How HFC-based Industrial IOT Gateways Improve Performance of Remote IOT Sensors

A Technical Paper prepared for SCTE•ISBE by

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Abstract

Outdoor Industrial IoT (IIOT) deployments are used in Smart Cities to optimize everything from parking lots to garbage collection. These large, spatially diverse networks consist of remote sensors (motes) that communicate wirelessly to network servers via gateways. Transporting the sensors' signals back to the network server is yet another way the MSOs can leverage their vast Hybrid Fiber Coaxial (HFC) networks to generate new revenues.

IIoT remote sensor solutions like LoRaWAN (Long Range WAN) are based on Chirp Spread Spectrum technology, which provides a means to conserve battery life while providing effective communication between devices. When sensors are placed further from gateways, the device changes the spreading factor and slows the transmission rate to ensure the two devices connect. However, the slower rate results in longer operation of the CPU, which in turn reduces the life of the battery. In essence, the greater the distance between the sensor and the gateway, the shorter the mote battery life.

Replacing these batteries will ultimately result in costly truck rolls for the cities that deployed them. The MSO can minimize these visits by deploying more gateways to shorten the distance to the sensors. This technique uniquely positions the MSO to provide a differentiated service to the customer. The end result is increased battery life cycle, minimizing the number of truck rolls and the overall cost for operating the IIOT network.

This paper will show how to densely deploy IIoT gateways on HFC networks to shorten the distance to the motes and increase battery life. In addition to the financial benefits, this paper will highlight other advantages of a dense HFC-based IIoT gateway solution, including improving the ability to locate motes using Time Delay of Arrival (TDoA) mote location resolution, improving overall communications resiliency, and enhancing the ability of the HFC system to provide reliable communications and powering to the gateways.

Summary

The Industrial Internet of Things (IIoT) is a subset of the Internet of Things (IoT) that targets governments and industrial use cases such as smart parking, smart waste collection, infrastructure and transportation monitoring, remote metering, energy and pipeline monitoring, just to name a few. There are several reasons for the segregation of this IoT market segment:

- The target users are primarily government and industrial entities
- The scale of the deployments can be many times what other IoT solutions encompass
- The solutions are designed to provide measurable direct value
- Most of the deployed devices are hardened and installed in remote locations

Deployment in hardened, outdoor, remote locations results in a unique set of requirements. The remote field devices or sensors, known as motes, must be better engineered for the environmental conditions, resulting in more expensive devices. Because of their remote locations, the cost for initial installation as well as ongoing maintenance is higher (e.g., truck rolls). The sensors and installations must be designed to lessen any chance of tampering or vandalism. They also require real-time monitoring and must be designed both mechanical performance and aesthetics. Clearly, the IIoT devices are distinctly different than conventional indoor IoT units.

While all IoT solutions must interconnect and provide information, the scale and remote nature of the information that must be gathered in these IIoT solutions make it impractical to directly wire these remote locations. Consequently, wireless methods are deployed to provide that connectivity.

There are many IIoT wireless communications standards both in use and under development to provide communications of the required information:

- LoRa, LoRaWAN (Long Range Wide Area Network)
- LTE-M (Long Term Evolution (4G) Category M
- SigFox
- NBIoT (Narrowband IoT)

These standards are very different from other IoT communications standards like BLE (Bluetooth Low Energy) and Wi-Fi as these IIoT standards are engineered to communicate over very long distances. The IIoT standards use various frequencies, modulation formats and power levels. The RF link budgets for most of these solutions approach 160dB, which means the receiver is able to receive the content at 1 quadrillionth ($\frac{1.0}{1{,}000{,}000{,}000{,}000{,}000}$) of the original transmit power. Many of the IIoT communications standards employ a limited bandwidth RF receiver to improve the communications. The remote IIoT communications standards can work with such a restriction in RF link budget because the remote sensor locations don't have a great deal of information they have to convey at any time. A parking sensor only needs to send a simple "cars here" or cars not here" message, which could easily be sent in a single bit toggle, so a few bytes of data suffice for almost all communications.

Many MSO operators in the US are investigating IIoT communications backhaul using the LoRaWAN standard. There are several advantages of the LoRaWAN communications definition which undoubtedly drove their decisions to investigate this standard:

- LoRa and LoRaWAN operate in the unlicensed ISM spectrum
- Claims of long-distance reliable wireless connection solutions
- Claims of optimized powering scenarios resulting in long battery life:
  - Safe, low power transmitters
  - No routine RF synchronization
  - Aloha-based communications
  - Routine communications optimization

This paper will examine the nuances of the Remote LoRaWAN Sensor Device (mote) and different ways to optimize the deployment and configuration of the mote and gateway to maximize the mote battery lifetime. Key topics include:

- Explanation of CSS, SF and other FHSS communication impacts and configuration
- LoRa channel requirements in an FCC based deployment
- Description and recommendations of LoRaWAN communication modes
- Attenuation contributors, their impacts and mitigation
- Deployment options to maximize the benefits of these items

Content

LoRaWAN Background

US LoRaWAN modulation is a unique modulation using Chirp Spread Spectrum (CSS) which is very resilient to noise. With CSS, there is a known modulation as a “frequency change over time ramp “of consistent amplitude the RF modulation and the dynamic changes in this ramp (chirp) up, down or dynamic frequency changes within the ramp are decoded into symbols.

The simplest analogy would be how humans can perceive certain sounds in noisy environments. For example, think of how you can identify the sound of a siren in your car with the windows rolled up and the radio playing. You understand the unique variations in pitch of a siren and can discern it through the noise of the environment. Chirp Spread Spectrum hardware acts much the same way and the hardware can identify the variations in energy across frequency and time, even through environmental noise and interference. Some describe this efficiency as equivalent to the signal decoded 20dB below the spectrum noise floor (in a 200kHz resolution bandwidth).

As with most communication modulation standards today, LoRa’s Frequency Hopping Spread Spectrum (FHSS) utilizing Chirp Spread Spectrum (CSS) modulation profile can be set to several different modes to optimize data rate versus signal integrity. These modes are called spreading factors (SF). Spreading factors effectively stretch the chirps by decreasing the rate of ramp, while increasing the time of the ramp. This allows the hardware more time to analyze the trend of the ramp better, identifying that information from interference or noise not part of that energy.

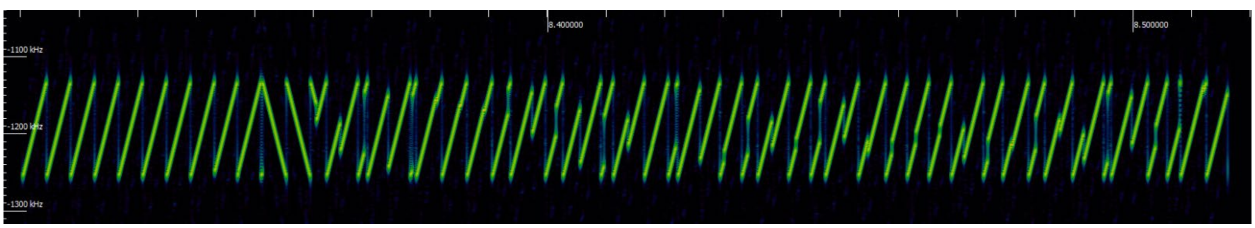


Figure 1 LoRaWAN CSS modulated signal example

Spreading factors in LoRaWAN are based in two RF bandwidths, 125kHz and 500kHz, and are a function of these bandwidths. For the 125kHz channels, spreading factors 7 to 10 are used; each step increase is a factor of 2 over the proceeding one where the time it takes to send each chirp is twice as long and the data rates are effectively cut in half. The same relationship is also true for the 500kHz wide channels with spreading factors in that bandwidth run from 7 to 12. European LoRaWAN has spreading factors up to 12 for the 125kHz bandwidth as well, which would be a factor of 4 over what the US defines, but the time period to send data over that modulation setting would exceed the FCCs mandate that FHSS signals should not exceed 400mS dwell time for an RF transmission of that type.

Table 1 LoRaWAN Data Rates (USA)

Data Rate	Modulation Configuration	bits/s	Max payload
DR0	SF10/125kHz	980	19

Data Rate	Modulation Configuration	bits/s	Max payload
DR1	SF9/125kHz	1,760	61
DR2	SF8/125kHz	3,125	133
DR3	SF7/125kHz	5,470	250
DR4	SF8/500kHz	12,500	250
DR8	SF12/500kHz	980	41
DR9	SF11/500kHz	1,760	117
DR10	SF10/500kHz	3,900	230
DR11	SF9/500kHz	7,000	230
DR12	SF8/500kHz	12,500	230
DR13	SF7/500kHz	21,900	230

Each increase in the spreading factor increases the effective range of the device by improving the signal's ability to be decoded by the receiver; however, the tradeoff is that the transmitter must be on for extended periods of time to transmit the more robust RF data. As the effective range is increased by each increase in SF, the time is also increased for the same amount of data is to be sent and decoded. In the https://avbentem.github.io/lorawan-airtime-ui/ttn/us902 calculation shown below, you can see the impact of the increase in time the transmitter would have to be on over the different spreading factors for the same data. The impact of the different spreading factors to the battery utilization will be covered later.

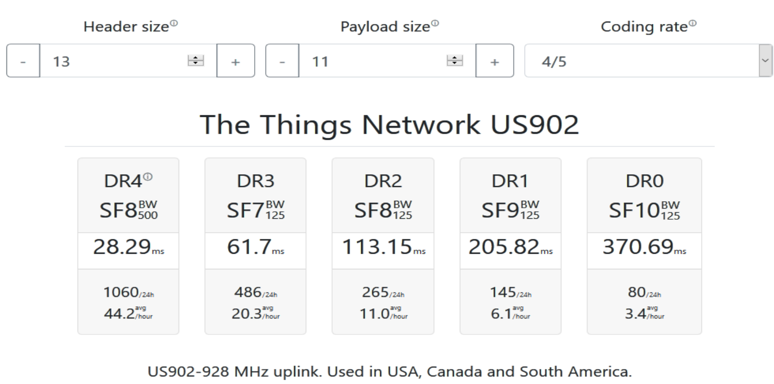


Figure 2 Github LoRaWAN calculator example for US

Below are some RF spectrum captures of various LoRaWAN spreading factors with similar chirp l counts. The first image is of what would be an optimal RF signal from a mote where the unit has a very good upstream connection, resulting in a DR 4 setting with a SF of 8 over a 500kHz resolution bandwidth. There are about 61 total chirps which were conveyed over about 28.8ms transmission.

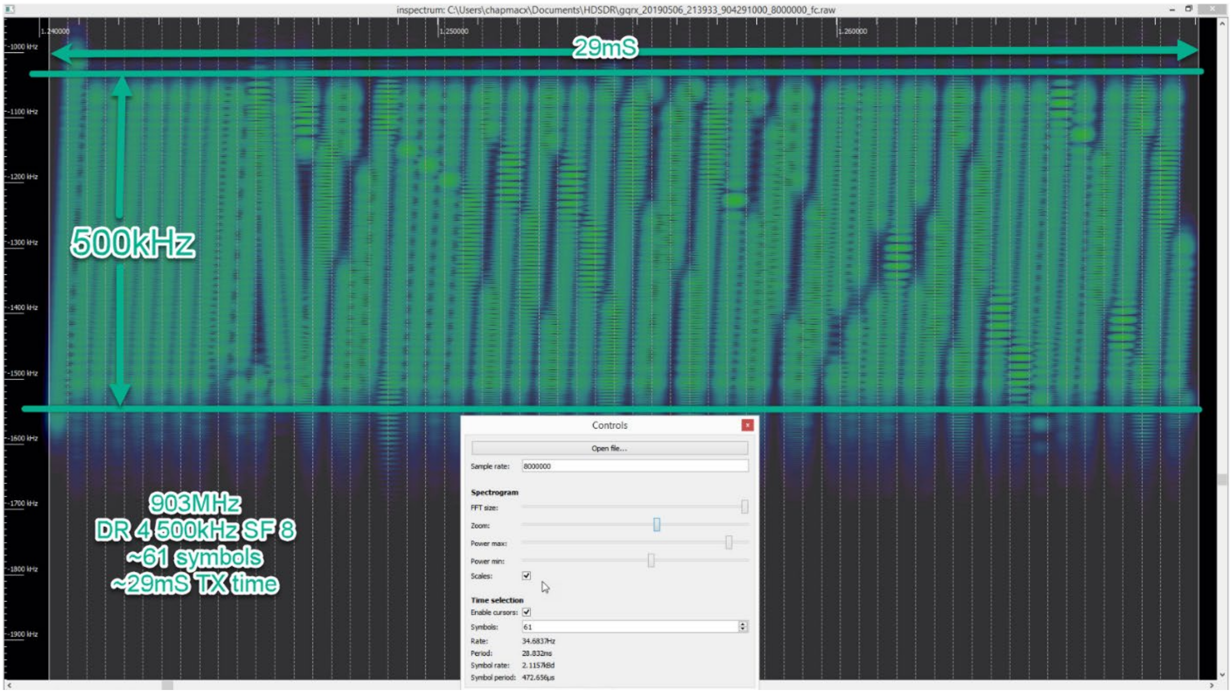


Figure 3 LoRaWAN signal with a higher order of modulation

The image below illustrates the impact of a mote with a much lower DR factor of 0 which equates to a 125kHz bandwidth signal modulated with an SF of 10. This would likely be from a mote with a great deal more noise or attenuation to the gateway. In this capture ~50 Chirps were captured over a 206 mS time period. A quick calculation correlates that that approach would take about 250ms to send the 61 chirps that the DR 4 capture sent in less than 29mS.

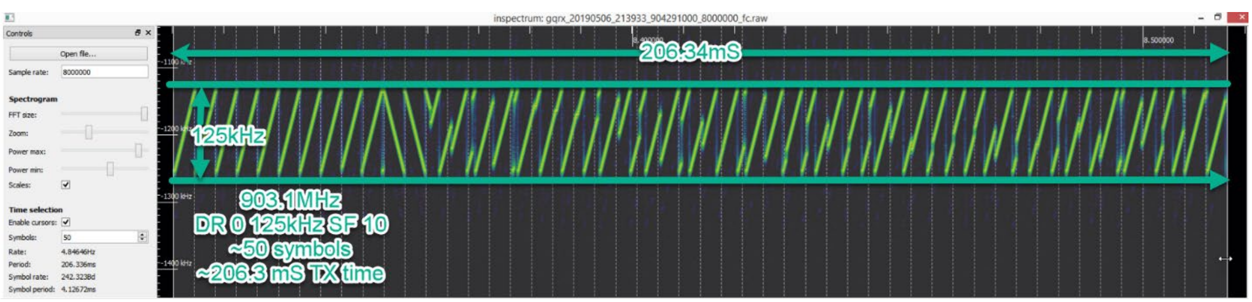


Figure 4 LoRaWAN signal with a lower order of modulation.

1. Implications for Utilization of Stored Energy in a Battery

First, realize that these IIoT LoRaWAN motes leverage hardware including the Semtech communication chips are designed to utilize energy efficiently.

- They are designed to maximize battery life
- They support deep sleep modes that are either triggered by events or by a schedule of elapse
- They can leverage an ALOHA based communications, primarily to send data to the gateway
- They try to return to deep sleep mode as quickly as they can after a transmission

The most common power mode for the IIoT motes is a deep sleep mode. This mode only requires micro Amps or Pico Amps of power to keep the sensors and timing operational. When a chronological subroutine or system-based event requires communications, the device will wake up, process the required data, then quickly and efficiently transmit the data to the gateway. After the transmission, the IIoT LoRaWAN will wait a small set period of time and then turn on the receivers for a short period to listen for a confirmation message or additional instructions from the gateway. There is an additional 2nd receive window that will activate after the first receive window for short period after that if the first window was not satisfied. If the message exchange is successful, then the unit returns deep sleep. Below is an example of the power demands of a battery-operated Mote, during a transmission cycle.

Figure 5 LoRaWAN Mote transmit / receive battery current demand over time trace

In this normal LoRaWAN mote ALOHA-based communication mode, the timing of the start of the communications process is dictated by the programming or an event detected by the unit. The transmitter will turn on shortly after the mote wakes up, and the hardware conveys the information to be transmitted. The transmitter will stay on for the length of the transmission, then the unit will idle as much as it can before the 1st receive window which is generally starts 1 second after the transmission is over for a short duration to allow data to be processed from the gateway and any information that needs to be conveyed to the mote to be conveyed the receiver will stay powered until the information is received. If no data is received or for a longer duration if data is received in the window. If the mote does not receive the required information in the first window a 2nd receive window is opened 1 second after that to allow delayed data to be received. If either receive window obtains a satisfactory response the unit will go back into the deep sleep mode until the next event triggers it again. The issue is if the data is not received and the mote is set to receive a confirmation message, the mote may try to resend the message cycle to verify the message data was received.

2. Power Requirements

Now that the communication process is understood we can look into the details of the power demands of a communication cycle. To obtain the transmit-based information, a scope was connected through a shunt in series with the battery of a LoRaWAN IoT mote and set to display the current scaled to the shunt. A trigger was set to just above the deep sleep current (a few µA) to trigger when a transmit event occurred.

In this unit, which was set to transmit a 14dBm signal DR 0 125kHz SF 10, the battery current draw during the transmit timeframe was 125mA with a duration of 400mS, which equates to the limit the FCC allows for this form of modulation. Figures 6 A&B, 7A&B and 8 A&B show various motes operating with this transmission modulation. Figure 9 A&B shows mote #3's battery power demand transmitting a DR 4 mode using 500kHz and a SF of 8; note the current demand is similar to mote #3's DR 0 demand, but the duration is more than a 10-fold decrease when compared to the same units DR 0 trace. Another interesting item to note is how close these duration results compare to the calculation provided by the Github calculator.

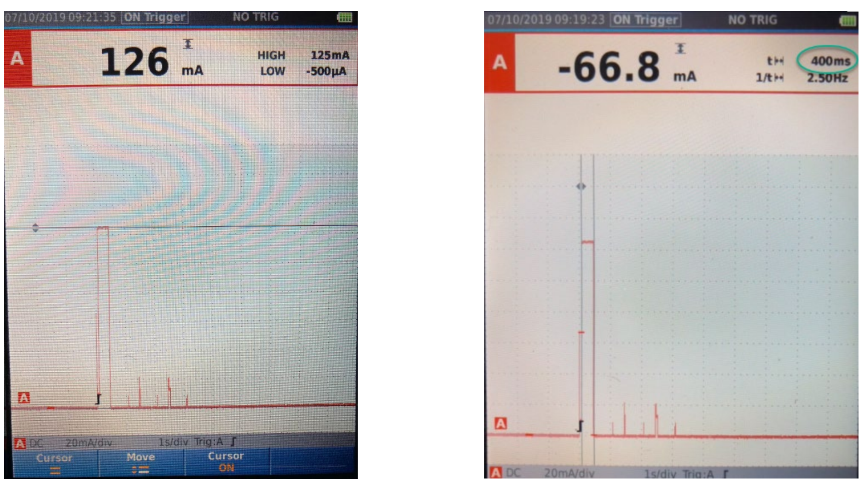


Figure 6 A and B LoRaWAN mote #1 transmitter demand on the 3VDC battery from both a power and time perspective.

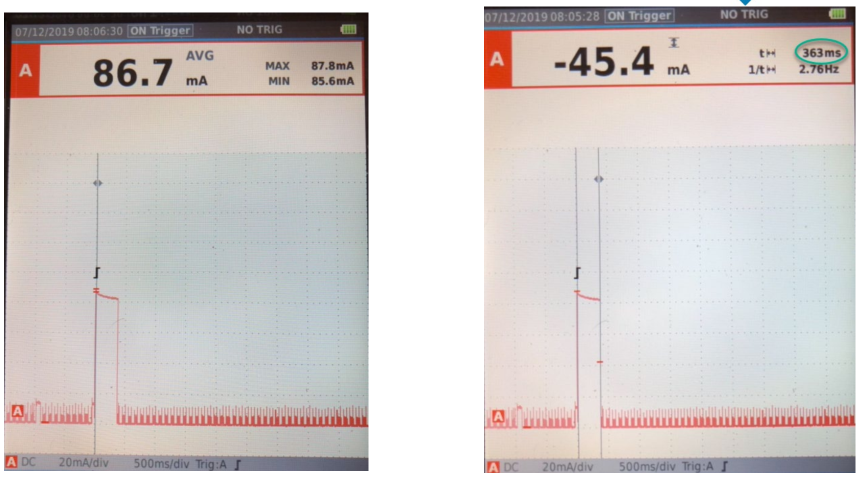


Figure 7 A and B LoRaWAN mote #2 transmit demand on the 3VDC battery from both a power and time perspective.

Figure 8 A and B LoRaWAN mote #3 transmit demand on the 6VDC battery from both a power and time perspective

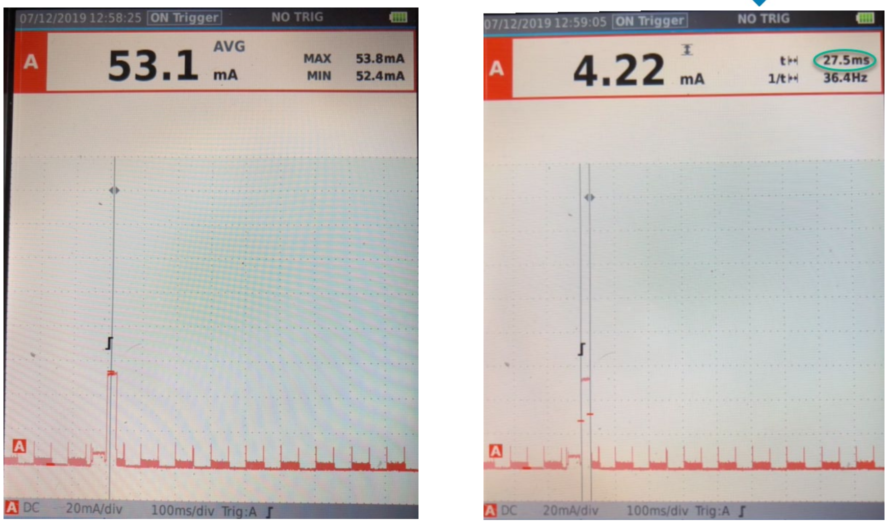


Figure 9 A and B LoRaWAN mote #3 transmit demand on the 6VDC battery from both a power and time perspective using DR 4.

Additionally, the motes can be commanded to change their transmit levels within the constraints of the accepted RF parameters of the area the device is operating with. In the US, the transmitter outputs can be adjusted in 2dB steps over a 28dB range. The actual output of the LoRaWAN mote is impacted both by the losses in the signal path and the antenna gain. From the information I was able to ascertain during these tests, adjusting the RF output to a lower level had a lesser effect on battery utilization than the potential impacts caused if the mote had to lower the modulation profile and SF changes that might have to make up for due to the signal strength and integrity.

There is an interactive feature in these LoRaWAN mote chipsets called "ADR" – Adaptive Data rate. A Semtech function where the Semtech field mote device transmits a signal to the gateway and the gateway uses the upstream data signal strength to determine the best transmit level and spreading factor to maintain reliable and efficient communications and sends that data back the mote to optimize the communications integrity.

More specifics around US LoRa and LoRaWAN transmission

Any device that is designed to communicate wirelessly in the United States must comply with US Federal Communications Commission requirements for the form of communication they intend to use. The FCC specifies what communications can be used and at what frequency, power levels for transmissions in those frequencies and details about the modulation allowed in those bands. Semtech LoRa and the LoRa Alliance LoRaWAN specification are designed to be used worldwide and each area or region leverages a subset of those abilities to comply to the local communications requirements like those laid out by the FCC for the US Channel coverage – The common name for the US regional LoRaWAN designation is "US 915" this specification leverages what the FCC has designated as the ISM (Industrial, Scientific and Medical) band operating in the 900MHz band covering from 902 to 928MHz for FHSS. The LoRa CSS modulation and channel hopping process falls into what the FCC has defined as Frequency Hopping Spread Spectrum (FHSS) RF communication standard and within this band has the capacity for 72 LoRa modulated Upstream (US) channels. The Channels are a combination of 64 125KHz wide channels spaced at 200kHz starting at 902.3 and 8 500KHz channel bandwidth starting at 903 MHz with 1.6MHz wide channel spacing. US Downstream channels are all 500kHz wide channels This definition is much greater than the European LoRa channel assignments which are typically 16 channels. This additional US channel availability over other regions has pros and cons where are the additional channel availability potentially reduces the chance of multiple motes operating on the same channel at the same and a potentially higher transmit level the capability requires the gateways to simultaneously receive on all the available channels all the time. This additional simultaneous receiver support can drive gateway costs up. Other unique requirements in the FCC US ISM FHSS definition is that any upstream transmission is limited to 400mS in length. With the spread spectrum devices hopping over 50 channels transmitting at a maximum of 30dBm.

Taking a look at the potential battery runtime under different LoRa transmitter conditions using the Semtech LoRa calculator results

Semtech the chip manufacture who makes the LoRa chips has a calculator that allows a user to set up a LoRa use scenario and review the potential outputs including estimated battery lifetime for the given scenario against the configuration of a target battery power source.

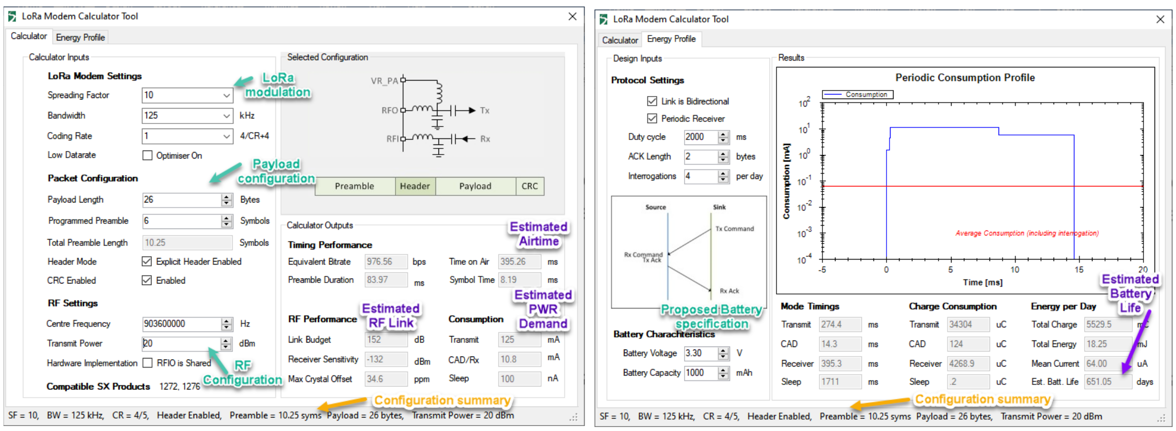


Figure 10 Semtech LoRa Calculator

The transmitter airtime and output consumption demand calculation of this tool closely followed the actual measured results. The battery lifetime results have yet to be proven and additional current demands from other mote sensors could impact the results, but the other calculations seem to be accurate so those should be accurate as well.

The first calculation is set up similarly to what most of the above captures used and is displayed below in the configuration summary:

SF = 10, BW = 125 kHz, CR = 4/5, Header Enabled, Preamble = 10.25 syms Payload = 26 bytes, Transmit Power = 20 dBm

The results are close to what was measured directly: Time on Air 395.26 ms

The transmitter power demands are similar to what was measured: Transmit 125 mA

The calculated battery life for a 1000mA 3VDC source an estimated 1 year 9 months Est. Batt. Life 651.05 days

The same configuration, only changing the DR to 0 with a SF of 8 and a 500kHz channel span:

SF = 8, BW = 500 kHz, CR = 4/5, Header Enabled, Preamble = 10.25 syms Payload = 26 bytes, Transmit Power = 20 dBm

Created a very similar TX airtime as measured under this modulation: Time on Air 27.26 ms

The transmitter output current is the same as above, and works out to what would be expected if the tested mote was run off 3VDC rather than 6VDC: Transmit 125 mA

The interesting part I found was in the battery lifetime estimation using the same battery as above under this modulation: Est. Batt. Life 4657.61 days the estimated battery lifetime with just the modulation change increased to almost 13 years proving the modulation is an important factor in maximizing battery lifetime in these IIoT mote devices.

The tool allows further investigation to other scenarios one of which would be the impact of reducing the output RF level. Dropping the level from 20dBm to 10dBm:

SF = 8, BW = 500 kHz, CR = 4/5, Header Enabled, Preamble = 10.25 syms Payload = 26 bytes, Transmit Power = 10 dBm

This change creates a large difference in the calculated current demand field: Transmit 31 mA

but does not seriously change the battery lifetime: Est. Batt. Life 4696.79 days or just a little over a month of predicted additional run time for this change which would likely cause the modulation to change negatively impacting the battery's runtime.

3. FCC Hybrid Mode

Even though the motes have to be capable of transmitting on all 72 US channels they can also be configured to operate in the FCCs "hybrid mode" definition, which dictates a lower total transmit power of 21 dBm and operation on a minimum of 4 channels with the same 400mS dwell time for each transmission. Most motes operating in the FCC's hybrid mode definition support 8 to 16 125kHz and 1 to 2 500kHz channels in the lower power level. Hybrid mode allows a much simpler gateway hardware design reducing costs for these hardware devices. If a mote device will be communicating to a gateway configured in in the FCCs hybrid mode it is best to configure the mote to work within the channel definitions the gateway is configured for; otherwise the mote will randomly transmit on channels not supported by the gateway and those messages would be lost and the mote would have to transmit a replacement message until the Gateway received it. There is a function in LoRaWAN called ChMaskCntl that defines the total amount of channels and group definitions of channels to be used in upstream communications.

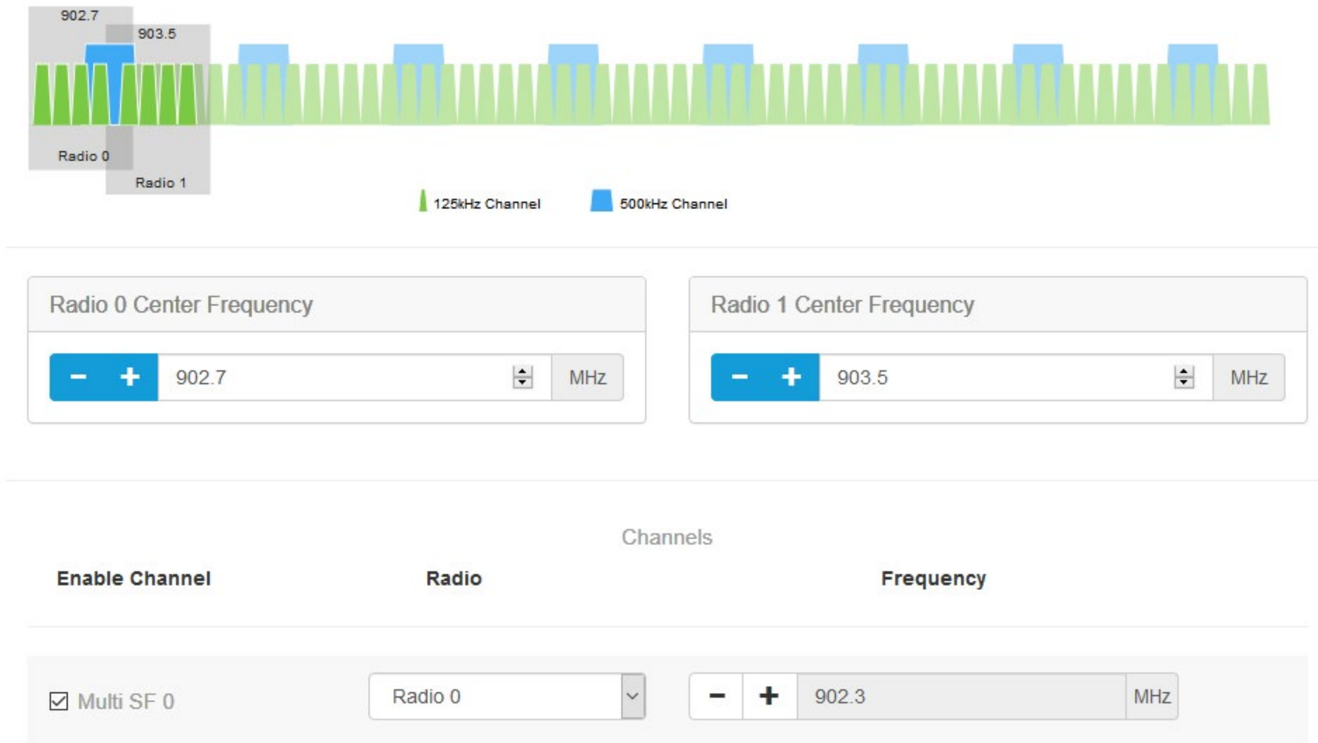


Figure 11 LoRa gateway RF Channel graphical representation showing 125kHz, 500kHz channels and selection of 1 hybrid group

Table 2 LoRa-LoRaWAN US FCC Channels divided up into Upstream Hybrid Channel Groups

LoRa - LoRaWAN defined upstream channels broken up into typical US FCC hybrid channel groups							
Channels 1-8	Channels 9-16	Channels 17-24	Channels 25-32	Channels 33-40	Channels 41-48	Channels 49-56	Channels 57-64
125kHz Channels	125kHz Channels	125kHz Channels	125kHz Channels	125kHz Channels	125kHz Channels	125kHz Channels	125kHz Channels
902.3	903.9	905.5	907.1	908.7	910.3	911.9	913.5
902.5	904.1	905.7	907.3	908.9	910.5	912.1	913.7
902.7	904.3	905.9	907.5	909.1	910.7	912.3	913.9
902.9	904.5	906.1	907.7	909.3	910.9	912.5	914.1
903.1	904.7	906.3	907.9	909.5	911.1	912.7	914.3
903.3	904.9	906.5	908.1	909.7	911.3	912.9	914.5
903.5	905.1	906.7	908.3	909.9	911.5	913.1	914.7
903.7	905.3	906.9	908.5	910.1	911.7	913.3	914.9
500kHz Channel	500kHz Channel	500kHz Channel	500kHz Channel	500kHz Channel	500kHz Channel	500kHz Channel	500kHz Channel
903	904.6	906.2	907.8	909.4	911	912.6	914.2

4. Improper Configuration Impacts on LoRaWAN US FCC Hybrid Modes in Motes and Gateways

If prices could be kept low, I would expect LoRaWAN mote and gateway configurations to always the entire US spectrum defined for FHSS; but due to increased costs of the gateway hardware necessary to support the entire spectrum a great deal of these devices are configured to operate in a US hybrid group. This hybrid configuration works sufficiently to support communications, but it does require all the devices operate in the same designated US FCC RF group of channels. The real driver is that the Gateway has to be configured in an equal or superset to the channels that the motes are configured in. There are 2 common mistakes that can lead to improper configuration and issues with communications:

- Motes that are configured to operate in the entire band, while the Gateway is operating in a single or multiple hybrid group(s)
- Motes that are configured to operate in a different hybrid group than the gateway.

Below is the configuration information from a LoRaWAN mote configured for operation in what the manufacture defined as "Channel Operating Group of Eight (CHE)" set to group 2 (which is shown above in Table 1 as channels 9-16).

AT+CHE=2

903.9 904.1 904.3 904.5 904.7 904.9 905.1 905.3

Note: AT commands for serial communications are used widely in mote configuration.

If the host gateway is defined to operate in a hybrid mode using Channels 1 to 8 in group 1 then using this combination of configurations would result in the mote and gateway never communicating.

The mote would continue to try to communicate unsuccessfully until the communication configuration was corrected or the batteries were exhausted. The example of a serial output from the mote during a failed communication attempt is shown below – not the repeated ****** UpLinkCounter= 4 ****** showing the same message is being re-sent as the mote hops from frequency to frequency and the failure to receive the required gateway response as *rxTimeOut*.

****** UpLinkCounter= 4 ******

TX on freq 904100000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 904500000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 905300000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 904900000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 904500000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 904300000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 905300000 Hz at DR 0

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 4 ******

TX on freq 904700000 Hz at DR 0

txDone

rxTimeOut
rxTimeOut

Another example of miss-configuration is shown below where the mote was configured to use all the US FCC channels (not hybrid mode) and the gateway was set to use Hybrid mode Channel group 2. The serial output of the operation showed below is an example of a LoRaWAN Over The Air Activation OTAA where the mote sends out a request with its Device ID and if the mote has been configured to work in the Gateways network it will come online. The OTAA process is interactive, where the mote sends the request, the gateway forwards the information to the network servers and the response from the servers is sent back through the gateway to the mote confirming activation. Because this is a more involved negotiation than a typical message the receive windows for the mote increase from 1 and 2 seconds after the transmit message to 5 and 6 seconds.

****** UpLinkCounter= 0 ******

TX on freq 907800000 Hz at DR 4

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 0 ******

TX on freq 912600000 Hz at DR 4

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 0 ******

TX on freq 909400000 Hz at DR 4

… (I am inserting a … to cover the data removed for simplicity)

TX on freq 903000000 Hz at DR 4

…

TX on freq 914200000 Hz at DR 4

…

****** UpLinkCounter= 0 ******

TX on freq 911000000 Hz at DR 4

txDone

rxTimeOut

rxTimeOut

****** UpLinkCounter= 0 ******

TX on freq 904900000 Hz at DR 0

txDone

rxDone

JOINED

Eventually the mote requested connection on a channel that was supported by the gateway, but there were a lot of wasted communications steps between. Figures 12 A, B and C show the timing of the transmitted message and the opening of the 2 receiver windows to attempt to obtain an answer from the gateway. The previous message is also visible, the timing between subsequent attempts is seven seconds. The receive window timing is defined in the LoRaWAN standard, but the subsequent message timing is a function of the mote firmware.

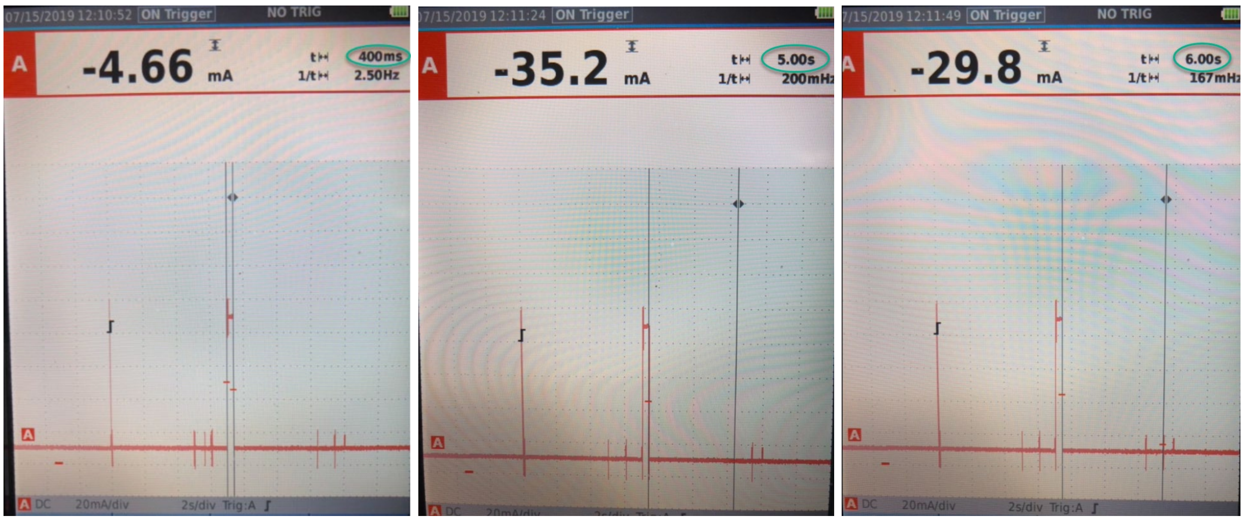


Figure 12 A, B, C Power timing OTAA multiple negotiations showing TX timing, RX window 1 and 2

5. Confirmation Message

Motes send messages on a routine basis, that is their purpose. The verification of reception of the message is configurable on whether the mote will receive and ACK or confirmation that the message was received. The confirmation of a message can be considered important as information would be lost if the message was simply sent and the mote assumed it was received. The routine message confirmation mode is generally a global setting for a mote where all application messages are expected to be confirmed or none are. The power impacts of using the confirmation message vary based on connection, where if you have the confirmation turned on, and you have reliable communication; the mote will generally only use the first receive window. In the mote I show below if the confirmation message is not turned on the mote will always use both receive windows (unless another unrelated message is sent from the gateway); which makes sense as the gateway would not send a confirmation message in either window. But because the mote is not expecting a confirmation message it returns to normal operation waiting for the next event. The issue you can run into using confirmation mode is if your communications is not reliable. The mote will not receive a confirmation message in either window and will retry the same message. This retry function varies by mote, I have motes that run from one retry to 7 retries. Each retry will use a different frequency hop until the retry is successful or the retry count has been specified. If you are investigating retries it is fairly easy to identify as the same message count number is repeatedly sent. The message count number can be seen through CLI on the mote or within the gateway communication diagnostic windows.

***** *UpLinkCounter= 12* *****

TX on freq 904100000 Hz at DR 0

txDone

rxDone

Previous message #12

***** UpLinkCounter= 13 *****
TX on freq 905100000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 904300000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 903900000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 904500000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 904700000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 905100000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 904900000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 13 *****
TX on freq 904100000 Hz at DR 0
txDone
rxTimeOut
rxTimeOut
***** UpLinkCounter= 14 *****
TX on freq 905300000 Hz at DR 0

Message # 13 is not confirmed and the mote will retry this message until it has satisfied its retry buffer. In this mote the retry buffer is set to 7; some motes as few as 1 retry.

Message #13 retries exhausted

Next Message #14

The confirmation message retry process does affect the motes battery life. If you have good communications and the confirmation messages are turned the messages are generally confirmed in the first receive window, which reduces the battery drain as well as increases the chances that all data will be received from the mote (Figure 13 A). if the communications are not reliable it can greatly increase the amount of communications-based power used as the transmitter and receiver will cycle additionally for each retry of a message (Figure 13 B). With the confirmation message turned off the mote may utilize the 2nd receive window as no message would satisfy the first receive window (Figure 13C).

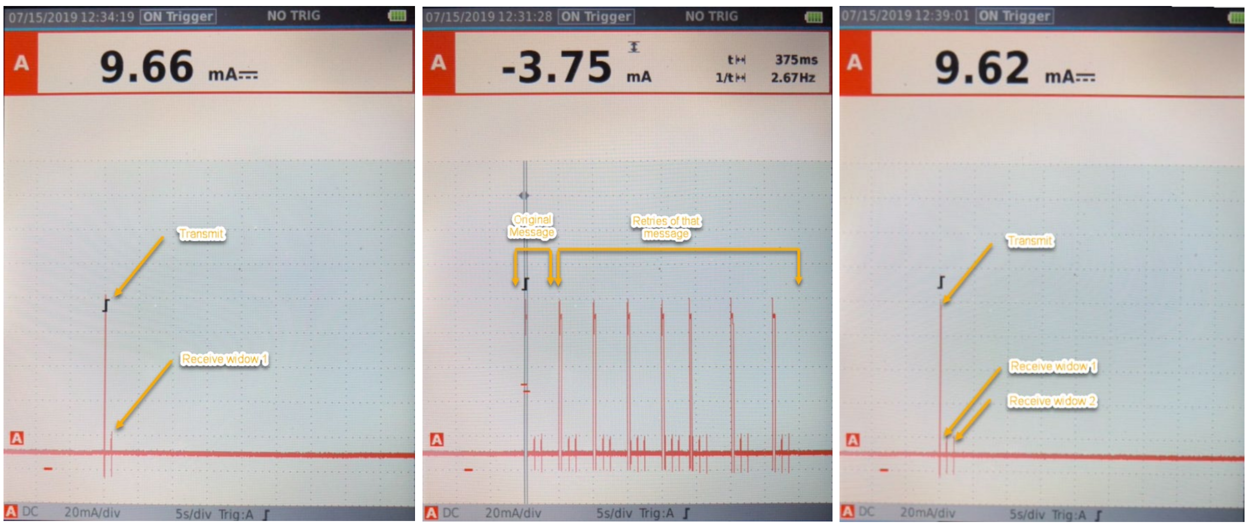


Figure 13 A, B, C Relative power draw on the mote battery based on different confirmation message situations.

The best approach is to leverage the confirmation message to assure data is delivered and assure there is reliable communications between the motes and the gateways to minimize any impacts of the message retries.

Motes do have an adjustable RF upstream power output feature, which can be set during configuration or dynamically during operation and helps optimize link budgets, power demands and attached antenna gains the output power must be configured not exceed the FCC power limitations for EIRP as defined by the FCC for a FHSS digital transmission definition.

Antenna gain can also affect transmit power levels, but the FCC's upstream EIRP power restrictions must be factored into any additional antenna gain deployment. There is a trade off in antenna gain as energy is not created in the antenna, the gain is derived from the focusing of the emissions into a pattern increasing antenna gain works both for receive as well as transmit, but the real gains are in the receiver improvements as the transmitter must be adjusted to limit the output power of the antenna.

Automatic Data Rate (ADR) as commented earlier will optimize mote communications power utilization through two methods as it will dynamically set the spreading factor which will change the time the transmitter is on the 2nd lesser impact is in changing the transmit level. The longer the spreading factor the more the increase the length of time the transmitter is on as well as the length of time the processor will be on to serialize the dispatch the data.

6. Conserve mote battery power by setting the desired LoRaWAN Class correctly:

A: ALOHA is the normal operating mode for most LoRaWAN IIoT motes, where the mote will transmit only when required by situation or by routine health notifications. Motes operating in the A LoRaWAN class will only turn on their receivers for a short burst window after a transmission. The A class has the best mote battery utilization of any LoRaWAN class.

B: Beacon is a mode where the motes will still operate in the A mode when required but will routinely turn on their receivers at specified intervals to listen for downstream commands. Class B mode uses substantially more battery power than the A class of operation.

C: Continuous, in continuous mode the mote's receivers will always be on listening for downstream commands. This LoRaWAN class definition has the highest battery utilization.

For optimal battery lifetime a mote should operate in the Mode A – ALOHA based communications mode, this is the default mode for most LoRaWAN mote devices.

Now that there is an understanding of the modulation impacts of various DR and SF factors on battery life let's look at how we can improve the signal path between these devices to optimize the signal strength and allow the motes to use the most efficient connection.

The signal path is the physical connection between the transmitter and the receiver – the physical path is both directly connected hardware as well as the wireless RF components of the path.

The simplest direct signal path is composed of the following elements:

- Transmitter (output power)
- Electrical connection between the transmitter and the antenna. (loss)
- Transmitting Antenna (gain or loss)
- Media loss components in the RF path (loss)
  - Free air attenuation
  - Media attenuation
    - Walls
    - Floors
    - Trees
    - People
    - Etc.
- Receiving antenna (gain or loss)
- Electrical connection between the antenna and the receiver. (loss)
- Receiver (received level)

Antennas – the only part of the passive signal path that can improve the link. Antenna design is an art as much as a science. The science part has to do with impedance, center frequency, frequency range, radiation pattern and polarization. The art part is getting the antenna to be small and cost effective with all the science remaining intact. Antennas for the US LoRaWAN coverage vary widely, but most are designed to operate:

- Creating a 50Ω impedance for the drive circuit.
- To provide the most gain in the 900 MHz range (900-930MHz)

- Most are connectorized with SMA, RPSMA, N or micro connectors.
- Some are designed to be extensions of the circuit board to reduce costs.
- Most are omni-directional
- Gains are often in the +0 to +8dB range.
- Most are designed to be vertically polarized.

Esthetically the Antennas are mostly the “Rubber Ducky” dipole format for indoor deployments and the fiberglass or PVC stick format in the outdoor environment. 900MHz has a 33.3cm wavelength and an 8.33cm ¼ wavelength. Most indoor antennas leverage the ¼ wave ½ wave or 5/8 wave whip design. Many outdoor antennas are cut leveraging the 5/8 wave, full wave or co-linear antenna segments. The size of the outdoor stick antennas ranges from a 3dBi gain loaded 5/8 wave antenna that is about 1 foot long to some that are 8 to 12 dB using co-linear antenna arrangements that are 5 to 8 feet long. Though antennas can create “Gain” by focusing their energy the result is a reduced coverage pattern, increased complexity and cost. When transmitting the mote or gateway must be configured to assure this gain does not exceed the FCC specification. So ultimately the antenna gains are really about improving the receiving signal gain. Polarization is another big impact in antenna design and from my experience LoRaWAN deployments are done using a single vertical polarization configuration. It may be difficult for all motes to support a vertical polarization in their design as they may have to have the antennas mounted above an expected media attenuation material and they have to fit within the confines of the mote space. Any installation should take into account the antenna specifics of the mote and they should be mounted so that the antennas are vertically polarized, with the least amount of media attenuation and external antennas should be used to improve communications if possible. HFC deployed antennas are routinely limited to 1 foot as the NESC clearance rules state that vertical displacement in the communications space is limited to 1 foot.

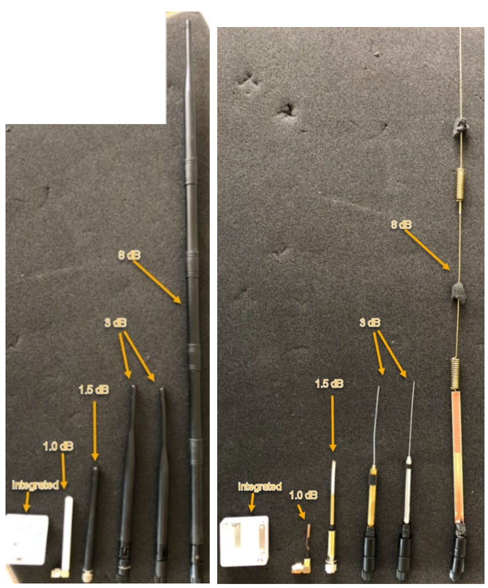


Figure 14 LoRa omni-directional antenna examples ranging from internal integrated low gain to 8dBi gain, the longest antenna, he 8dBi is about 2 feet in length.

7. Antenna Radiation Patterns

There are many antenna types, and each has a name, orientation, and radiation pattern or how it is going to apply its energy to the universe. The basis for all antenna comparisons is the isotropic radiator. This is an imaginary antenna that if it could exist would emit its energy in all directions equally. Since this design is really not practical as the energy heading into the earth would not be very usable most designs are either designated as omni-directional, bi-directional or uni-directional. The Dipole antenna referred to above is considered an omni-directional antenna, providing some gain but emitting a kind of donut pattern from the center of the radiating element. As the dipole is further engineered to provide RF gain increases the donut pattern of emissions is flattened to emit further out in all directions horizontally, but not so much in the vertical directions. Figure A, B and C illustrate different radiation patterns for the Isotropic, low gain dipole and high gain dipole.

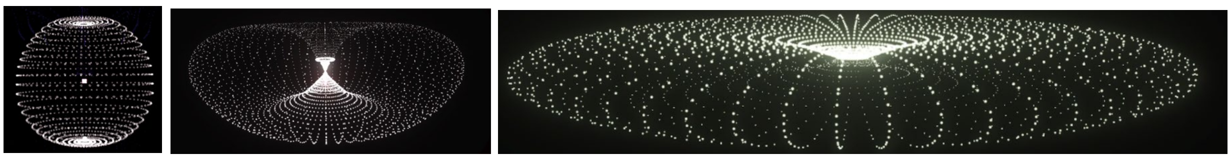


Figure 15 A, B, C RF radiation patterns for Isotropic radiator, low gain dipole and high gain dipole

One of the most important items to remember is that the orientation of the antenna can impact its polarization and if the polarizations of the individual antennas are out of phase the RF energy will not be conveyed efficiently affecting the signal strength.

The components that make up the signal path for the most part create loss to the signal, the antennas are the only component that can really add apparent gain through focusing of the energy, short of an additive RF reflection from the field. Figure 16 displays a visual representation of the path loss concept with demarcation in the dashed vertical lines and with the red undulating line at the bottom representing the signal level through the path.

8. Path Loss and the Contributors

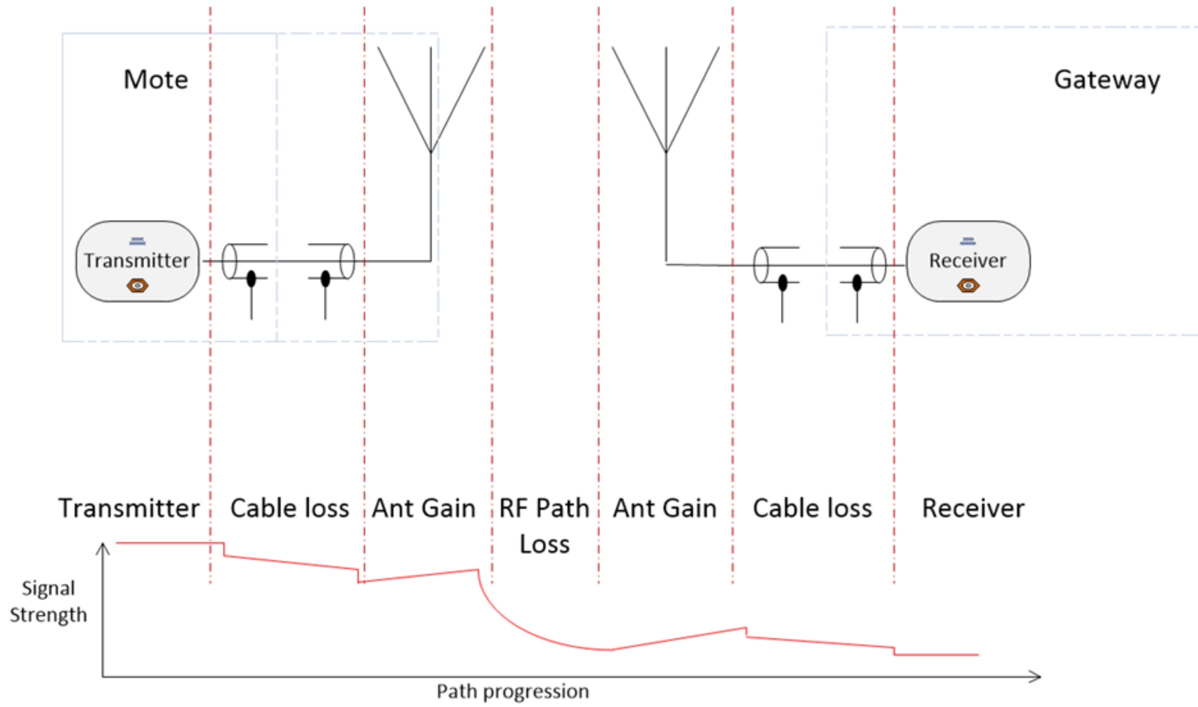


Figure 16 Path loss concept

One of the items to note is that we who work in coaxial plant have always understood the variable loss of cable across frequency and linear loss due to length, LoRa frequencies are very close together spectrally so what we see is more of is only the linear loss through coax length. Also note each attachment point or connector in the representation has an RF impact reflected in the signal strength response. The real loss component both in this drawing and in practice is the RF path loss between the antennas, what is shown is the logarithmic loss caused in free air which is logarithmic based on the distance between the antennas.

There are many expressions to cover free air attenuation – depending on the units used and the results desired. One such formula for Free Space Path Loss (FSPL) that would be expressed in dB of path loss based on frequency and distance is

$$FSPL(dB) = 20Log_{10}\left(\frac{4\pi df}{c}\right)$$

Where d is the distance in meters, f is the frequency is Hertz, c is the speed of light

There are a few formula reductions that leverage that pi and the speed of light are constant (quickly accessible in Wikipedia) that address ranges of frequencies vs ranges of distance.

For frequencies in MHz and Distance in Meters

$$FSPL(dB) = 20Log_{10}(d) + 20Log_{10}(f) - 27.55$$

any non-free air attenuation caused by another media, like wood, concrete or people would have more of a vertical loss impact caused by the media's RF attenuation and reflectance.

9. Examples of Media Attenuation Impacts

The logarithmic impact of free air attenuation has a lesser impact on the LoRa communications than it would a higher frequency or faster data rate required by other communication solutions resulting in its very long-range capabilities. Media based attenuation has a more similar impact especially when you are considering long range communications in denser environments. Most of the articles that represent distance information on LoRa coverage examine open environments without obstruction when discussing LoRa's range. A good case in point is the "LoRaWAN packet received at 702 km (436 miles) distance," where the mote was broadcasting from a balloon mounted radiosonde at very high altitude. It is easy to overcome free air attenuation with a large dynamic range budget where the losses have logarithmically less impact as the distance increases. Where the issues come in is when along with the free air attenuation you have media attenuation in the RF path. Media attenuation is considered as a function of the media's direct attenuation of the RF signal and reflectance of said signal. Reflectance can be a good thing in systems designed to leverage it, like 802.11ac where MIMO and antenna arrays can effectively recover energy from these reflections. LoRaWAN, though it can receive a reflected signal is not natively designed to leverage that and the direct energy into a better signal; you just end up with multipath. Free air attenuation is affected by frequency, there is a direct relationship, but many compounds that create media attenuation may not have a direct frequency / loss relationship. A great many studies by NIST and other entities have looked into media attenuation, many researching different construction materials. The results vary widely between materials and their component makeups and there is really not a single rule of thumb for a generic media attenuation contribution of loss. Also as stated earlier; even something as simple as the attenuation of a concrete wall varies widely based in frequency of the RF, composition of the concrete, thickness and reinforcing materials. In a 200-page document put out by the NIST they tested the RF transmission and absorption of various building materials; it is interesting that their testing also included information on both wet and dry materials as the propagation is even impacted by that influence.

Below is a list of a few of the attenuation impacts of various construction compounds around the 900MHz LoRa frequency range as noted in the NIST document:

Masonry Block wall 1 course thick 203mm = -11dB, 2 course 406mm -17dB, 3 course610mm – 28dB

Brick faced block wall: -10.75dB

Concrete wall 22% cement with a thickness of 102mm: -12dB, 203mm: -23dB, 305mm: -35dB

Concrete wall 25% cement with a thickness 0f 102mm: -13dB, 203mm: -28dB, 305mm: -45dB

Reinforced Concrete with rebar 203mm thick; unreinforced reference: -26.5dB, reinforced 1% steel: -27dB, 2% Steel: -29dB

Drywall, various thickness < ½ to 1 db.

Glass 6mm: -0.75dB, 13mm -2dB, 19mm: -3dB

Lumber, Spruce Pine, Dry 38mm: -2.8dB, 76mm: -2.9dB, 114mm: -3.6dB, 152mm: -5.8dB

Lumber, Spruce Pine, Wet 38mm: -1.8dB, 76mm: -2.9dB, 114mm: -4.5dB, 152mm: -7.5dB

Plywood, Dry Panels 6mm: -0.4dB ,13mm: -0.45dB, 19mm: -0.7dB, 32mm: -1.3dB

Plywood, Wet Panels 6mm: -1.6dB ,13mm: -1.8dB, 19mm: -1.9dB, 32mm: -2. dB

The above measurements don't even take into account major reflective surfaces like metal and even window tint.

Media attenuation is probably the biggest range limiting factor in most dense LoRaWAN deployments in urban and suburban areas. In the same breath if a city or municipality wants to maximize battery life, this range limiting factor is going to drive the motes to a higher spreading factor increasing transmission time, reduced reliability as moving media attenuators like trucks interfere with signal path creating message retries and physical mounting to media attenuation materials creates directionality. It is easy to see that the motes could operate using Data Rate DR 4 mostly, but only going as low as DR 2

In the area below a gateway is placed on the left side to cover the entire area.

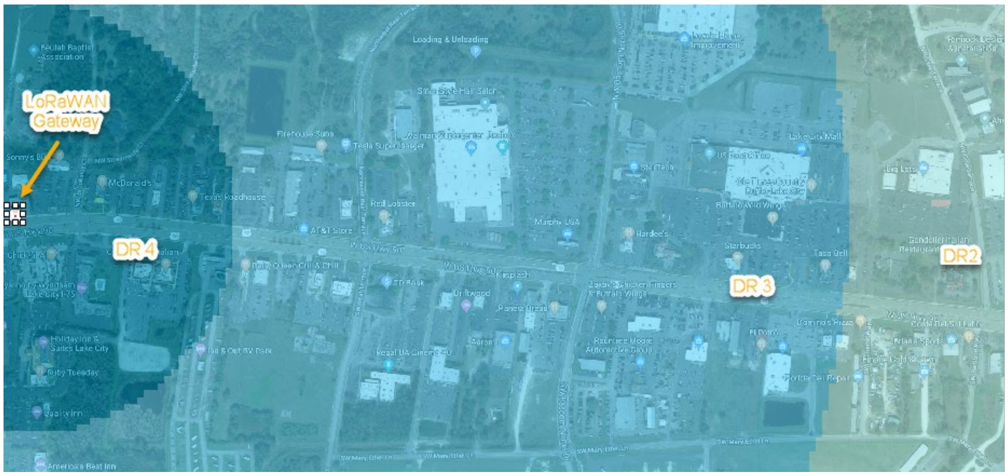


Figure 17 LoRa Coverage without considering media attenuation

Figure 16 displays the coverage when large media attenuation objects are taken into account. The effect of the RF shadowing would be dependent on the LoRa gateway and mote antenna height, but a worse case of a device at low elevation was used to show the effect of a gateway low on the horizon. Impacts here show possible DR 1 operation of the motes and likely dropping to DR 0 at severely shadowed areas.

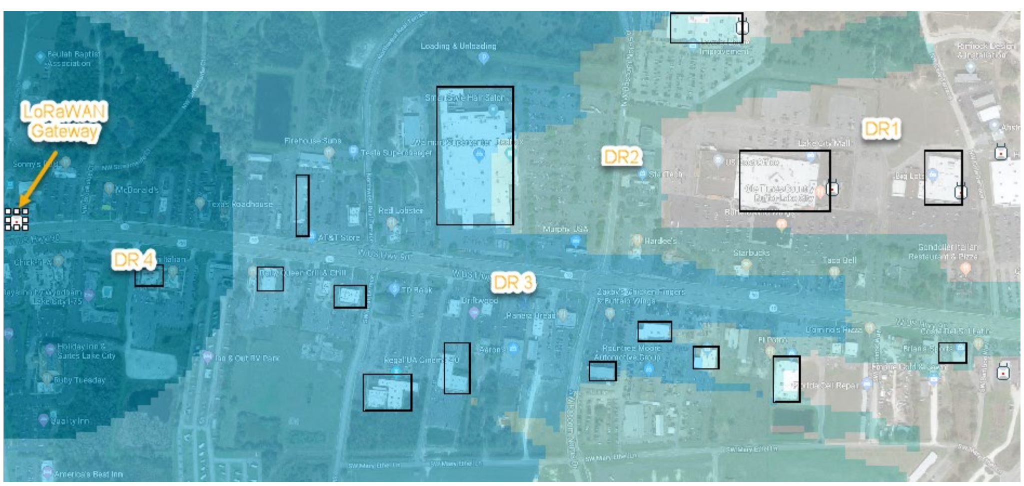


Figure 18 LoRaWAN expected data rates based on media attenuation impacts

Adding a 2nd LoRaWAN gateway on the far side of the same field of view has a significant impact on the RF shadowing of the objects creating media attenuation. This result is shown in Figure 17 and the expected data rate throughout would be DR 4 and DR3, though reality states there might be some shadowing below those rates the coverage is good to all sides of the buildings where industrial IIoT motes would be mounted.

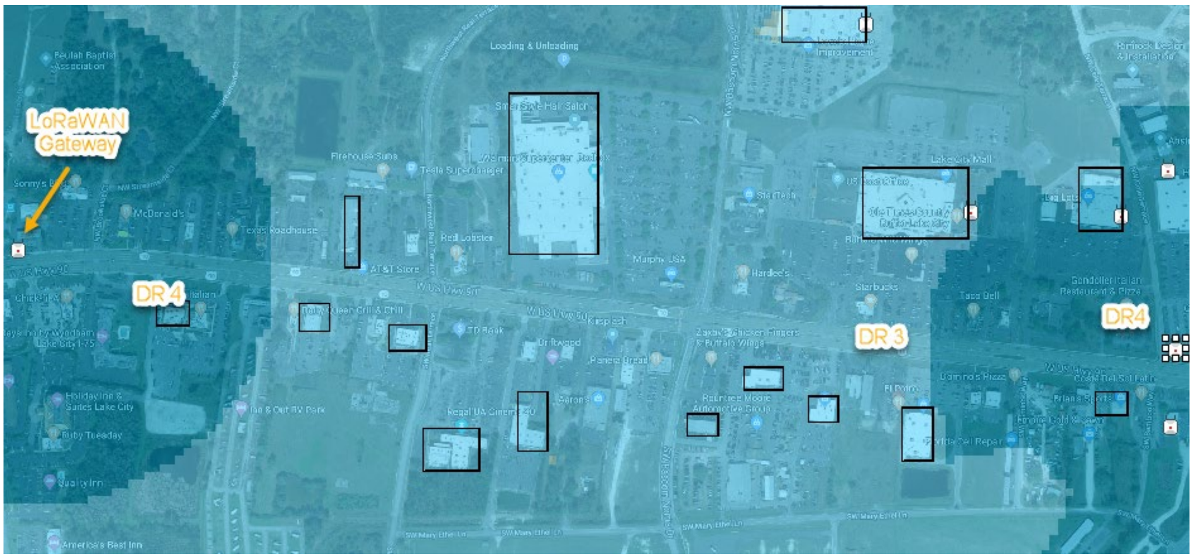


Figure 19 Media attenuation results after adding a 2nd LoRaWAN gateway on the far side of the visible area.

This is the power of an HFC based deployment, the gateway could easily be added to the strand at any point that has sufficient power. These gateway devices including the modems pull less than 50W typically as they only transmit around 100mW.

Gateways -Providing connection to the LoRaWAN motes

For an IIoT Mote to be an IoT it must have a connection to a network of server. This connection is provided by a LoRaWAN Gateway or forwarder.

There are a lot of different LoRaWAN Gateways that are designed to be installed in various locations based on their environmental handling, packaging, connection options and mounting options. A portion of these are designed to be mounted outdoors and can be mounted almost anywhere. There are various backhaul arrangements for these gateways including Ethernet, PoE, Cellular and Wi-Fi. The data handling for the motes is actually pretty light, even in a heavy deployment, so throughput is rarely an issue. The main considerations for a gateway are mounting location, powering and some form of connectivity.

10. Location, location, location…

Just like small cells provide connection to phones, IIoT gateways provide connection to motes. And one of the big issues is that both these new verticals have to have hardware installed, generally outside, to provide the backhaul locations. Below are just a few of the current deployment models:

- Gateways mounted to buildings.
- Gateways mounted on towers.
- Gateways installed in homes and businesses.

- Gateways mounted to HFC.

Tower mounting of a LoRaWAN gateway can be difficult as the operator would have to negotiate with the tower owner or worse yet have to go through the process of getting a new tower location approved by the municipality, permitted and erected. In building and on building deployments vary widely in their complexity as the operator has to understand who owns the building and who is interested in placing the gateway. Recurring costs and maintenance can be an issue in these deployments. Initially if the building tenant or owner is interested in IIoT for their own purposes deploying a gateway on the building is fairly easy as they will allow the mounting location and assist with power and communications connections. The problem can be seen later if the building tenant moves out, the building changes ownership or the owner is no longer interested in the IIoT driver that allowed the gateway. If these changes occur, they may want the gateway removed or will no longer provide access, power or communications connection. The removal of the gateway can affect other IIoT users in close proximity to this gateway as they would no longer be able to connect to it.

The HFC mounted LoRaWAN strand mounted Gateway.

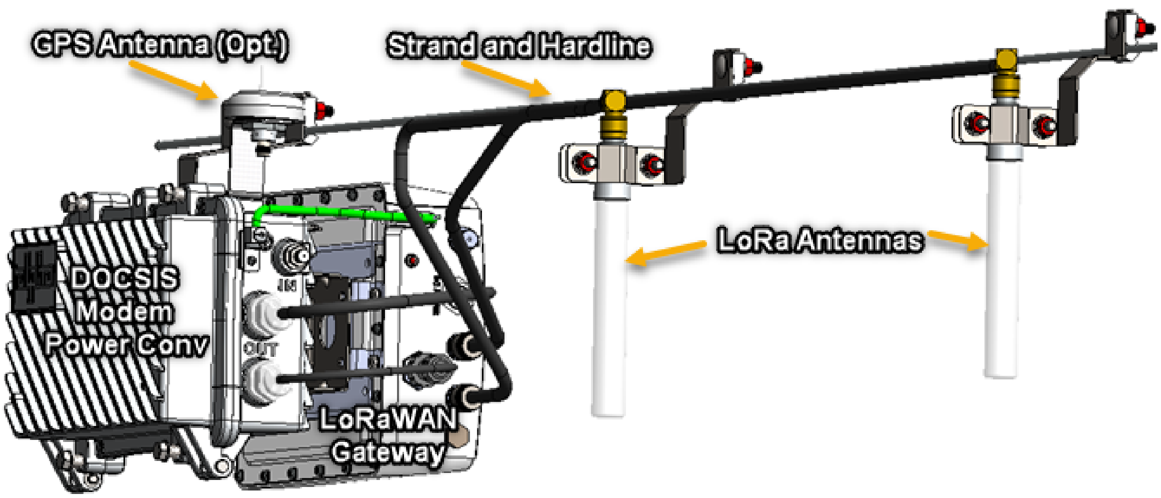


Figure 20 LoRaWAN HFC strand mounted gateway.

For MSOs who want to operate as LoRaWAN IIoT providers, their own HFC provides the 4 required support components for LoRaWAN gateway deployments: power, backhaul, real estate and ownership. This value statement also applies to small cells and other new service offerings. HFC provides these solutions from a single wire making it a preferable solution over other deployment locations. One of the important items I have chosen to note is that the MSO's have ownership control of this environment. They provide reliable backup power and reliable communications infrastructure as well as monitor and react quickly to issues or changes. One final reason is that there is little chance in a change of ownership affecting a deployed system.

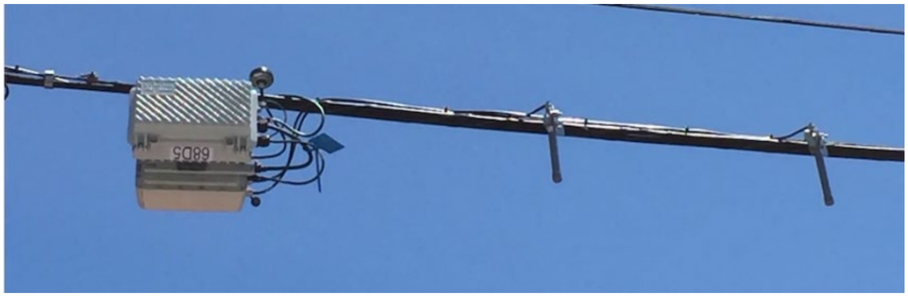
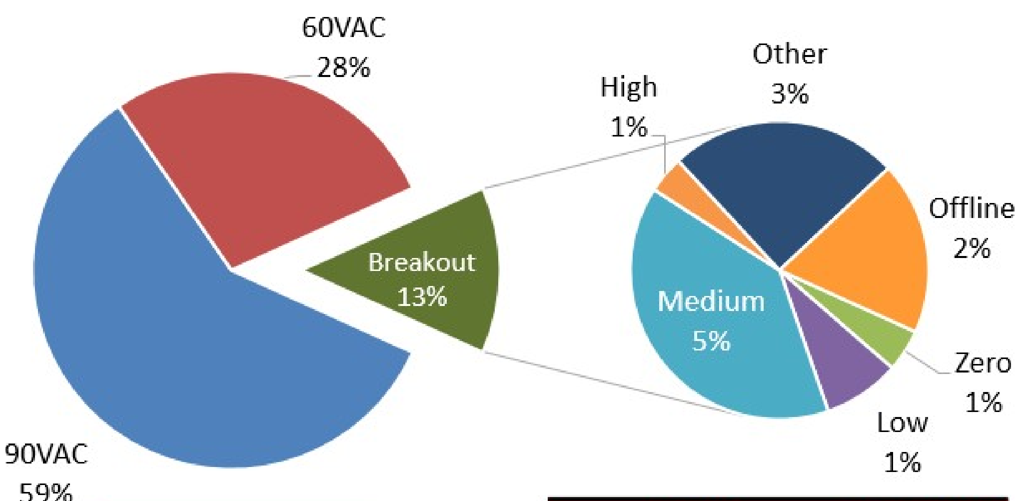


Figure 21 HFC deployed LoRaWAN Gateway and Antennas

From a power perspective most HFC systems in the North America have some real power advantages:

A document Alpha put together in 2018 correlated research on North American HFC powering and showed that HFC power is delivered using low voltage AC over the same hardline coax as the MSOs HFC communications services. The results show ~90% reported standard HFC power supply voltages of 63, 72 and 90VAC with about 60% of power supplies operating on 90VAC, the most capable standard today.



Output	Percentage
60VAC	28%
90VAC	59%
Other	13%

Output	Percentage
ZERO	0.6%
LOW (1V – 60V)	1.1%
MEDIUM (65V – 88V)	5.3%
HIGH (>90V)	0.5%
OTHER	3.4%
OFFLINE	2.5%

Figure 22 North American HFC power results in 2018.

Another item to note is that a majority of these HFC power supplies are a standby powering variety and have batteries to back up the plant if mains AC is lost. From a LoRaWAN perspective this makes for a more reliable connection minimizing impacts to connectivity during AC failure events and if message confirmation operation is in use the required retries during the AC outage event.

Below is an example of a coverage map of an HFC deployment of LoRaWAN gateways in an area. The red circles indicate expected coverage figuring a 2.5-kilometer coverage area for each device. If the operator was attempting to maximize battery lifetimes, depending on the target terrain and construction the expected coverage indicators may cover a smaller area to assure the best DR and spreading factor are realized.

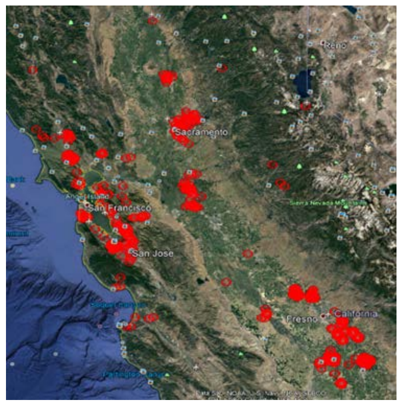


Figure 23 LoRaWAN coverage map on HFC with gateways and antennas mounted ~21 feet high

11. Additional thoughts on HFC mounted Gateways.

HFC Strand deployments must follow the NESC, Utility or Municipality mandates for inter utility and overhead clearance. The most limiting factor in the installation of LoRaWAN gateways is this environment has been limiting antenna gain by reducing antenna length. Most of these installation use onmi-directional dipole antenna's that are directly mounted to the strand to allow the maximum gain within the 12" inter utility clearance. Some externally mounted power supply mounted LoRaWAN gateways have been able to use longer antenna lengths but can be impacted if the power supply cabinet creates an RF shadow over a portion of the coverage area. Pedestal mounting of LoRaWAN gateways has been prototyped in composite enclosures, with most antenna mounting interior to the enclosure.

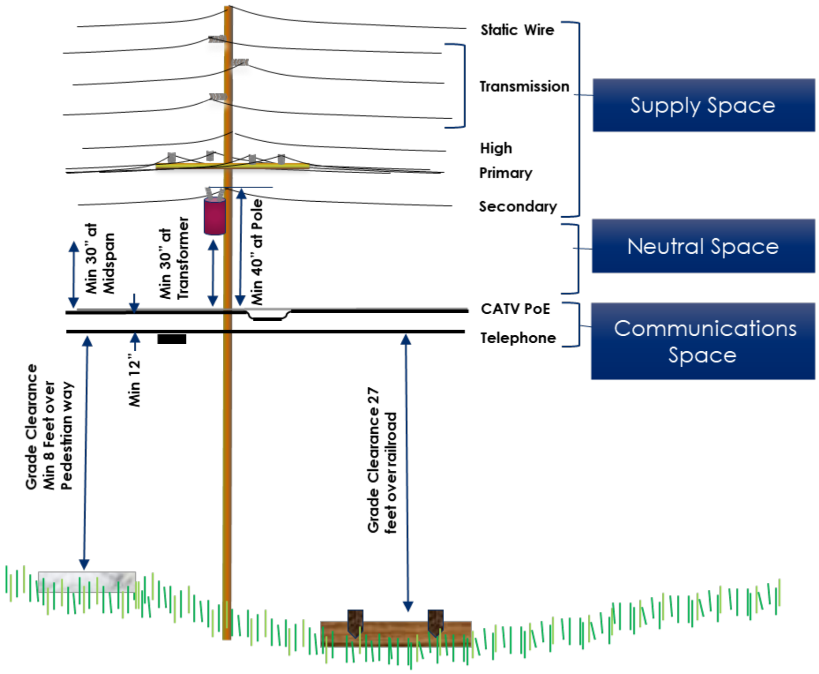


Figure 24 NESC, utility clearance illustration

HFC Gateway and antenna deployments should take into account terrain and building obstructions:

Figure 25 HFC Based questionable deployment RF blocked by terrain and structure.

Even though a location may look to be the best from a planning tool, reality will win out. In this deployment the Gateway was moved to another location after they found the coverage was affected by the media attenuation of the house and the terrain on the other side.

12. TDoA, Time Delay of Arrival

TDoA is an interesting add on feature to LoRaWAN gateways that allow a stratum 1 clock from a GPS receiver to create a precision time source across multiple gateways. This precise timing allows the arrival time of a mote message to be accurately timestamped; and worked backwards to determine the mote transmission point of origin through identifying the delay associated with each gateways time delay created by the transmission speed (speed of light in air mostly). In other words, to leverage the Time Delay of Arrival of the message to identify the location. Semtech and the LoRa Alliance have produced works around this, but the summary information is what is important:

- LoRaWAN TDOA geolocation is able to provide positioning accuracies of 20m to 200m.
- Benefits of LoRaWAN geolocation are achievable with long-lived, battery-powered Class A end-devices at zero additional BOM cost.
- Mitigation of multipath errors and sound gateway-placement geometry will provide accuracies approaching 20m.

The accuracy of the TDoA has a great deal to do with the bandwidth of the RF signal and bandpass; many online papers minimize the value of LoRa TDoA because the transmissions use such a low bandwidth communications channel (125kHz vs 30MHz) which decreases the accuracy of the determined value. This being said, a dense deployment of HFC based LoRaWAN gateways will enable the higher bandwidth DR to be used (500kHz) which should provide some accuracy improvement due to the increased bandwidth. Additionally, the "Mitigation of multipath errors" comment in the LoRa Alliance summary information highlights another value in a dense HFC deployment as it is applied to TDoA. For TDoA to work, there has to be at least 4 gateways that can receive the motes transmission. Most TDoA systems have the ability to discard some Gateway TDoA data if it does not correlate to the majority of the Gateways TDoA information. Most of these discrepancies are related to multipath reception of the Motes RF transmissions. The more gateways you have above 4 the more chance you have to have to receive credible timing information, and the more values you can afford to discard because of multipath impacts to those motes to gateway RF paths.

Summary Conclusions:

- The LoRaWAN CSS FHSS PHY, Transmit Time, Retries, Attenuation Ultimately impact battery life.
- Motes are disparately located, remotely deployed to cover specific targets.
- Some have batteries, some use energy harvesting.
- Motes can be difficult to access, ultimately making battery replacement difficult and expensive.
- Motes use more power if the signal is weak (low SNR) as they change RF PHY to compensate.
- Mote to Gateway distance can be long – but only in open environments
- Media attenuation affects this range.
- Deploying more Gateways can address range issue and clear RF shadowing of obstructions.
- HFC based IIoT Gateway deployments are fast, easy, reliable and secure in open space.
- Deployment prediction models are great – but sometimes need to be verified.

HFC IIoT Gateways are a great way to improve battery life

.

Abbreviations and Definitions

IIoT	Industrial Internet of Things
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
Mote	Remote sensing system including sensor and communications module.
RF	Radio Frequency
FHSS	Frequency Hopping Spread Spectrum
CSS	Chirp Spread Spectrum
Chirp	The reference to a single element of content in CSS based on the frequency change over time.
SF	Spreading Factor: The duration of a chirp; The defined rate of change in frequency vs time
DR	Data Rate – not so much as bps or Mbps, but as a defined arrangement of SF and BW
ISM	Industrial, Scientific and Medical
US	Upstream RF communications, also United States
US915	The LoRaWAN regional definition following the US FCC rules
DS	Downstream
FCC	Federal Communications Commission
OTAA	Over The Air Activation – as opposed to ABP – Activation By Personalization
Github	repository hosting service for collaborating software projects
HFC	Hybrid Fiber Coax
MSO	Multi System Operator
Symbol	The RF known signature of a single element of content based on its amplitude, phase and frequency component defined within the form of modulation used.
ISBE	International Society of Broadband Experts
SCTE	Society of Cable Telecommunications Engineers

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