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eBook

Wi-Fi Convergence with IoT and 5G

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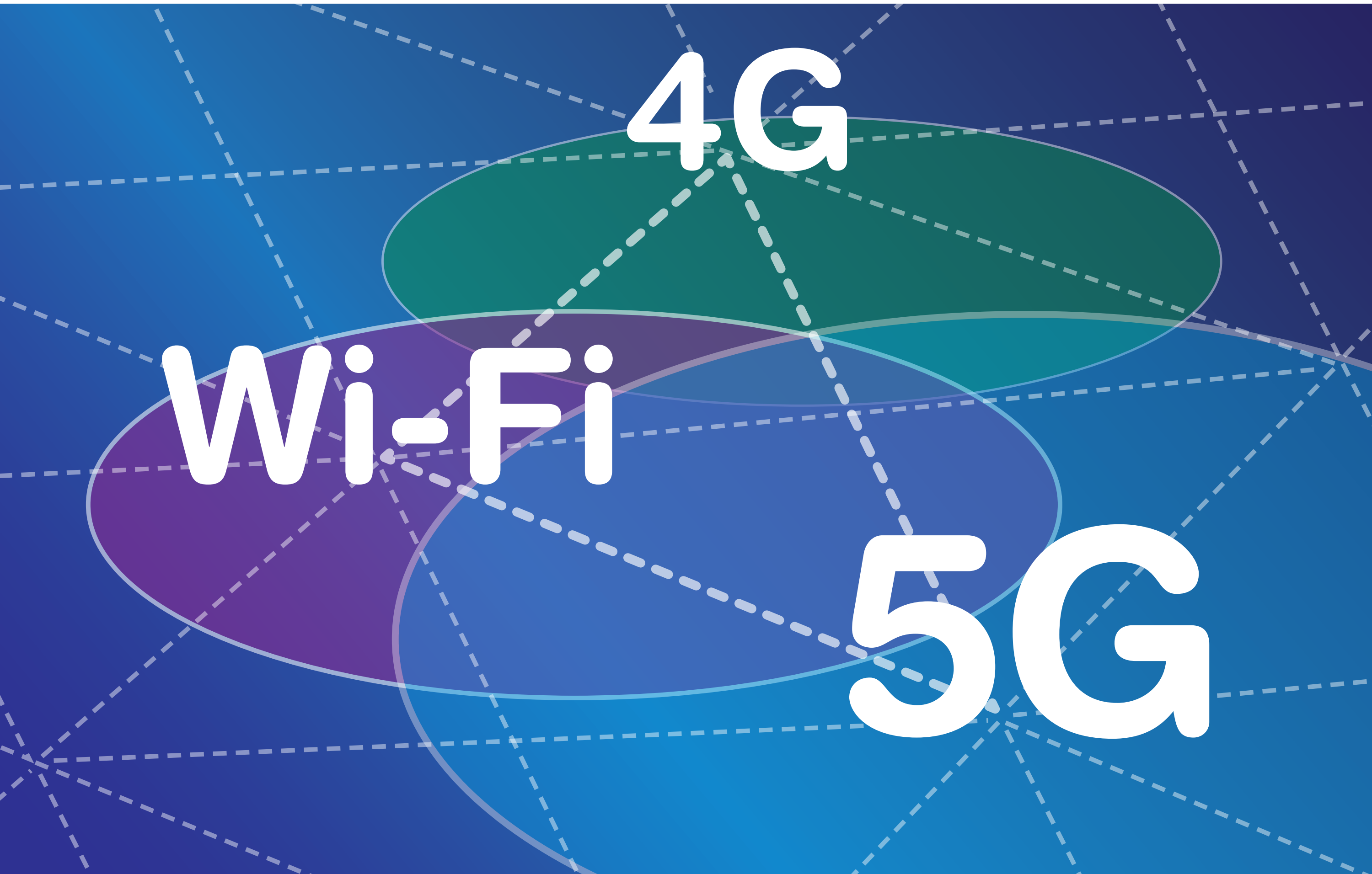

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Wi-Fi Convergence with IoT and 5G

As 5G, Wi-Fi 6 and various IoT connectivity standards roll out together, many people wonder how these technologies will work together to benefit businesses and consumers. There are so many standards being used for wireless connectivity including short range IoT technologies like IEEE 802.15.4 (ZigBee, 6LoWPAN…), Bluetooth/BLE, Z-Wave, and IEEE 802.11ad (Wi-Gig); medium range IoT technologies such as Wi-Fi, IEEE 802.11ah (Wi-Fi HaLo), IEEE 802.11p (vehicular transmission systems); long range LPWAN technologies like LoRa®/LoRaWAN®, SigFox, Wi-Sun, Ingenu, DASH-7, Weightless; and long range cellular technologies including 2G-GSM/GPRS/IS 95 (CDMA 2G), 3G UMTS/CDMA, LTE, NB-IoT, LTE-M (Cat M1), CBRS, Multi-Fire, and 5G. Luckily, there are many alliances and standards groups working to coordinate these technologies so that they can work together.

According to the RAN Convergence White Paper developed by the Wireless Broadband Alliance (WBA) and the Next Generation Mobile Networks (NGMN) Alliance, Wi-Fi and 5G convergence offer improved visibility into Wi-Fi networks, allowing them more control over customer experiences and the ability to provide better service while mobile operators are in a better position to provide enterprise Wi-Fi network management solutions. As the two technologies converge, Wi-Fi operators will also be able to provide an enhanced user experience through increased visibility and improved transition management as they operate overlapping cellular and Wi-Fi networks. Enterprise Wi-Fi networks will gain the ability to access operator-provided 5G services too.

This eBook presents a number of products and technologies that enable Wi-Fi, IoT and 5G wireless systems to work together without interference. New filter and front-end modules are key products that enable these wireless technologies to work together seamlessly. The first two articles feature Qorvo products that allow these wireless technologies to work together with excellent performance. This is followed by a short update on the release of Wi-Fi 6 and then a thorough article covering the various Wi-Fi and IoT deployment synergies.

We thank Qorvo and RFMW for sponsoring this eBook so we can bring it to you at no cost. We hope it will show how all of these wireless technologies can work together seamlessly to benefit businesses and consumers.

Pat Hindle, Microwave Journal *Editor*

WHITE PAPER

Improving Wi-Fi Range and Capacity with Qorvo's Bandedge BAW Filters

Abstract

Qorvo's bandedge BAW filters improve Wi-Fi range and capacity by allowing Wi-Fi systems to maintain maximum RF output power on all channels in the 2.4 GHz Wi-Fi band. They solve a key challenge for Wi-Fi system engineers: how to maximize output power on all non-overlapping Wi-Fi channels while meeting strict FCC (Federal Communications Commission) limits for emissions in restricted bands. In the 2.4 GHz Wi-Fi band, only three non-overlapping channels are available in the U.S.: channels 1, 6, and 11. Without BAW filters, systems need to back off output power in channels 1 and 11 to meet FCC regulatory requirements, significantly reducing range and capacity. Qorvo bandedge BAW filters have steep skirts that allow the system to operate at rated power in channels 1 and 11 without violating FCC limits; this typically regains 6-10 dB of power, which can increase range by 100% or even more. There are multiple filter solutions that exist, but only Qorvo supplies 2.4 GHz bandedge BAW filters that address this issue in its entirety.

Introduction

Over the years, the IEEE (Institute of Electrical and Electronics Engineers) has developed new standards to progressively address the worldwide advancement of Wi-Fi, as shown in Table 1. Each IEEE 802.11 Wi-Fi protocol operates within specific frequencies, known as ISM (Industrial, Scientific and Medical) unlicensed bands. These bands are free of licensing restrictions, but they are shared among Wi-Fi users and with a variety of other non-Wi-Fi devices and users.

Table 1: Summary of IEEE 802.11 protocol evolution and features.

IEEE 802.11 Protocol	Release Date	Frequency Band(s) (GHz)	Bandwidth (MHz)	Max Throughput
801.11 – 1997	1997	2.4	22	2 Mbps
11b – Wi-Fi 1	1999	2.4	22	11 Mbps
11a – Wi-Fi 2	1999	5	20	54 Mbps
11g – Wi-Fi 3	2003	2.4	20	54 Mbps
11n – Wi-Fi 4	2009	2.4/5	20/40	600 Mbps
11ac – Wi-Fi 5	2013	2.4/5	20/40/80/160	6.8 Gbps
11ax – Wi-Fi 6	2019	2.4/5	20/40/80/160	10 Gbps

While the advances in Wi-Fi standards have increased the maximum data rate from 2 Mbps to 10 Gbps, each advance also adds complexity, making Wi-Fi product design more difficult. Adding to the challenge is the need to meet U.S. FCC limits on emissions in restricted or forbidden bands. Table 2 below lists the FCC 15.205 restricted band limits (stated in 47CFR 15.247) for the 2.4-2.5 GHz frequency band. The FCC limits allow a maximum of 1-Watt RF output power and up to a +6 dBi antenna gain on Wi-Fi channels within the operating band. Additionally, products must also comply with limits for power leakage in restricted bands below and above the operating band. This regulation makes it difficult for Wi-Fi product designers to achieve optimal transmit power across all usable Wi-Fi channels within the 2.4-2.5 GHz band.

Table 2: FCC restricted bands of operation.

Restricted bands of operation (FCC 15.205)

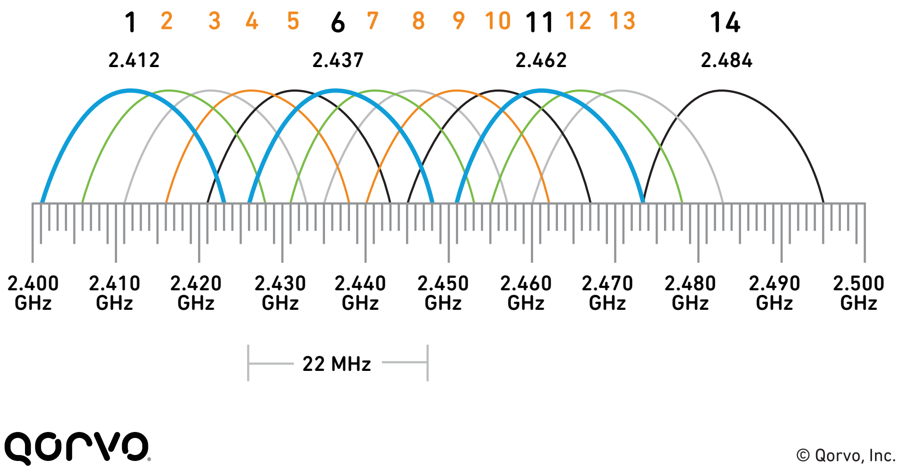
MHz	MHz	MHz	GHz
0.090-0.110	16.42-16.423	399.9-410	4.5-5.15
[1]0.495-0.505	16.69475-16.69525	608-614	5.35-5.46
2.1735-2.1905	16.80425-16.80475	960-1240	7.25-7.75
4.125-4.128	25.5-25.67	1300-1427	8.025-8.5
4.17725-4.17775	37.5-38.25	1435-1626.5	9.0-9.2
4.20725-4.20775	73-74.6	1645.5-1646.5	9.3-9.5
6.215-6.218	74.8-75.2	1660-1710	10.6-12.7
6.26775-6.26825	108-121.94	1718.8-1722.2	13.25-13.4
6.31175-6.31225	123-138	2200-2300	14.47-14.5
8.291-8.294	149.9-150.05	2310-2390	15.35-16.2
8.362-8.366	156.52475-156.52525	2483.5-2500	17.7-21.4
8.37625-8.38675	156.7-156.9	2655-2900	22.01-23.12
8.41425-8.41475	162.0125-167.17	3260-3267	23.6-24.0
12.29-12.293	167.72-173.2	3332-3339	31.2-31.8
12.51975-12.52025	240-285	3345.8-3358	36.43-36.5
12.57675-12.57725	322-335.4	3600-4400	([2])
13.36-13.41	–	–	–

[1] Until February 1, 1999, this restricted band shall be 0.490-0.510 MHz
[2] Above 38.6

Some Background: Wi-Fi Channels, Range and Capacity

Wi-Fi channels - The IEEE 802.11 allows roughly 80 MHz of bandwidth in the 2.4 GHz band in devices designed for worldwide use. However, in the U.S., the FCC limits the usable bandwidth to 70 MHz, divided into 11 20 MHz overlapping channels. These channels are just 5 MHz apart, and only three are non-overlapping: channels 1, 6 and 11. (see below Figure 1) Because channels 1, 6 and 11 are non-overlapping they are used the most, as it reduces possible interference between channels.

Figure 1: Non-overlapping Wi-Fi channels 1, 6, 11.



Range and capacity - A very important criterion for a Wi-Fi unit is RF range. The parameter most closely related to range is Wi-Fi output power. In the U.S., the most challenging design task is meeting FCC limits for spurious emissions in the restricted bands. To meet these limits, output power must be backed off in the 2.4 GHz lower and upper Wi-Fi channels (channels 1 and 11). This reduces capacity and range in these channels, resulting in performance degradation for users. Providing a way in which no back off is required will create a more optimum outcome for meeting range and capacity.

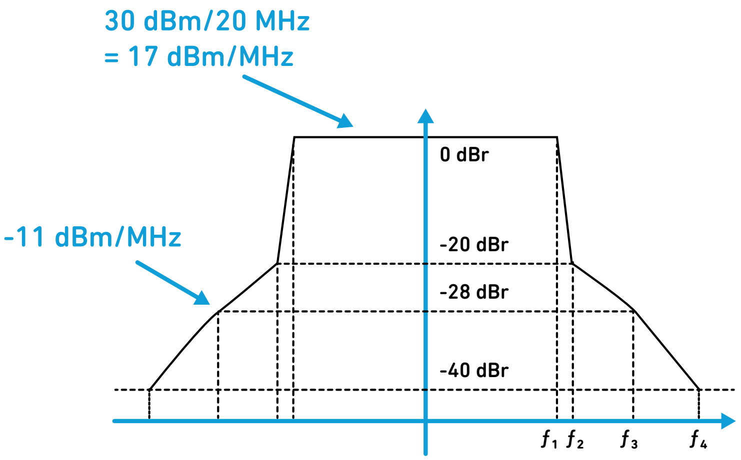
Spectral Masks vs. Bandedge Tests

One question that bothers many RF system engineers is: 'My Wi-Fi system passes the IEEE 802.11 spectral mask tests, so why do I need to lower output power as much as 10 dB to pass the FCC bandedge regulation tests? Is there a difference between these two tests?'

Let's explore this a bit further. The spectral mask test is part of the IEEE 802.11 standard. It sets limits for how much power from the in-band channels is allowed to leak into the adjacent channels. It is mainly a measure of interference within the Wi-Fi band. Bandedge testing is an FCC requirement that measures how much power leaks outside of the operating band into the restricted bands (2310-2390 MHz and 2483.5-2500 MHz). The question is, why doesn't passing the IEEE spectral mask test guarantee a green light on FCC bandedge testing? The short answer is that the FCC bandedge regulation is a tougher specification to meet. To fully qualify your product this specification must be met.

Let's look at an example. In a typical Wi-Fi system, spectral regrowth is due to both the Wi-Fi chipset and the amplifier in the transmit chain (mostly caused by the amplifier). For an amplifier operating on channel 1 centered at 2412 MHz with a 20 MHz bandwidth signal capable of delivering 30 dBm output power (per FCC regulations), power density is 17 dBm/MHz. To meet the IEEE Wi-Fi 5 spectral mask specifications, spectral regrowth at -20 MHz (2392MHz, f3 in Figure 2 below) needs to be lower than -11 dBm/MHz. At 2390 MHz, the spectral mask limits are -13.4 dBm/MHz. In contrast, the FCC's bandedge limit is much lower, at -41.25 dBm/MHz. Thus, the FCC bandedge limit is a much tougher test, requiring spectral regrowth that is about 30 dB lower in this example. The same calculation also applies to channel 11 centered at 2462 MHz.

Figure 2: IEEE Wi-Fi Spectral Mask.



Channel Size	f_1	f_2	f_3	f_4
20 MHz	9 MHz	11 MHz	20 MHz	30 MHz
40 MHz	19 MHz	21 MHz	40 MHz	60 MHz
80 MHz	39 MHz	41 MHz	80 MHz	120 MHz
160 MHz	79 MHz	81 MHz	160 MHz	240 MHz

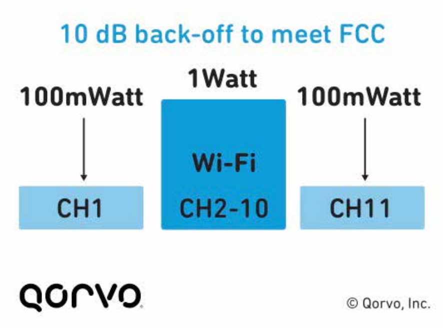
How do system designers overcome the bandedge output power problem?

Traditionally, there have been two approaches to solving this issue.

- The first is to avoid using edge channels altogether (channels 1, 2, 10 and 11), and use only the center channel (channel 6). However, this approach creates yet more network traffic in channel 6, which is already crowded.
- The second option is to lower in-band transmit power for the edge channels until the power leaking into the FCC restricted bands is within the FCC limits. This usually implies 8-10 dB lower transmit power on the edge channels than the center channels, as shown in Figure 3 below. It is common knowledge that lowering the power by 6 dB cuts the Wi-Fi range by half. In some cases, linear power is reduced by as much as 10 dB, with an even bigger negative effect on system range and capacity.

Obviously, neither of the above approaches are good solutions because they load the channels unevenly, limit system capacity and reduce the useful range of the Wi-Fi router.

Figure 3: Back-off in edge channels to meet FCC regulations.



A better solution: RF filters

Fortunately, there is a better solution to the problem: RF filters. These filters pass the ISM frequency band and attenuate out-of-band (OOB) signals. These are some of the most common types of filters used in the 2.4 GHz ISM band:

- Dielectric-resonator
- Surface acoustic wave (SAW)
- Bulk acoustic wave (BAW)
- Film bulk acoustic resonator (FBAR)

What is the best filter for this application?

When selecting a filter to solve Wi-Fi bandedge problems, it is important to consider the following parameters:

- Low in-band insertion loss
- High out-of-band attenuation (rejection)
- High power-handling capability
- Low non-linearity (harmonics generated by the filter)
- Low TCF (TCF – temperature coefficient of frequency)
- Small footprint
- Low cost

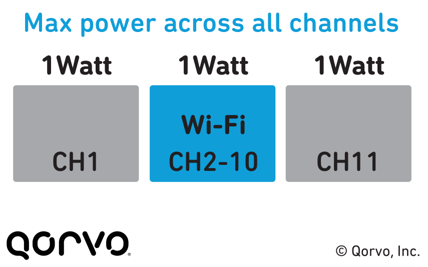
Of these conditions, low TCF and high out-of-band rejection are the most difficult parameters to achieve.

As Wi-Fi units pack high-levels of integration into smaller, sleeker form factors, performance over temperature and high power is a growing concern. The two filter technologies that meet this need are FBAR and BAW as they achieve the form factor and required performance criteria. But, BAW out performs FBAR in power handling, temperature drift (low TCF), spurious suppression and ruggedness.

Temperature performance and out-of-band rejection become even more important when the filter is embedded inside an integrated front-end module (FEM), as this causes increases in operating temperatures. BAW filter technology is the best choice to meet these high operating temperature shifts. Thus, meeting the difficult high out-of-band rejection.

Let's use channel 1, with a 20 MHz bandwidth, as an example. At the channel's lower corner frequency of 2402 MHz, the power density is approximately 17 dBm/MHz. At 12 MHz below this point (2390 MHz), the spectral regrowth needs to be lower than -41.25 dBm/MHz to meet FCC regulations. To meet this requirement, the filter's frequency response profile needs to have a steep roll-off and out-of-band rejection (30 dB as discussed above). BAW filters have these characteristics and are the best candidates for improving bandedge power in a Wi-Fi system. Using a BAW bandedge filter allows you to maximize linear power output across the entire Wi-Fi band and provide flat power across all channels within the full band (see Figure 4).

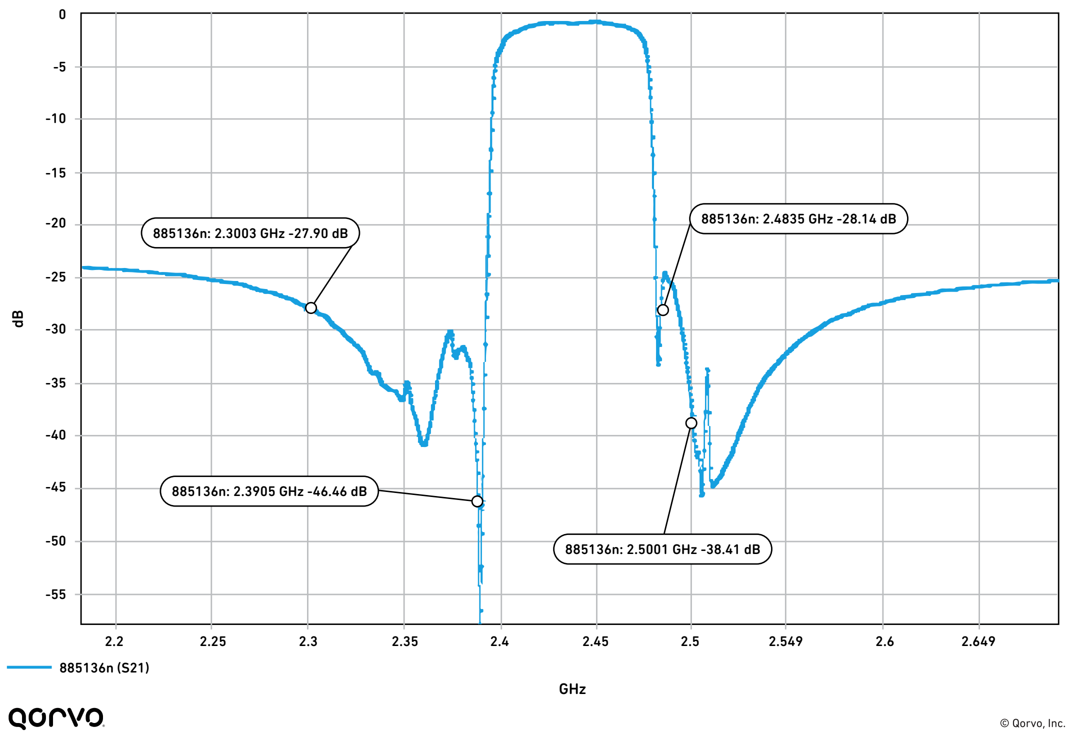
Figure 4: Flat power across all usable Wi-Fi channels can be achieved by using a Qorvo bandedge BAW filter.



How does the Qorvo BAW filter improve linear power and help pass the FCC bandedge test?

As discussed, the 2.4 GHz Wi-Fi band has a total of 14 available 20 MHz channels; in the U.S., FCC restrictions allow only 11 of those channels to be used, and only three of the channels are non-overlapping. Below (Figure 5) is a typical BAW filter frequency response showing the pass band, typical insertion loss, and rejection at the FCC restricted band.

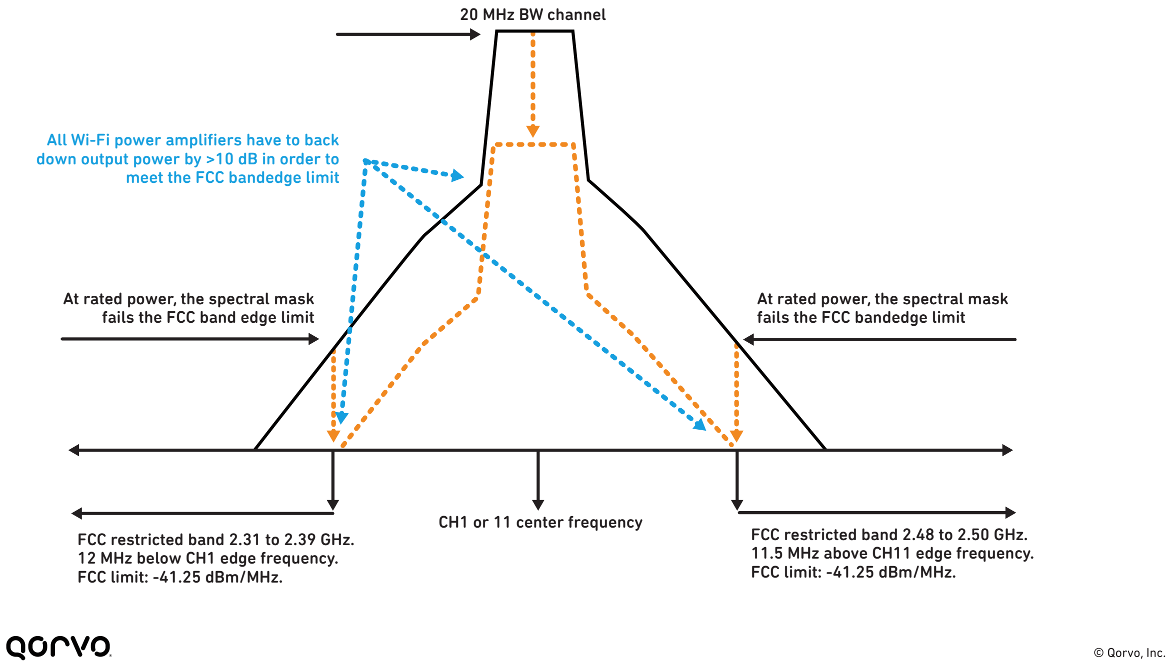
Figure 5: Typical frequency response for bandedge BAW.



Figures 6-8 show the bandedge failure response and illustrate how Qorvo BAW filters help recover linear power while rejecting unwanted transmissions in the FCC restricted bands. The figures show the effect on a 20 MHz signal in channels 1 and 11, which are severely impacted non-overlapping channels within the passband.

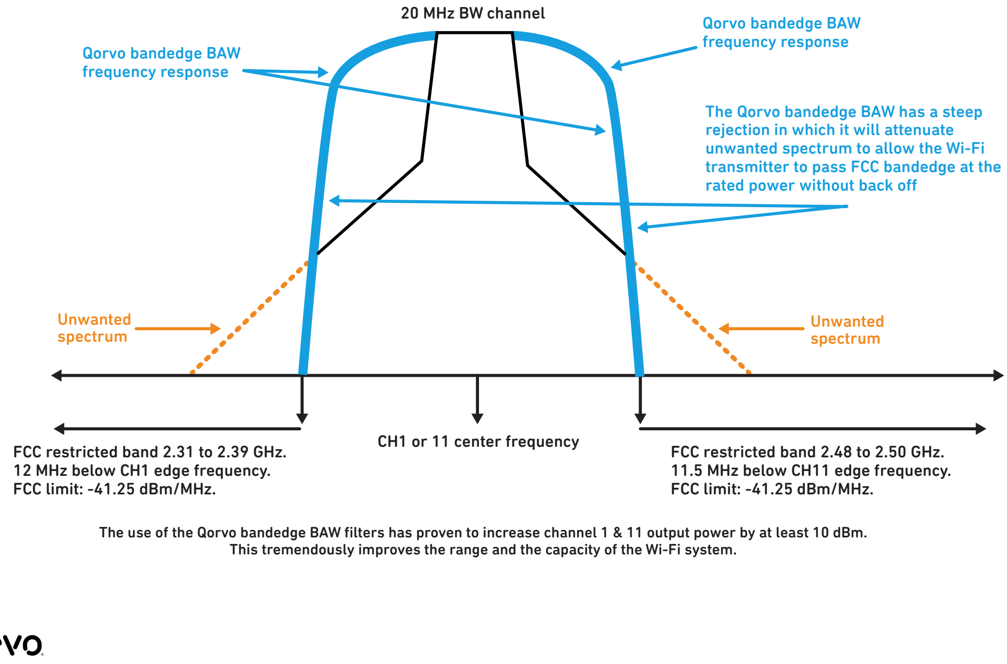
Figure 6 illustrates the FCC bandedge issue for a Wi-Fi transmitter set to channel 1 and 11, which are two of the three non-overlapping channels in the 2.4-2.5 GHz band. The FCC allows maximum output power of 30 dBm, but since the restricted band is only 12 MHz below the edge of channel 1 and 11.5 MHz above the edge of channel 11, the spectral mask violates the FCC limit for the restricted band and therefore will not gain regulatory approval.

Figure 6: Without BAW filter, power back-off on channel 1 and 11 is required to meet FCC bandedge limits.



As shown in Figure 7, the use of the Qorvo bandedge filters has been shown to increase Channel 1 and 11 output power by at least 10 dB by rejecting the unwanted spectrum.

Figure 7: With Qorvo BAW filter: Steep frequency response profile at the bandedge helps to recover linear power on channel 1 and 11.

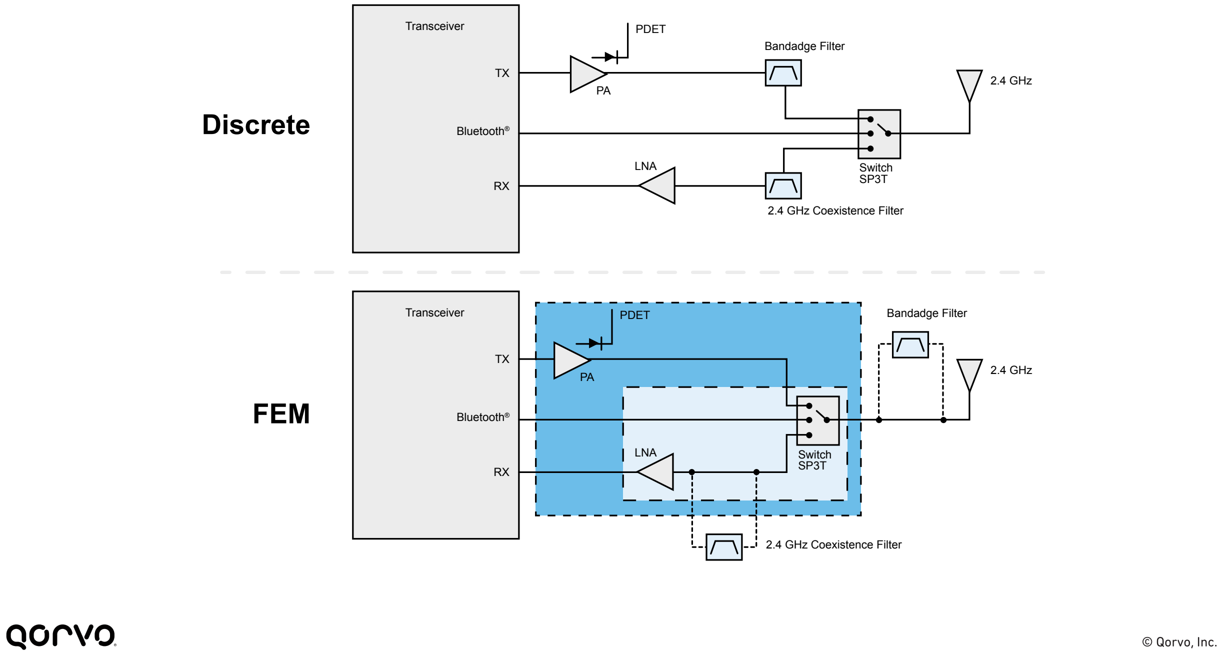


As shown in above Figures 6-7, the BAW filter greatly improves linear output power on edge channels 1 and 11. Now let's explore where best to place the filter in the system.

BAW Filter Placement and Trade-Offs in a System

The ideal placement for the bandedge BAW filter is between the PA (power amplifier) and switch on the transmit side. This configuration takes full advantage of the BAW OOB rejection and reduces distortion levels of the system. But, this placement may not always be possible when using a FEM that has a PA, switch, etc. If a FEM is used, the BAW filter should be placed at the common antenna port.

Figure 8: Bandedge and coexistence filter placement in application.



While the BAW placement improves OOB rejection, it also adds to RF path insertion loss, which needs to be considered. Thus, it may degrade the receive noise figure, which contributes to lower receiver sensitivity, and reduced linear power on the transmit side, by the amount of the insertion loss. When placing your filter, make certain you compensate for any degradation in performance.

Conclusion

Qorvo is the only supplier of Wi-Fi bandedge BAW filters at 2.4 GHz. Bandedge filters improve quality of service for Wi-Fi systems by allowing systems to maintain maximum power, range and capacity for all channels in the 2.4 to 2.5 GHz Wi-Fi band. As shown in below Table 3 and 4, Qorvo offers a family of BAW bandedge and LTE to Wi-Fi coexistence filters.

The list of products is below, for reference:

Table 3: 2.4 GHz bandedge filtering.

Part Number	Function	Wi-Fi Channels	Insertion Loss (dB)	Attenuation 2370-2390 MHz (dB)	Attenuation 2483.5-2500 MHz (dB)	Attenuation 2500-2520 MHz (dB)	Size (mm)
885136	2.4 GHz FCC Bandedge	1-11	0.8	31	24	25	1.1x0.9
885070	2.4 GHz FCC Bandedge	1-11	0.8	19	24	38	1.7x1.3
885135	2.4 GHz EU Bandedge	1-12	0.8	19	20	33	1.7x1.3

Table 4: Wi-Fi/LTE coexistence filtering.

Part Number	Function	Wi-Fi Channels	Insertion Loss (dB)	Attenuation 2300 - 2370 MHz (dB)	Attenuation 2370 - 2375 MHz (dB)	Attenuation 2375 - 2380 MHz (dB)	Attenuation 2500 - 2505 MHz (dB)	Attenuation 2505 - 2570 MHz (dB)	Size (mm)
QPQ1907	2.4 GHz Wi-Fi/BT to LTE Coexist	1-13	1.0	41	45	42	36	61	1.4 x 1.2
885128	2.4 GHz Wi-Fi/BT to LTE Coexist	1-13	1.1	39	42	34	41	55	1.1 x 0.9
885062	2.4 GHz Wi-Fi/BT to LTE Coexist	1-13	1.5	53	55	45	41	55	1.4 x 1.2
885071	2.4 GHz Wi-Fi/BT to LTE Coexist	1-13	1.5	53	49	30	57	54	1.4 x 1.2

For more information about Qorvo's BAW filters, please visit the below link: **https://www.qorvo.com/innovation/technology/baw**

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About the Author

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Ahmad has 20+ years of RF and system experience that relate to multiple wireless systems such as Wi-Fi, IoT, Smart energy, etc. Ahmad manages Qorvo's wireless connectivity business unit application team that support customers around the world.

Acknowledgement:

The author would like to acknowledge all colleagues who participated in this article.

Industry's First Solution that Seamlessly Integrates Wi-Fi 6 and IoT

Qorvo, Greensboro, NC

QPK8642 Supports all Tri-Band Wi-Fi and Major IoT Protocols in Extremely Small Footprint.

Qorvo recently launched the world's smallest, highest-performing Wi-Fi 6 solution with seamless IoT integration. The Qorvo QPK8642 kit provides leading Wi-Fi performance in capacity and coverage, along with Zigbee, Thread and Bluetooth® Low Energy connectivity, all while minimizing cross-radio interference in the connected home.

With this solution, Qorvo is helping designers meet the changing requirements of the rapidly growing global connectivity market. According to International Data Corporation (IDC), the worldwide market for smart home devices is expected to grow from nearly 815 million device shipments in 2019 to more than 1.39 billion devices in 2023.[1]

Cees Links, GM, Qorvo's Wireless Connectivity business, said, "Wi-Fi 6 is positioned to provide the connectivity backbone for tomorrow's smart homes. Our new kit has been designed specifically to speed time to market by delivering capabilities that enable Wi-Fi, Zigbee, Thread and Bluetooth® Low Energy to play together in one box, without interference. Now that's a coexistence feat!"

The Qorvo QPK8642 kit advances the company's concept of a smart, connected home where there is a pod in every room. It includes the QPQ1903, QPQ1904 and QPF4551 (all 5 GHz) and the QPF7219 (2.4 GHz) Wi-Fi filters, along with the QPG7015M IoT transceiver. This transceiver seamlessly manages coexistence with Wi-Fi and Zigbee, Thread and Bluetooth® Low Energy protocols in a fully concurrent fashion.

TABLE 1
QORVO QPK8642

Qorvo edgeBoost™	In the QPF7219 filter; maximizes output power at channels close to the band edge, nearly tripling Wi-Fi capacity
Qorvo bandBoost™	Achieved by combining the QPQ1903/QPQ1904 filters with Qorvo's latest-generation 5 GHz FEMs; enables high-performance, tri-band designs with footprints 20x smaller than those using traditional filtering technologies
Qorvo coexBoost™	In the QPG7015M transceiver; provides IoT connectivity and coexistence with in-box Wi-Fi – essentially boosting coexistence between different radios

The QPK8642 combines three unique Qorvo capabilities designed to maximize capacity and range. It will be available in Q2 2020.

More information about the company's Wi-Fi innovation can be found at https://www.qorvo.com/innovation/wi-fi

References

1 "Worldwide Smart Home Devices Forecast to Maintain Steady Growth Through 2023," IDC, September 2019

Wi-Fi 6 is Certified, an Evolution in Delivery of Wi-Fi Connectivity

Wi-Fi Alliance

160 MHz channels, 1024 QAM, beamforming & MU-MIMO

The Wi-Fi CERTIFIED 6™ certification program from the Wi-Fi Alliance® is available and delivers the best user experience with devices based on the IEEE 802.11ax standard. The certification program brings new features and capabilities that enable substantially greater overall Wi-Fi® network performance in challenging environments with many connected devices, such as stadiums, airports and industrial parks. With adoption of the latest Wi-Fi generation increasing, product vendors and service providers can trust Wi-Fi CERTIFIED™ will distinguish Wi-Fi 6 products and networks that meet the highest standards for security and interoperability. Wi-Fi CERTIFIED 6 provides significant capacity, performance and latency improvements to the entire Wi-Fi ecosystem, while ensuring products across vendors work well together to deliver greater innovation and opportunity.

Wi-Fi CERTIFIED 6 supports a more diverse set of devices and applications, from those requiring peak performance in demanding enterprise environments to those requiring low power and low latency in smart homes or industrial IoT scenarios. Wi-Fi CERTIFIED 6 delivers nearly four times the capacity of Wi-Fi 5 and is an evolutionary advancement for Wi-Fi's ability to deliver high-performance infrastructure and optimized connectivity to all devices on a network simultaneously — bringing noticeable improvements in densely connected Wi-Fi environments. Wi-Fi CERTIFIED 6 delivers critical connectivity that supports cellular networks and leverages high speeds, low latency, power efficiency, greater capacity and enhanced coverage to deliver many advanced 5G services.

"Wi-Fi CERTIFIED 6 is ushering in a new era of Wi-Fi, building on Wi-Fi's core characteristics to provide better performance in every environment for users, greater network capacity for service providers to improve coverage for their customers and new opportunities for advanced applications," said Edgar Figueroa, president and CEO, Wi-Fi Alliance. "Wi-Fi CERTIFIED 6 will deliver improvements in connectivity, including in high density locations and IoT environments."

Wi-Fi CERTIFIED 6 delivers advanced security protocols and requires the latest generation of Wi-Fi security, Wi-Fi CERTIFIED WPA3™. Advanced capabilities available in Wi-Fi CERTIFIED 6 include:

- **Orthogonal frequency division multiple access (OFDMA):** effectively shares channels to increase network efficiency and lower latency for both uplink and downlink traffic in high demand environments.
- **Multi-user multiple input multiple output (MU-MIMO):** allows more downlink data to be transferred at once and enables an access point to transmit data to a larger number of devices concurrently.
- **160 MHz channels:** increases bandwidth to deliver greater performance with low latency.
- **Target wake time (TWT):** significantly improves battery life in Wi-Fi devices, such as Internet of Things (IoT).
- **1024-QAM:** increases throughput in Wi-Fi devices by

encoding more data in the same amount of spectrum.

- **Transmit beamforming:** enables higher data rates at a given range resulting in greater network capacity.

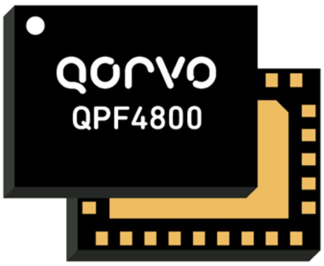
"Wi-Fi 6 brings greater speeds and more efficiency to Wi-Fi networks, expanding its role as a critical communication platform," said Phil Solis, research director at IDC. "Wi-Fi CERTIFIED 6 drives a higher quality experience for all Wi-Fi's many use cases, further propelling the Wi-Fi market and ensuring Wi-Fi maintains its strong position as the connectivity landscape evolves."

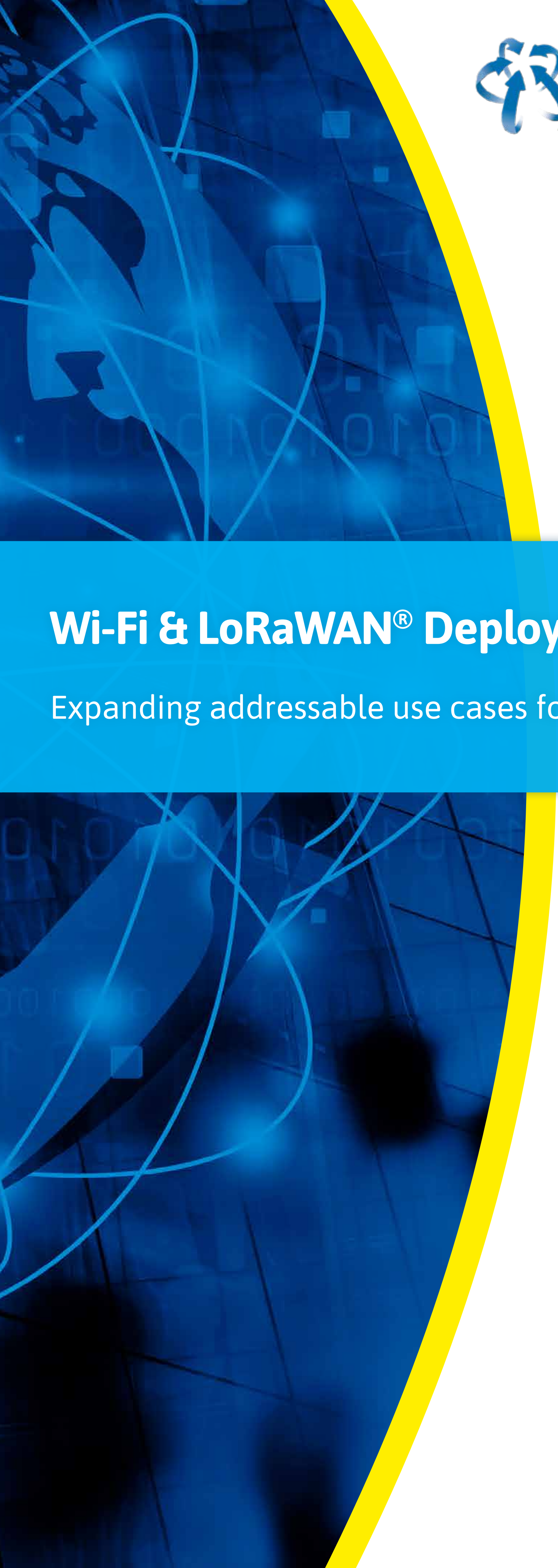
Wi-Fi CERTIFIED 6 expands on Wi-Fi's core strengths including affordable performance, efficient operation, commitment to security, ease of use, self-deployment and long-term compatibility, while also supporting a more reliable user experience in areas of high user demand. Wi-Fi CERTIFIED 6 leverages Wi-Fi's global ubiquity to more efficiently connect users in more environments, support growing data requirements and expand advanced use cases including augmented and virtual reality (AR/VR), streaming high-definition content, real-time monitoring and mission critical applications. As more spectrum is made available for Wi-Fi, Wi-Fi CERTIFIED 6 will only continue to drive greater global Wi-Fi innovation and economic contributions.

The Samsung Galaxy Note10 is the first Wi-Fi CERTIFIED 6 smartphone, and Wi-Fi Alliance expects most leading phones and access points will soon support the latest generation of Wi-Fi. The first products designated Wi-Fi CERTIFIED 6 which comprise the test bed for certification include:

- Broadcom® BCM4375
- Broadcom® BCM43698
- Broadcom® BCM43684
- Cypress CYW 89650 Auto-Grade Wi-Fi 6 Certified
- Intel® Wi-Fi 6 (Gig+) AX200 (for PCs)
- Intel® Home Wi-Fi Chipset WAV600 Series (for routers and gateways)
- Marvell 88W9064 (4x4) Wi-Fi 6 Dual-Band STA
- Marvell 88W9064 (4x4) + 88W9068 (8x8) Wi-Fi 6 Concurrent Dual-Band AP
- Qualcomm® Networking Pro 1200 Platform
- Qualcomm® FastConnect 6800 Wi-Fi 6 Mobile Connectivity Subsystem
- Ruckus R750 Wi-Fi 6 Access Point

More information on Wi-Fi CERTIFIED 6 is at https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-6.■





WIRELESS BROADBAND ALLIANCE
DRIVING NEXT WIRELESS EXPERIENCE

LoRa Alliance®

Wi-Fi & LoRaWAN® Deployment Synergies

Expanding addressable use cases for the Internet of Things

Source: Wireless Broadband Alliance and LoRa Alliance

Author(s): LoRa Alliance & WBA IoT Work Group

Issue Date: September 2019

Version: 1.0

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ABOUT THE WIRELESS BROADBAND ALLIANCE

Founded in 2003, the vision of the Wireless Broadband Alliance (WBA) is to drive seamless, interoperable service experiences via Wi-Fi within the global wireless ecosystem. WBA's mission is to enable collaboration between service providers, technology companies and organizations to achieve that vision. WBA undertakes programs and activities to address business and technical issues, as well as opportunities, for member companies.

WBA work areas include advocacy, industry guidelines, trials and certification. Its key programs include NextGen Wi-Fi, 5G, IoT, Testing & Interoperability and Roaming, with member-led Work Groups dedicated to resolving standards and technical issues to promote end-to-end services and accelerate business opportunities. WBA's membership is comprised of major operators and leading technology companies, including Broadcom, BSNL, Orange, Facebook, Google, HPE Aruba, Huawei, Microsoft, NTT DOCOMO Ruckus, Shaw, SK Telecom and T-Mobile US.

The WBA Board includes AT&T, Boingo Wireless, BT, Cisco Systems, Comcast, Deutsche Telekom AG, GlobalReach Technology, Intel and KT Corporation. For a complete list of current WBA members, please **click here**.

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ABOUT THE LORA ALLIANCE

The LoRa Alliance is an open, nonprofit association that has become one of the largest and fastest-growing alliances in the technology sector since its inception in 2015. Its members closely collaborate and share expertise to develop and promote the LoRaWAN® protocol, which is the de facto global standard for secure, carrier-grade IoT LPWAN connectivity. LoRaWAN has the technical flexibility to address a broad range of IoT applications, both static and mobile, and a robust LoRaWAN Certification program to guarantee that devices perform as specified. The LoRaWAN protocol has been deployed by more than 100 major mobile network operators globally, and connectivity is available in more than 140 countries, with continual expansion.

LoRa Alliance®, LoRaWAN® and LoRaWAN Certified^{CM} are trademarks of the LoRa Alliance.

UNDERTAKINGS AND LIMITATION OF LIABILITY

CONTENTS

1 Introduction and gap analysis

Wi-Fi® and LoRaWAN® are two of the most adopted unlicensed technologies and together they address a large proportion of IoT use cases. The approaches for these technologies are on the disruption of private-public business models and also enabling participation in 5G success.

The Wi-Fi & LoRaWAN® Deployment Synergies white paper intends to demonstrate how these two widely deployed IoT Connectivity technologies can be utilized in tandem to effectively support a vast array of use cases. This paper will summarize the strengths of each technology, their individual positions in the IoT ecosystem, state their complementary nature, the way that both technologies can be easily deployed simultaneously and provide testimonials.

The work aims to showcase to Wi-Fi network owners and/or network service providers how **LoRaWAN® can be deployed on the top of an existing Wi-Fi network and, as a complement**, will allow for operational costs optimization.

The opposite is also relevant in **raising Wi-Fi awareness through the LoRaWAN® ecosystem.** The ingredients of the recipe: **network roll-out**, targeted **use cases**, **interconnection**, and **security** are described in this document.

Due to the disperse requirements of all potential use cases, multiple IoT connectivity technologies have been developed in the IoT domain for the last 20 years, previously known as M2M. The Technology choice is driven by factors such as cost efficiency, data rate, battery consumption, and range requirements.

Below is a list of the most deployed IoT Connectivity technologies:

- Short Range: IEEE 802.15.4 (ZigBee, 6LoWPAN…), Bluetooth/BLE, Z-Wave, IEEE 802.11ad (Wi-Gig).
- Medium Range: Wi-Fi, IEEE 802.11ah (Wi-Fi HaLo), IEEE 802.11p (vehicular transmission systems).
- Long Range LPWAN: LoRa® / LoRaWAN®, SigFox, Wi-Sun, Ingenu, DASH-7, Weightless.
- Long Range Cellular: 2G-GSM / GPRS / IS 95 (CDMA 2G), 3G UMTS / CDMA, Long Term Evolution, NB-IoT, LTE-M (Cat M1), CBRS, Multi-Fire, 5G.

Some IoT Connectivity technologies are based on cellular networks and use licensed spectrum (LTE-M, NB-IoT, 2G, 3G, 4G, 5G) that can only be deployed by Mobile Network Operators (MNO's). Recent advancements in 3GPP (LTE LAA, and 5G NR Standalone) and Multi-Fire have made it possible for non-MNOs to deploy cellular networks in the unlicensed spectrums, commonly known as Private LTE networks. Examples include the 2.6 GHz Time Division Duplex (TDD) band available in France for local PMR like services and the CBRS in the US. While there are certain advantages to Private LTE Networks, they commonly rely upon significant investments in infrastructure, support and administration.

Other IoT connectivity technologies operating in the unlicensed spectrum (Wi-Fi, LoRaWAN®, Zigbee, Zwave, and Bluetooth) can be potentially deployed by any type of actor: MNO's, Internet Service Providers (ISP), Multi-Service Operators (MSO), enterprises, cities, and/or developer communities. Some are predominant on the consumer market (mostly short-range technologies including Wi-Fi), others are more predominant on enterprise market (including LoRaWAN® and Wi-Fi). As stated earlier the primary focus of this paper is centered upon Wi-Fi and LoRaWAN®.

Recent IoT market developments and analysis prove that unlicensed and licensed spectrum band technologies are not only complementary but that it is essential to leverage both. Two leading unlicensed technologies in IoT are Wi-Fi and LoRaWAN®. Wi-Fi is the unprecedented leader in broadband connectivity and LoRaWAN® is the leader in long-range, low power connectivity.

With over 20 years of history and advancements, Wi-Fi has become the world's most common radio network for consumers and IoT. For example, today most MNOs around the world rely upon Wi-Fi networks to offload data generated by devices (voice, internet) located in buildings or in dense urban environments such as malls or venues. In 2018, Wi-Fi carried 67% of all mobile traffic in the US and 83% in Japan [1]. Likewise, LoRaWAN® has enjoyed similar rapid success. In just 3 years LoRaWAN® has been adopted by more than 100 network operators, including leading MNOs such as Objenious, Orange, Proximus, KPN, NTT Docomo, SKT, KDDI, Swisscom [2] and Tata Communications, a digital infrastructure provider.

As a reminder, the objective of this **Wi-Fi & LoRaWAN® Deployment Synergies** white paper is NOT to make a comparison of all IoT Connectivity technologies. The purpose of the paper is to focus on:

- Demonstrating **Wi-Fi's complementary** role with a globally adopted unlicensed technology: **LoRaWAN®**, driven by **similarities of go to market structures**. The combination of these unlicensed technologies allows covering the **large majority and diversity of most IoT use cases**, rolled out by **any type of market actor**.

Looking at the market structure, Wi-Fi and LoRaWAN® market proponents show great similarities. All kinds of market actors exist and may interconnect with each other: MNOs, MSOs, Enterprises, Cities, Open Developer communities, etc. Organic growth from enterprise and private networks is currently supplementing targeted network growth from MNOs.

As mentioned below (GSMA[3]), IoT covers typically two main categories of use cases which can apply to any IoT Connectivity technology:

Figure 1 - Type of IoT Use Cases

- **Massive IoT**, connecting billions of objects, transmitting a low amount of data, at a low data rate, mostly battery powered, designed to optimize energy consumption and lasting up to 15 years once installed. One can find applications in many verticals such as: utilities, cities, agriculture, logistics, buildings (airports, hotels, stadiums, multi-dwelling units, home, venues…), and supply chain or transportation.
- **Critical IoT**, connecting millions of objects, communicating high amounts of data, at a higher data rate, with low latency and high reliability, which mostly also results in higher power consumption. We find applications in transportation (connected vehicle, traffic control …), smart health (surgery, patient monitoring…), and industry (real-time applications, robots, remote manufacturing).

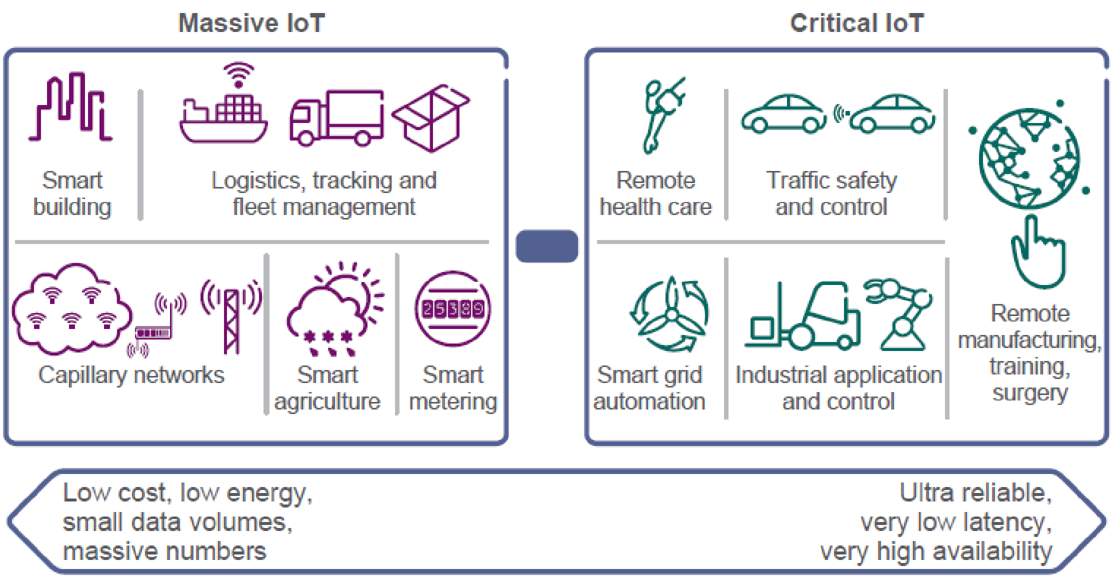


Figure 2 - Massive IoT versus Critical IoT

Today Wi-Fi is most often deployed to support critical IoT use cases whereas LoRaWAN® is utilized for massive IoT use cases. When used in tandem, the two technologies support a vast array of IoT use cases in the following verticals:

- Smart building / smart Hospitality
- Smart cities / smart villages
- Smart venues
- Smart automotive and transportation
- In-home consumer

Technical options to deploy Wi-Fi and LoRaWAN® in a mutualized infrastructure are covered in later sections with the purpose of highlighting that an **existing Wi-Fi infrastructure can be easily leveraged** to deploy LoRaWAN® as plug-in on Access Points (APs) or in Customer Premise Equipment. The level of integration (colocation or equipment convergence) will depend on coverage needs, sensor density and business requirements like SLAs. Technical integration will be discussed from the frontend (equipment) and backend integration (cloud) viewpoints, also covering security and interconnection processes. The lower cost and operation efficiency of a mutualized rollout compared to the deployment of both Networks separately will become obvious.

Testimonials in later sections from Wi-Fi providers deploying LoRaWAN® will reinforce the message that Wi-Fi and LoRaWAN® are widely implemented globally in real use cases supported by a strong ecosystem, while also being strongly synergistic. Examples of these use cases include:

- Equipment suppliers working on mutualized software and hardware solutions (e.g.: Multi-Tech[38], Gemtek, Ufi, or Ruckus have combined Wi-Fi / LoRaWAN® access points).
- IoT device makers offering embedded Wi-Fi & LoRaWAN® combined solutions, such as multi-technology trackers like Abeeway, OFO, Maxtrack, Chipsafer, and Gemtek.
- Cities or public bodies moving to IoT: ER-Telecom in Russia deploying citywide Wi-Fi and LoRaWAN® in top 60 cities [4] or city of Calgary who has complemented its Wi-Fi network with a LoRaWAN® infrastructure.
- MNOs driving a harmonized licensed and unlicensed strategy such as Orange [5] and BT [6].
- Unlicensed operators focusing on LoRaWAN® IoT strategy like Unitymedia [7] in Germany, and Tata Communications in India, Charter and Comcast in the US.
- Roaming / Interconnection leaders driving a harmonized strategy to interconnect multiple IoT Connectivity technologies such as Orange, Syniverse, or BSG.

Lastly, we expect that simultaneous deployments of Wi-Fi and LoRaWAN® to support IoT will have long term benefits. Both technologies have a strong history of market success, long term roadmaps and have a clear direction to support the future 5G world.

2 Wi-Fi technology

Wi-Fi is a family of radio technologies commonly used for **wireless local area networking** (WLAN) of devices. It is based on the **IEEE 802.11** family of standards. Wi-Fi is a trademark of the Wi-Fi Alliance**.** Wi-Fi uses multiple parts of the IEEE 802 protocol family and is designed to seamlessly interwork with the wired protocol Ethernet.

Devices that can use Wi-Fi technologies include desktop and laptop computers, smartphones and tablets, smart TVs, printers, digital audio players, digital cameras, cars and drones, etc. Compatible devices can connect to each other over Wi-Fi through a wireless **Access Point** as well as to connected Ethernet devices and may use it to access the Internet. Such an **Access Point** (or Hotspot) has a range of about 20 meters (66 feet) indoors and a greater range outdoors. Hotspot coverage can be as small as a single room with walls that block radio waves, or as large as many square kilometers achieved by using multiple overlapping access points.

The different versions of Wi-Fi are specified by various IEEE 802.11 protocol standards, with the different radio technologies determining the ranges, radio bands, and speeds that may be achieved. Wi-Fi most commonly uses the 2.4 GHz Ultra High Frequency (UHF) and the 5 GHz Super High Frequency (SHF) SHF & Industrial, Scientific and Medical (ISM) radio bands; these bands are subdivided into multiple channels. Each channel can be time-shared by multiple networks. These wavelengths work best for line-of-sight**.** Many common materials absorb or reflect them, which further restricts range, but can tend to help minimize interference between different networks in crowded environments. At close range, some versions of Wi-Fi, running on suitable hardware, can achieve speeds of over 1 GBps (Gigabit per second).

IEEE 802.11	Frequency bands used
802.11a	5 GHz
802.11b	2.4 GHz
802.11g	2.4 GHz
802.11n	2.4 & 5 GHz
802.11ac	Below 6 GHz
802.11ad	Up to 60 GHz
802.11af	TV white space (below 1 GHz)
802.11ah	700 MHz, 860MHz, 902MHz, etc. ISM bands depend on country
802.11ax	1 to 7 GHz

Figure 3 - Wi-Fi Standards

Wi-Fi 6 (11 ax) delivers improvements and new features that enable Wi-Fi devices to operate efficiently even in dynamic environments involving a large variety of device types. Below are the Wi-Fi 6 key capabilities:

Feature	Description	Business Advantage / Impact
OFDMA Uplink & Downlink	With uplink/downlink OFDMA technology, more data can flow simultaneously, resulting in more efficient transmissions. Increases efficiency and reduces latency as several devices communicating concurrently in portions of the frequency spectrum allocated proportional to their needs.	Wi-Fi becomes a much better solution for public hotspots, service provider Wi-Fi, and for Wi-Fi/LTE Aggregation. Particularly in high density, high throughput environments, boosting data rates and allowing more simultaneous clients to be supported is key.
Transmission Scheduling	Scheduling allows transmissions to be orchestrated, users are scheduled so that data requests on the uplink do not clash with each other.	Managed approach results in better resource utilization and an increase in efficiency, and therefore, better operator control over quality of service.
Multi-User MIMO Uplink	Increase channel capacity when servicing multiple simultaneous devices (up to 8x8). In addition to downlink MU-MIMO (from 802.11ac) that is important for keeping real-time traffic flowing smoothly on congested networks, uplink was added to address further use cases.	Serve up to 8 users simultaneously for a significant capacity boost. Address use cases from enterprise networks, large public venues and multi-dwelling buildings.
Gigabit Speeds	Allow peak gigabit speeds by adding the ability for devices to send traffic along wider channels (up to 4x-6x faster than the last generation). Faster modulations schemes as 1024 QAM.	Support new use cases such as UHD Video, AR/VR, Next-gen e-Classrooms and requirements of high-density environments (such as enterprise and condominiums).
Flexible Channel Sizes	Channel sizes are chosen based on the wide range of applications. Has flexible arrangement with channel sizes of 20/40/80/160 MHz, but a 20 MHz channel may break down into smaller blocks. Able to divide channels into small parts by using the sub-carriers enabled by OFDMA	The use of smaller channel sizes for IoT devices allows them to more efficiently use spectrum when lower data rates are required and allows devices to use less power consumption.
Target Wake Time	Orchestrate specific times when clients awake / sleep and reduces access contention by allowing devices to wake up at periods other than the beacon transmission period.	Reduce power consumption significantly improves device battery life.
Spatial Reuse	Enables devices to differentiate transmissions in their own network from transmissions in neighboring networks. Thus, allows APs to more efficiently share channel capacity.	Collision between communications of nearby users is mitigated. Tool to help making intelligent decisions on when to transmit data.
Dual Band Frequencies	Support both 2.4 GHz and 5GHz - works in both bands in a unified way.	All previous Wi-Fi generations are compatible and spectrum usage possibilities expand.
SON	Self-optimizing network functionality includes mesh networking: security automation, bandwidth optimization, channel & traffic management.	Full infusion of these features on the market, mostly in consumer mesh router products, re-enforces simplicity.
Guard Interval	Doppler Bit field impacts - used to eliminate inter-symbol and inter-carrier interference.	Targeted to improve outdoor performance.

Figure 4 - Wi-Fi 6 Key Capabilities (source: Wireless Broadband Alliance)

3 LoRa®/ LoRaWAN® technology

LoRa® is a Chirp Spread Spectrum (CSS) physical layer supported by major silicon providers such as Semtech, ST Micro Electronics, Microchip and module makers such as Murata, IMST and many others. LoRa® is an abbreviation of Long Range.

Figure 5 - LoRa Alliance Sponsors and Contributor Members (source: LoRa Alliance)

LoRaWAN® defines the media access (MAC) protocol (open networking protocol) and the system architecture for a wide area network. The LoRaWAN® specification is driven by the LoRa Alliance whose members (500+) are responsible for making and maintaining the MAC specifications on top of the LoRa® physical layer.

LoRa®

The term "LoRa" (**Lo**ng **Ra**nge) refers to the extreme long distance which can be achieved with very little power using a dedicated physical layer (PHY) based on CSS modulation. Transmission takes place in the license-free sub-gig ISM bands. Given the ultra-low power consumption measured in micro amps, LoRa® is a preferred choice for battery operated sensors, which only require small data packets to be sent, or received. By using very **low and adaptable bit rates (ADR),** the sensor **batteries will last for many years** depending on transmission frequency. Given the range of a LoRa® enabled gateway, enabling data transfer **over long distances,** the derived benefit is **very low Capital Expenditure (CAPEX) and Operational Expenditure (OPEX)** when deploying a LoRaWAN® network. Long range is achievable thanks to a correlation mechanism based on band spreading methods. This mechanism allows even extremely small signals disappearing in the noise, to be successfully de-modulated by the receiver. LoRa® receivers are still able to decode signals, which are up to 19.5 dB below the noise.

LoRa® signals have the following unique strengths:

- **Highly Robust**, resistant to both in-band and out-of-band interference mechanisms.
- **Multipath / Fading Resistant**, modulation is relatively broadband and thus LoRa® offers immunity to multipath and fading, making it ideal for use in urban and suburban environments.
- **Long Range Capability**, for a fixed output power and throughput, link budget of LoRa® exceeds conventional FSK.
- **Doppler Resistant**, Doppler shift introduces a negligible shift in the time axis of baseband signal.
- **Enhanced Network Capacity**, orthogonal spreading factors enables multiple transmissions with different data rates at the same time and on the same channel. Ideal to manage high capacity demand.
- **Ranging / Localization**, inherent property of LoRa® is the ability to linearly discriminate between frequency and time errors.

LoRaWAN®

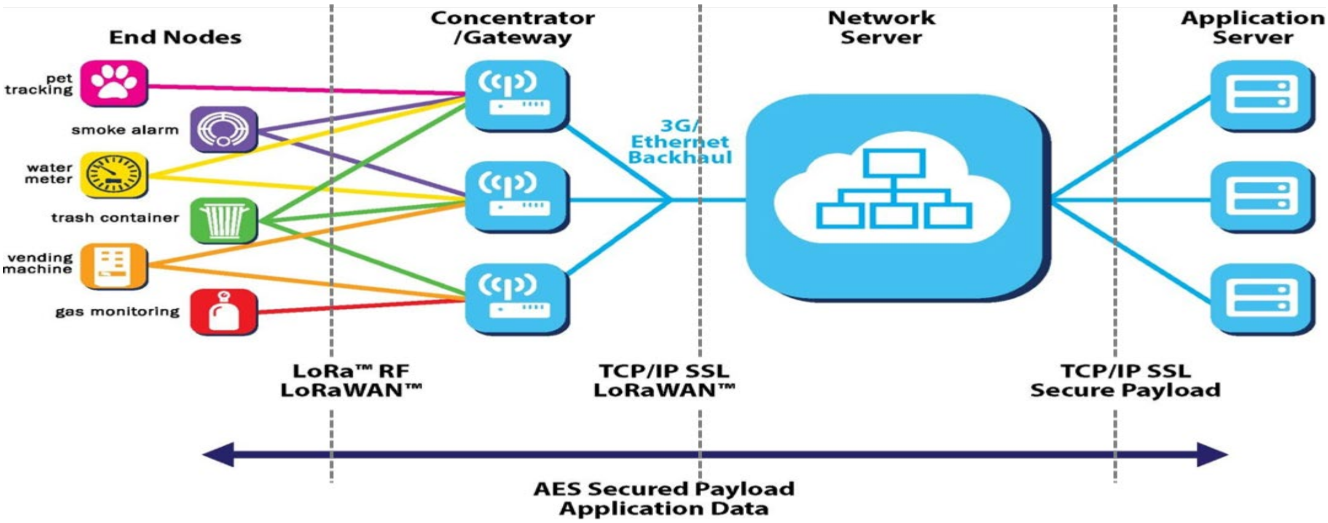


Figure 6 - LoRaWAN® system overview (source: LoRa Alliance)

A typical high-level system overview is built up of end nodes (**sensors**), **gateways**, a **network server** and an **application** server.

The LoRaWAN® specification is a Low Power, Wide Area networking protocol designed to wirelessly connect battery operated "things" to the Internet in campus, regional, national or global networks, and targets key IoT requirements such as bidirectional communication, end-to-end security, mobility and localization services.

The LoRaWAN® network architecture is deployed in a star-of-stars topology in which gateways relay messages between end-devices and a central network server. Gateways are connected to the network server via standard IP connections and act as a transparent bridge, simply converting RF (radio frequency) packets to IP packets and vice versa. The wireless communication takes advantage of the long-range characteristics of the LoRa® physical layer, allowing a single-hop link between the end-device and one or many gateways. All modes are capable of bidirectional communication, and there is support for multicast addressing groups to make efficient use of spectrum during tasks such as Firmware Over-The-Air (FOTA) upgrades or other mass distribution messages. The capability to receive the same message by multiple gateways increases the network SLA and prevents to manage "hand-over" between networks cells.

The specification defines the device-to-infrastructure (LoRa®) physical layer parameters & LoRaWAN® protocol and thus provides seamless interoperability between manufacturers, as demonstrated via the device certification program. While the specification defines the technical implementation, it does not define any commercial model or type of deployment (public, shared, private, enterprise) and thus offers the industry the freedom to innovate and differentiate to create competitive advantages.

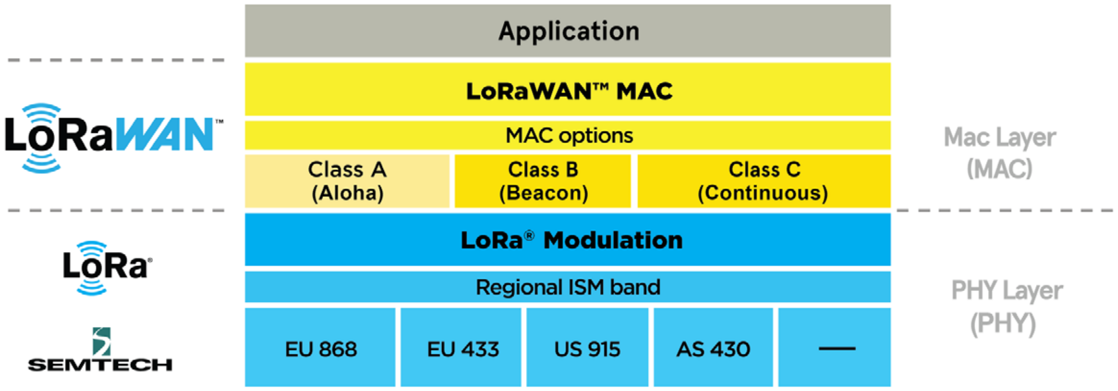


Figure 7 - LoRa / LoRaWAN® architecture (source: LoRa Alliance)

LoRaWAN® has three different classes of end-point devices to address the different needs reflected in the wide range of applications:

Class A – Low power, bidirectional end-devices

The default class, which must be supported by all LoRaWAN® end-devices, class A communication is always initiated by the end-device and is fully asynchronous. Each uplink transmission can be sent at any time and is followed by two short downlink windows, giving the opportunity for bidirectional communication, or network control commands if needed, a so-called ALOHA type of protocol. The end-device is able to enter low-power sleep mode for as long as defined by its own application: there is no network requirement for periodic wake-ups which makes class A the lowest power operating mode. Downlink communication must always follow an uplink transmission with a schedule defined by the end-device application; downlink communication must be buffered at the network server until the next uplink event.

Class B – Bidirectional end-devices with deterministic downlink latency

In addition to the class A initiated receive windows, class B devices are synchronized to the network using periodic beacons, and open downlink 'ping slots' at scheduled times. This provides the network the ability to send downlink communications with a deterministic latency, but at the expense of some additional power consumption in the end-device. The latency is programmable up to 128 seconds to suit different applications, and the additional power consumption is low enough to still be valid for battery-powered applications.

Class C – Lowest latency, bi-directional end-devices

In addition to the class A structure of uplink followed by two downlink windows, class C further reduces latency on the downlink by keeping the receiver of the end-device open at all times if the device is not transmitting (half duplex). Based on this, the network server can initiate a downlink transmission at any time on the assumption that the end-device receiver is open, resulting in no latency. The compromise is the power drain of the receiver (up to ~50mW) and as such class C is suitable for applications where continuous power is available. For battery-powered devices, temporary mode switching between classes A & C is possible and is useful for intermittent tasks such as firmware over-the-air updates.

In addition to frequency hopping, all communication packets between end-devices and gateways also include a variable “Data rate” (ADR) setting. The selection of the DR allows a dynamic trade-off between communication range and message duration. In addition, due to the spread spectrum technology, communications with different DRs do not interfere with each other and create a set of virtual ‘code’ channels increasing the capacity of the gateway. To maximize both battery life of the end-devices and overall network capacity, the LoRaWAN® network server manages the DR setting and RF output power for each end-device individually by means of an Adaptive Data Rate (ADR) scheme. LoRaWAN® baud rates range from 0.3 kbps to 50 kbps. In a highly dense network with end devices close to gateways, the battery lifetime is dramatically increased.

Security is a primary concern for any massive IoT deployment and the LoRaWAN® specification defines two layers of cryptography. LoRaWAN® embeds security by design:

- Unique 128-bit Network Session Key (NwkSKey) shared between the end-device and network server.
- Unique 128-bit Application Session Key (AppSKey) between the end-device and the application.

AES algorithms are used to provide authentication and integrity of packets to the network server and end-to-end payload encryption to the application server. By providing these two levels, it becomes possible to implement ‘multi-tenant’ shared networks without the network operator having visibility of the user payload data. Keys can be Activated By Personalization (ABP) on the production line or during commissioning, or can be Over-The-Air Activated (OTAA) in the field. OTAA allows devices to be re-keyed if necessary.

4 Wi-Fi / LoRaWAN® complementarity

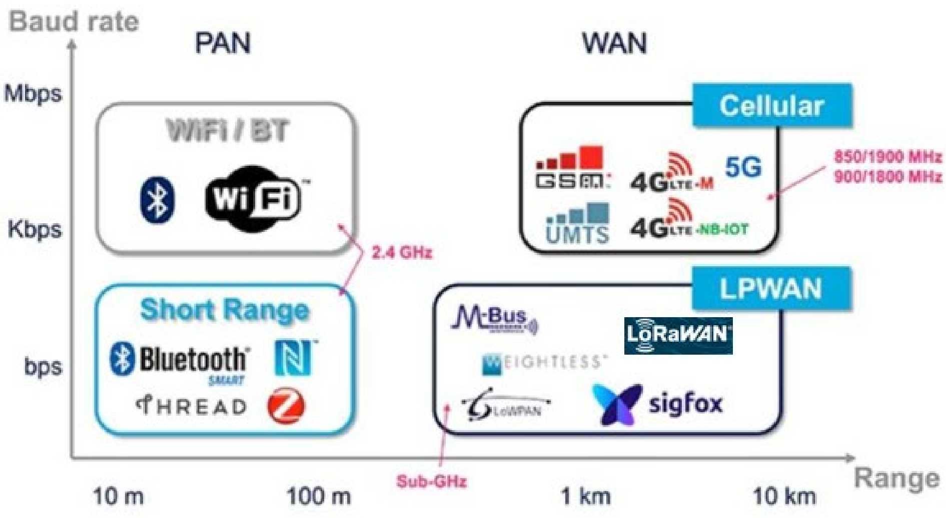


Figure 8 - Wi-Fi / LoRaWAN® complementarity (source: STMicroelectronics)

The scheme above shows IoT connectivity technology split in range and data rate:

- **Wi-Fi** covers **short,** and **medium range** use cases, at **high data rate** (can reach up to 1 GBps under certain conditions). It has an obvious cost in terms of **battery consumption**.
- **LoRaWAN®** covers **long range** use cases, at **low data rate** (0.3 KBps up to 50 KBps), with extremely **low battery consumption**, meeting up to 5 to 10-year battery lifetime, depending on device communication frequency.

For instance, **Wi-Fi** will be relevant in transmitting real-time video information or internet browsing, where **LoRaWAN®** will seamlessly deliver event-based information coming from a temperature sensor, although we can find some overlaps in the smart building and smart home areas where Wi-Fi has been operating for 20 years.

Another illustration of the above complementarity is that we usually see in the smart building / smart home spaces: “Wi-Fi devices where people usually are” whereas “LoRaWAN® devices where people usually are not (hard to reach areas)“.

5 Market overview

Wi-Fi market estimate

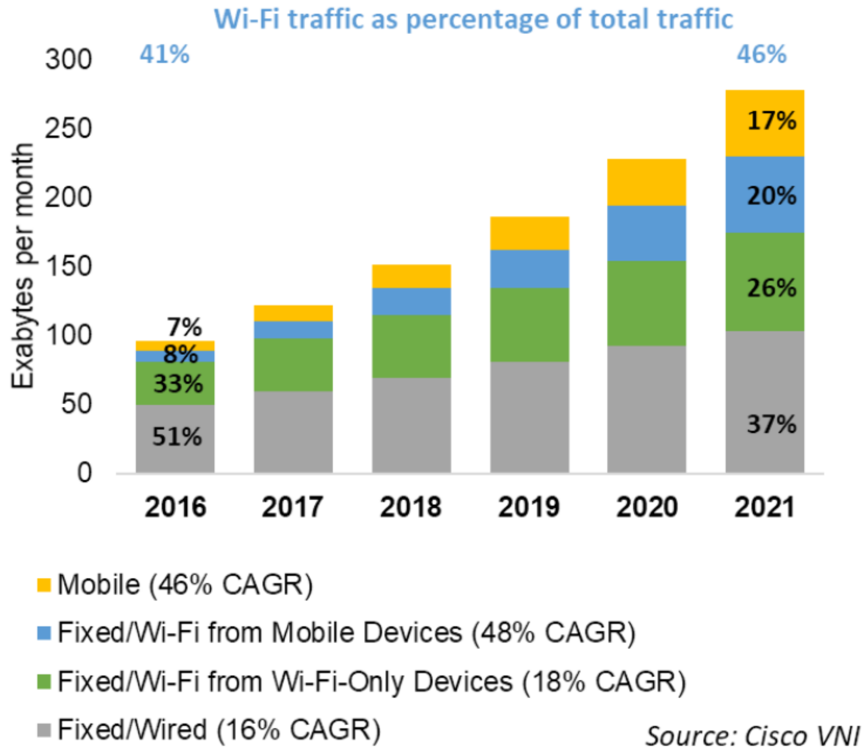


Figure 9 - Wi-Fi broadband traffic ratio on 2016-2021 period

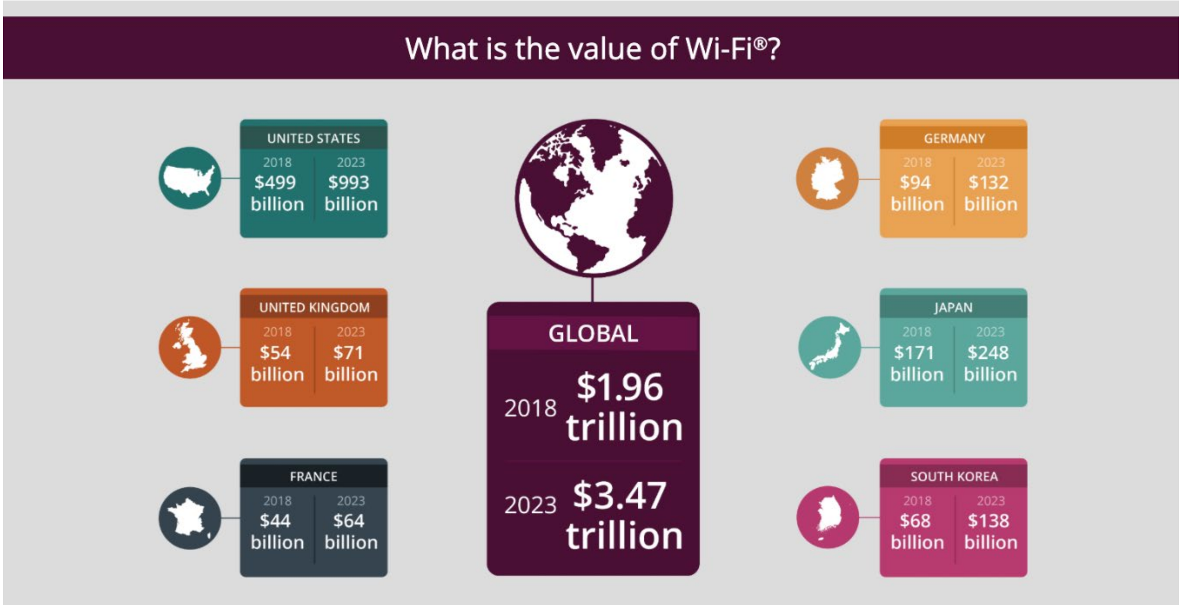


Figure 10 - Wi-Fi market value (Source: Wi-Fi Alliance)

Based on the WBA Annual Industry Report 2019 [1], Wi-Fi technology has strong perspectives of growth in the next years:

- Wi-Fi growth continues unabated, 9 billion Wi-Fi devices in use and 3 billion devices shipped every year (Wi-Fi Alliance).
- The introduction of 5G will not affect the prominence of Wi-Fi: Cisco VNI predicts that Wi-Fi as a percentage of global IP traffic will grow from 41% in 2016 to 46% in 2021.
- Next Generation Hotspot (NGH) and Passpoint® are seeing an adoption breakthrough, with operators such as AT&T, Charter, Boingo Wireless, Softbank, Sprint and T-Mobile, strengthening their commitment to these technologies to ensure seamless and safe connectivity for their subscribers when they visit their partners' Wi-Fi networks. At the Mobile World Congress (MWC) Americas in San Francisco in 2017, attendees used Passpoint® for 65% of Wi-Fi connections.
- Wi-Fi 6, the next-generation Wi-Fi technology based on IEEE 802.11ax, is coming soon. We already have pre-standard equipment and limited commercial deployments and we expect wider commercial availability in 2019 and final standard specifications by Q4 2019, with the timeline for Wi-Fi 6 slightly ahead of that for 5G New Radio (NR). The two technologies complement each other and are both necessary to realize the ITU's IMT-2020 vision of a pervasive connectivity fabric that reaches both people and things.

LoRaWAN® market estimate

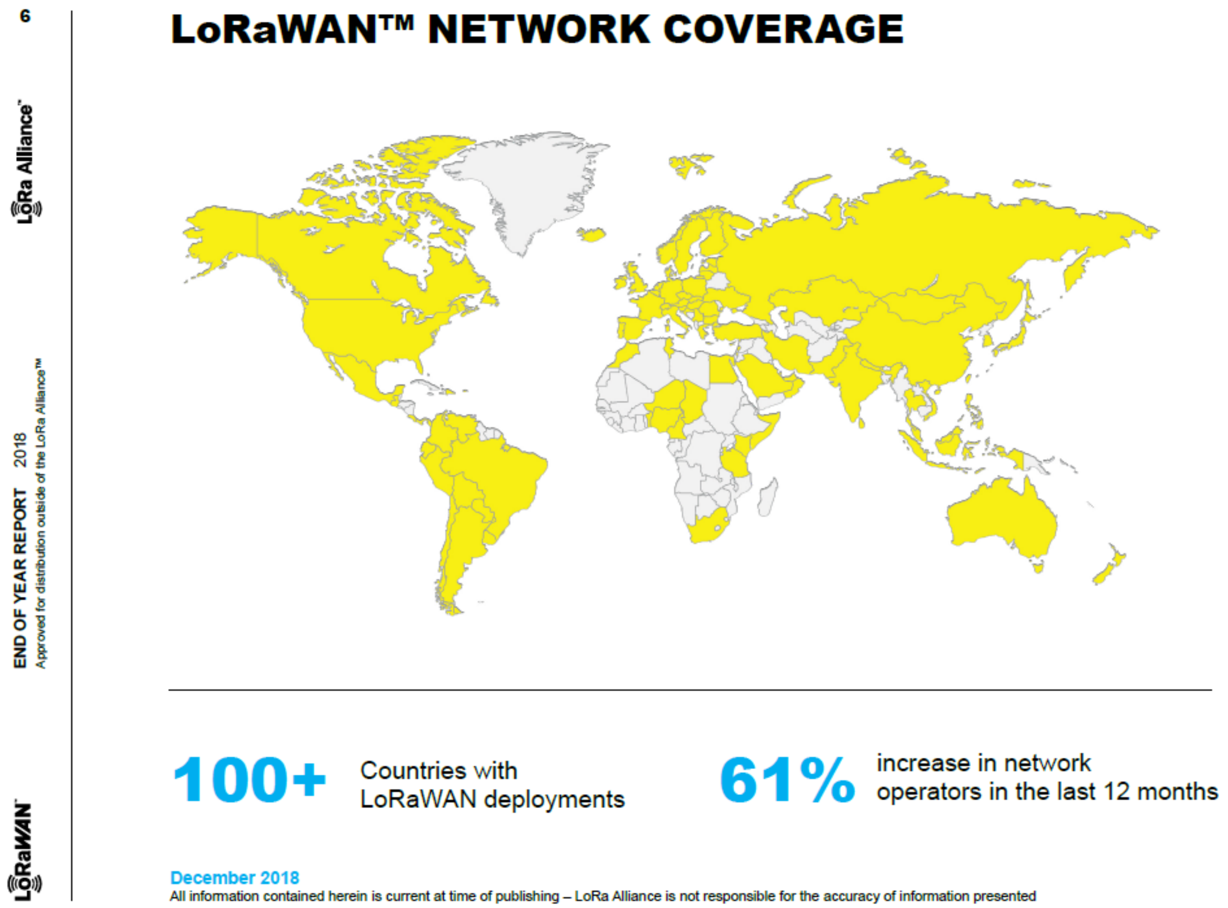


Figure 11 - LoRaWAN® global footprint (source: LoRa Alliance)

In 2018 and beginning of 2019, LoRaWAN® development has confirmed LoRaWAN® as the leading LPWA unlicensed technology. More than **100M** LoRa® devices have been deployed across the world, showing a growth of **60%** in 2018.

The number of operators increased by **61%** in 2018, reaching more than **100** LoRaWAN® operators. **30+** MNO's are deploying LoRaWAN® in parallel to cellular IoT connectivity technologies.

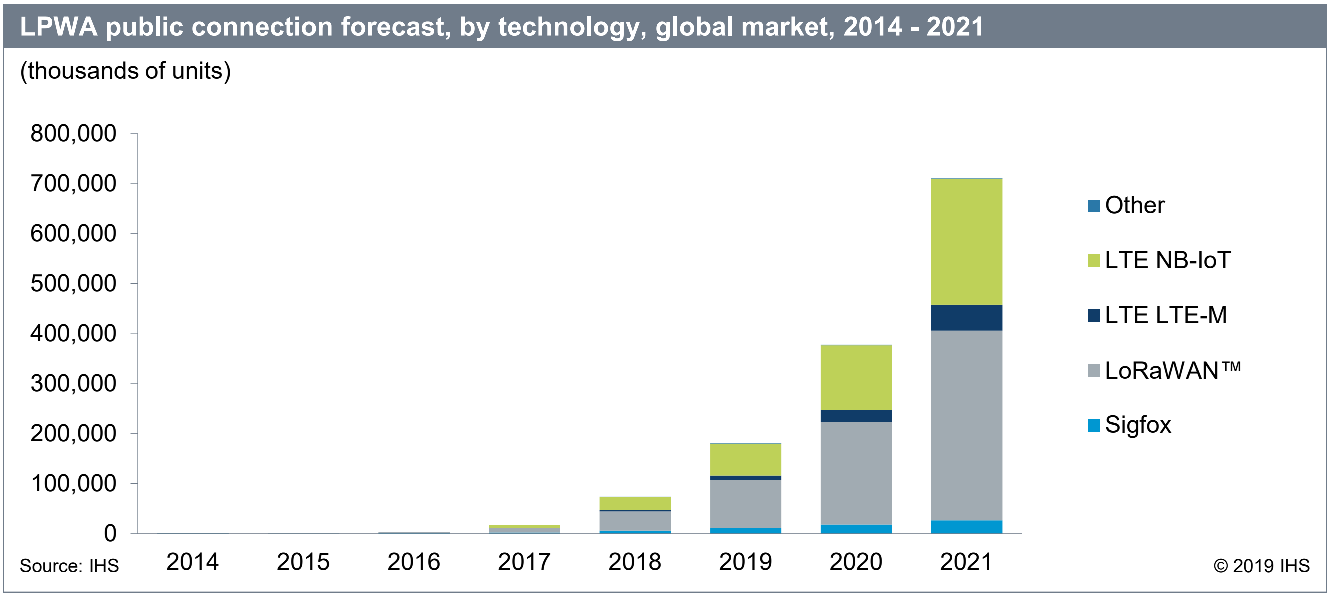


Figure 12 - HIS LPWA connection forecast

As per IHS forecast, LoRaWAN® is expected to represent more than 50% of IoT LPWA connections by 2021, confirming the current global market traction.

6 Market actors

IoT challenges

IoT is transforming end-customer business models. The main goal of IoT market leaders in the next two years is to SIMPLIFY the below process and decrease the lead-time for adoption and implementation.

- Identify the problem to tackle and potential savings or additional revenue.
- Identify and test potential IoT connectivity technologies while keeping in mind end-to-end integration (end devices, network, cloud integration, data management and data sharing with third parties).
- Set-up technical, business and organization frameworks to meet return on investment.
- Choose between make (private network) and buy (operator public network).
- Secure the end-to-end communication and data through the devices <-> access/core networks <-> application services.
- Benefit from Wi-Fi and LoRaWAN® complementarity by making convergent products (hardware and software). For example: collect data via LoRaWAN® on Access Points (performs the role of the IoT connector) from many devices around in building and transmit data via Wi-Fi to network servers.

Mobile Network Operators

The challenge for MNOs is to leverage their existing 3G / 4G infrastructure and optimize spectrum usage. Historically, MNOs have been focusing on connecting mobile phones for their customers with ever-increasing throughput requirements. With the rise of M2M, most operators also developed strategies to provide connectivity for Telematics or Navigation devices. The use of the network is controlled, and secured, by a SIM card and billing is mostly on a per device and data consumption basis. The implementation of Cellular IoT (NB-IoT, LTE-M) can be cost prohibitive depending on use cases.

Unlicensed band operators

The majority of Wi-Fi and LoRaWAN® adopters do not have access to licensed spectrum. It drives a diverse array of new and existing network players. Thus, triggering development of various strategies to participate in the IoT value chain: solution companies, venue owners, start-ups, utilities, MSOs, satellite operators, enterprises, railway companies, tower companies, utilities, real estate actors, equipment suppliers, industry 4.0, etc., diversifying to provide IoT services, disrupting roll-out, go to market and roaming business models, but also bringing fragmentation. Therefore, interconnection has become a key factor of success for IoT.

Enterprises

As per Vodafone IOT 2019 barometer [8], the majority of private companies are moving or planning to move to an IoT inclusive digitalization strategy. Companies are starting to experience the benefits of IoT and adoption is rapidly increasing. Almost every adopter says their projects are delivering results, and over half say that the benefits are significant. These benefits range from cost reductions to improved safety; from increased responsiveness to entirely new revenue streams. Unsurprisingly, the companies that are seeing the biggest advantages are those that are the most committed to the technology. But it's not all or nothing — there are benefits to be gained throughout the journey, from first steps to the most highly sophisticated, fully integrated solutions.

Public actors (city, council, region, government)

Cities, councils, and governments across the world are all developing IoT strategies and in many cases deploying their own infrastructure to enhance the life of its citizens or foster innovation by letting businesses use the infrastructure. In addition, anchor use cases, such as water metering, are driving network build out that can then be used for subsequent use cases.

More and more, cities tend to use a mix of public and private networks depending upon the criticality of the use-cases. Public networks such as Objenious and Orange in France or Swisscom in Switzerland already cover more than 95% of the population, thus make it quick and easy for cities to deploy LoRaWAN® use cases over a large territory.

Open communities

It is close to impossible to predict all possible use cases and potential business models which call for open communities, driven by developers, to explore any potential solutions in a simplistic way. LoRaWAN® open developer communities like The Things Networks, Actility, Loriot, Everynet, and Digital Catapult have enabled local initiatives in around 140 countries, attracting 50 000+ developers [9].

Consumer Market

The ease of use, decreasing cost and increasingnumber of end devices with LoRaWAN® and Wi-Fi support will unleash the penetration of both technologies into the mass market for smart homes and beyond. It is also more than likely that business models will follow the Wi-Fi monetization model, as Wi-Fi is already massively rolled-out in the smart home, and not a per end-device subscription model.

7 Licensed / Unlicensed band strategy

MNOs who have barely deployed LTE and have yet to derive the financial benefits of this evolution will shortly have to face quite a few challenges when moving to 5G. The overall strategy for 5G is around latency and throughput, however:

- Existing services (voice and data on 2G, 3G, 4G) have still to be operated for years.
- Licensed band is not free of charge and use of spectrum should be optimized.
- IoT Total Cost of Usage on a cellular backbone infrastructure is a challenge.
- 3GPP starts pushing for cellular IoT in unlicensed band.
- Majority of current LPWA Networks are using unlicensed band for nimble low-cost deployments. Therefore, several MNOs and MSOs tend to use unlicensed technologies to optimize cost and performance. IoT might not justify roll-out cost of Cellular technologies in urban / rural areas however unlicensed has cost justification and shorter ROI time periods. Market adoption of mobile traffic off-loaded to Wi-Fi has already been proven and IoT is following the same path. Site acquisition in urban areas has become a challenge where Wi-Fi Networks are already positioned on the strategic last mile.

MNOs have to decide the best cost-efficient roll-out strategy to meet customer demand, develop promising massive IoT business, and prepare 5G challenges on Enhanced mobile broadband and critical IoT.

8 Addressable use cases

Within this section you will see the vast amount of market segments and use cases that Wi-Fi and LoRaWAN® can support when utilized as complementary services.

8.1 Smart Building / Smart Hospitality

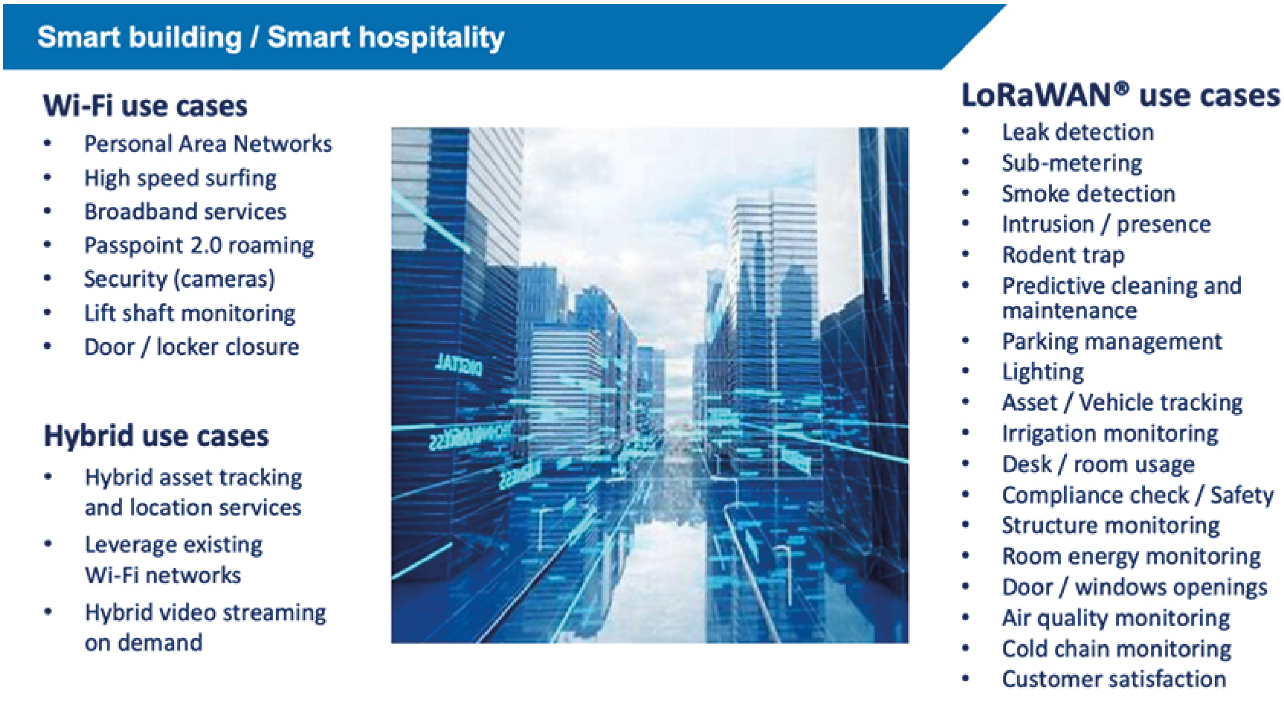


Figure 13 - Smart building vertical. (Source: Wireless Broadband Alliance / LoRa Alliance)

Context

Smart Buildings have been around for decades but have primarily focused on the day-to-day operations of the building such as ventilation, lighting and access control. These systems were generically proprietary. With new, standardized, wireless technologies and the rise of data analytics, many new use cases are now commercially feasible. Businesses have an incentive to more efficiently use expensive leased space, reduce utility energy / water consumption and to increase employee productivity as well as enable remote features such as locking and unlocking. The flexibility offered by wireless devices now allows placement anywhere in a building without pre-planning sensor locations or even seeking permission from the building owner in some cases. Building compliance and people safety are also areas of relevant IoT use cases (fire detection, water quality, amongst others).

Wi-Fi use cases

Wi-Fi on campus connects student or employee personal devices (PAN) (mobile, laptop or tablets) at high-speed and reliably, as well as offers the maximum coverage so that students can sit wherever they want.

Wi-Fi has always been strongly relevant for high-speed internet surfing mostly indoor. New roaming strategies based on Next Generation Hotspot (NGH) - combination of automatic authentication from the Wi-Fi Alliance's Passpoint® with seamless roaming experience advocated on the WBA's Wireless Roaming Intermediary eXchange framework - are significantly improving customer experience and offer a seamless connection.

Indoor security cameras are also a value added by Wi-Fi deployed in campuses, buildings and cities.

As we have all experienced, Wi-Fi is deployed in nearly 100% of hotels globally, as a platform for broadband and customer focused services (tourist information, web services, etc.). Wi-Fi also supports the operations of the hotel through lift shaft monitoring, roof space and door / locker closures.

LoRaWAN® use cases

LoRaWAN® is ideal for any number of use cases, which require deep indoor coverage and long battery life [10]. For many applications, sensors are placed in remote areas, where coverage is hard to ensure and where access for battery replacement is difficult. Some examples of these types of applications would be leak detection, sub metering, smoke detector alarms, intrusion and presence monitoring, rodent trap monitoring and predictive cleaning and maintenance. LoRaWAN® also offers the ability to cover outdoor areas cost effectively to enable things like smart parking, smart lighting, beam lighting, asset / vehicle tracking, or smart irrigation and allows the smart building to be part of a larger Campus or city.

Energy optimization within buildings is a key part of every company‘s sustainability / green initiatives. Savings of up to 25% can be achieved thanks to simple actions based on the analysis of smart-counter index information provided by LoRaWAN® enabled smart-meters.

LoRaWAN® can also be used in a number of ways to monitor how space is being utilized. One example is conference room usage: either straightforward occupancy or actual counting of the number of people in a room. Studies indicate that up to 30% of the time a conference room is booked, it is not used. Likewise, the average size of conference room holds 6-8 people while the most common meeting size is 2-3 people. Desk / Meeting room occupancy monitoring is a growing trend, especially in “hot desk” environments. The evolution of the white-collar office is clearly towards shared workspaces and remote work. Reducing the amount of space used has an impact 10x greater than energy savings alone when leasing costs are considered. As a tenant, it is almost impossible to know if you have leased the optimal square footage and implemented efficient usage programs to house your operation. Property management firms cannot be omniscient to observe space utilization. How well is a hot-desk program running? Where are the available desks? Do we really need this many meeting rooms? Occupancy sensors give you real-time availability of information as well as historical usage over time. Real data provides evidence needed to right size your real estate footprint, potentially saving up to 25% in rent or lease expense.

As co-working spaces are disrupting the competitive landscape for office tenants, facilities managers are under increasing pressure to ensure tenant workers are happy, comfortable and delighted. Workers are demanding amenities and refuse to settle for office space that is sub-par. Healthy environments are not only essential to keep tenants, they are also cost effective. Real-time monitoring of temperature, humidity and CO_2 levels (smart health monitoring) leads to real energy savings across a floor, a whole building or multiple buildings. Consolidating data over multiple facilities over time provides a comprehensive view of trends and performance including impact of external forces such as weather that leads to more-informed and better decisions.

Most facility managers spend significant budget cleaning areas that are already clean, emptying waste bins that are only partially full and responding to predictable crises because they do not have real-time insight about when to intervene. This approach is expensive and inefficient. This problem of predictive cleaning has become key. Data generated by actual use allows you to move from wasteful schedule-based cleaning services to more efficient just-in-time cleaning. For example, you could set a usage threshold on a space that would trigger an alert to a cleaner when that threshold was met. With insight into usage patterns, you can transition from simply reacting to crises and customer complaints to proactively addressing issues before they become problems, thus improving the experience of your customers. In addition, service sensors keep you apprised of cleaning activities so you can monitor and enforce your service level agreements with your vendors and staff and can be combined with Customer satisfaction buttons (Green, Yellow, and Red).

Creating safer building evacuation systems is another of the applications where LoRaWAN® technology brings a high value. Being able to regularly monitor the proper functioning and the battery level of an Exit sign for example, helps to avoid any risk of failure during an evacuation event. A simple light bulb failure could have major consequences in case of an emergency. Using LoRaWAN® communication between luminaires and stations now makes it cost effective to cover large indoor areas at a fraction of the cost. This also minimizes the need of routers and need of upgrading building infrastructure.

The impact of early leak detection cannot be overstated. Insurers, building owners and tenants all have a vested interest in detecting leaks early. The damage caused by even a slow leak over one weekend can run into the $10k's to $100k's very easily. If expensive equipment is damaged or the leak is more substantial, the costs can be significantly larger.

Hotels and smart Hospitality are another area where LoRaWAN® brings great value in IoT: air conditioning and energy monitoring, door / window opening alarms, room usage, leak detection, temperature and humidity monitoring, and air quality monitoring are all use cases which can be enabled. Moreover, hotel kitchens offer the opportunity for even more LoRaWAN® use cases such as: temperature monitoring, cold chain monitoring, smoke detectors, intrusion monitoring, energy monitoring, and presence detection.

Hybrid Wi-Fi / LoRaWAN®

Wi-Fi broadband is present in most buildings. Wi-Fi can be combined with LoRaWAN® to bring about accurate asset tracking indoor or near buildings.

Hybrid Wi-Fi / LoRaWAN® devices can provide long battery life devices with on-demand streaming. Events from low power LoRaWAN® sensors can trigger higher resolution data on Wi-Fi when needed. For example, a motion sensor / camera device can report motion to the cloud but enable the device to preserve battery except when an event is triggered. Algorithms can decide to turn on the camera or not. Such a device can be battery operated and still have long life. Furthermore, series of LoRaWAN® sensors (motion, sound, vibration…) can be aggregated in the cloud for more precise decision making.

As an additional example, NomoSense has built a hybrid solution relying on Wi-Fi and LoRaWAN® to reinforce work force safety in remote hazardous areas where Cellular networks are rarely available. NomoSense has iteratively designed a solution leveraging local Wi-Fi hot spots back-hauling LoRaWAN® Gateways. It relies on LoRaWAN® sound sensors to monitor remote construction site health combined with Wi-Fi hot spots to localize local work force in case of alert, thus increasing staff safety. So, Wi-Fi hot spots both provide location services and back-haul to LoRaWAN® Gateways.

8.2 Smart City / Smart Village

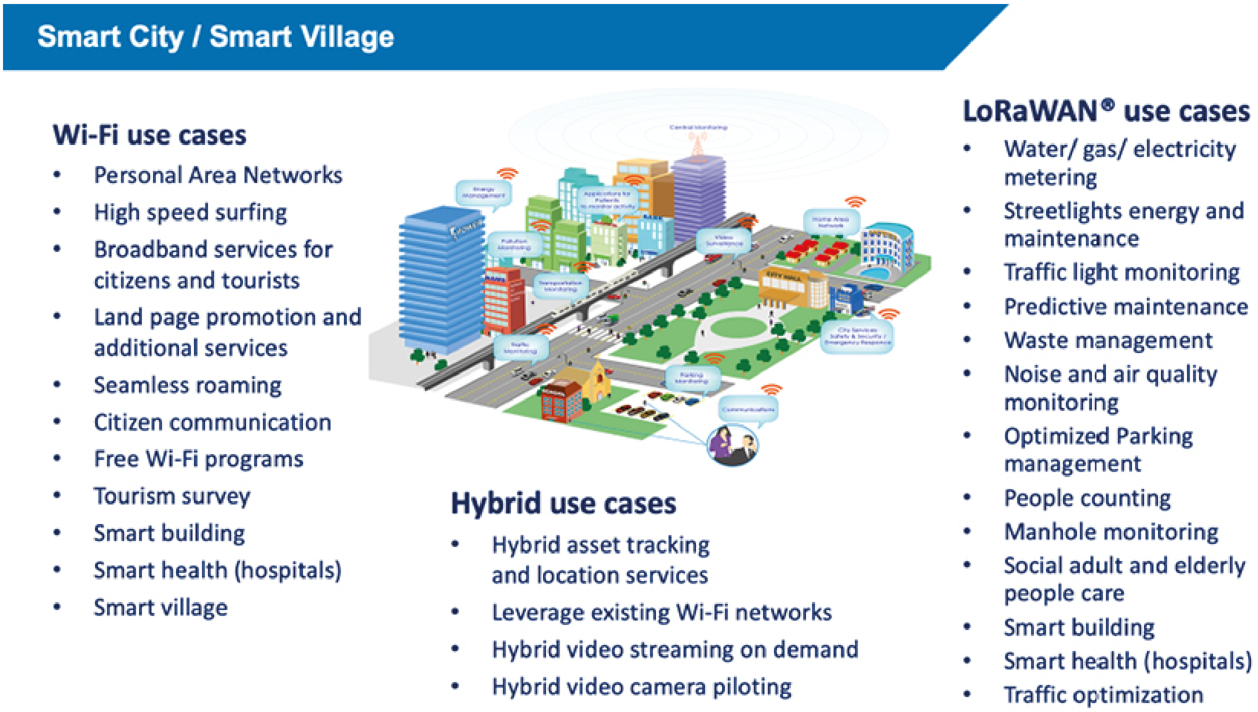


Figure 14 - Smart cities vertical (Source: Wireless Broadband Alliance / LoRa Alliance)

Context

Cities are under constant pressure to provide adequate services to their citizens and local businesses despite shrinking budgets and increasing populations. The creation of additional infrastructure to cope with the growing demand such as transportation, residential and business development is a costly and lengthy process and often lags well behind the real-world demands. An increasingly growing aging population (in some regions) puts immense strains on social care services. The disproportional increase in housing prices as compared to incomes drives more people into social housing. This has pushed many local authorities and cities to operate at their limit for public service delivery.

The current method of public service delivery is not sustainable anymore as it severely affects the quality of life of residents or/and challenge their economic basis and underlying financially viability.

Many cities have started to respond to these challenges by embracing digital innovations with the hope of increasing the efficiencies of public service delivery. This could be achieved by better predicting and managing peak demand on public services, cutting down costs of service delivery, minimizing environmental impact or improving operational efficiencies. Operationally, these initiatives are supported by **smart city** strategies and **digital master plans**. In practice a variety of smart city deployments have started to emerge mainly focused around IoT technologies to improve the delivery of public services in many areas ranging from smart parking and traffic management, multi-modal transportation, the management of social housing and residential care services, smart lightning or waste management services.

Providing an affordable IoT connectivity infrastructure is crucial to enable the realization of a variety of use cases in a city environment. Both Wi-Fi and LoRaWAN® technologies play an increasingly strategic role, which will be discussed below in more detail.

Wi-Fi use cases

Smart City

Medium-range implementation of Wi-Fi has become the table stake to provide public broadband services in cities. Wi-Fi presence is now part of the city brand as it's being used as a service towards tourists and inhabitants. Location based content on landing pages gives nearby information to tourists in multiple languages. Cities are forced to deploy concurrently backbone networks (fiber optics) to back-haul Wi-Fi collected data to centralized cloud servers. Wi-Fi service must be faster than mobile data connection in order to be used by citizens. For tourists, Wi-Fi is an opportunity to avoid roaming costs in some foreign countries.

Mesh technologies are challenging in cities due to the missing lines of sight. Wi-Fi and other wireless technologies provide easy to deploy off-the-shelf solutions. Moreover, Wi-Fi mesh has gained traction as connectivity for smart city use cases like smart lighting controller. Since the streetlights are at 12-24 feet height, Wi-Fi Mesh as backhaul solution is getting more traction. There are other solutions for the controller back haul including LoRaWAN®, cellular and proprietary connectivity.

Cities are under political pressure and need to get permanent citizen feedback to improve local services. Wi-Fi is the perfect technology to handle that.

In the last 2-3 years, there has been a trend in cities to offer free Wi-Fi to tourists and citizens. The counter part is to get an efficient citizen and tourist attendance monitoring system. Moreover, the European Union has set up a program called "Wi-Fi for EU" – or WiFi4Eu as it has officially been branded -, funding Wi-Fi projects that offer free internet service to tourists and citizens. As a result, cities have started to implement Wi-Fi access points at crowded places or places where people hang out.

With the Wi-Fi 6 supporting low latency and target wakeup time, Wi-Fi can be also used for smart city applications such as smart parking.

Smart Village

As highlighted by the government owed Centre for Development of Telematics in India (C-DOT), Wi-Fi as a technology has a potential to convert a village into a smart village with very low investment and sustainable business models. The concept of smart village is defined as any village equipped with technology which enables its habitants to connect to the mainstream digital economy of their country. The main goal of the smart village is to effectively address the day-to-day needs such as health, education, farming, irrigation, through technology which otherwise might not be available all the time with other conventional resources. Another major goal is to create local employments, encourage entrepreneurship among the people living in the village with the help of technology. Internet connectivity is mandatory to make all these goals possible, to create e-health, e-education etc. infrastructure which require a robust connectivity to interact with remote experts or contents.

In a country like India, VLE (Village Level Entrepreneurship) is a flagship program enabled through Digital India where local people are encouraged to own the digital infrastructure.

Wi-Fi as technology has inherent features which are suitable for providing access to internet connectivity in a smart village. To provide connectivity in a smart village, the technology we choose must have following features:

- Very low CAPEX & OPEX.
- Scalability must be easy and with the least amount of investments.
- Easy to maintain the technology at local level as maintenance cost is recurring.
- The available ecosystem of the devices to connect for the internet connectivity. If villagers require to buy new devices, then they should not be reluctant to do so.
- Wi-Fi being unlicensed technology is most suitable to meet all the above requirements for a smart village.

Two examples of implementation are described below:

Public Wi-Fi Hotspot at the Government / post office building: maintaining the Public Wi-Fi infrastructure in the Government or post office is easy as it provides a safe place with security and constant power supply. Villagers travel to Government office to get subsidies, to get their land record update, to register a newborn child, to register marriage, to register death, to understand new schemes launched by the government, etc. They visit the post office to send or receive letters. Post offices also allow the opening of bank accounts and can sometimes function as hubs for financial transactions in villages across India. Public Wi-Fi hotspots in and around the office buildings help villages to get this information faster. Villagers can also access this information online to save time.

Enabling Village Level Entrepreneurship using Wi-Fi network: Wi-Fi enables interesting use cases in the smart village scenario. For example, villagers typically use bicycles on their local commute. Those having to visit nearby farms or village also use motor cycles. People with increased economic status also prefer motor cycles. Cars which are generally considered a luxury in these countries require a regular maintenance as they move on non-concrete roads. These maintenances are generally performed by local mechanics with limited expertise. In towns/cities, we find authorized repair/maintenance stores for such activity. But having such full-fledged facility in a village is not sustainable due to the cost of establishing such infrastructure and creating a business model out of it due to low number of vehicles.

Now there is a use case where using Wi-Fi network (suitably Wi-Fi 6) can enable a local mechanic with little expertise to provide service at par with authorized stores. Here, the expert sitting in the authorized store can help the local mechanic to repair the motorbike or car remotely with the help of Augmented Reality over robust Wi-Fi network streaming the images to the remote expert for their opinion and help. Here, we are solving the local issues and creating employment opportunities. This investment in the Wi-Fi network helps the bike / car owner in many ways, from building trust with customers, to building brand recognition, to maintaining the life of vehicle and making a business case.

LoRaWAN® use cases

Smart City

Utilities [11] are at the forefront of employing IoT technologies on their journey toward digital transformation. The technology leading this charge is smart metering. For utilities, smart meters are foundational toward building tomorrow's smart grid, ultimately enabling new operational efficiencies, new service opportunities, and new revenue streams. According to a recent report by ABI Research, in 2018 there was an installed base of 617 million smart meters and by 2023 this install base will double to reach 1.34 billion meters. Smart electricity meters are just the first wave of technology that is driving the utility market's transformation; a second wave—through the deployment of smart water and gas meters — is just beginning. The example of Veolia choosing Orange to connect over 3 million smart meters in France is a good illustration [12]. Another example of large implementation: Tata Communications LoRaWAN® network will enable the customers of Indraprastha Gas, India's leading natural gas distribution company, to monitor their gas usage more accurately, in real-time, against available credit and pave the way for greater operational efficiency. Cities have still costly manual processes to both monitor their infrastructure and meet compliance requirements. The water network is a prime example of a large system, covering a wide area with many of the meters located in hard to access areas where automated monitoring can relieve the challenges of manpower access [35].

Electricity from streetlights [13] is a significant municipal expense, and by better managing it, cities can save money and cut greenhouse gas emission by reducing energy consumption. Smart light system provides the data that cities need to reduce energy usage while maintaining well-lit streets. Some LoRaWAN® sensors can be included on the pole to provide more value and insight to the city and control the light based on situations. Few examples include, water flooding sensors that help the city identify near flooding areas, proximity sensors and counting sensors that identify the number of people walking around to optimize luminaria intensity for operational cost savings. Environmental and pollution particle sensors help people with risky medical conditions to know what to expect in specific areas before they plan their outing.

Traffic light monitoring [13] allows municipalities to quickly respond to burned out lights, broken light poles from accidents, or malfunctioning signalling equipment. This helps with traffic congestion, accident prevention, and other hazardous situation management. Moreover, smart intersection monitoring can increase pedestrian safety and increase vehicular traffic fluidity.

Collective waste is an essential City service, but too often, resources are used to collect under-filled waste containers when others are overflowing. Smart waste management systems [13] can help detect garbage levels in containers to optimize the waste collection routes for efficiency and cost effectiveness.

As more people move to cities, noise and air pollution [13] become bigger challenges. Smart noise and air pollution monitoring can provide data that can improve citizen wellbeing and systemic health issue correlation. Air quality in schools in particular is a high potential use case because of the impact it has on family's concerns.

As more and more cities are facing challenging traffic congestions, better managing parking's (smart parking) [14] - used first for the monitoring of dedicated parking place such as handicap or police places - has become critical. LoRaWAN® based sensors combined with credit card enabled parking meters provide municipalities with a total solution for expanding the payer base of a parking infrastructure. With a mobile app, an enforcement officer is able to immediately see from anywhere which parking places are currently occupied or unpaid. These benefits also extend into the workforce since with LoRaWAN® technology parking attendants do not need to drive or walk specific routes. They can see where they are needed via a cloud-based application. This means need for fewer enforcement officers to maintain parking lots, and better utilization of the work force which could lead to additional savings.

As detailed below, Wi-Fi connections are partially used to track visitor and tourist attendance. Smart people tracking case can be adapted to several LoRaWAN® use cases combined with Wi-Fi data collection: people counting in demonstration, monuments, venues, hot traffic spots, etc.

Cities across the world see manholes stolen, with a double impact on municipality cost and security. Sensor based smart manhole monitoring allows quicker interventions for replacement or prevention.

Cities own tens to thousands of buildings, not to mention social housing and hospitals, where we can see smart building use cases.

Finally, yet importantly, Cities are going to invest more and more in adult social care and independent living solutions which will require IoT support to improve elderly people wellbeing: patient activity monitoring, fall monitoring, people monitoring, panic buttons, and medication usage tracking, etc.

Hybrid Wi-Fi / LoRaWAN®

Location and video streaming use cases are the same as the smart building section.

8.3 Smart Venue

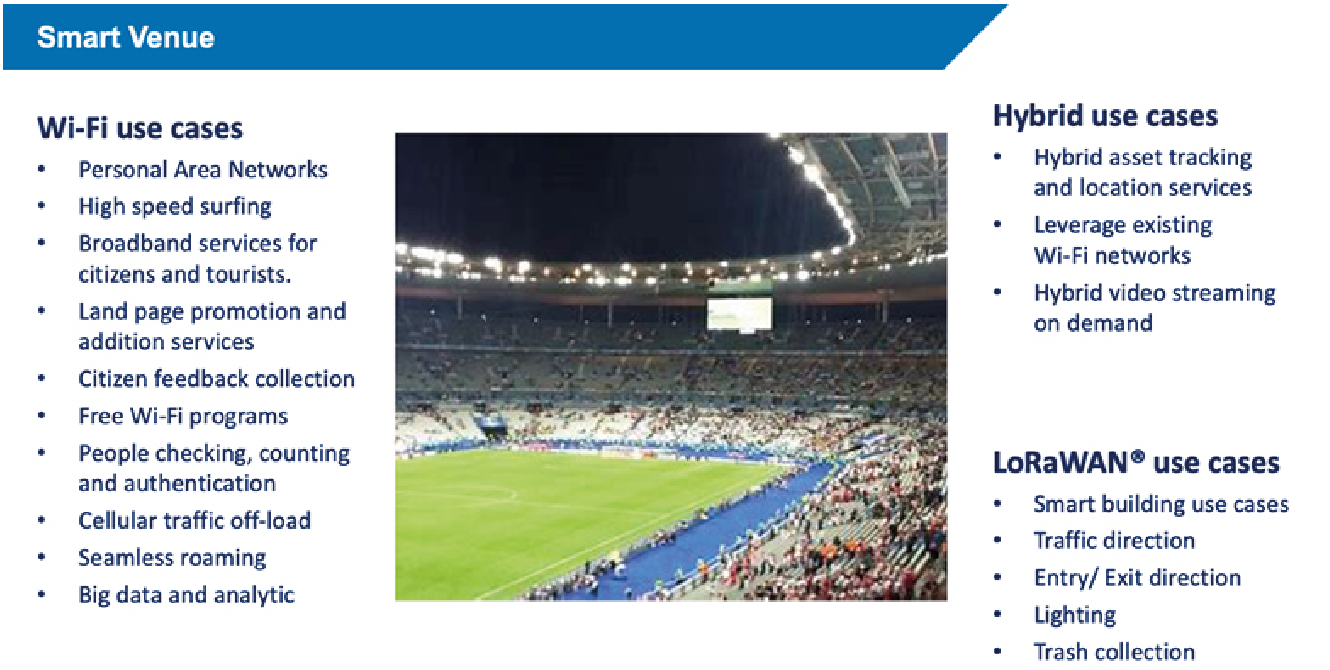


Figure 15 - Smart venue vertical (Source: Wireless Broadband Alliance / LoRa Alliance)

Context

Venues are places where there are large concentrations of people, such as squares, stadiums, transport stops, metro stations, and public transports. In these areas, cellular networks may be overflowed in certain periods of time.

Wi-Fi use cases

Wi-Fi Access Points are located in urban public venues, in which Local government may sponsor Wi-Fi placements.

The latest evolution of Wi-Fi technology and specifically Wi-Fi 6 have improved the customer experience. Enhanced types of authentication participate to the better customer experience: Open Authentication, Web Authentication (Web-Login or One-Click), Voucher-based Authentication, Prepaid (with quoted time), or Open Transparent Auto Logon.

A venue is the perfect place to offload cellular traffic on Wi-Fi infrastructure where cellular networks show coverage and capacity limitations. Roaming is a service offered by the Wi-Fi network service providers to end-users based on Next Generation Hotspot (NGH)seamless roaming. End-users are not even aware of moving to venue Wi-Fi networks when using their cell phone due to automatic network discovery and authentication from Passpoint®.

Wi-Fi in malls is mainly used for customer tracking and recognition, the focus is not so much on free internet service.

Wi-Fi landing page information are used as communication tool to potential customers (announcing upcoming events) similar to the Smart City vertical. Big data and analytics applications reinforce the benefit for Venue owners and Cities.

Security driven by Wi-Fi video in Offices, Enterprises, and Public Places (such as cafes, restaurants, hotels, oil stations, and so on) has become a critical use case (workforce, customer and territory control).

High people density on a small area requires optimizing staff presence at the right place at the right time to optimize maintenance and customer services via end to end tracking solutions.

With the Wi-Fi6 supporting low latency and target wakeup time, Wi-Fi can be also used for smart venues supporting applications like temperature control, automated ticketing, etc.

LoRaWAN® use cases

LoRaWAN use cases are similar to Smart Building use cases with the addition of traffic direction, parking exit and entry directions, lighting, and trash collection.

Hybrid Wi-Fi / LoRaWAN®

Location and video streaming use cases are the same as the Smart Building section.

8.4 Automotive and Smart Transportation

Automotive/ Smart transportation

Wi-Fi use cases

- Connected car
- Access control
- Wi-Fi hubs
- Broadband services
- Land page promotion services
- People counting
- Security (cameras)
- Seamless roaming (open authentication)
- Tracking and location
- Asset tracking and logistics
- Passenger entertainment
- Reservation
- Car sharing

Hybrid use cases

- Location services.
- Leverage existing Wi-Fi networks

LoRaWAN® use cases

- Asset tracking/ logistics
- Inventory / supply chain
- Fleet tracking
- Vehicle maintenance
- Speed management
- Vehicle tire pressure
- Guidance and control systems
- Compliance management
- Parking management
- Smart vehicle
- Toll / ticketing system monitoring
- Driver safety

Figure 16 - Automotive and Smart Transportation (Source: Wireless Broadband Alliance / LoRa Alliance)

Context

The automotive and transportation industry shares similar challenges with other verticals: logistics for manufacturing (vehicles manufacturers), people safety and predictive and corrective maintenance as well as smart building applications on the production sites.

Automotive and transportation drives a large number of use cases [15].

- Fleet management solutions
- Transport logistics applications
- Guidance and control systems
- Inventory and supply chain management solutions
- Passenger entertainment and commerce applications
- Smart vehicle applications
- Reservation, toll, and ticketing systems
- Peer-to-peer services like car sharing
- Security and surveillance systems

Wi-Fi use cases

Wi-Fi has already entered the connected vehicle space. A dedicated white paper has been released by the Wireless Broadband Alliance [16]. All carmakers are now installing Wi-Fi hubs access in cars to provide passengers with onboard broadband services.

In general, Wi-Fi in transportation is focused on passenger broadband services. The challenge here is to manage mobility with the same quality of service in trains, buses or planes. As for cities, Wi-Fi is the perfect media to promote additional web-based services (free or charged) with a variety of business models (free, freemium, prepaid, etc.).

Next, Wi-Fi participates to reinforce and simplify access control for passengers on trains, buses and flights (on-boarding cards, QR codes...).

Additionally, as for cities, transportation hubs (train station, underground, etc.) need digitalized people counting potentially based on Wi-Fi.

Finally, Wi-Fi can be an enabler of car sharing business models (authentication, monitoring, invoicing).

LoRaWAN® use cases

Automotive and aircraft industrial players are adopting LoRaWAN® rapidly for returnable asset tracking and smart logistics. These assets are metal racks used to carry car or airplane parts between the supplier's plants and the manufacturer's warehouses and assembly lines, those usually being close to each other. After parts are consumed in the assembly lines, racks come back empty to their original location. For cars, the main categories of involved parts are gearboxes, engines, dashboards, windshields, transmission, exhaust, bumpers, interior and steering column. Given the cost of the racks, the efficiency of these closed loops is key.

Both automotive and aircraft manufacturers have started to deploy private networks on site, and they have less than one-year Return on Investment (ROI) without the need of extensive coverage during transport. Operators or system integrators can also operate these networks.

The benefits of this solution are:

- Automated inventory with complete synchronization between plants in multiple countries, different entities of the company and eventually including tier-1 suppliers.
- Maintenance OPEX savings around 10% of the CAPEX per year because of assets loss reduction. Loss is mainly related to the challenge to keep track of empty assets (racks): manual operations like scanning or reading are not 100% reliable. Therefore, the goal is to reduce the number of empty assets.
- CAPEX reduction for the same number of loops based on the decrease of the number of unused empty assets.

This use case is already enabled by on site rack presence detection, but sometimes customers also want indoor geolocation to identify the area where the assets are within the factory. The advantage of the solutions using LoRaWAN® is that they provide seamless indoor and outdoor geolocation without manual intervention.

Once the LoRaWAN® network infrastructure is up and running on site, it can be mutualized with any other IoT use cases, leading to improve the ROI: monitoring tools, wiper fluid replacement, gas tank monitoring, cable drums management, or any smart building use case.

The automotive industry is under financial pressure to increase performance. They have implemented the "just in sequence" production model and the car customization trend increases the part diversity which is a huge challenge. Car maker Key Primary Indicators aim to reflect the ability of parts to arrive in time and in sequence at the assembly line: "On Time In Full" (OTIF). Furthermore, extending LoRaWAN® coverage to transportation routes between sites will help to improve this indicator.

Vehicle fleets (smart fleet management) [17] of trucks, cars, ships, trains, planes, etc.- are the lifeline of many businesses that need to ship products or provide transportation services. With IoT fleet tracking, these businesses can reduce costs by keeping fleets in the field longer with better fuel economy, increased driver safety, better visibility on maintenance issues, and overall improvements in operational efficiency. Benefits of IoT based fleet management include also more data for better analytics and data driven decision making, real-time customer shipment updates, and lost or stolen vehicle tracking. By implementing a fleet tracking solution composed of LoRaWAN® sensors and gateways, organizations can help improving their logistics, thus reducing costs, and optimizing transportation timeliness.

Additionally, LoRaWAN® applications can cover many other areas like guidance and control system, vehicle telematics and maintenance, toll and ticket system monitoring, speed and compliance management, or smart parking management in cities.

Hybrid Wi-Fi / LoRaWAN®

Location and video streaming uses cases are the same as the Smart building section.

8.5 In Home / Consumer

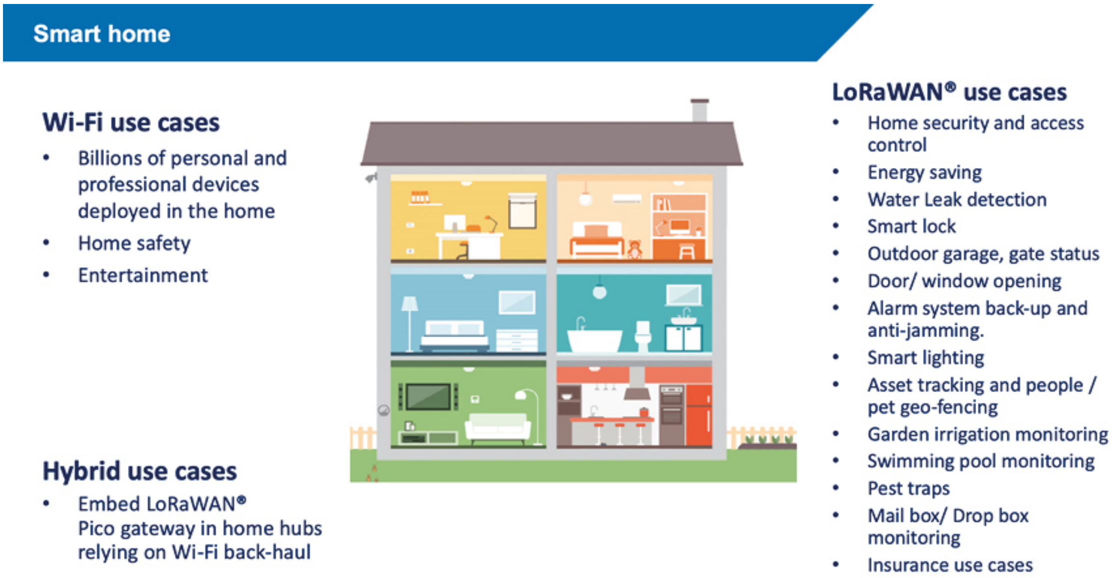


Figure 17 - In-Home / Consumer (Source: Wireless Broadband Alliance / LoRa Alliance)

Context

Most smart home systems are closed in the sense that you need to either buy only from the provider or must add certified products to ensure interoperability. Most of Smart Home solutions sold today are so-called, point solutions. However, cloud-based control, such IFTTT, in combination with unified user interfaces, such as Amazon's voice assistant Alexa, can provide a point of intersection for multifunctional control.

Smart home has evolved from competition of smart hardware into competition among intelligent platforms. Integration of various point-solutions into multifunction and whole-home systems has been a strong trend these last years and is expected to continue. The role of Smart Home platforms will change even further from only providing interoperability and a common User Interface to one that incorporates Artificial Intelligence in the cloud.

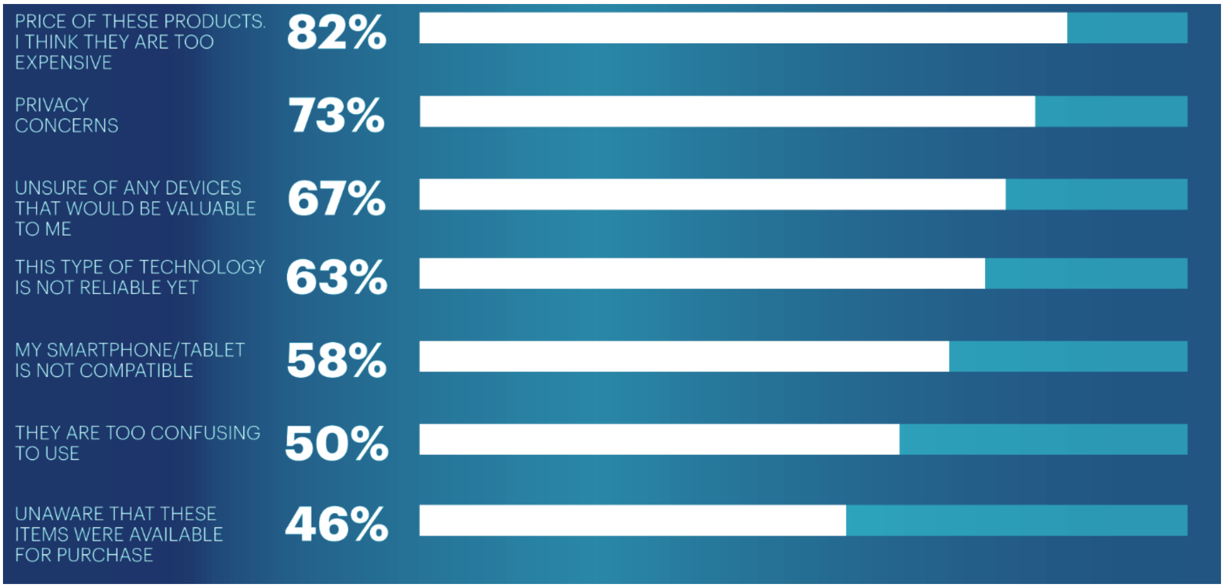


Figure 18 - Race to the Smart Home - Accenture, 2017

In the smart home space, we can see a number of IoT connectivity technologies. Based on consumer feedback, the winning technologies are expected to meet to the following requirements:

- Seamless device **provisioning** (customer experience).
- Service **continuity**: in home / public space or in the home / garden
- Multi-technology **interoperability** at the cloud level (materialized by smart phone drive)
- Reasonable **cost**

Wi-Fi use cases

More than 9 billion Wi-Fi devices have already enabled hundreds of use cases in the home. Since most customers have a CPE at home connected to Wi-Fi back-haul, there is an opportunity to develop hybrid in home / outdoor coverage approaches. Possibly a double SSID system, where in-home is on private SSID and public SSID can be used in the neighborhood.

With Wi-Fi 6 evolution, Wi-Fi can potentially replace Zigbee and BLE hubs and support most of the applications currently being supported by them such as home monitoring, in-home health care and other smart home (home alarms, doorbells, etc.) end-euser devices.

LoRaWAN® use cases

LoRaWAN® connectivity technology has started to be implemented in the smart home these last two years, as it brings key step changes in this specific context:

- Greater coverage: able to reach 'far to reach' areas (attic, garden, secondary house), or outdoor continuity with the same device
- Low battery consumption improving user experience and service continuity
- Low cost deployment based on a star easy to install network configuration
- LoRaWAN® interoperability
- Improved security as it is more difficult to hack devices on LoRaWAN networks
- Can back-up Cellular or Wi-Fi networks

The main areas of development for LoRaWAN® in the smart home are as follows:

- Home access control (door, windows, smart lock, outdoor garage and garden gate status…).
- Home security (alarms back-haul, anti-jamming, cellular backup, intrusion, presence…).
- Energy saving (water leak detection, water-gas metering, heat allocator management).
- Pet/ people geo fencing.
- Garden irrigation monitoring.
- Swimming pool monitoring.
- Pest trap monitoring.
- Mailbox / drop box monitoring.
- Any smart building application as a home is building.

Emerging business models are under development where insurance companies equip homes with LoRaWAN® sensors to prevent disasters (water leak detection, security). Insurance companies significantly reduce disaster costs and may reduce insurance fees as a consequence. Set of use cases can expand outside the home like for example put a tracker on a bike or a car to present theft. Home is clearly a space of business model disruption and new paradigm between operators and services providers.

Hybrid Wi-Fi / LoRaWAN®

Operators – such as Orange, for example - have deployed LoRaWAN® Pico cells leveraging Wi-Fi backhaul to the user Set Top Box (home-hub) to expand coverage of home services to the neighborhood. Such neighborhood IoT networks support new geolocation services (e.g. Orange's "C'est ici" personal tracker), but in the future could also serve as a communication backbone for demand response services e.g. for multicast thermostat control, or for EV chargers which are hard to reach by other means in urban underground parking's of condominiums.

Some operators are looking at deploying pico-cellular IoT networks leveraging LoRaWAN® which require even less energy than macro cellular networks and present excellent connectivity performance in hard to reach areas due to large macro-diversity. Light reading paper [18] and Comcast high-density network webinar [19] illustrate this network design opportunity.

Such networks will provide unbeatable infrastructure for next generation services such as automated water & gas metering (leak detection), smart lighting, home security (intrusion and presence detection), asset tracking, and interconnection of urban appliances.

8.6 Location services

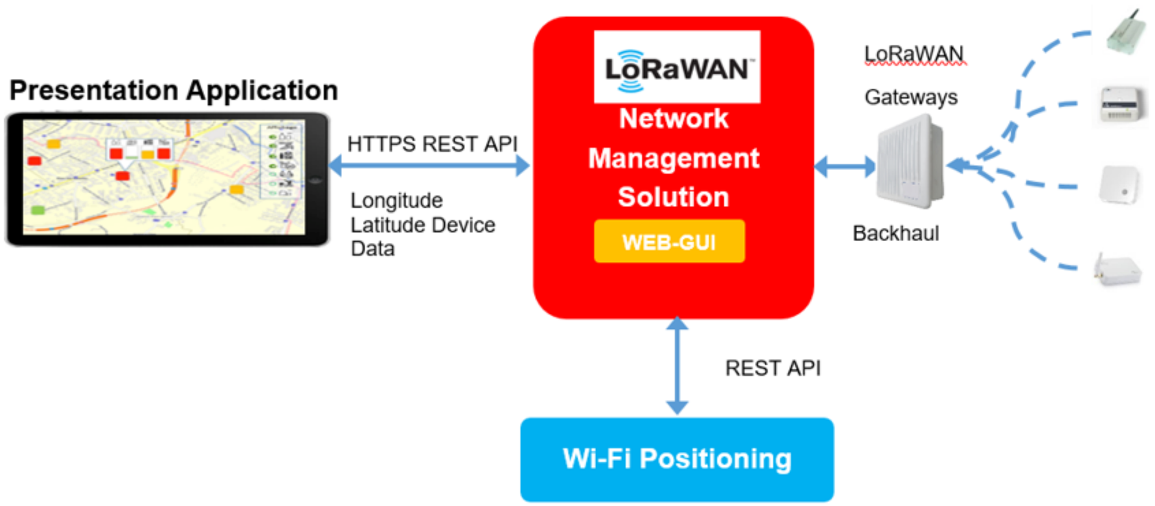


Figure 19 - Wi-Fi & LoRaWAN location services

Location determination services are a good opportunity to show complementary between Wi-Fi and LoRaWAN®.

The device will periodically scan for Wi-Fi Access Points [20] and transmit the result over LoRaWAN®, typically RSSI and (partial) MAC address for each AP detected [36]. LoRaWAN® geolocation is realized by triangulation and precise timestamping, the precision is of around 50m and needs minimum 3

Gateways, better 4-5. This is suitable for outdoor places with no / low Wi-Fi coverage. LoRaWAN® Network is also an enabler for other LoRaWAN® applications and allows additional use cases.

A single IoT device can perform a relatively accurate Wi-Fi based geolocation in indoor and urban areas. The positioning estimation is based on 3D map of Wi-Fi Access-Points. Actual error in positioning depends on density of APs. Normally for an indoor environment it is achieved a median error less than 10m and a correct floor detection >95%. Accuracy is typically <5m with 5 strong Wi-Fi RSSI. Outdoor mobile device with Wi-Fi can be located in urban areas with an average accuracy for around 20 meters. Further improvement can be achieved using Fine Timing Measurements or also called RTT (Round Trip Time) measurements as defined in 802.11mc. If APs and devices have support for this, the error will be in the order of 1m.

LoRaWAN® can provide less accurate network-based location requiring very low battery consumption, in large outdoor areas up to 50m accuracy as demonstrated by KPN in the Netherlands [21]. It is up to the solution provider to develop applications on the edge (e.g. in the IoT device) or in the cloud to opportunistically switch between the two location technologies, or use both to increase reliability, depending on its needs at any given moment in time.

Wi-Fi based geolocation is not only very accurate but can be also very conservative in power consumption. Wi-Fi scanning can be done over multiple RF channels and bands. In the urban environment, it is common to see very large number of APs (tens to hundreds). Sending all observed APs to a cloud server can be optimal for positioning accuracy, however it may require sending on the uplink large packets of more than 500 bytes. There are various techniques to reduce Wi-Fi scan payload (down to 12 bytes even) and scan power consumption energy (down to 50mWs) as developed and described by Skyhook in [22].

Demand for location services is extremely elastic and sensitive to price. The total Cost of Ownership of a location service includes the initial hardware investment as well as recurring connectivity and battery charging/replacement costs. The low hardware cost and extreme power efficiency of LoRaWAN® created a massive disruption of geolocation TCO and made possible many new use cases.

Geolocation for campuses, such as large factories and airports, is becoming extremely popular as we can see at Pittsburg international airport rolled-out by Actility [23] and Zaventem airport rolled-out by Proximus Network [24].

The main use cases are as follows:

- Reduce search time for lost objects: there are upwards of 5000 moving objects in any large airport; this is also very popular with large parkings of used car dealers, rental companies or car / truck makers.
- Verify utilization rate of assets, e.g. on campus car pools. This allows checking whether such pools are oversized or undersized.
- Safety badges, tracking location of users in case of emergency evacuations.

For countries with nationwide networks, tracking is also popular for many use cases, such as car theft prevention (a booming service in the Netherlands operated by KPN [bike tracking]), child monitoring for outdoor school activities, etc.

Most use cases require use of hybrid LoRaWAN® / Wi-Fi and sometimes Bluetooth and GPS location methods, making such trackers sophisticated multi-radio devices. LoRaWAN® / Wi-Fi is the core location method, as the ubiquity of Wi-Fi makes this location method as accurate as GPS in most urban environments, and available indoor. Tests of Abeeway, the company manufacturing Orange "C'est ici" multi-technology tracker shows that in over 95% of cases, Wi-Fi geolocation is better than GPS in urban environment: not only the accuracy is similar, but also power consumption for each fix is much lower. Low-Power GPS techniques have also been developed [25], but they are relevant only for outdoor country geolocation where Wi-Fi is not present. In urban areas, the combination of LoRaWAN® and Wi-Fi is ideal: large shared bike/scooter projects selected it as it is both low-cost and low power. Wi-Fi chips and modules are in massive volume and very cheap. Cheaper and easier to integrate than GPS. Also, the power consumption of using Wi-Fi as just a receiver to find APs is less than GPS.

The bidirectional nature of LoRaWAN® is key to the performance of multi-technology trackers, as the control system can dynamically adjust the preferred technology in use depending on use case and location. For example, rely on periodic low power, low-resolution methods such as LoRaWAN® Time-based network triangulation (TDoA) most of the time, and then based on geo fencing or on-demand require high-accuracy fix.

Indoor geolocation is a much-segmented market with many niche applications; however the LoRaWAN® / Wi-Fi and LoRaWAN® / Wi-Fi / Bluetooth combination addresses most use cases when an accuracy of 5 to 10 meters is sufficient - Tata Communications is deploying employee safety solutions for workers who are at the risk of exposure to hazardous areas by combining these technologies. Wi-Fi itself, with recent fingerprinting techniques, such as developed e.g. by HERE technologies, has around 10m of accuracy, depending on Wi-Fi deployment density. Often this is sufficient for most of the indoor areas, with occasional requirements for higher accuracy tracking, or rather check pointing, is specific areas such as work positions. The latter requirement is fulfilled by dedicated deployment of Bluetooth beacons in such checkpoint places. Overall, the combination remains ultra-low power and serves the vast majority of use cases. Large factories use this technology for smart-employee badges, which also beep or vibrate when entering hazardous areas, and in case of emergency allow rescue teams to monitor evacuation.

Hybrid LoRaWan® / Wi-Fi provides both indoor and outdoor tracking as well as the possibility for transitioning between indoor / outdoor with only two radios. This is a unique value proposition that meets the needs of large construction projects, industrial manufacturing, campus' and mining.

9 Network Roll-out

9.1 Deployment models

Network strategy: a game changing opportunity

Network deployment strategies have been widely documented based on the experience of operators. The emergence of Low Power Wide Areas technologies has game changed the roll-out options as follows:

- **Diversity**: shift from a cell topology (1 frame received by only 1 gateway) to a macro diversity topology (same frame received by several gateways).

- **Densification**: easy cost-efficient densification (emergence of small form factor low cost gateways).
- **Multi factor design:** use of multiple optimization factors (channel plan, adaptive data rate, macro diversity, densification, and time diversity), to optimize spectrum usage, coverage, level of service (SLA) and device battery consumption.
- **Domestic roaming**: LoRaWAN® networks deployed in the same country may roam with each other.

Network diversity and complementarity

Let us take a look at existing networks topologies:

- A) **Campus / Venue / Airport networks** (mostly private). It is the area of Wi-Fi and LoRaWAN® private petworks. It provides both **indoor coverage** and **increased traffic capacity** (small cells).
- B) **City networks**: Smart City private networks are flourishing, massively expanding to LoRaWAN®. Concurrently, operators have developed attractive network as a service offering based on rivate-Public business models. Cities benefit from 'free' towers on public premises. Several agreements are being set up with operators to use these existing assets. These networks provide both **outdoor** and **indoor coverage** on a limited footprint (a few square kilometers), while offering hard to find sites in urban areas.
- C) **Nationwide / Regional networks:** mostly built on towers, they offer long range **outdoor** coverage. These networks are the space of LoRaWAN® operators, MNOs or tower companies.
- D) **Consumer networks** (home-hubs, set-top boxes), based on low height sites bringing mostly **indoor coverage.** Wi-Fi is the predominant IoT technology in homes as concurrently providing backhauling to any other IoT technology. LoRaWAN® is a recent fast rising IoT Connectivity technology in that space. Most of MSOs roll-out this category of Networks.

Hybrid networks leveraging different topologies are the solution to provide indoor and outdoor services on a national / international scale. Objenious by Bouygues Telecom proposes a hybrid network offering (private-public), allowing industrial companies to open their LoRaWAN® private use-cases nationwide and even international wide based on roaming agreements setup by Objenious with other LoRaWAN® operators.

Wi-Fi has massively expanded on A), B) D) types of networks where LoRaWAN® is mainly present in A) B) C) and recently emerging on D). It becomes clear that Wi-Fi can expand on LoRAWAN® addressable use cases based on A) B) D) topologies.

LoRaWAN® (C) networks can be scaled gracefully by adding more gateways. Optimizing Adaptive Data Rate (ADR) and power consumption algorithms comprise a two-pronged force that yields a ~10X reduction in both power consumption and operator TCO while increasing the capacity of the network massively [26].

Wi-Fi Networks do not only trigger the development of strategic IoT use cases but are a strong lever to massively:

- Increase indoor coverage performance.
- Increase capacity by reducing inter-cell collisions. Semtech / Comcast carried out a meaningful experimentation in Philadelphia and concluding than over densifying a LoRaWAN® Network increases Quality of Service (QoS) while scaling-up capacity [27].
- Reduce device to gateway distance and significantly reduce battery consumption and expand device lifetime thus reduce Total Cost of Ownership (TCO).
- Improve accuracy of Network based location services.

Last but not least, **domestic roaming** is a unique powerful lever to aggregate and complement or densify all **four types of networks**, optimizing the network costs.

Leverage LoRaWAN® macro and indoor Wi-Fi network layers to meet full coverage

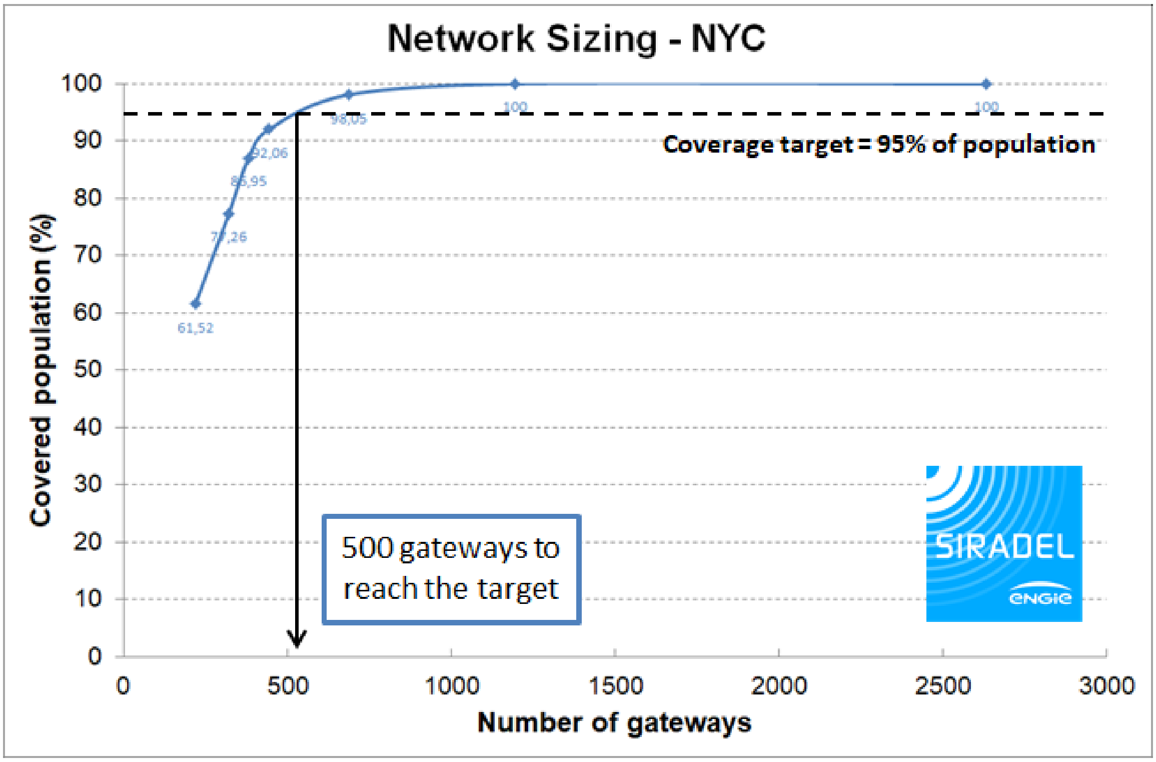


Figure 20 - Limitation in macro site roll-out (Source: Siradel Engie)

Here above, we can see an insightful network sizing study made by SIRADEL - leader in radio planning solutions for carriers and private companies - on New York City business case in the 800 MHz unlicensed band.

The study aims to evaluate the **network cost** (number of required sites or Gateways) to meet specific population coverage targets for light indoor and deep indoor service objectives. On the above figure, the radio simulation shows that we need **500 macro sites to cover 95 %** of population with a light indoor service. The simulation shows that **we at minimum need to triple the number of macro sites (1200) to reach the near to 100 % population coverage**. We can notice that it would cost **half the number of sites** to cover like **60 %** of the population.

Assuming the cost and the challenge to find towers in New York City (not to mention interference issues):

- Macro networks are **cost efficient to reach 60 to 80%** of population coverage with a light indoor objective. Above the threshold, the multiplication of **macro sites does hardly justify** the rollout.

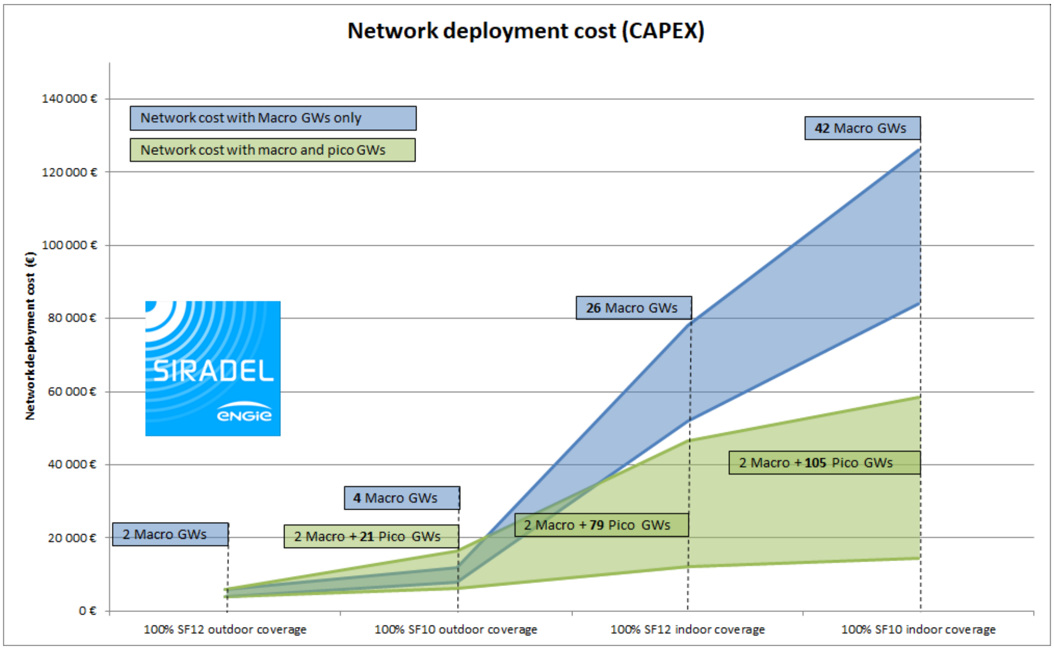


Figure 21 - Limitation in macro site roll-out (Source: Siradel Engie)

Let us now look at a second SIRADEL study evaluating **total network cost** based on the following two scenarios:

- 100% macro site deployments.
- Combination of Macro Gateways (high sites) and Pico Gateway (indoor low height sites).

We come to the conclusion that:

- It is always cheaper to mix the two layers.
- The more we target indoor service (smart home, smart building, smart industry, utilities, etc.) the more a macro site network combined with Pico sites is cost efficient. Additionally, Pico cell roll-out can be focused on areas where business is confirmed and thus timely synchronize roll-out and revenue.

9.2 Frontend integration.

The opportunity here is to leverage either **existing Wi-Fi Access Points networks** to deploy LoRaWAN® Gateways at incremental cost or mutualize rollout of **both technologies on new locations**. The emergence of indoor small form factor LoRaWAN® Gateways has enabled the opportunity to use Wi-Fi locations without facing challenging lease negotiations or space management issues. Last generation of LoRaWAN® indoor gateways are not much bigger than a smart phone.

Integration options are diverse:

- **A Colocation**: Access Points and LoRaWAN® Gateway on the same locations with no physical connection (zero touch). Wi-Fi Access Points potentially provides LoRaWAN® Gateway back-haul. LoRaWAN® Gateway can be powered either:
    - On a separate energy supply.
    - Connected to the Access Point USB port.
    - Powered by Ethernet connection (Power On Ethernet).

  Intelligent edge gateway vendors such as Kerlink, and Multi-tech all provide Micro and Femto (very small) gateways.

- **B Fully Managed service**: Access Point operates LoRaWAN® Gateway via an USB port (switch-on, switch-off, alarm monitoring). Access Point provides Wi-Fi backhauling to LoRaWAN® Gateway. Semtech has built a dedicated ref design: Pico Gateway V1.0 [39].

- **C Fully embedded:** LoRaWAN® Gateway is embedded into the Wi-Fi Access Point or potential home hub at the silicon level. There is only ONE mutualized gateway solution using LoRaWAN® and Wi-Fi modules.

The three options of implementation are available on the market. Feel free to reach to **LoRa Developer portal** [28] to get through more detailed implementation. Choice of implementation option is based on:

- LoRaWAN® business maturity. Option **A** or **B** are quick to set up with no impact (zero touch) on Wi-Fi Access Point operation and roadmap. Once LoRaWAN® business has taken off, option **C** can be envisioned for scalable seamless operation of Wi-Fi and LoRaWAN® CPEs.

- Access Point configuration. In case, AP have no USB ports neither Power over Ethernet, options **A** or **C** are best suited.

9.3 Backend integration and security processes

Wi-Fi security model

The massive growth in Wi-Fi device types, from smart home appliances to personal health monitoring equipment, has brought unprecedented convenience and value, and has changed the landscape of Wi-Fi networks. As the industry grows, Wi-Fi Alliance and the Wireless Broadband Alliance have been there to nurture the growth with solutions that help standardize the technology we use and bring a better Wi-Fi experience.

Particularly the Wi-Fi Alliance, since its inception, has continually worked to provide Wi-Fi users with secure Wi-Fi connections to protect user data. The evolution of Wi-Fi security solutions brings user confidence that helps underpin the success of Wi-Fi today. In 2003, Wi-Fi Alliance introduced the Wi-Fi Protected Access® family of technologies to help users protect their data. Since 2006, every Wi-Fi device has shipped with **WPA2™** security, and over time the program has been enhanced to keep up with the changing security landscape.

Wi-Fi Alliance is committed to providing Wi-Fi users with strong levels of security using standards-based mechanisms and security interface tools that are easy to use and that promote adoption of security best practices. At the same time, Wi-Fi Alliance recognizes that there is a need for distinct solutions to meet the security requirements of different use cases and devices.
Next generation connectivity includes the need to easily on board a variety of device types to Wi-Fi networks. Wi-Fi Alliance has introduced programs to improve secure connection to Wi-Fi networks, such as Wi-Fi CERTIFIED Easy Connect™, which enables the simple, secure configuration and on boarding of devices with little or no user interface onto Wi-Fi networks.

Wi-Fi security for the next generation of connectivity should also provide enhanced data protections for security-sensitive segments, such as financial institutions, healthcare, and governments. These needs are addressed in the next evolution of the Wi-Fi Protected Access family, which provides protections specified for personal and enterprise settings.

Wi-Fi CERTIFIED WPA3™ delivers the capabilities necessary to meet the requirements of different network deployments—ranging from highly controlled corporate environments to more flexible home networks—and to operate in different device form factors. Regardless of the environment or device type, all WPA3™ devices deliver two key benefits:

- **Cryptographic consistency**: WPA3 reduces the susceptibility of networks to a successful attack by mandating policies around the use of Advanced Encryption Standard (AES) with legacy protocols, such as Temporal Key Integrity Protocol (TKIP).
- **Network resiliency**: Protected Management Frames (PMF) deliver a level of protection against eavesdropping and forging for robust management frames. The consistent use of these protections improves the resiliency of mission-critical networks.

LoRaWAN® Security Model

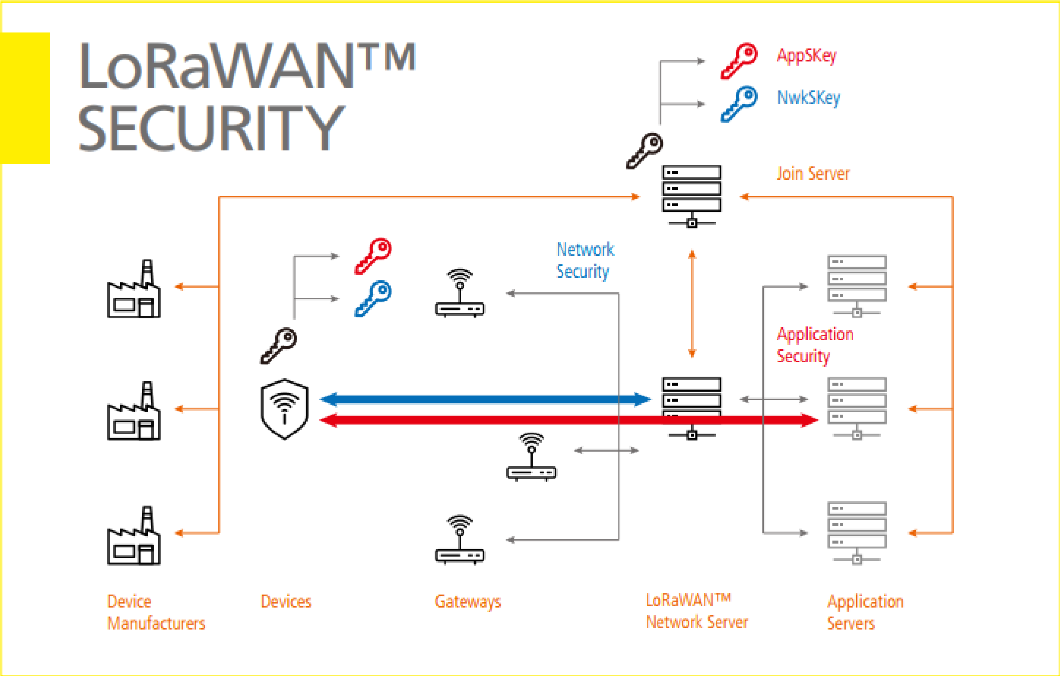


Figure 22 - LoRaWAN® Security Model (source: LoRa Alliance)

LoRaWAN® is a **secured by design** technology. LoRaWAN® security model is based on the following rules:

- Frame encryption (uplinks and downlinks) is based on AES128 encryption scheme.
- Cryptographic keys used to encrypt frames are different for every single device.
- Keys are never transmitted over the air, so an attacker has no way to guess a device's key even if he is able to intercept the whole LoRaWAN® traffic on air.

Payload encryption

Each payload is encrypted with using AES128 algorithm based on 128bits key: **Application Session Key.** Each device gets its own Application Session Key only known by end device and Application server and only used for encryption. Encryption uses a frame counter as input (specific to each frame) so that the same payload derives a different encrypted payload for every single frame. The application Session key is derived from the **Application key + frame counter**, only known by the end device and the application Server. Application keys are stored in a secure database named **Join Server**.

Frame signature

All frames (payload plus headers plus metadata) contain a 32bits cryptographic **MIC (**Message Integrity Check) signature computed using an AES128 algorithm with a 128bits secret key: **Network Session Key**. Network Session key is different from the Application Session key. Each end device has its own

Network Session key only known by the end device and the Network server. This key is only used for signature. The Frame signature (Message Integrity Code) is computed over the entire frame. Therefore, a frame cannot be modified between end device and network server without compromising the signature. Only components involved are end device and network server. Gateway and Gateway back-haul are fully transparent as regards to the LoRaWAN® security model. It is nevertheless highly recommended to secure the backhaul link between Gateways and Network server. Network session keys are derived from the **network key**, only known by the end device and the Network Server and stored in a secured data base name **Joined Server**.

Uplink authentications

Upon reception of each frame, network server checks that the received frame signature matched the one computed using the network session key derived and stored by the Join Server. If two signatures match, the frame is really coming from legitimate device and the content has not been modified in any way. The encrypted payload can be routed to the Application server for final delivery to the application.

Downlink authentications

Same process applies for downlink. The network nerver signs each frame with a MIC computed over the entire transmitted packet, using the destination end device Network Session key.

- Using MIC, the Network Server can differentiate a legitimate end device from one trying to steal the end device's identification (Dev Addr), in case of a cloning attack.
- The end device can check that the commands coming from the Network Server are legitimate.
- Additionally, each frame contains a frame counter (FCnT) forbidding "replay attacks". Only frames using a fresh Frame counter value are processed.

Join Server and Join Procedure

Join server derives and stores Application and Network keys. Join Server is tasked to derive Network Session keys and Application Session key and to provide them to Network Server and Application Server. The session keys (network and application) are computed when a device connects to the Network for the first time or reconnect to another Network in case of roaming: it is called the **Join Procedure or Re-join in case of roaming.** The join procedure can be processed over the Air (Over The Air Activation) or by pre-provisioning on the device production bench (Activation By personalization).

10 Interconnection processes

Wi-Fi interconnection model

Based on WBA Roaming white paper [29] Wi-Fi roaming is designed as follows:

There are three primary stakeholders in the Wi-Fi Roaming ecosystem. Due to the communal nature of Wi-Fi, often a single company is involved in providing more than one element of the ecosystem.

Home Service Provider (HSP) Subscriber Owner(s) –Companies who enable Wi-Fi access to their customers/subscriber provide preconfigured mechanisms to allow preconfigured access at trusted partner Wi-Fi locations. The customers may have an app, which provides connection assistance, or a profile may be preloaded on their device. The subscribers, who also have an existing relationship with their Provider, have accepted the HSP's terms and conditions, including acceptable use policies, and have a plan that includes Wi-Fi Roaming.

Visited Wi-Fi Provider (VNP) - The owner/operator of a Wi-Fi network enables access to their roaming partner's customers as a way to monetize access to their network or as a part of a reciprocal roaming relationship.

HUB & Clearing House – These companies provide the interconnection and routing of Radius requests and accounting between networks. They also provide the reporting, data clearing, billing and settlement of usage between roaming partners.

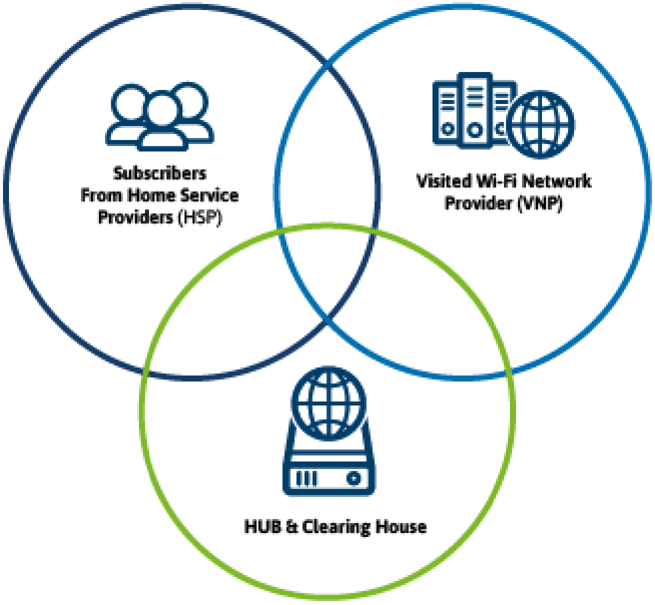


Figure 23 - Different entities involved in providing a Wi-Fi roaming service

How Wi-Fi roaming works

The Wireless Broadband Alliance developed the Next Generation Hotspot (NGH) specifications to make the Wi-Fi user experience as easy, seamless and secure as a cellular experience. NGH takes the established hotspot model and builds new levels of ease of discovery, security of connection and efficiency of service, leveraging the Wi-Fi Alliance's Hotspot 2.0 specification. When a Hotspot 2.0-capable Wi-Fi device comes within the range of a Hotspot 2.0-capable Access Point, it will automatically start a signalling exchange with that Access Point to determine its capabilities. Some of the data that is exchanged may include:

- The name of the Wi-Fi network operator / service provider.
- List of roaming partners that are supported.
- Other things related to the service, such as backhaul bandwidth, current load etc. The device is able to use this information to automatically decide whether to connect to a particular Wi-Fi network, e.g., in preference to possibly other overlapping networks. After having selected a network, the Wi-Fi device initiates an EAP authentication. Unlike cellular systems which have been built on a foundation of identities based on International Mobile Subscriber Identities (IMSIs) and SIM based authentication, Wi-Fi roaming is based on the concept of Network Access Identifiers (NAIs) which are of the form “user@realm” and a flexible authentication framework.
- An EAP-Response/Identity message is used by the device to signal its NAI to the Visited Network Provider. Unlike in cellular, the Wi-Fi device may choose to hide its true identity from the access network and may signal “anonymous@realm” to the visited network.
- The visited Wi-Fi access network uses the “realm” portion of the identifier to identify the home service provider. The visited Wi-Fi access network embeds the NAI and EAP message in a RADIUS Access Request message and routes the message towards the home service provider, possibly via a direct signalling link, but more commonly via one or more roaming hubs.
- The roaming hubs use the realm portion of the NAI to further route the message towards the home service provider. The home service provider embeds an EAP message in the returned RADIUS message and this is signalled all the way back to the visited network operator which recovers the EAP message and forwards it to the Wi-Fi device. In this way, the EAP exchange is directly between the Wi-Fi device and the Home Service provider.
- An EAP dialog follows which is used to support the chosen EAP methods, which for Passpoint® certified devices include either EAP-SIM, EAP-AKA, EAP-TLS or EAP-TTLS. As part of the EAP method, the Home Service provider can recover the permanent identity of the device in a secure fashion.
- After the home service provider has authenticated the device, it replies with an EAP-Success message and includes keying material, generated as part of the EAP exchange, in the RADIUS Access Accept message, as well as an optional Chargeable User Identity that should be used in accounting records generated by the visited network provider.
- The visited network provider forwards the EAP-Success message to the device which will have independently generated its own keying material as part of the EAP exchange. The keying material is then used to protect the Wi-Fi air interface.
- The visited network provider generates RADIUS accounting messages for the Wi-Fi usage including the Chargeable User Identity and signals these to the home service provider.

Interoperability

The WBA's **WRIX Guidelines** is a modularized set of specifications and best practices to enable roaming between operators. It includes WRIX-n (network configuration) **WRIX-i** (Interconnect), **WRIX-l** (Location information exchange), **WRIX-d** (Data Clearing) and **WRIX-f** (Financial Settlement). Each of these can be deployed between Visited Network Providers (VNPs) and Home Service Providers (HSPs) either directly or through an intermediary hub provider.

Traditionally, Wi-Fi Roaming was deployed in an unstructured fashion between roaming partners across the industry this approach did not scale well and was difficult to implement and maintain. In order to clarify and standardize these requirements, the WBA created the Interoperability Compliance Program (ICP). This program provides operators with a common technical and commercial framework for Wi-Fi Roaming by utilizing the best practices as defined by the WBA's WRIX guidelines. Also, the ICP outlines a framework which defines the requirements for roaming and settlement from basic connectivity to more advanced models. The ICP program ranks companies based on their capabilities so that roaming partners are better able to set expectations ahead of time. The WRIX framework and ICP simplifies the implementation and management of roaming relationships. The ICP program provides the following assessments:

- Interconnect Options Supported
- Types of Authentication Methods Supported
- Connection Bandwidth.
- Network Discovery and Selection Features
- NGH Network Security
- NGH Network Management
- Network Access Security Types
- User Experience
- WRIX-i WRIX Attributes Supported
- WRIX-d Charging Models and Data Clearing
- WRIX-f Settlement Methods
- WRIX-L Directory File Management - Location Type Classification
- Customer Care/Support
- Information Exchange

There are currently more than 20 global operators, across 5 different continents who have currently achieved an ICP tier level to support the development of their businesses. For more information on the WRIX Framework or the ICP program contact the WBA PMO.

LoRaWAN® interconnection model

LoRaWAN® interconnection has been specified by LoRa Alliance under LoRaWAN® 1.03 [40] specification.

Public LoRaWAN® operators already began to interconnect, such as Objenious, Proximus, and Swisscom, as well as Orange and KPN. Moreover, several LoRaWAN® Network operators connected to the Actility roaming hub (ThingPark Exchange). Objenious expects more than 6 countries interconnected by end of 2019 in Europe and more than 50 on an international level in 2020. The use case for network interconnect is not limited to moving objects such as trackers. One of the main drivers is ubiquitous activation of devices using “activation away from home”, and simplification of security procedures by avoiding complex key ceremonies. Large manufacturers like Schneider Electric interconnect to Orange or Swisscom network via the ThingPark Exchange roaming hub (international roaming hub), making it possible to activate devices out of factories anywhere in France or Switzerland leveraging roaming capabilities. This greatly simplifies logistics when devices transit via a complex distribution network. Major Secure Element suppliers such as STmicro collaborate with interconnected providers to allow secure remote network joining via such roaming hubs without any key transfer.

Other roaming hubs like Everynet or Syniverse and more in the near future will become available to provide additional roaming capabilities to the LoRa® ecosystem.

Progressively, it is expected that all public networks will be interconnected, and all major module makers and device vendors will also support activation via roaming platforms, simplifying the life of solution providers, distributors and end users. Either through Peer2Peer connections or Hub connections, the roaming agreements between LoRaWAN® operators will provide international connectivity for customers.

Interconnection options between Wi-Fi and LoRaWAN®

As frequently highlighted in most of IoT papers, the key challenge of IoT is to receive the benefit from data analytics and also to serve use cases on different verticals. It raises the question of how to merge valuable information coming from Wi-Fi and LoRaWAN® technologies. The interconnection may happen at multiple levels:

- **Silicon level**: module dual mode embedding Wi-Fi chip and LoRa® chip on the same silicon to address combined use cases. Location services mentioned in this document are a good example of implementation.
- **Gateway level:** It means that LoRaWAN® network server and Wi-Fi cloud (IoT controller) functions are collocated on Gateway premises. This architecture makes sense in remote areas where back-haul latency is an issue and cloud can be directly back-hauled through a satellite connection. As mentioned earlier, LoRaWAN® gateway and Wi-Fi Access Point can also be embedded in the same hardware.
- **Cloud level:** application servers are able to manage payload coming from different IoT technologies. Need to get reliable back-haul infrastructure to join Gateway/ Access Point locations.

When designing the combined Wi-Fi / LoRaWAN® network, the following questions have to be addressed in order to optimize operations and quality of service:

- Decide to **collocate LoRaWAN® networks server with Wi-Fi service controllers** (or not) to have the opportunity to meet low latency and save back-haul cost.
- Mutualize traffic back-haul on the same back-bone (fiber optics…) which leads to locate LoRaWAN® Gateways on traffic concentration points.
- Mutualized monitoring traffic.
- Use or not Access Points as a LoRaWAN® Gateway backhaul depending on level of target SLA.

11 Testimonials for actors deploying LoRaWAN® and Wi-Fi

This section shows real implementations of leading Wi-Fi players having deployed LoRaWAN® in one or multiple verticals.

ER-Telecom: Smart Region Project (Yekaterinburg, Sverdlovsk Region) [30]

The first IoT network deployed in Yekaterinburg will become the basis for the implementation of services within the Smart Region project.

Currently, ER-Telecom LoRaWAN® network covers a significant part of the city. A pilot deployment of IoT solutions is being prepared for resource-supplying organizations, new residential areas and industrial enterprises.

The main areas of industrial Internet of things are the energy efficiency of housing and utilities and resource supplying organizations, site monitoring, transport telemetry, interactive urban environment, smart parking.

ER-Telecom: Smart City Project (St. Petersburg) [31]

More than 70 base stations with indoor and outdoor coverage are already located in St. Petersburg. Each station is capable of receiving signals from 3 million sensors. Now the company together with the state unitary enterprise "Lensvet" is testing "smart lamps". The pilot project is designed for six months to work out all possible situations. Today we already can say that the replacement of ordinary city lamps with the solution offered by ER-Telecom will provide energy savings and operating costs up to 50%. IoT network covers more than 50 cities of Russia, including St. Petersburg, and by the end of 2018 the number of such cities should exceed 60.

ER-Telecom Holding has already launched pilot projects on the Internet of things in the oil, agricultural and energy sectors.

ER-Telecom: IoT in oil and gas industry [32]

ER-Telecom recently successfully completed the first pilot of industrial IoT technologies implementation. Pilot project took a year: during this time, a subsidiary of ER-Telecom Holding, LLC Prestige-Internet (Enforta trademark), has digitized a number of “Volgodemin-oil” wells based on IoT environment using LoRaWAN® technology and a cloud platform working with data “AVIST.Operation” which was developed by the Russian group of companies ITPS. ER-Telecom has equipped an oil well with IoT sensors. The sensors transmitted the main technological parameters from the equipment (well and automatic group metering installation) to the base station LoRaWAN®, then to the cloud platform for data processing and remote monitoring of technological process parameters. At the same time, the distance from the base station of the LoRaWAN® network, built by the operator, to the well was 15 km, and the distance from the well to the mining company's base was 100 km.

The pilot project allowed reducing the accident rate up to 12% by identifying recurring events, as well as reducing losses up to 8% by reducing the time to resolve the incident. The sensors on the LoRaWAN® network worked stably both in winter and in summer.

Connexin (UK): Smart City

Connexin has rolled out LoRaWAN® macro-cells leveraging a variety of backhaul technologies to provide deep LoRaWAN® coverage across UK communities supporting demanding use cases such as Smart Water Metering. Broadly speaking the LoRaWAN® macro-cells have been rolled out at in two different types of locations.

Locations where we have an existing presence are the easiest to roll out in. LoRaWAN® is layered on top of our existing networks that support services such as Wi-Fi, with the gateways' utilising existing power and connectivity.

In the most challenging locations where the availability of power and traditional connectivity cannot be guaranteed, to ensure the robust delivery of LoRaWAN® connectivity we have utilised dual SIM Cellular connectivity ensuring that in the event of an MNO outage we still have backhaul connectivity for our macro-cells. Furthermore, we have developed our own internal battery-backed power supply unit that can provide power to a macro-cell for up to 7 days in the event of a mains power failure. This degree of high reliability is driven by demand from the utility providers for guaranteed regular meter readings and high SLAs. LoRaWAN® Smart Water Metering drives several behaviours including:

- Centrally collecting all the meter reading data and eliminating the requirement for drive-by metering allowing for more frequent meter reading and reducing operational costs.
- Providing real-time insights on water usage driving customer behaviour to better utilise resources.
- Building a network of sensors to detect water leakage - in the UK over 3.1 billion litres of water are lost from utility networks every day.

So far Connexin has deployed LoRaWAN® networks supporting this use case for several DMAs (District Metered Area) across the UK and we are intending to roll this technology out nationwide.

Calgary: building a foundation for pervasive connectivity [33]

The city of Calgary information technology (IT) business unit has achieved its long-term vision for a connected city. Over the past 20 years, it has acted as a comprehensive development plan to build a critical communication infrastructure with a goal to improve city services. This was accomplished, in part, by connecting as many of the city assets as possible, including staff, buildings, streetlights, fleet vehicles, cameras and traffic controllers using an expansive fiber optic network, and variety of wireless solutions. The city owns 10 radio towers, which are connected through the MPLS network. On these towers, the city implemented a broadband fixed wireless network. Wi-Fi access points were also installed at many traffic intersections. This private wireless telecommunication network provides coverage and data transfer for public safety organizations, water, transit, camera monitoring, and supervisory control and data acquisition. This last mile technology allowed Calgary to avoid monthly service expenses, including leased lines from carriers, and optimized asset tracking for its 3345 city vehicles.

The city of Calgary has evolved over the past two decades into the most innovative cities in Canada. In this white paper [33], City of Calgary explores implementation of LoRaWAN® use cases.

NomoSense: counting, flow analysis and geolocation solution provider [37]

Counting and analyzing a location attendance is an essential information for all companies or territorial collectivities who are facing massive public attendance. Various sensor's solutions exist and are deployed: infrared sensors, video analytics, carpet… These devices require a specific installation while source of information is generally available since several years through Wi-Fi infrastructure. NomoSense proposes to mix all these solutions to capitalize on an existing Wi-Fi infrastructure.

In the modern world, mobility is a crucial issue. Daily, public or private location owners (venues, cities, touristic places, malls…) see increasing people flows in a constant unrespectable trend. So, it is necessary to track in real time these flows to adapt the strategic site configurations (road works, station, venues…). Moreover, flow monitoring methods have been strongly improved and refined in terms of accuracy in the recent years.

Since the emergence of Wi-Fi in 90's, more and more devices have been connected through this technology and nowadays most smartphones are using Wi-Fi 24h/24. Recently, LoRaWAN® technology has enabled new Low Power Sensors, complementary to Wi-Fi.

Moving flow analysis through Wi-Fi

Counting, flow analysis and geolocation is a solution able to keep track of people flows across specific areas (venue, city areas…), based on Wi-Fi device tracking (smartphone, computer, laptop gaming device…). The collected data is anonymized to be compliant with regulation and is processed through **NomoSense platform** to display key primary indicators. Thanks to NomoSense, the location stakeholders can analyze moving flows bringing game changing capabilities:

- User counting to track the numbers of visitors or attendees.
- Trace general movement flows to collect information and optimize public / private locations configuration and create heat maps to show the most frequented locations.
- Detect crowd unexpected movements to improve people safety.

Counting flows through LoRaWAN®sensors

Each organization can deploy analysis and counting sensors. These sensors will help for a more detailed view of any location. NomoSense mixes different types of LoRaWAN® sensors depending of the information needed: (bicycles, cars, trucks, or people) counting. Based on data collection, a public infrastructure owner like a train station can leverage this solution for reinforcing safety, optimizing local network and reducing environment impact, by bringing accurate information … A local authority can use this for optimizing and reducing traffic, optimizing public transit usage and place configuration…

Wi-Fi and LoRaWAN® for the same objective

NomoSense has deployed technologies relying on Wi-Fi and LoRaWAN® in order to meet the same use case. All the data is processed to be exposed on a unique dashboard. Mixing data from both technologies helps NomoSense to reinforce his solution with regards to competition. With this kind of solution, public authorities and private infrastructure operators can improve location management to maximize customer journey.

MaximaTelecom Russia: smart transportation relying on Wi-Fi and LoRaWAN®

MaximaTelecom (MT) completed test case on smart transportation. In the process of working on the case, MT developed in house devices with 3G / LTE (4 modems cat.4), Wi-Fi (2.4/5 GHz) and BLE adapter. The device carried out the role of universal HUB of data and provides a stable channel to the ground infrastructure. Devices collect and transmit data from passenger counters (via Ethernet), CCTV (via Ethernet), drive quality sensor (via BLE) and onboard telemetry (via RS-485). All data was preprocessed on device and transmitted via aggregated 3G / LTE channel or via Wi-Fi if available.

In the near future, the plan is to integrate additional modules like Zigbee and LoRaWAN® for connecting sensors and provide additional services for both transport companies and for the mass market.

Solutions can be used not only on transport, but also as a local data HUB installed to the analogy with femtocell.

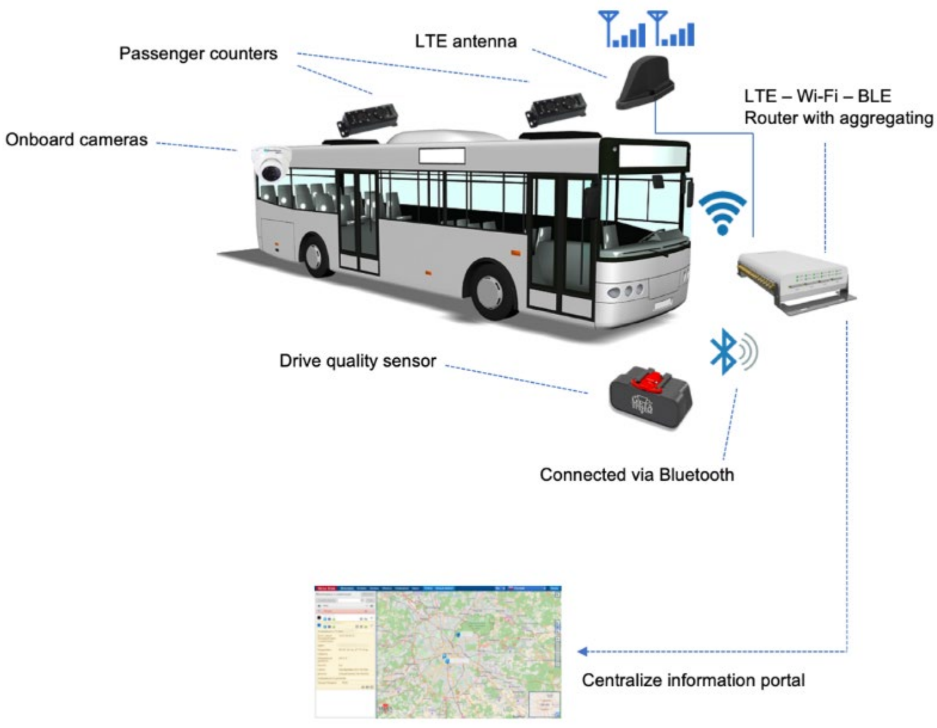


Figure 24 - Smart transportation IoT solution example 1

MaximaTelecom (MT) develops also solutions for Russian railways. Solutions provide universal real time and high speed access to the train with universal data HUB onboard.

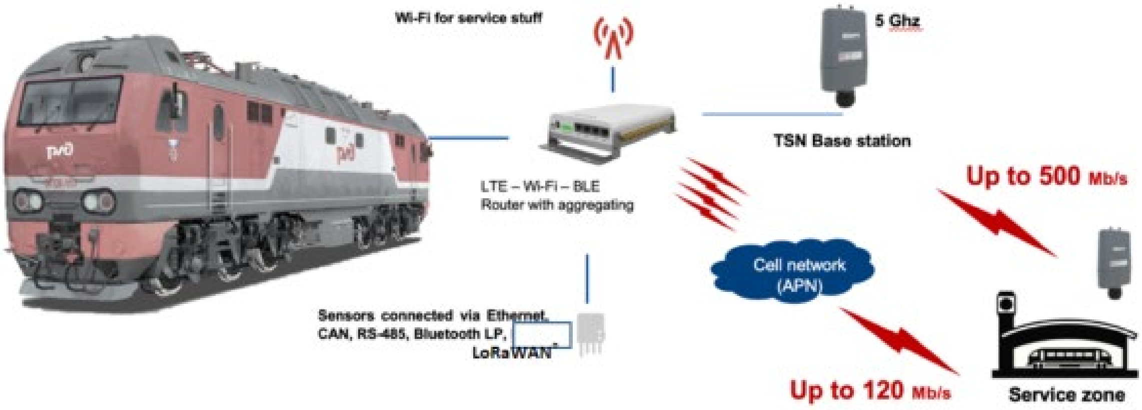


Figure 25 - Smart transportation IoT solution example 2

12 Envisioning the future

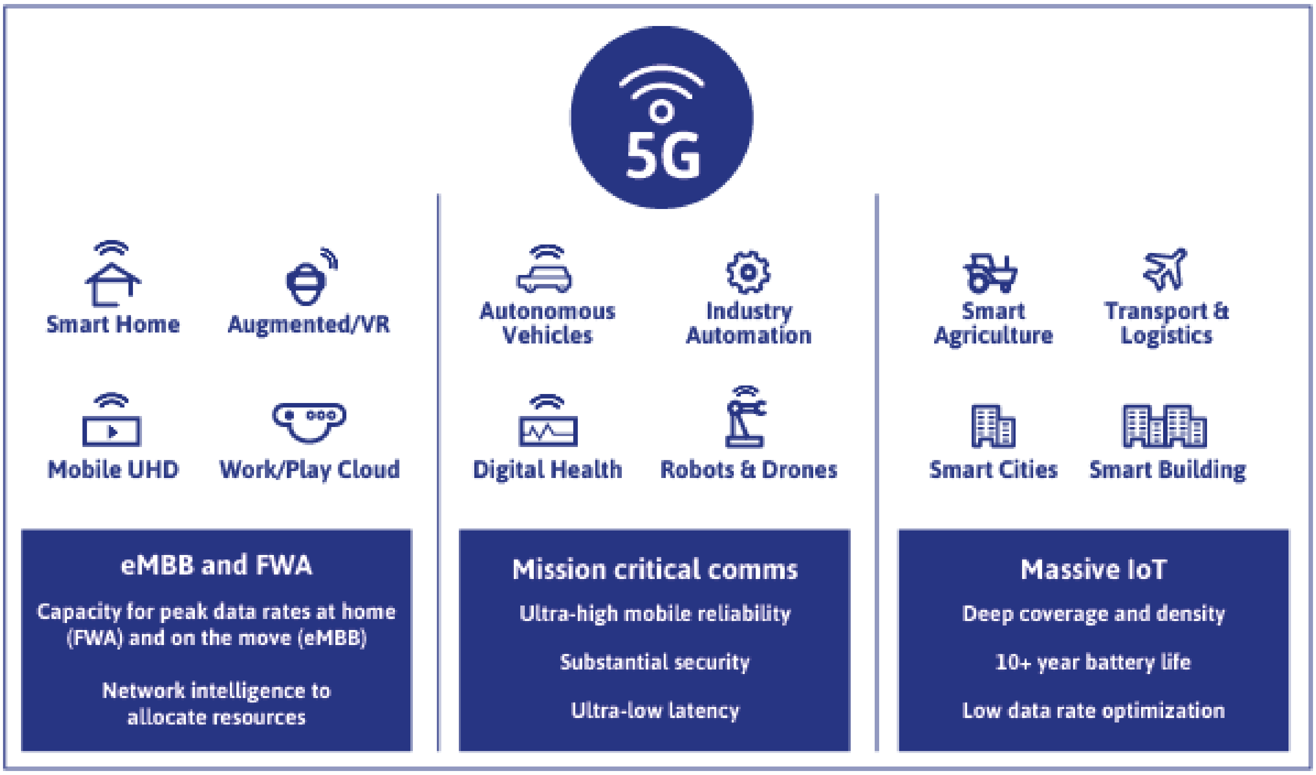
When envisioning the future, people may think of disruptive innovations where 80% of compelling inventions are incremental and, in a way, very simple to implement. Based on this white paper, there is a low hanging fruit that is **leverage existing Wi-Fi Networks across the world by rolling-out Wi-Fi 6 and LoRaWAN®** to address new IoT use cases as described in the vertical section. Nevertheless, let us raise some key areas of collaboration.

Reinforce the strength of unlicensed technologies in 5G

Is anybody challenging the combination of 4G and Wi-Fi today?

When our internet web surfing or voice conversation seamless shifts to the mall Wi-Fi hot spot where we are hanging out or going shopping, nobody is surprised. More than 10B devices connected to 200M Wi-Fi Access Points have been invading our private and professional spaces...MNO's are more than happy to offload 60+ % of global broadband traffic on Wi-Fi unlicensed networks around the globe. Wi-Fi is clearly referred to as one of the 5G sliced technologies today.

5G needs unlicensed technologies to address all use cases



There is a little doubt that 5G will play a major role in our society's future. Not many people know that 5G is not just an evolution of 4G. 5G is the first version of 3GPP specifications [29] which opens the standard to any type of communication technology: mobile, wired, fixed wireless, satellite, licensed and **unlicensed technologies** like Wi-Fi and LoRaWAN®. 5G, in its incredible versatility targets to provide value into many verticals [34].

Conversely, the complexity and breadth of supported use cases means that some will be suboptimal due to 5G simply being "too much." This opens the door for "right-size" technologies instead of reinventing the wheel, to support these applications and one can already see this happening in the market today. 5G main challenge is clearly leveraging millimetre wave's spectrum (> 6 Ghz) to develop broadband very high throughput services (up to 20 Gpbs!).

LoRaWAN® and Wi-Fi cover hundreds of complementary uses cases on each of the 5G market segments: enhanced Mobile Broadband, mission critical communication, and massive Internet of things. Wi-Fi has been engaging for years into 3GPP 5G specification process. Why LoRaWAN® would not follow the same route as Wi-Fi? Just looking back as how Operators have been using Wi-Fi in combination with 4G, we have the perfect example of how 5G could leverage unlicensed technologies strong capabilities. Let us not oppose licensed and unlicensed technologies and focus on complementarity to serve any customer use case.

LoRa Alliance and Wireless Broadband have here the opportunity to present a synchronized approach to 3GPP, and at least **share valuable information**.

Improve interconnection and colocation

Being massively rolled out in the same types of locations like smart home, smart building and smart city Wi-Fi and LoRaWAN® need to set-out best practices to interconnect at different levels.

The **gateway route** of interconnection is already partially addressed via the several implementations of Wi-Fi backhauling of LoRa gateways. We see also use cases of LoRaWAN® backing up Wi-Fi in the smart home. In case of Wi-Fi failure, local devices frames are sent to the cloud servers via LoRaWAN® Network. The biggest challenge to support device scale-up will be to develop **Access Points or home-hubs fully integrating LoRaWAN® gateway**.

The **cloud route** of interconnection is already under implementation, although **device authentication** process, **data models**, and **security end to end processes** could become an area of alignment. Interconnection discussion might probably start to consider the impact on 5G interconnection.

Increasing massive cohabitation of devices may lead to discussion to **best colocation and device set-up practices** (in smart home for example) to avoid spectrum or interferences issues.

Develop device intelligence

In parallel to the hype of cloud computing-based applications, there is a real development of edge computing or device computing, leading to better handle network issues, as well as optimizing battery consumption by reducing needs of device communication with cloud servers. The goal is to make device more clever or self-sufficient in the decision-making process.

So, the **chip interconnect route** aims to combine Wi-Fi & LoRaWAN® application driven by the device application software and implemented on a chip module (dual source modules). This interconnection route is the most developed today on the ground via **dual chip modules** in most of geolocation services. Wi-Fi & LoRaWAN® location technics are a good example of leveraging strengths of the two technologies.

The emergence of Wi-Fi 6 improving throughput and latency could bring new ideas to develop high throughput functions like **Firmware Upgrade Over The Air** supporting LoRaWAN® devices, transmitted through the Wi-Fi connection of the device, assuming a trade-off on battery consumption. This can be an area of research, like any other applications benefiting from the strengths of the two technologies.

We may imagine a lot of other areas of development. We all know that as usual, the market is going to decide. We probably have here enough on our plate to boost the LoRaWAN® and Wi-Fi collaboration based on strengthening the two ecosystem experiences on similar market organizations.

13 Summary

Wi-Fi and LoRaWAN® are two of the most-adopted unlicensed technologies and together they address a large percentage of IoT use cases. The approaches for these technologies are disrupting private-public business models and also enabling participation in 5G rollouts.

As mentioned in the Introduction, our purpose in writing this white paper was to demonstrate how the Wi-Fi and LoRaWAN® technologies are complementary in nature, summarize the technical aspects of each and provide real world use cases and testimonials. Our goal was to inspire network operators who have deployed either Wi-Fi or LoRaWAN to consider to extend their offerings by deploying the other technology OR to give an existing operator who has deployed both technologies new ideas for how to future leverage their capabilities to support new use cases.

I want to thoroughly thank and congratulate the **25 companies** of both Alliances (**listed in the paper**) from all regions, contributing and bringing an incredible meaningful and insightful content. Americas, Europe and Asia are represented with companies representing all types of market actors. I also want to thank **Jaap Groot (Semtech),** WBA IoT Work group vice chair, **Dan Klaeren (Syniverse)**, WBA IoT Work group chair and white paper co-project leader, as well as Steve Dyett (BT), white paper co-projects leaders. It has been an outstanding journey during at least one year, and we hope that it will help to accelerate IoT adoption.

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FIGURES

ACRONYMS AND ABBREVIATIONS

ACRONYM / ABBREVIATION	DEFINITION
ABP	Activated By Personalization
AP	Access Point is a WLAN transceiver that connects a wired Local Area Network (LAN) or Personal Area Network (PAN) to one or many wireless Devices.
ADR	Adaptive Data Rate
ALOHA	Multiple access protocol at the datalink layer
B2C	Business to Consumer market (consumers)
B2B	Business to Business market (enterprises)
CPE	Customer Premise Equipment (can be home-hub or set-up box)
CSS	Chirp Spread Spectrum modulation
DSL	Data Subscriber Line
DR	Data Rate
EAP	Extensible Authentication Protocol
FOTA	Firmware Upgrade Over The Air
FSK	Frequency Shift Keying modulation
HGH	Next Generation Hotspot
ICP	Interconnection Compliancy Program
IFTT	If This Then That
IoT	Internet of Things
IoT Connectivity	Wireless technology connecting a device or machine to a network Ranging from Broadband to Narrow Band.
IoT DEVICE	Connected object
IP	Internet Protocol
ISM	Unlicensed Spectrum band for industrial, scientific and medical application, authorized for IOT applications.
ISP	Internet Service Provider
LPWA(N)	Low Power Wide Area Networks
LTE	Long Term Evolution (4G)
MAC	Media Access Control layer
MIC	Message Integrity Check
M2M	Machine To Machine. Historically 2G/ 3G/ 4G connections.
MNO	Mobile Network Operator
MSO	Multi Service Operator (cable-operators, fibre-optics, satellite…)

NAI	Network Access Identifier
NR	New Radio
OTAA	Over-The-Air Activated
OTIF	On Time In Full
PA	P. Amplifier
Public Network	LoRaWAN® Network provider selling connectivity to third parties.
Radius	Wi-Fi network element in charge of device Authentication and roaming management
ROI	Return Of Invest
RF	Radio Frequency
RSSI	Received Signal Strength Indication
SOHO	Small Office Home Office
SLA	Service Level Agreement (quality of service)
TCO	Total Cost of Ownership
TDoA	Time Difference Of Arrival
Wi-Fi Access Points	Manage Wi-Fi end device radio communication locally.
WBA	Wireless Broadband Alliance
WGC	Wireless Global Congress
Wi-Fi	Short and medium range technology dedicated on radio wireless local area network access of devices within a limited area, based on the IEEE 802.11 standards. Wi-Fi is a trademark of the Wi-Fi Alliance. Wi-Fi compatible devices can connect to the Internet via a WLAN managed by a Wireless Access Point.
WLAN	Wireless Local Area Network (or Wireless LAN) in which data is transmitted from point to point without the use of wires. WLANs are also known as Wi-Fi networks.
WPA	Wi-Fi Protect Access
WRIX	Wireless Roaming Intermediary Exchange
WWD	World Wi-Fi Day™
802.11	Set of standards for wireless local area network (WLAN) computer communication, developed by the IEEE LAN/MAN Standards Committee (IEEE 802).

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