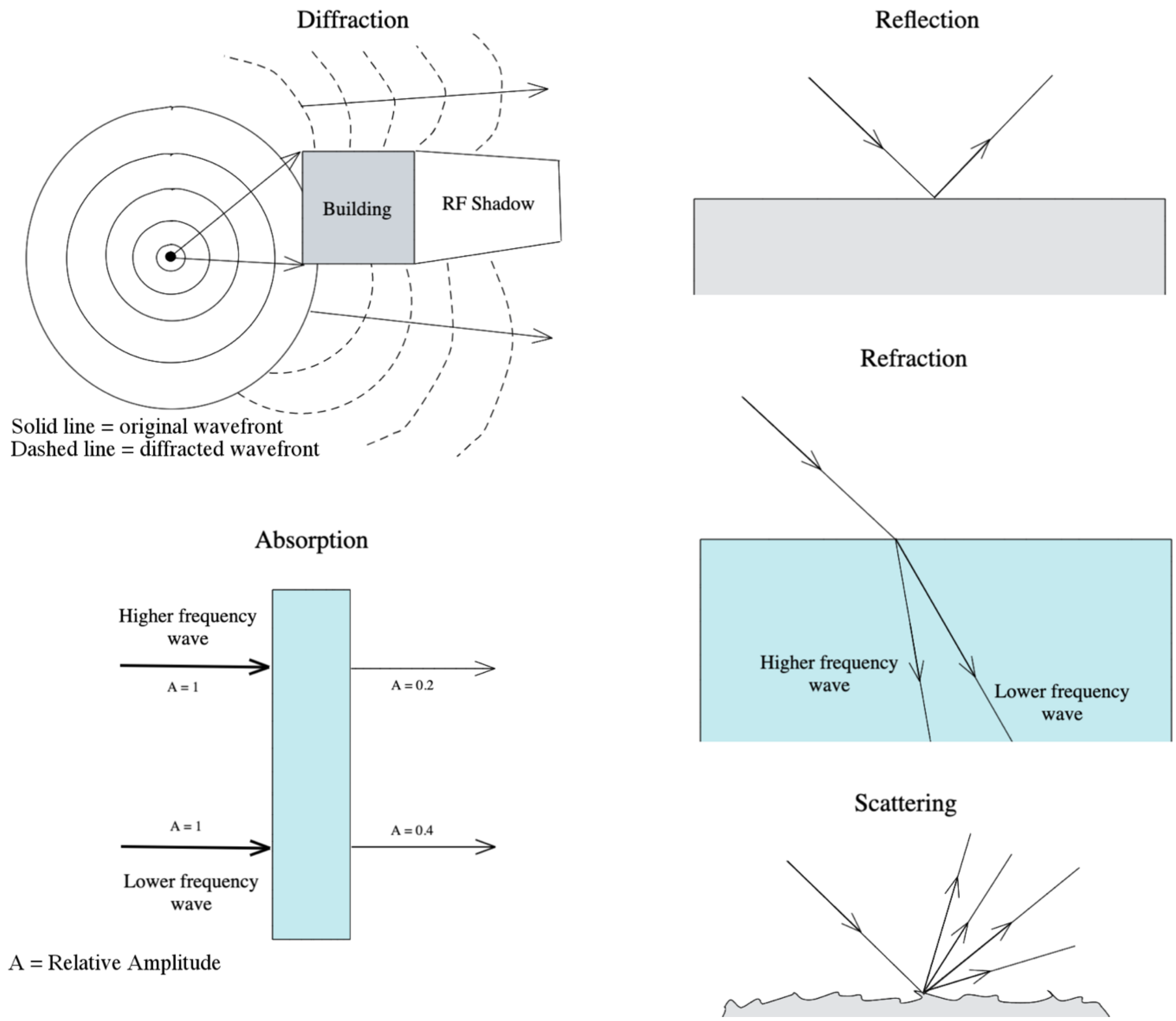

Figure 6: Schematic diagrams showing diffraction, absorption, reflection, refraction and scattering of RF waves. Arrows represent direction of travel of the wave.

Interference from Other RF Waves

When two waves are travelling in the same space, they interfere with each other and can alter the resulting signal which is received by the antenna. When two waves interfere, you can find the resulting wave by summing the amplitudes of both waves at every point along the wavelength. Interference can be **constructive**, where the amplitudes add up to give a larger amplitude, thereby boosting the signal, or **destructive**, where the amplitudes are of opposite sign; one positive, one negative, and therefore cancel each other out. Consider the case of **destructive interference** where you have two waves with the same frequency but at exactly opposite phases to each other – this is the worst-case scenario, since summing the amplitudes at each point along the waves will result in the waves exactly cancelling each other out. This results in signal not being received. The opposite case of perfect **constructive interference** is where two waves are of the same amplitude and phase, they are perfectly aligned with their maximum and minimum points aligned in time, their amplitudes add to create a wave with twice the amplitude.

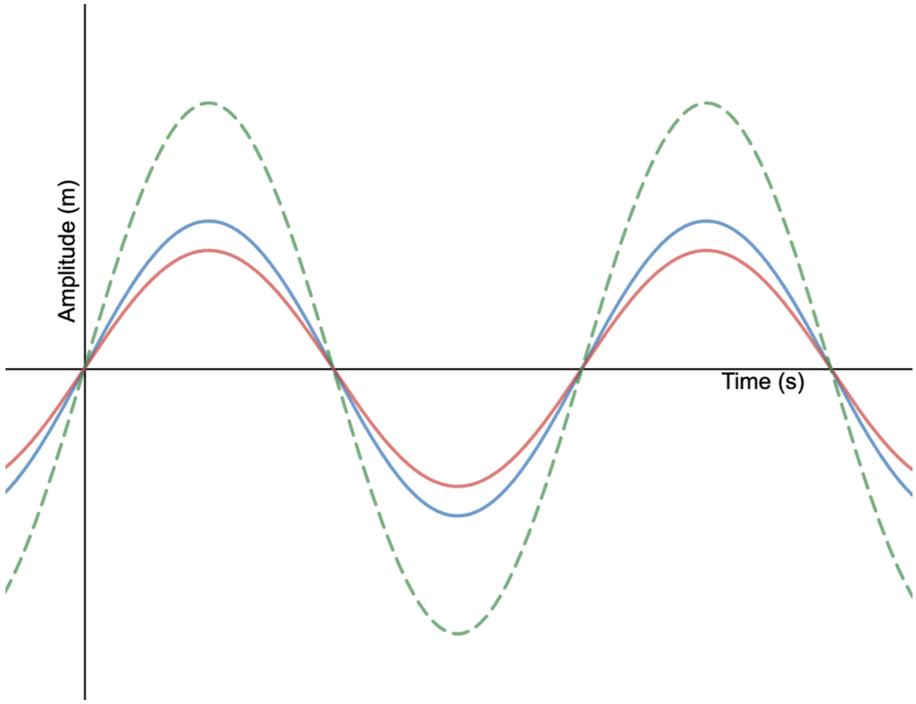

Figure 7: Constructive interference; two waves in perfect phase (red and blue lines) add constructively to give a larger amplitude resulting wave (green dashed line).

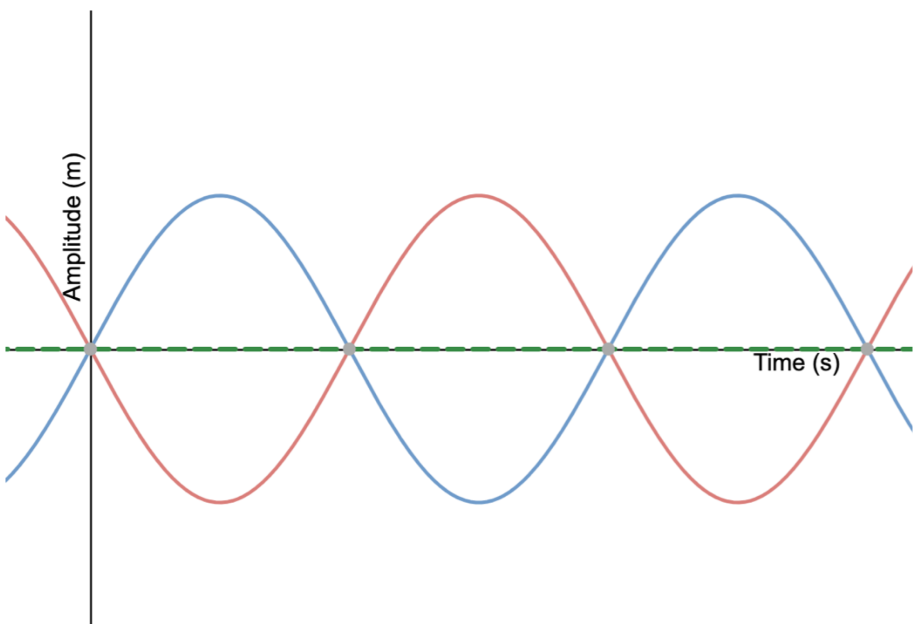

Figure 8: Destructive interference; two waves in exactly opposite phase (red and blue lines) act to cancel each other out leaving no amplitude (green dashed line).

Background Noise

Interference can also come in the form of background noise. Background noise can make your signal harder to discern if the amplitude of the background noise is similar to your signal. Background noise naturally occurs within the RF range and can also be caused by other common electronic devices, such as microwaves. Many receiving devices have a threshold for the required **signal-to-noise ratio** (SNR) in order to operate well. This ratio is simply the ratio of the power of the signal at the receiving antenna divided by the power of the ambient background noise. If you are operating in a built-up area, such as a town or city with a lot of buildings, it is likely that there will be considerable background noise, so the threshold SNR of the equipment used must be lower than in an area that is not built up. Figure 9 shows a schematic of a range of frequencies detected by the receiving antenna. The SNR is given as the square of the ratio of amplitudes: amplitude of the signal to amplitude of the background noise. The larger the SNR, the less sensitive the equipment must be to receive and process the signal.

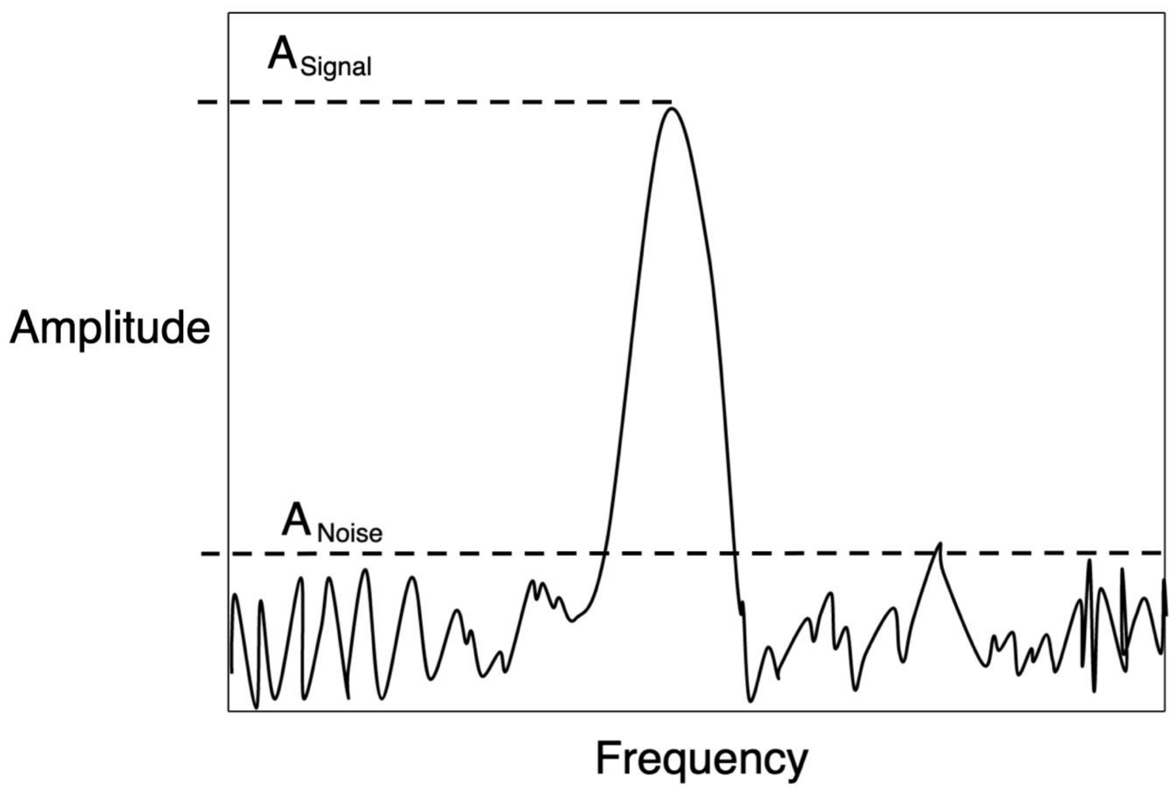

Figure 9: Graph showing the amplitude of signal measured at different frequencies, the transmitted signal amplitude is higher than the amplitude of the background noise and so the SNR, proportional to A_{Signal}:A_{Noise}, is greater than 1.

RF Spectrum

The RF spectrum is a part of the wider electromagnetic (EM) spectrum. This wider spectrum also includes other types of electromagnetic waves, such as X-rays and gamma-rays. The RF spectrum runs from frequencies of around 3kHz up to those of 300GHz.

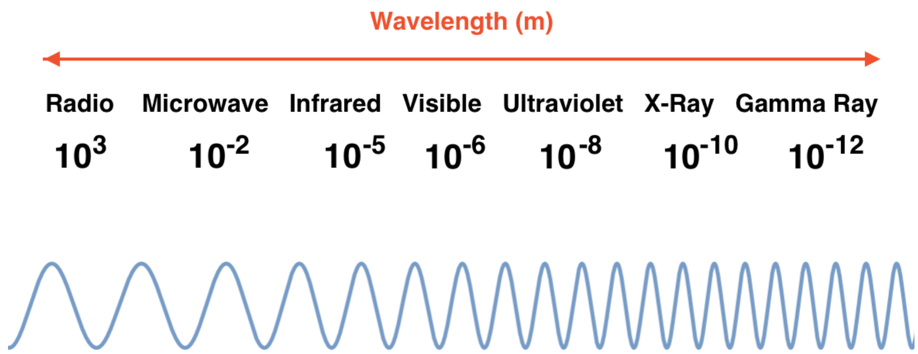

Figure 10: The EM spectrum showing the classifications of EM radiation.

Ranges of spectrum are grouped together in **bands** by bodies such as the International Telecommunication Union (ITU), and each band is then further governed by national regulatory authorities such as the Federal Communications Commission (FCC) in the U.S. Some frequencies are licensed while others are unlicensed. However, when using the unlicensed spectrum, users must conform to local regulations such as time spent broadcasting per day.

Figure 10, below, shows where in the spectrum some of the technologies we will discuss in the next section fit, specific to the U.S. We can see that within band 9, LoRa and Sigfox have a relatively low frequency at 900-930MHz, compared to Wi-Fi and Bluetooth at 2.4-2.5GHz, despite being in the same band grouping. Given our previous knowledge, we can see that since LoRa and Sigfox are lower frequency, they can therefore have a lower data speed but higher range than Wi-Fi 802.11 and Bluetooth.

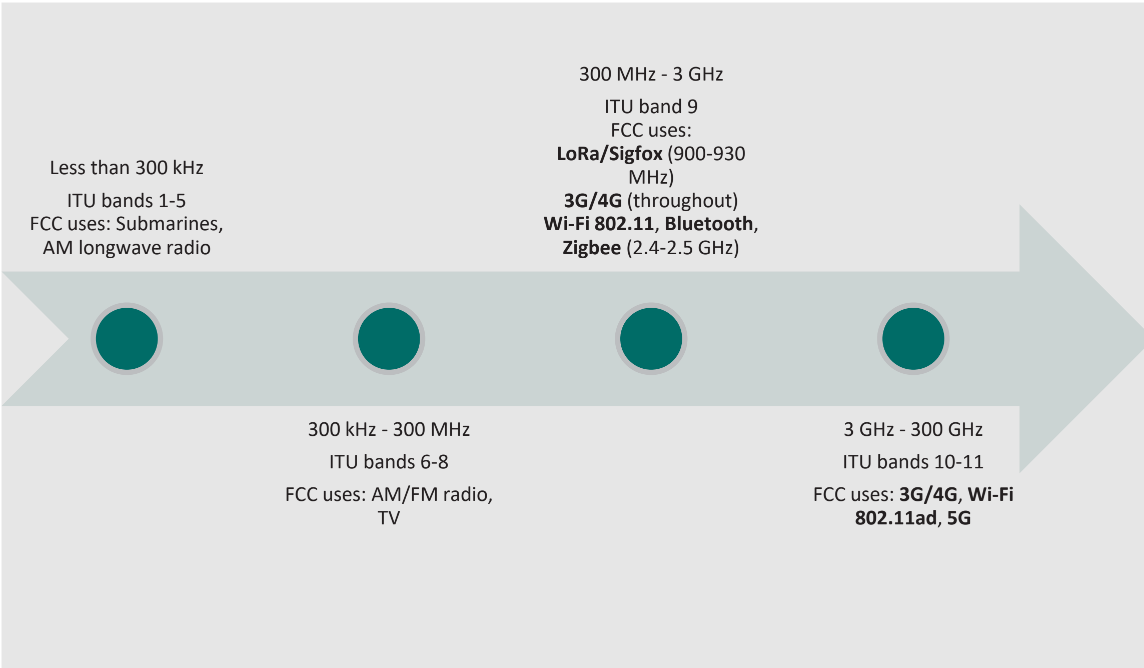

Figure 11: The RF spectrum showing where some popular RF options sit in relation to each other.

Summary: RF Fundamentals

We have learned that a technology broadcasting with a higher frequency will be able to transmit more data, with a faster bitrate, than a lower radio frequency. A higher frequency will require more power and will not travel as far as a lower frequency. In a building, built-up area, or an area with other sources of interference, the range will be lesser still.

Any frequency will achieve a greater range in a flat, open area (such as a farm without trees) than it would in a built-up area, as there are fewer forms of interference.

Keeping these fundamentals in mind, read on to learn how to select the right technology based on your IoT use-case, considering the amount of data you need to transfer, the power sources available and the range you wish to achieve.

RF-based Networks for IoT

There are many solutions for IoT device communications which are based on RF. For the purposes of this discussion we will group them into two categories:

1. Short range, or **WPAN** (Wireless Personal Area Network) – technologies that have a relatively short range, such as Wi-Fi, Bluetooth, Z-Wave and Zigbee. These can have a high or low bitrate and may consume higher or lower amounts of power.
2. Long range, or **LPWAN** (Low Power Wide Area Network) – technologies with a long range, low bitrate and low power usage.

Wireless Personal Area Network (WPAN)

WPAN technologies have a limited range, although this can be extended using a mesh topology, a networking implementation whereby each device repeats the signal to other devices nearby. As we explore below, you'll see that the primary use cases for WPAN are those where range is not as important. Each WPAN technology brings its own unique advantages and disadvantages.

Wi-Fi

Wi-Fi can operate at 2.4GHz or 5GHz. Because these are higher frequencies, Wi-Fi has a high data rate. There is a 1:1 relationship between each device and the network router. As we have seen previously, since the frequency of the RF waves is high, the range of the communication will be short.

Traditionally Wi-Fi devices have had higher power requirements, meaning most available devices are required to be mains powered. The new Wi-Fi 6 specifications are designed to reduce the power consumption of Wi-Fi IoT devices, enabling battery-powered IoT devices to use Wi-Fi. However, it will take time for devices using these new specs to become readily available.

Wi-Fi is highly suited to use cases where there are large amounts of data that need to be transferred quickly. For example: a camera device which needs to upload a 4K video clip.

Wi-Fi solutions are best suited for applications requiring:

- High data rate
- High quality of service (likelihood of the message getting through)
- Low latency

Wi-Fi solutions are less suited to applications requiring:

- Very wide ranges between a device and the router
- Battery powered devices

Bluetooth

Bluetooth has multiple modes. The most relevant mode for IoT is Bluetooth Low Energy (BLE). BLE operates at 2.4GHz, but only transmits a small amount of data. Additionally, it uses the Frequencyhopping Spread Spectrum (**FHSS**) modulation technique to combat interference. The Bluetooth 4 implementation of BLE transmits at a data rate of 1Mbps. Bluetooth 5 increases this to up to 2Mbps. Bluetooth Mesh allows the range of BLE to be increased by passing messages between nodes, however, you must have a large number of nodes to maintain connectivity over a wide area.

BLE solutions are ideal for applications requiring:

- Low power
- High quality of service
- Low latency
- Moderate range when using Bluetooth Mesh.

BLE solutions are less suited to:

- Long range applications

Zigbee and Z-Wave

Zigbee operates at both the sub 1000MHz range, and also at 2.4GHz. Z-Wave operates at approximately 900MHz. Using lower frequencies makes signals less susceptible to interference and better able to pass through walls and other obstacles. Lower frequencies also means low data rates. While the range of Zigbee and Z-Wave is short, using multiple devices in a mesh can extend the overall range of the network. Both Zigbee and Z-Wave were designed for low power usage.

Zigbee and Z-Wave are well suited to devices that require a high quality of service and which use a small amount of data, such as light switches and temperature sensors in a home.

Zigbee and Z-Wave are ideal for applications requiring:

- Low power
- High quality of service
- Low latency
- Flexible range with multiple devices

Zigbee and Z-Wave are less suited to applications with:

- Large amounts of data
- Long range (unless there is a device mesh covering the whole area)

Low Power Wide Area Network (LPWAN)

LPWANs are used to meet the needs of long range, low power networks. If your network needs to cover a long range or pass through obstacles such as buildings, you should definitely consider an LPWAN solution. There are LPWAN solutions across a range of frequencies in both licensed and unlicensed frequency bands. We discuss some of the more popular LPWAN technologies in the following sections.

Cellular

Cellular networks use licensed frequency bands, typically in the region of 500MHz to 4GHz, although 5G technologies could use frequencies approaching 100GHz. Originally, Cellular networks were built for high data rate communications such as voice calls, which operate at higher frequencies, to carry larger amounts of data. Higher frequencies have shorter ranges, so there are now standards for Cellular networks specializing in IoT communications operating at lower frequencies to achieve greater ranges.

There are two key cellular specifications to consider for IoT applications. Both of these are classified as 5G technologies:

- **NB-IoT** (Narrow Band Internet of Things). Sometimes referred to as Cat-M2 or Cat-NB, NB-IoT is a Cellular communication category which uses very narrow frequency channel widths. NB-IoT both consumes less power than LTE-M (see below) and has a longer range.
- **LTE-M** (Long-Term Evolution – Machine Type Communication). LTE-M has a higher data rate and lower latency than NB-IoT. LTE-M also has the advantage over NB-IoT of supporting device mobility, so that if a device is moving during data transmission it is able to switch to another cell tower.

Data rates on cellular networks are higher than other LPWAN solutions, which increases the packet size you can send.

The frequencies used in cellular solutions are licensed, reducing interference and messages can be sent as frequently as required. Cellular technology, therefore, has a high quality of service and low latency. If your use case requires immediate actions and responses – for example turning off a gas valve over a long distance as soon as a leak is detected – you may want to consider Cellular.

Cellular networks are usually owned by mobile network providers. By selecting cellular for your IoT solution, you can take advantage of an already well-established infrastructure, depending on the coverage in your target area. However, the cellular IoT specifications are relatively recent, so network providers are still setting up their systems to support these specifications. You may also find that network providers in your country have limited coverage, and likely will have chosen one or another specification (NB-IoT or LTE-M), to offer customers. (**Note:** It's unlikely that a given network provider has implementations for both.) GSMA has a deployment map of current mobile IoT deployments which may be used to find links to providers in your location. Cellular networks require a subscription to the network provider and can be more expensive than other unlicensed options.

A use case that would fit a cellular IoT implementation is **electric metering**:

- High data rate and payload length
- High quality of service
- Low latency

Sigfox and LoRa

Two other leading LPWAN technologies, Sigfox and LoRa, both use unlicensed bands between 433MHz and 928MHz, to transmit low frequency signals over long distances. These technologies share some characteristics, as we will see.

Unlike Cellular networks, networks based on either Sigfox or LoRa are built using a star network topology; this means that a broadcast message may be received and transmitted to the Cloud by any base stations (gateways) within range. This increases the chance of a signal being picked up when a device is at the outer range limits of multiple base stations.

Both Sigfox and LoRa can achieve greater distances and consume less power than Cellular. Conversely, both have slower data transfer speeds and more limitations on the amount of data you can transmit and the frequency with which you can transmit it. You can send larger amounts of data per message, and broadcast more frequently using LoRa, while you can obtain the farthest potential range with Sigfox.

Common advantages of Sigfox and LoRa:

- Long range
- Low power

Sigfox

Sigfox, founded in 2010, was the first modern LPWAN as we now define the term.

Sigfox uses unlicensed bands at frequencies between 862MHz and 928MHz, and transmits messages 100Hz wide, using **ultra-narrowband modulation.** This means that Sigfox devices transmit on a random channel within the given operating range, helping to reduce the chance of interference from background noise.

Sigfox can achieve the greatest range of all the options we are analyzing, at the expense of a low data rate, due to the narrow band used. The data transmitted per message must therefore be small, less than 12 bytes. Sigfox users must not send more than six messages from a device to the Cloud (**uplink**) per hour, and no more than four messages from the Cloud to a device (**downlink**) per day. These limitations mean Sigfox is ideal for applications which need to communicate just a few simple values each day, with low power requirements

Until recently, to use Sigfox you had to subscribe to their public network. However Sigfox is currently in the process of offering Private Area Network (PAN) technology to allow you to run a private instance of the network.

- Advantage of Sigfox: Longest range of all LPWAN options.

LoRa and LoRaWAN

LoRa uses unlicensed bands between 433MHz and 928MHz, depending on region, and uses a proprietary **Chirp Spread Spectrum** (CSS) modulation scheme to transmit data using a narrow band (125, 250 and 500kHz) spread over a wider channel bandwidth, ensuring low noise levels and resilience to interference. It is possible to vary the modulation scheme by changing the **Spreading Factor** to achieve greater distances at the expense of power. **LoRaWAN** is an open standard networking protocol (built on top of LoRa) that defines how devices communicate with gateways.

The range of LoRa is greater than Cellular, but less than Sigfox. However, the packet size limitations are flexible, and with the right configuration you can transmit much more data per packet than with Sigfox.

The maximum packet size for a LoRa message depends on the region you are in and the data rate you wish to support. By varying the spreading factor and bandwidth used, you can achieve different data rates. A higher data rate means a shorter range, since the frequency is higher. The maximum message size you can transmit can range from 11 to 242 bytes, and you can control this based on your use case.

Table 4: Bitrates and maximum payload sizes for different combinations of spreading factor and bandwidth available in the EU868 US915 and CN470 regional specifications.

<table>
<tr><th>Region</th><th>Spreading factor</th><th>Bandwidth (kHz)</th><th>Bitrate (bits/sec)</th><th>Max payload size (bytes)</th></tr>
<tr><td rowspan="7">EU868</td><td>SF12</td><td rowspan="6">125</td><td>250</td><td rowspan="3">51</td></tr>
<tr><td>SF11</td><td>440</td></tr>
<tr><td>SF10</td><td>980</td></tr>
<tr><td>SF9</td><td>1760</td><td>115</td></tr>
<tr><td>SF8</td><td>3125</td><td rowspan="2">222</td></tr>
<tr><td>SF7</td><td>5470</td></tr>
<tr><td>SF7</td><td>250</td><td>11000</td><td>222</td></tr>
<tr><td rowspan="10">US915</td><td>SF10</td><td rowspan="4">125</td><td>980</td><td>11</td></tr>
<tr><td>SF9</td><td>1760</td><td>53</td></tr>
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<tr><td>SF7</td><td>5470</td><td>242</td></tr>
<tr><td>SF12</td><td rowspan="6">500</td><td>980</td><td>33</td></tr>
<tr><td>SF11</td><td>1760</td><td>109</td></tr>
<tr><td>SF10</td><td>3900</td><td rowspan="4">222</td></tr>
<tr><td>SF9</td><td>7000</td></tr>
<tr><td>SF8</td><td>12500</td></tr>
<tr><td>SF7</td><td>21900</td></tr>
<tr><td rowspan="7">CN470</td><td>SF12</td><td rowspan="6">125</td><td>250</td><td rowspan="3">51</td></tr>
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<tr><td>SF10</td><td>980</td></tr>
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<tr><td>SF7</td><td>5470</td></tr>
<tr><td>SF7</td><td>500</td><td>21900</td><td>222</td></tr>
</table>

There are a number of public LoRaWAN network providers. It is also possible to set up a private network using your own gateways and software. This allows you to provide connectivity anywhere you can access a location to install a gateway. A private LoRaWAN network also enables you to keep the data entirely in your own domain. The ability to set up your own network is unlike any of the other technology options described thus far, and gives you complete control over your system, data and costs.

LoRa has multiple classes of operation:

- Class-A: Requires the least power. Devices spend most of their time asleep and will wake upon a change in sensor value to send an uplink message. There are very limited windows in which to receive a message from the server (downlink).
- Class-B: Also requires very little power. Devices spend much of their time asleep, but can wake on schedule, as well as when a sensor reading changes, to report the current reading. There are limited windows in which to receive a message from the server (downlink).

- Class-C: Requires more power than Class-A and Class-B devices, but devices are always listening for downlinks, except when broadcasting an uplink.

The flexibility from these multiple classes of operation means LoRaWAN serves a wider range of use cases.

Advantages of LoRaWAN:

- Control over maximum packet size, which can be higher than Sigfox.
- Easy to set up a low cost private network.
- Flexible, with a combination of devices with differing power needs and latency requirements working together.

Summary

Lower frequencies will have a longer range, but carry less data than higher frequencies.

WPAN technologies such as Bluetooth, Wi-Fi, Zigbee and Z-Wave all operate at higher frequencies at the expense of range. These technologies are unsuitable for scenarios where range is important. LPWAN technologies are all able to achieve a far greater range than WPAN technologies, and operate at much lower frequencies.

We have established that the correct LPWAN technology depends on your use case. Cellular technologies such as NB-IoT and LTE-M are more suited to situations where there is Cellular coverage, and where quality of service, low latency and larger amounts of data are more important than power, since the range can be lower. Sigfox suits a scenario where you have a very small amount of data and wish to transmit over a long range with low power. LoRa allows the most control, with ease of setting up a private network, configurable ability to send larger amounts of data and Class-C enabling a lower latency.

Table 5: Summary of the relative range, responsiveness, mobility and data rate for the leading LPWAN technologies.

	Range	Responsiveness	Mobility	Data rate
NB-IoT	Medium	Higher	Not supported	Higher
LTE-M	Medium	Highest	Supported	Highest
LoRa	Long	Lower	Supported	Lower
Sigfox	Longest	Lowest	Supported	Lowest

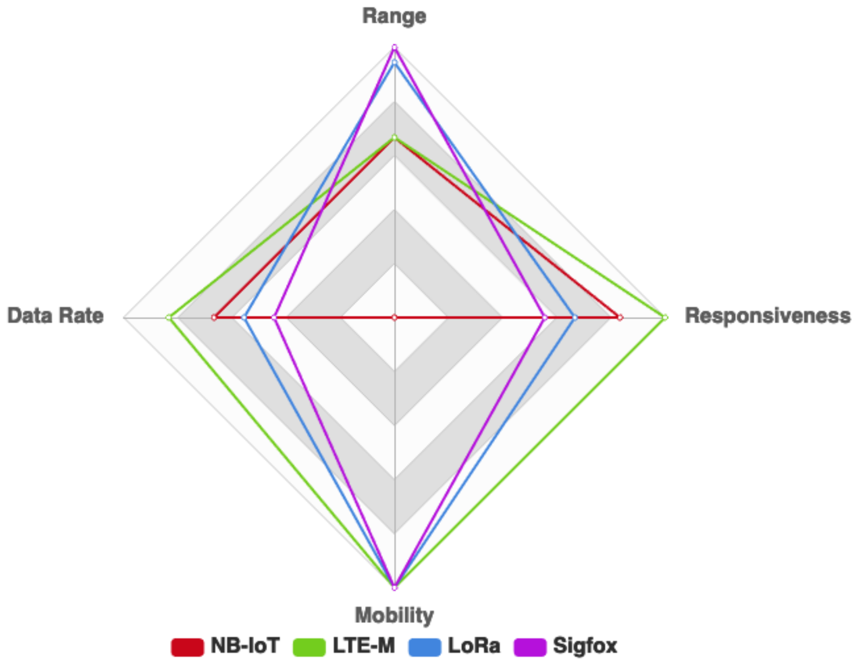

Figure 12: Comparison of range, responsiveness, mobility and data rate for the leading LPWAN technologies.

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