The Pivotal Role of Cable Gateways in the Internet of Things

A Technical Paper prepared for SCTE•ISBE by

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Introduction

The term the Internet of Things, IoT, was coined in 1999, the same year IEEE 802.11 b standard was released, and the beginning of the age of the internet. At the time the IoT was strictly conceptual, but as the connected home continues to explode through improvements in cellular, Wi-Fi, cable standards, IoT continues to become more relevant. Despite the growing interest in IoT, the lack of conformity throughout the industry is resulting in a kludgy user experience, in most cases, requiring each device to be connected to individual hubs, which are subsequently connected to the home gateway. Previously IoT implementations created awkward user experiences discouraging the average consumer from fully immersing themselves in the technology, and restricted the customer base to technology-savvy individuals. Driving conformity in IoT by consolidating the hubs into the gateway, gives the end user to the ability to easily commission and control their video, Wi-Fi, and IoT devices through one interface. More importantly, the gateway provides insight into the entire connected home ecosystem through a constant flow of data provided by connected clients, allowing different subsystems in the home to coexist, and improve performance. In summary, consolidating IoT infrastructure and services into the gateway can signifcatly improve customer experience by driving coexistence performance between individual subsystems through the gateway.

Overview of Cable Gateway

To increase performance, and improve user experience the cable gateway continues to add functionality. A typical gateway, consists of Wi-Fi for high throughput wireless applications such as streaming video, Docsis serves as the data pipeline in and out of the home, and IoT provides home automation and home security capabilities. Despite having different functions, all of these different standards and protocols together create a whole home experience, providing the end user with an entire ecosystem that cannot be replicated with individual sub systems. The key differentiation from an individual subsystem implemention is the coextistence benefits, particularly for the the wireless systems. The most common IoT protocols share the same ISM band as Wi-Fi creating many challenges for IoT devices the can result in truck rolls for services providers.

1. IEEE 802.11

Wi-Fi is the primary protocol utilizing the IEEE 802.11 standard in gateways. The IEEE 802.11 standard has had multiple iterations supporting a large range of data rates from 1 Mpbs to 1201 Mbps, as well as DSSS, OFDM, and OFDMA modulations techniques. Each iteration in the standard has provided additional techniques to improve throughput, and optimize channel utilization through different modulation, coding schemes, and bandwidths. The current standard supports 2.4 GHz and 5 GHz, with additional frequency bands in the horizon. The end goal is to maximize data rates, and is ideal for streaming services, and high throughput applications. Operating channels occupy either 20 MHz, 40 MHz, 80 MHz, or 160 MHz bandwidth in the 5 GHz frequency band and 20 MHz or 40 MHz in the 2.4 GHz frequency band. The typical operating channels in the 2.4 GHz frequency band are illustrated in Figure 1

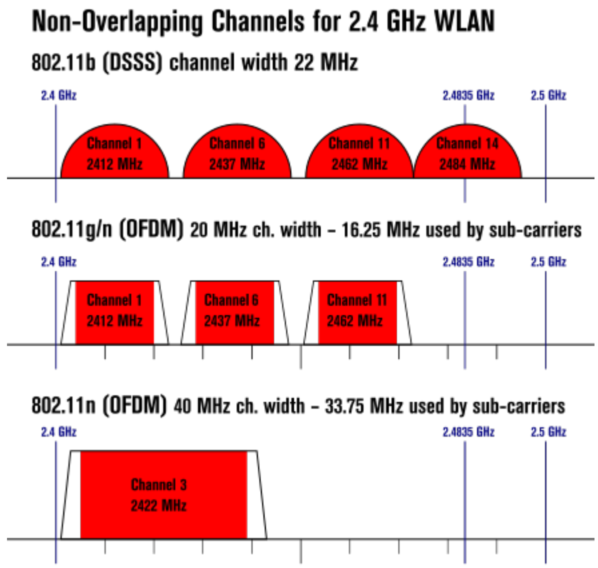

Figure 1 - Typical North American Wi-Fi channels in the 2.4 GHz ISM Band

2. IoT

2.1. IEEE 802.15.4

The two primary IoT protocols utilizing IEEE 802.15.4 are Zigbee and Thread. The primary applications of Zigbee and Thread devices are low power sensors for home automation and home security. IEEE 802.15.4 supports O-QPSK, GFSK modulated signals with data rates of 250kbps, 40 kbps, and 20kbps at 2.4GHz, 915 MHz, and 868 MHz subsequently. The protocols are designed to be as robust and as low power as possible. Devices are typically sleepy end devices, waking up on user interactions, and periodically providing device diagnostics to report device status. The 2.4 GHz frequency band supports 16 channels with 2 MHz bandwidth and 5 MHz spacing. The primary operating channels, listed in Table 1, have the least spectral overlap with 2.4 GHz frequency band IEEE 802.11 channels, and are illustrated in Figure 2. Zigbee and Thread have ability to dynamically change channels, however due to protocol restrictions it is not trivial. Devices can potentially get stranded, as well as impact battery life.

Table 1 - Typical North American IEEE 802.15.4 channels in the 2.4 GHz ISM Band

Channel	Center Frequency(MHz)
15	2425
19	2445
20	2450
25	2475

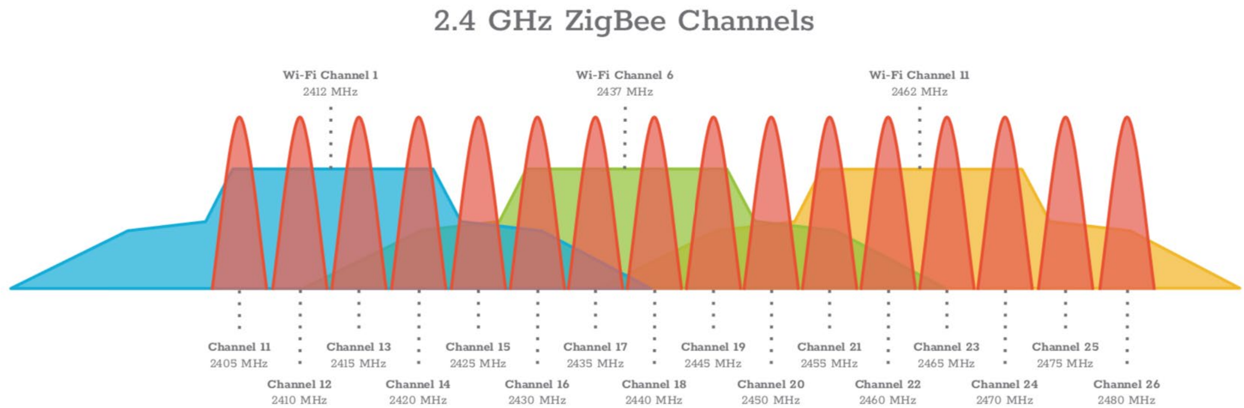

Figure 2 - Typical Wi-Fi channels and IEEE 802.15.4 channels

2.2. Bluetooth Low Energy

The primary application of Bluetooth Low Energy is low powered streaming devices, and low power sensors including; door locks, medical devices, wearables, and audio streaming devices. Bluetooth Low Energy channels are illustrated in Figure 3. Bluetooth Low Energy supports GFSK modulation with 125kbps, 500kbps, 1 Mbps, and 2 Mbps data rates which are achieved by varying the spreading factor. Bluetooth Low Energy channels occupy the 2.4 GHz frequency band consisting of 40 2 MHz channels. Bluetooth Low Energy takes advantage of the tightly spaced channels through frequency agility changing channels at predetermined intervals, and channel masks can be implemented to avoid channels with high interference. Three of those channels are designated as advirtising channels, and cannot be avoided with a channel mask and are illustrated as the green channels in Figure 3.

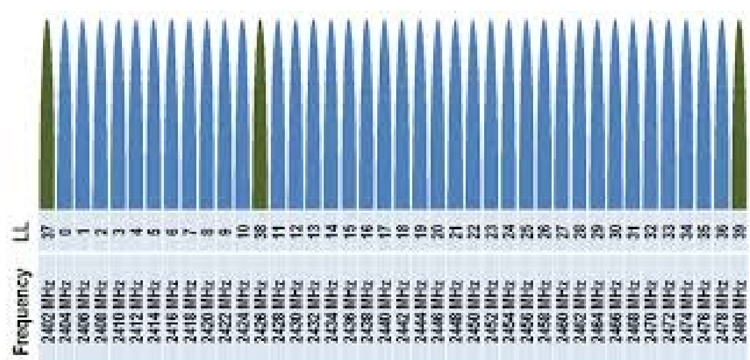

Figure 3 - Bluetooth Low Energy operating channels

Physical Layer Coexistance

I/Q based communications is a form of digital modulation where in-phase, and quadature data are mixed together to form a modulated carrier. The in-phase data is respresented by Equation 1 and quadrature data is represented by Equation 2. The in-phase and quadrature data can be manipulated by adjusting the amplitude represented by Ac, the frequency represented by fc, or phase represented by ϕ. Different implementations of I/Q modulated carriers produce different power sprectral densities. These power spectral densities can be used to estimate the Signal-to-Interferer Ratio, SIR, which can be used to calculate chip error rate, bit error rate, and packet error rate. The CER, BER, and PER determines whether or not a signal of interest can be received. Individual wireless subsystems, can determine SIR with respect to adjacent networks. Essentially, a Zigbee network can easily determine how well it can coexist with other Zigbee networks, but not necessarily a Wi-Fi or Bluetooth network, and vice-versa. Consolidating IoT device traffic to the cable gateway, provides the opportunity to calculate if devices in other networks can concurrently communicate on the physical layer.

Equation 1 $x_{i(t)} = A_c \cos(2\pi f_c t + \phi)$

Equation 2 $x_{q(t)} = A_c \sin(2\pi f_c t + \phi)$

3. PSK & QAM

Phase shift keying is a form of digital modulation where IQ, In-phase and Quaduture, data is mixed together at different phase offsets to represent bit(s). BPSK represents 1 bit per symbol where in-phase data remains constant, but quadrature data phase, ϕ, is shifted . QPSK, illustrated in Figure 4 - Inphase and Quadature QPSK data, represents 2 bits per symbol where both in-phase data, and quadrature data phase, ϕ , is shifted. Quadature amplitidude modulation consists of both phase, ϕ, and amplitude, Ac, is shifted for both in phase and quadrature data. QAM can support 2, 4, 6, 8, and 10 bits per symbol by increasing the amplitude variations. The number of bits represented by the modulated carrier as an interferer is directly correlated to the spectral desensity and, as a result QAM, BPSK, and QPSK will have different impact on devices as an interferer.

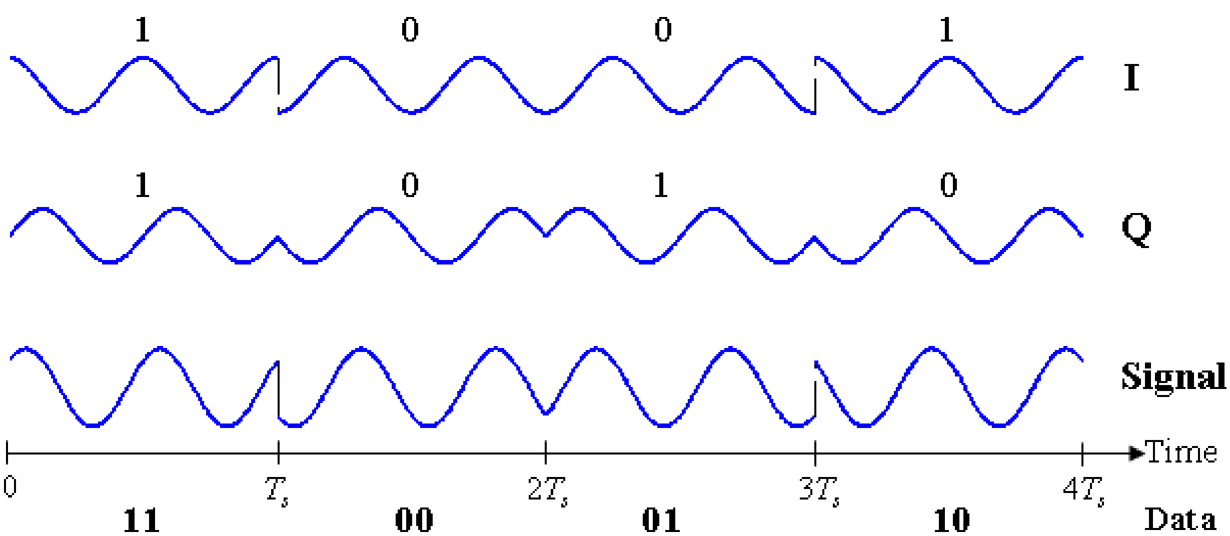

Figure 4 - Inphase and Quadature QPSK data

The power spectral density of the these modulations can be calculated using Equation 3, where fc is the center frequency, bw is the signal bandwidth, and M is number of constellation symbols. An example of the modulated carrier over frequency is illustrated in Figure 5. QAM and PSK PSD can both be calculated using Equation 5 as both carriers are typically modulated similarly. This equation provides the ability to estimate the interference seen by a receiver over any given bandwidth at any center frequency. For instance, if Wi-Fi is currently operating on channel 1 the power of the side lobes interfering with a IEEE 802.15.4 signal on channel 19 can be estimated. This determines if Wi-Fi can transmit and IEEE 802.15.4 can receive concurrently, and is the basis of coexistence on the physical layer.

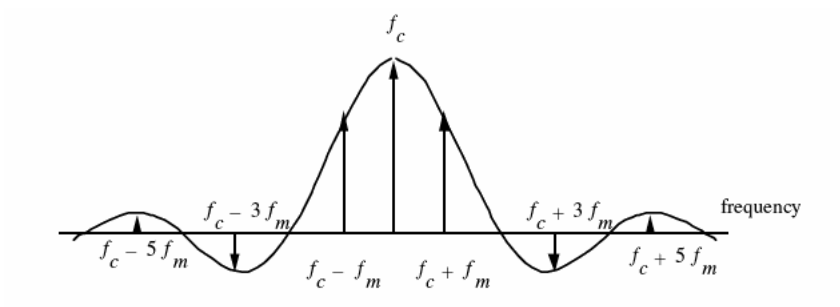

Figure 5 - Power spectral density plot of PSK and QAM signal

Equation 3

$$\mathrm{p_{psk}}(f) = \left(\frac{\sin\left(T_s\pi(f - f_c)\right)}{T_s\pi(f - f_c)}\right)^2$$

Equation 4

$$\mathrm{T_s} = \frac{\log_2 M}{b_w}$$

Equation 5

$$\mathrm{p_{psk}}(f) = p_{qam}(f)$$

4. FSK

Frequency shifted key is a form of digital modulation where in-phase and quadrature frequency fc is adjusted to represent a bit, and is illustrated in Figure 6. GFSK is adaptation of FSK that is passed through a Guassian filter to smooth signal allowing for a much more narrow bandwidth.

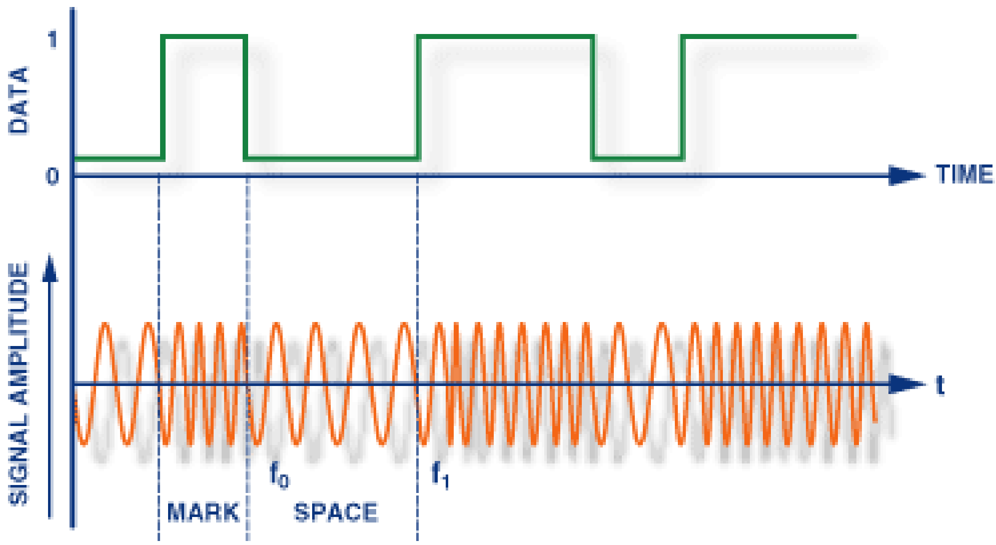

Figure 6 - FSK IQ data set example

The spectral density of a frequency shifting key can be calculated using Equation 6 where fc is the center frequency of signal , D is ½ distance between mark and space frequencies, and bw is the bandwidth of the signal. The distance between the mark and space is directly correlated to the spectral, and as a result different GFSK modulations with have different impact as an interferer, and provide different challenges with coexistence.

Equation 6

$$p_{fsk}(f) = \left[\frac{1}{D^2 - (f - f_c)^2}\right]^2 \frac{\left[\cos\left(\frac{2\pi D}{b_w}\right) - \cos\left(\frac{2\pi(f - f_c)}{b_w}\right)\right]^2}{1 - 2\cos\left(\frac{2\pi D}{b_w}\right)\cos\left(\frac{2\pi(f - f_c)}{b_w}\right) + \cos^2\left(\frac{2\pi D}{b_w}\right)}$$

5. OFDM & OFDMA

Orthogonal frequency-division multiplexing is digital modulation technique where multiple subcarriers are multiplexed over a single bandwidth, and is illustrated in Figure 7 - OFDM Modulated Carrier as the addition of multiple subcarriers In IEEE 802.11 OFDM implementation consist of PSK, and QAM subcarriers.

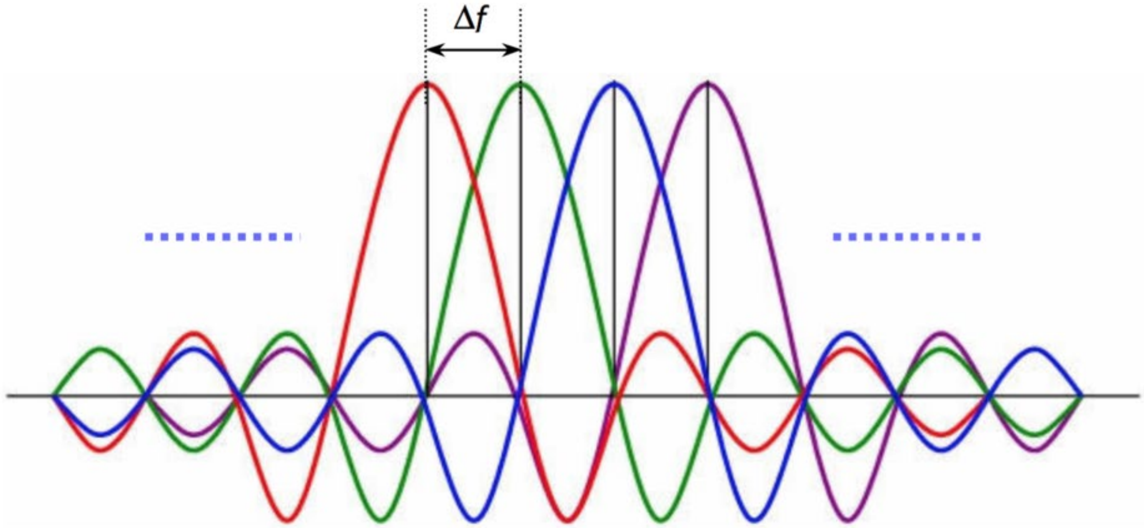

Figure 7 - OFDM Modulated Carrier as the addition of multiple subcarriers

The power spectral density of the OFDM signal an be calculated by summing the individual sub carriers power spectral density, and is represented by Equation 7 & Equation 8, where Δf is the subcarrier bandwidth, and N is the number of subcarriers. OFDM will exhibit a different spectral mask than a standalone modulated carrier. An OFDM QPSK signal occupying 20 MHz of bandwidth versus a DSSS QPSK occupying 20 MHz will have different side lobes, that can have coexsistance advantages or disadvatnages dependent on the relative position spectrally.

Equation 7

$$p_{OFDM(f)} = \Sigma_{k=\frac{-\mathrm{N}}{2}}^{\frac{N}{2}} P_{psk}(f - f_{sc}(k)\ )$$

Equation 8

$$\mathrm{f_{sc}(k)} = \frac{k}{|k|}\frac{2|k|-1}{2}\,\Delta f$$

Orthogonal frequency-division multiple access is an implementation of OFDM breaking up the subcarriers, and assigning them to individual clients over time, and is illustrated in Figure 8 - OFDMA signal separated into individual subcarriers over frequency and time. The power spectral density of an OFDMA signal can be calculated by determine the PSD of the active sub carriers using equation, and dynamical changes with time depending on the active sub carriers. OFDMA provides the ability to coexist spectrally by utilizaing the time domain. The benefit of the small subcarriers, and the ability to dynamical disable them is the additional granularity provided on the side lobes to increase the ability to coexist. Whereas OFDM will be restricted strictly to the channel spacing provided by the standard.

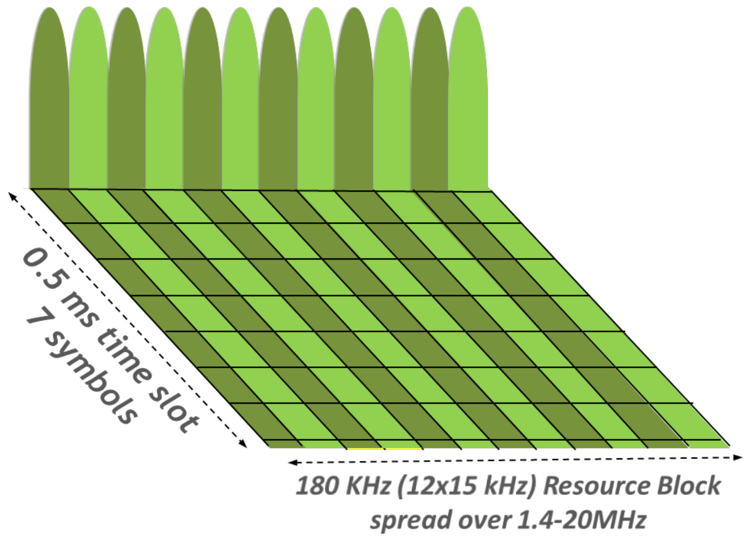

Figure 8 - OFDMA signal separated into individual subcarriers over frequency and time

6. IEEE 802.11

The IEEE 802.11 standard take advantage of multiple modulation techniques focusing on DSSS and OFDM, and PSK and QAM. Each modulation technique has different requirement for spectral density mask requirements to follow FCC regulations. The spectral density mask for IEEE 802.11 b DSSS signals is illustrated in Figure 9, and the spectral density mask for IEEE 802.11 OFDM signals is illustrated in Figure 10. Depending on the operating modulation, and bandwidth spectral density can be calculated. This calculation is not effected by coding rates or spreading factors. The criteria for calculating spectral density in the 2.4 GHz and 5 GHz is found in Table 2 & . IEEE 802.11 ax spectral density can be calculated using the same criteria, by determining the active subcarriers in the OFDMA modulated carrier. The large bandwidth requirements pose challenges to the smaller bandwidth protcols such as IEEE 802.15.4 and Bluetooth, but supports a large amount of modulations techniques providing flexibility to coexist on the physical layer.

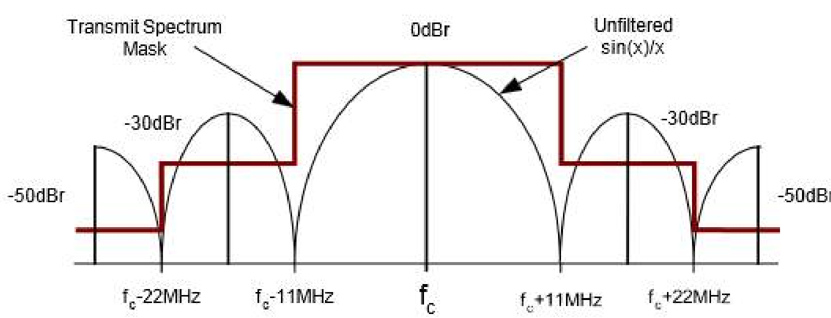

Figure 9 - Transmit spectral density mask of an IEEE 802.11 DSSS 20 MHz signal

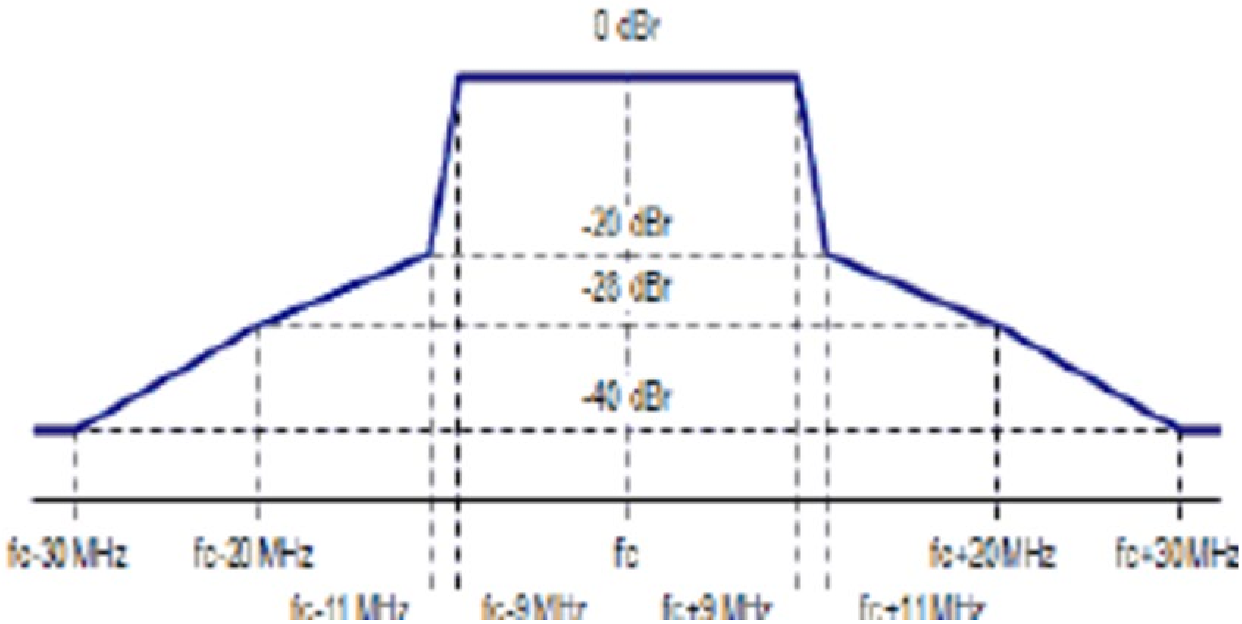

Figure 10 - Transmit spectral density mask of an IEEE 802.11 OFDM 20 MHz Signal

Table 2 - Critertia for calculating IEEE 802.11 spectral density

M(bits)	Bw (MHz)	Modulation
2	10, 20, 40, 80, 160	BPSK
4	20, 40, 80, 160	QPSK
16	20, 40, 80, 160	QAM16
64	20, 40, 80, 160	QAM64
256	20, 40, 80, 160	QAM256
1024	20, 40, 80, 160	QAM1024

7. IEEE 802.15.4

IEEE 802.15.4 specificies the spectral mask for the DSSS O-QPSK signal, and is illustrated in Figure 11 - IEEE 802.15.4 Transmit spectral density mask Spectral desnity for IEEE 802.15.4 in the 2.4 GHz band, and be calculated using Equation 3 with the criteria in Table 3. IEEE 802.15.4 only supports one bandwidth and one modulation in the 2.4 GHz, thus power spectral desnity can only be can only be calculated one way. Although IEEE 802.15.4 offers sub GHz channels with GFSK modulation. Those frequency bands are not as widely used as the 2.4 GHz frequency band, and are minimally impacted by Bluetooth Low Energy or IEEE 802.11 due to sufficient spectral separation. The 2.4 GHz band does not have flexibility on different modulation techniques, however due to low bandwidth occupancy with many channels interference is minimal in comparison to Wi-Fi.

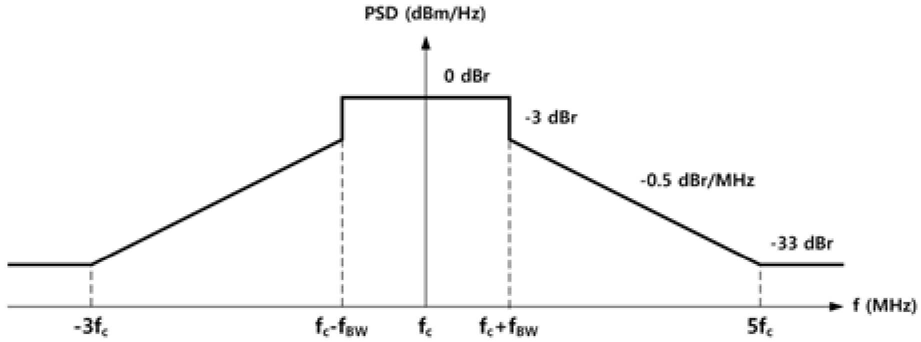

Figure 11 - IEEE 802.15.4 Transmit spectral density mask

Table 3 - Criteria for calculating IEEE 802.15.4 spectral density

M(bits)	Bw (MHz)	Modulation
4	2	O-QPSK

8. Bluetooth Low Energy

Bluetooth Low Energy specificies the spectral mask for FHSS GFSK signal, and is illustrated in fig Spectral desnity, and be calculated using equation with the criteria in table . Bluetooth offers two PHY's 4-GFSK, for higher throughput, and 2-GFSK. 4 GFSK is only available from BLE 5.0 on. As the data rate is increased the modulated carrier become more spectrally dense. Spreading codes introduced in the BLE 5.0 standard improve BER vs SNR, however have no impact on the spectral density of the modulated carrier. Due to the flexibity of both modulation techniques and low channel bandwidth Bluetooth has multiple advantages in physical layer coexistence.

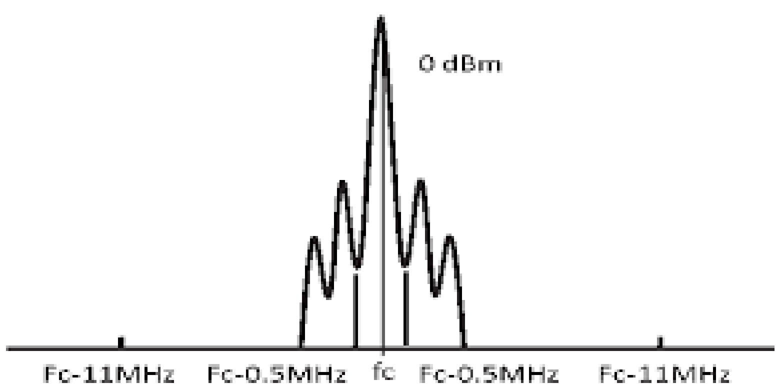

Figure 12 - Bluetooth Transmit Spectral density mask

Table 4 - Criteria for calculating IEEE Bluetooth Low Energy spectral density

M(bits)	Bw (MHz)	Modulation
2	1	2-GFSK
4	1	4-GFSK

9. Theoretical Calculations

The spectral density of a signal is the effective power of a signal over a given bandwidth. Understanding the bandwidth and center frequency of the signal of interest, and the modulation, bandwidth, and center frequency of the iterferrering signal the SIR can be calculated. IEEE 802.15.4 on Zigbee channel 25, 2475 MHz, SIR measured with respect to a Wi-Fi DSSS signal on channel 1, 2412 MHZ, is demonstrated in Equation 9. The results of the SIR calucation can be applied to the SNR curve illustrated in Figure 13 - IEEE 802.11, IEEE 802.15.4, IEEE 802.15.1, Bluetooth, Bit error Rate vs Signal to Noise Ratioto estimate bit error rate. This logic can be applied to any combination of channels, bandwidths, and modulations between 802.11, 802.15.4, and Bluetooth low energy to determine the impact of other in band signals. Having multiple radios consolidated gateway enables a large scale understanding of the entire ecosystem from a physical layer perspective. It provides insight into what operating channels, bandwidth, and modulation techniques are used by every device, unveiling what devices can communicate concurrently. If devices cannot communicate concurrently the gateway acting the as the network coordinator has the ability to adjust the modulation, channels, and bandiwidth to improve physical layer coexistence. Understanding the SIR between each device on the network is not possible with individual subsystems, and elminates the ability to effectively manage multiple networks within one home, or determine the impact of bandwidth, modulation, or channel selection on other subsystems.

Equation 9

$$\int_{2475MHz}^{2476MHz} P_{psk}(f)$$

$$f_c = 2412\ MHz, 2437\ \text{MHz}, 2462\ \text{MHz}$$

$$b_w = 11\ MHz, 22\ MHz$$

$$M = 2, 4$$

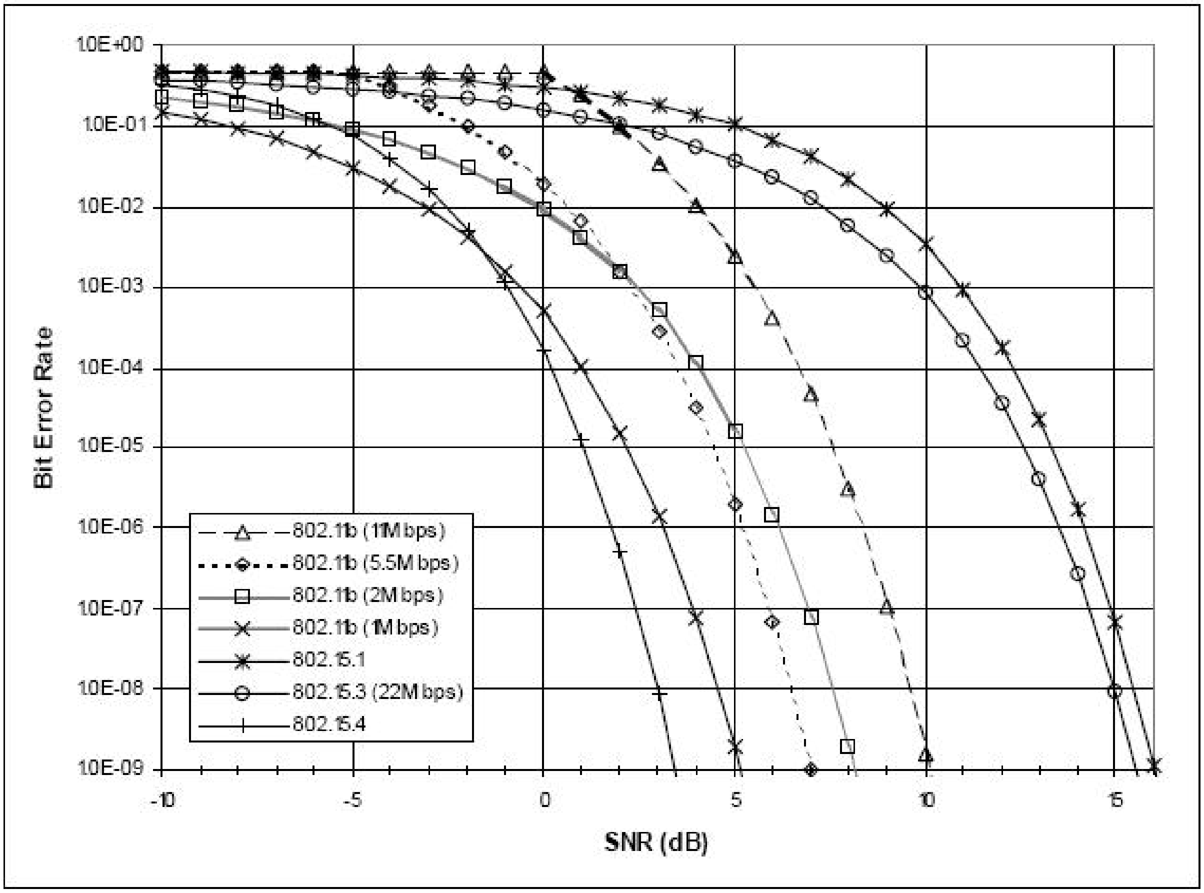

Figure 13 - IEEE 802.11, IEEE 802.15.4, IEEE 802.15.1, Bluetooth, Bit error Rate vs Signal to Noise Ratio

Network Coexistance Techniques

Coexistance is a balance of maintaining high throughput for Wi-Fi devices based on optimal links and channel utlization, optimizing battery life for IoT devices by reducing retranmissions, network rejoins, or other battery draining network interactions. In a cable gateway decisions to optimize performance on one subsystem can be influenced by the other sub systems in the gateway. The cable gateway can make decisions not only based on connected devices but also based on other connected devices effecting the ecosystem, such as other Wi-Fi or IoT devices in a multi-family home. Although the gateway can't directly impact the non-connected devices it pass on that data to the other sub-systems. For instance, if, the gateway's Wi-Fi is occupying channel 1 in 2.4 GHz band, but has detected other Wi-Fi networks on channel 6, Bluetooth, and IEEE 802.15.4 can adjust channel selection accordingly. Similar decisions can be made when scheduling free air time, adjusting modulation or bandwidth, and these decisions can be made by understanding the SIR between the networks.

10. Network Management

10.1. Scheduling

Bluetooth Low Energy, Zigbee, and Thread end devices device typically are sleepy to preserve battery life. These sleepy end devices send status updates to the network coordinator on an interval basis that free air time can be scheduled to mitigate intereference with Wi-Fi. Bluetooth Low Energy operates on a interval basis, transferring data through that interval, and then switching channels. Dynamically scheduling freeing RU's in 802.11 ax based on BLE current operating channels opens oppurtunities to have free air time in the network. An example of the RU's available in a 20 MHz IEEE 802.11 ax channel is illustrated in Figure 14. Increasing BLE throughput and increasing battery life. Using the power density calculations l it can be determine how many RU's need to be inactive so the current IEEE 802.15.4 and BLE operating channels will have sufficient SIR to get the packet to be recieved. Older 802.11 standards are more restrictive requiring that the free airtime be scheduled, having an negative impact on throughput. Essentially, scheduling is determined by understanding what devices cannot communicate concurrently based on SIR, ensuring that those devices are given separate air time, and that all protocol timing restrictions are met. An individual subsystem not only does not have access to the the ecosystem SIR, but also is strictly limited to the scheduling and timing restrictions of the devices that it manages. Due to the inability to consider scheduling and SIR constraints of other individual sub systems, consolidated gateways have scheduling performance advantages.

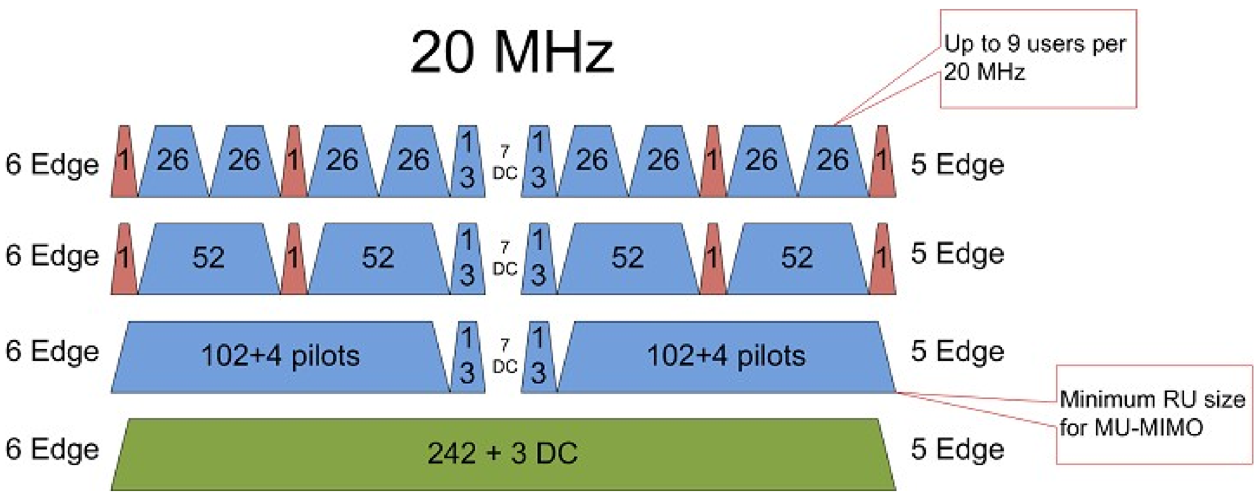

Figure 14 - IEEE 802.11 ax 20 MHz channel resource units

10.2. Channel Selection

Ideal channel selection for IEEE 802.11 and IEEE 802.15.4 would be spectrally separating as much as possible. Bluetooth low energy ideal channel mask would include a list of all channels that spectrally separated enough that the device has sufficient SIR to receive a packet. In a single family with no neighbors nearby, coexistence may be as simple as that. However, in congested environments with networks competing for air time, channel selection may not be as straight forward. If the current operating IEEE 802.11 channel is to congested, it may be desirable to move to a less congested channel. However, the channel will adjust the SIR of the other devices connected to gateway, and as result should be part of the overall decision making process on channel changes, including adjusting channel bandwidth. For instance, an IEEE 802.11 network with no competing networks operating on channel 1 2412 MHz at 20 MHz with sufficienct SNR for a 40 MHz. If the IEEE 802.15.4 and BLE networks are operating on channel 17, 2435 MHz, and channel 15, 2436 MHz they would then be co-channel with the IEEE 802.11 network, and as a result will most likely not have sufficient SIR resulting retransmission, or loss of connectectivity to the network resulting in negative impacts on battery life of those devices. Channel selection is made by understanding the channel selection of all networks being managed by the gateway, as well as competing unmanaged networks. A combination of SIR, and free air time is used to determine the channel that will be most effective for the networks being managed by the gateway.

11. Prioritization

Determining which subsystem has overall priority can be simple or complex depending on the ecosystem that the gateway is placed in. For example, if a cableway is supporing a Home Securirty network while that network is armed, those devices may have priority, or while streaming video content the Wi-Fi system may have priority. A complex dynamic approach to priority provides the opportunity to improve performance on a case by case basis, but requires insight into other networks, and their priorities. Priority can be applied to channel selection as well scheduling, and typically is determined by importance. Optimal channels can be selected for devices with the highest priority, but this decision can only be made by understanding the current state of the entire ecosystem, and each network managed by the gateway. Individual subsystem's dynamic priority capabilities are restricted in comparison to a consolidated gateway solution simply due to the lack access or control other individual subsystems.

12. Spatial Mapping

Understanding relative distance between connected devices and the gateway as well relative distance between connected devices is key for optimizing channel selection as well as scheduling. Assume a single IEEE 802.15.4, and IEEE 802.11 device are connected to the gateway line of sight. The IEEE 802.15.4 has an RSSI of -37 dBm, and IEEE 802.11 has an RSSI of -40 dBM. Assume both devices have a perfectly onimidirectional TRP, total raidiated power, of +20dBm, implying the IEEE 802.15.4 is experiencing 57dB of free space path loss, 7 meters using equation Equation 10, and the IEEE 802.11 is experiencing 60 dB free space pathloss, 10 meters assuming equation. Worst case scenario both devices are directly in the same line of sight with distance of 50 dB, 3 meters, between each other, however best case scenario the devices are 64 dB, 17 meters, apart on the same line of sight in the opposite axis spatially. In the first scenario where the devices are 3 meters away they are spatially very close, and therefore will need to be separated spectrally. However, in the second scenario the devices are 17 meters away with 64 dB of pathloss between them, and as a result may not need to be as separated spectrally. Using phase differences between antenna's on different IEEE 802.11, IEEE 802.15.4, and BLE devices the AoA, angle of arrival, of other devices be detected, and is illustrated in Figure 15. By maping that information to devices addresses and RSSI data, each network can create a map of devices spread throughout an ecosystem. This map of all the devices is key to the gateway determining best operating channels, modulation, and bandwidth for each network as it can calculate the SIR between every device in the ecosystem. Individual subsystems can apply a similar technique however, the subsystem will be limited to mapping devices of the same protocol impacting the the ability to coexist.

Equation 10

$$FSPL_{dB} = 20\log_{10}\frac{4\pi df}{c}$$

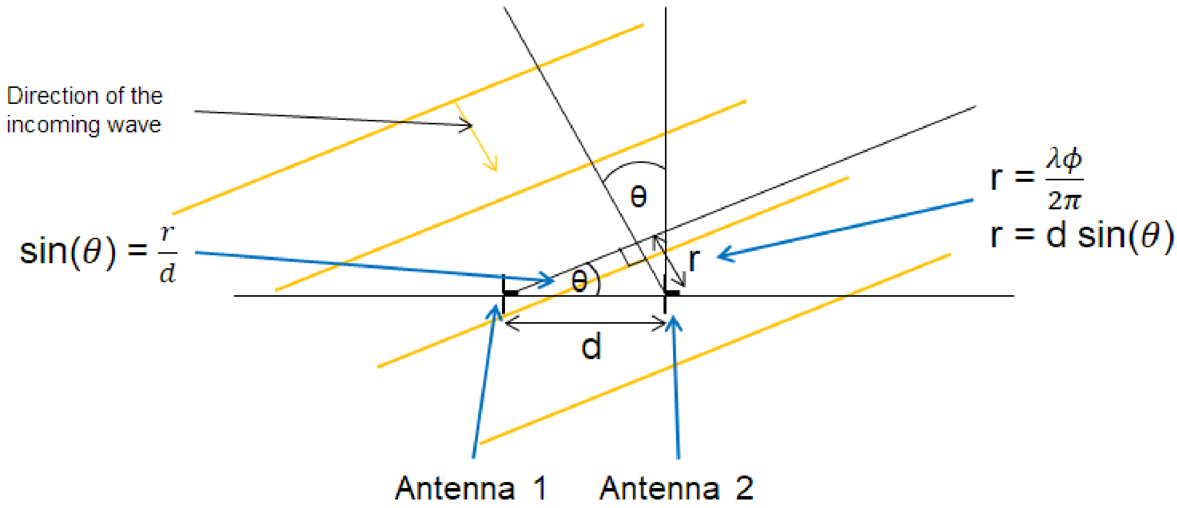

Figure 15 - Angle of Arrival calculation using multiple antennae

Conclusion

Consildating IoT traffic through the cable gateway has significant impact on system performance. Reducing IoT device retranmissions with minimal impact on IEEE 802.11 improves device battery life, reduces latency, resulting in an overall improved user experience. These improvements are achieved by optimizing network performance by understanding physical coexistence and SIR of the devices in network. SIR can be collected on individual IoT subsystems, however it cannot necessarily be correlated to other systems SIR, or spatially correlation. More importantly changes cannot be made to those out of network devices systems from that network. The lack of the correlation and control between other networks precludes optimal performance. Continued consolidation of IoT traffic into the gateway will continue to optimize the entire whole home experience.

Abbreviations

AP	access point
BER	Bit Error Rate
BLE	bluetooth low energy
bps	bits per second
BPSK	binary phase shift keying
CER	chipping error rate
DSSS	Direct Sequence Spread Sprectrum
FCC	Federal Commuication Commission
FHSS	frequency hopping spread spectrum
FSK	frequency shift keying
GFSK	gaussian frequency shift keying
IEEE	Institute of Electrical Electronics Engineers
ISM	industrial, scientific and medical
IoT	Internet of Things
IQ	inphase and quadature

Hz	hertz
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multi access
O-QPSK	offset quadature phase shift keying
PSD	power spectral density
PSK	phase shift keying
QAM	Quadature Amplitude Modulation
QPSK	quadature phase shift keying
RU	resource unit

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