MOBILE EXPERTS

Mobile and Wide-Area IoT: LPWA and LTE connectivity

Technical and Economic Analysis: Matching each application with the best standards

Abstract

The Internet of Things has begun with simple home automation, with Wi-Fi and Bluetooth technologies. As IoT goes mobile, the industry faces the question of which wireless formats are best for link budget, as well as fundamental economic questions about the Total Cost of Ownership for SigFox, LoRa, Weightless, Telensa UNB, RPMA, QoWisio, DART, and other options. 3GPP based options such as LTE Category 0 and Category 1, and "NB-IoT" are also examined for performance and cost, along with short-range wireless options such as ZigBee, 802.11ah and 802.11af, ISA100.11a, and WirelessHART. .

This report compares emerging standards to the LTE evolution path for wide-area IoT applications, to investigate the viability of each technology. The key outcome of the report is to show how each technology matches up with 86 different IoT applications.

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Executive Summary

The low-power wide-area (LPWA) market is in a hype cycle that is closely tracking the evolution of IoT. Hundreds of startups, aside from established companies, expect LPWA to create a new big market. Our research of LPWA markets and technologies explores the potential for LPWA to be have a disruptive impact in IoT connectivity. We accomplish this by taking a systematic, layered approach:

First, we explored LPWA and 3GPP cellular technologies in deep technical detail, along with other formats that we call short-range wide-area (SRWA) technologies that are extensively used in both industrial and commercial applications. Our analysis is conducted within the framework of spectrum regulations that immensely impact performance. The LPWA technologies we cover include: LoRa, SigFox, RPMA, Weightless (P, N, and W), Qowisio, N-Wave, Telensa, and DART.

Second, we derived key performance metrics and estimated the CAPEX and OPEX required for an effective network, to benchmark the economic feasibility of wide-area technologies. We additionally analyzed the business models of LPWA proponents which will be critical to understand future market evolution.

Third, we mapped the requirements of 86 IoT applications to performance characteristics of the three categories of IoT connectivity technologies above to pinpoint the market segments where each category can take hold.

With this framework, we find that LPWA technologies are primarily targeting applications that SRWA networks address today. In fact, the competitive nature between LPWA and SRWA is the most underestimated and least understood in the market. The importance of this point cannot be over-stressed as it will set the tone for future market development. While LPWA currently compete on secondary-basis with 3GPP technologies, the competitive positioning between these two categories has been fiercest as they both expect to tap in the future into the same share of the IoT connectivity market. This competition is largely responsible for much activities, interest, and even hype, in this market.

In light of the above market qualification, some of our conclusions include:

- 3GPP technologies are 2-4 years away from providing a competitive solution with similar performance characteristics to LPWA technologies. The lynchpin of 3GPP strategy is the development of LTE Cat-m1 and NB-IoT technologies, both defined in 3GPP Release 13, with anticipated commercial availability in early and late 2018, respectively.
- This time-gap provides the LPWA ecosystem an opportunity to establish market presence, the success of which will be the result of a complex interplay of different

factors that include foremost the ability of LPWA proponents to penetrate a fragmented market landscape with long-sales cycle.

- The LPWA ecosystem has the advantage of diversity and vitality which include startups as well as major technology players in adjacent markets that see LPWA as an opportunity to chip away at the traditional service provider market. For this reason, mobile network operators have been making investments in LPWA technologies which are essentially insurance policies on future market uptake in light of the late arrival of a standardized technology which they consider critical requirement.
- LPWA are set to play a major role in private networks that address specific application requirements. Their success in public networks is gated to a great extent on the service value proposition and return on investment, the regulatory framework, and the competitive landscape.
- Licensed-exempt spectrum regulations strongly impact network performance and the investment required to build LPWA networks, and consequently impact the financial viability of LPWA networks. The regulatory framework in the United States is more advantageous than it is Europe where between 2x – 8x more in capital expenditure is required to achieve a similar level of service as in the US, depending on technology. The regulatory framework in many other major markets such as Japan, Korea, China, and others is still evolving.
- ISM and SRD-band spectrum regulations are defined according to the type of the air interface. The capacity of LPWAN networks based on DSSS/CSS and UNB technologies is limited by duty cycle requirements and the range is limited by transmitted RF power limits whereby:
    - LoRa cell range performance exceeds that of SigFox in both Europe and the US, but its capacity falls below SigFox which supports a larger number of devices per base station. This increases operational efficiency, especially in loaded networks characteristic of mature markets and provides SigFox with an edge in public networks. On the other hand, LoRa offers wider technology options than SigFox which makes it amenable for customization and for use in private networks.
    - RPMA cell range is competitive with LoRa in the US and exceeds LoRa in Europe for outdoor deployments. RPMA offers the highest capacity among LPWA technologies. However, its cell range performance is limited for indoor applications.
    - Weightless-P offers a competitive mix of range, capacity, and a host of other features not available in LoRa or SigFox. It differentiates by being the only LPWA technology that is based on an open standard. Weightless-P offers the highest competitive challenge to 3GPP technologies from a technical perspective. Its success will be based on the ability of the Weightless SIG to develop and grow an ecosystem, especially larger companies in market segments where LPWA has a competitive advantage.
- Mobile network operators (MNOs) are likely to base their business model around 3GPP technologies over the long-term, especially LTE Cat-m1 devices as defined in 3GPP Release 13. The NB-IoT standard provides the ultimate in range and

performance, but it is the last of the reviewed standards to become commercially available. For some service providers, existing radios can be used with a software upgrade, so the business case for NB-IoT vs. LPWA will depend on the pricing set by the network OEM for the software upgrade. Many network operators will need to deploy IoT in new bands, which will require a hardware upgrade.

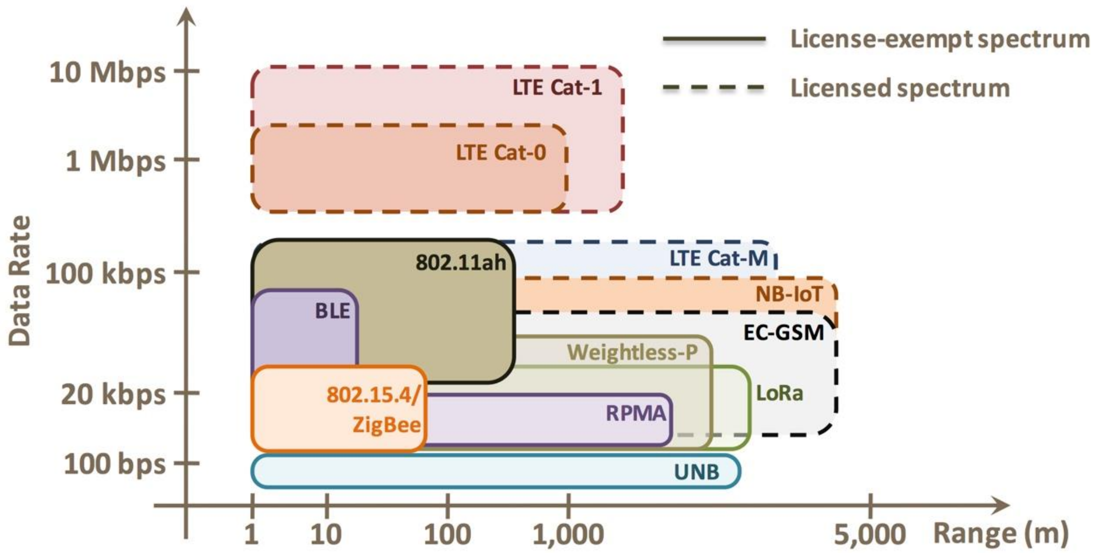

Figure 1 Range vs. data rate for IoT connectivity technologies.

Table 1 Relative ranking of LPWA technologies.

Rank	Indoor Cell Range Performance		Capacity
	US	Europe	
1	LoRa	LoRa	RPMA
2	SigFox	Weightless-P	SigFox
3	Weightless-P	SigFox	LoRa
4	RPMA	RPMA	

Note: No information is available yet on Weightless-P capacity; standard was released at the same time as this report.

- MNOs have a major strategic advantage in licensed spectrum holdings, physical infrastructure assets, and operation and maintenance processes efficiency over IoT service provider entrants. IoT service providers must leverage their agility to tailor a nimble go-to-market strategy that addresses a fragmented market with differing requirements where custom services will play an important role in business success (i.e. no "one-size fits all" in IoT).
- LPWA is well suited to target private networks with optimized performance for specific applications. However, the success of LPWA in public networks is less certain and will play out over a longer term than it would in private networks. We foresee the key factors impacting the success of LPWA in public networks as follows:
  - The requirement for open standards that assure multi-sourcing in all stages of the value chain

    - Long-term assurance of the business model, as timeframe for IoT connectivity stretches into years unlike broadband subscriber services where users can switch service providers at any time. The engagement of large companies plays a stabilizing role which LPWA proponents, many of whom are small companies, need.
    - Licensed-exempt spectrum which raises infrastructure demands on the service provider to assure reliability in addition to imposing restrictions on scalability.
- Wireless IoT connectivity is a commodity. Therefore, scalability to support high volumes of connected devices is critical for capital efficiency. LPWA networks are not as capital intensive as broadband mobile networks which have a higher operational costs as a percentage of total expenses. Technologies such as NFV and SDN will play a key role in enabling cost effective scalability by leveraging data center economics for the IoT connectivity core network to further lower operational costs. From a revenue perspective, service providers need to move higher in the value chain to provide data management and analytics services in order to improve the return on investment. This is an area that MNOs have been slow to develop, but whose value will become more important in IoT connectivity networks. The importance of data management is amplified in IoT networks.
- LPWA protocols have relatively low-complexity waveforms. 3GPP technologies use more complex waveforms and require higher levels of integration in semiconductors to compensate. LPWA devices use commodity-priced micro-controllers while 3GPP technologies rely on SoCs that require high initial investment. SRWA technologies leverage existing device markets to achieve economies of scale. Overall, LPWA technologies have the potential to achieve a sub-$5 device cost target more quickly than LTE. This distinction will be key in the short term, as volumes will be low in the early stages of the IoT market.
- The prime applications for LPWA networks include agriculture, smart city, transport and environmental monitoring. Applications where LPWA should have the lowest adoption rate include smart health and smart buildings. LPWA should have mixed adoption in smart living, smart manufacturing, smart industry and smart energy segments where it competes against other technologies.

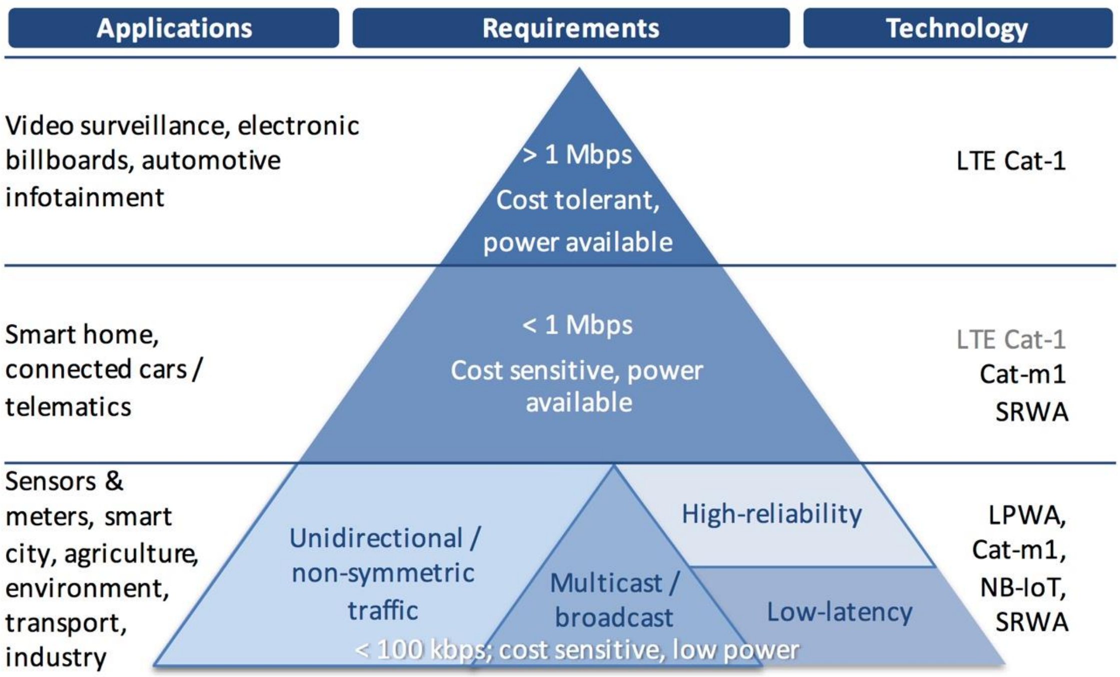

Figure 2 IoT connectivity market structure.

- We estimate that organic growth of LPWA devices will reach only 200-250 million units by 2020. By this, we mean that new wide-area business opportunities will grow pretty slowly over the next 5 years. The relatively slow short-term uptake in LPWA is due to multiple factors, including:
  - Deployments driven by industry and private sector in agriculture, environment, industry utilities and transport with limited adoption in smart buildings, consumer, and smart city applications where traditional LPWA forecasts are focused. Long sales cycles will affect volume uptake in the short term.
  - Fledgling public networks require time to evolve to provide the required coverage and density to support volume deployments. To achieve mass volume, public networks play an important role by expanding the access for multiple users and suppliers in the ecosystem.
  - Fragmentation of the market within the next 2 years works to slow down big deployments, as enterprises and service providers face some confusion about multiple options, and economy of scale is delayed due to multiple parallel activities.
- In the longer term, we expect that public LPWA networks and ecosystems will be more developed, and the number of confusing options will be reduced, driving economy of scale in one or two specific options. In the 2020-2025 timeframe, we expect accelerating growth of LPWA into the billions of units per year.

- In addition to "organic" growth of LPWA applications, we believe that there is a larger opportunity in the near term for LPWA to steal IoT business from short-range technologies such as Wi-Fi, Bluetooth, and Zigbee. This growth holds the potential for larger numbers in the next five years, as the existing installed base for short-range IoT devices is roughly 7.5 billion units today.

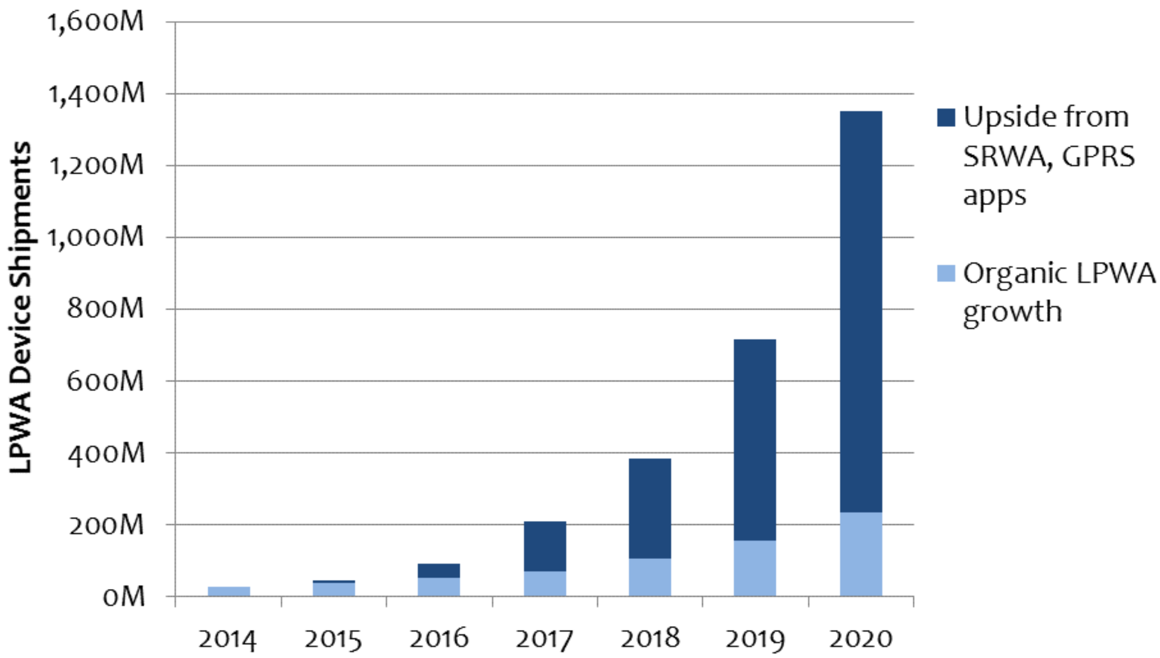

Chart 1. Global Forecast of LPWA device shipments

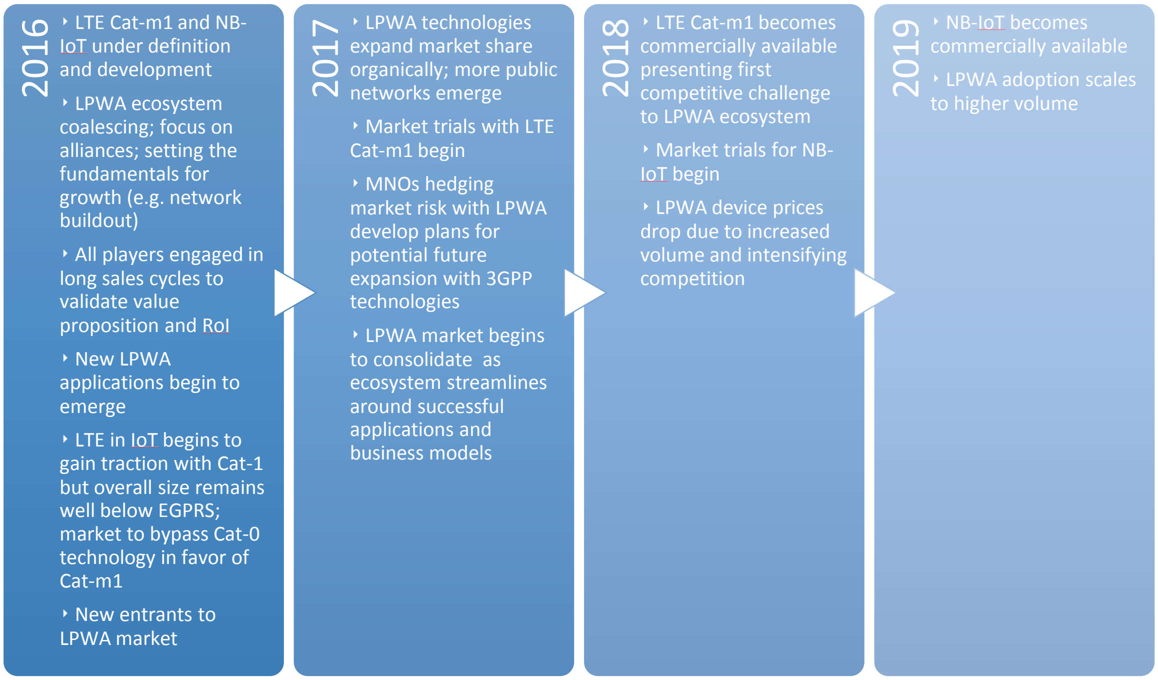

Figure 3 Market prognosis and evolution roadmap for LPWA and 3GPP IoT connectivity technologies.

The Spectrum Landscape

Licensed-Exempt Spectrum for IoT connectivity

The sub 1 GHz frequency bands offer the most favorable performance characteristics for wide-area IoT connectivity. The 868 MHz SRD band in Europe and 915 MHz ISM band in the Americas receive the highest considerations for LPWAN deployments. This is followed by the 2.4 GHz ISM band which, unlike its sub 1 GHz peers, is globally harmonized. License-exempt spectrum in sub 1 GHz band is fragmented with different non-overlapping bands (Table 2).

Table 2 ISM and SRD bands available for LPWAN.

Frequency band	Band	Region	Technology
433.05 – 434.79 MHz	ISM	Asia, Europe*	RFID
470 – 698 MHz	TV Whitespaces	US, UK, Canada, Singapore	IEEE 802.11af
779 – 787 MHs	SRD	China	WPAN 802.15.4
866 – 870 MHz	SRD 860	European Union	SigFox, LoRa, Weightless
902 – 928 MHz	ISM	Americas	SigFox, LoRa, Weightless, IEEE 802.11ah
915 – 928	SRD	Japan, Australia, Taiwan, Korea+	RFID
1880 – 1930 MHz	1: 1880-1900 MHz 2: 1895 – 1918 MHz 3: 1900-1920 MHz	1: Europe 2: Japan 3: China	
2400 – 2483.5 MHz	ISM	Global	RPMA, Wi-Fi, Bluetooth, ZigBee

*** Germany, Austria, Bosnia and Herzegovina, Croatia, Macedonia, Liechtenstein, Montenegro, Portugal, Serbia, Slovenia and Switzerland.**
+ Exact band varies among countries.

Regulatory Framework for License-Exempt Spectrum

Regional variations in sub 1 GHz band regulations heavily influence the performance of LPWA technologies and consequently impact the service offering and the cost model. Regulations allow high transmit RF output power for systems implementing frequency hopping (FH) or direct sequence spread spectrum techniques (DSSS). Therefore, LPWA systems fall under of these two general classes to maximize range and coverage area. FHSS and DSSS techniques take different approach to interference management which is critical aspect for license-exempt operation. For instance, narrowband technologies are characterized with long transmission time which increases the liability of being subject to interference. Multiple redundant transmissions is one way to increase reliability in this case. On the other hand, DSSS systems rely on the gain of the spreading code to recover the signal in a noisy environment.

FCC Regulations

LPWA devices operate under FCC CFR Title 47 Part 15 (or simply Part 15) rules for intentional radiators. The regulations for the 915 MHz and 2400 MHz bands allow for high RF transmit power operation suitable for LPWA applications (Table 3). Frequency hopping systems have to meet requirements for the length of the transmission and dwell time on a specific frequency which should not exceed 0.4 seconds. This is an important parameter that ultimately affects system capacity.

Table 3 FCC 915 MHz regulatory requirements covering LPWA.

Frequency Band	Transmission Type	EiRP[1] (dBm)	Dwell time	Channel Bandwidth	Hopping frequencies
902 – 928 MHz	Frequency Hopping	+36	< 0.4 sec in any 20 sec period	< 250 kHz	≥ 50 channels
		+30	< 0.4 sec in any 10 sec period	≥ 250 kHz	≥ 25 channels
	DSSS	+36			
2400 – 2483.5 MHz	Frequency Hopping	+36	< 0.4 sec in any 0.4 sec x number of channels		≥ 75 channels
		+30	< 0.4 sec in any 0.4 sec x number of channels		≥ 15 channels
	DSSS	+36			

[1] EiRP is based on 6 dBi antenna. Power reduced proportionally for higher gain antennas.

European Union Regulations (CEPT/ETSI)

The Electronic Communications Committee (ECC) defined in ERC/REC 70-03 requirements for devices in non-specific applications as well as requirements for devices in 13 different classes of applications in the 860 MHz SRD band (Table 4). The user has an option to operate under the guidelines of non-specific application or under a specific application if one exists. The regulatory framework is a national matter and individual countries must adopt the requirements to be binding which result in some differences between member countries.

Table 4 ECC regulatory requirements covering LPWA.

Frequency	EiRP (dBm)	Duty Cycle	Channel Spacing
863 – 870 MHz	16.13	0.1%	FH: ≤ 100 kHz, ≥ 47 channels DSSS or other wideband modulation
868 – 868.6 MHz	16.13	0.1%	No spacing, for FH or DSSS/wideband
868.7 – 869.2 MHz	16.13	0.1%	No spacing, for FH or DSSS/wideband
869.4 – 869.650 MHz	29.13	10%	25 kHz, for FH or DSSS/wideband
869.7 – 870 MHz	16.13	0.1%	No spacing, for FH or DSSS/wideband
2400 – 2483.5 MHz	+10	None	No requirement

The duty cycle is defined as the ratio, expressed as a percentage, of the maximum transmitter "on" time on one carrier frequency, relative to a one-hour period (Table 5). This is a critical parameter that impacts system capacity.

Table 5 Duty cycle characteristics for SRD requirements.

Duty cycle limit	Total on time within one hour	Maximum on time of one transmission	Minimum off time between two consecutive transmissions
< 0.1%	3.6 seconds	0.72 seconds	0.72 seconds
< 1%	36 seconds	3.6 seconds	1.8 seconds
< 10%	360 seconds	36 seconds	3.6 seconds

Note that FCC regulations allow for higher RF output power and more relaxed transmission frequency than European regulations. On the other hand, FCC requirements mandate much shorter transmission duration – limited to 0.4 seconds – while European limits support transmissions on the order of seconds (e.g. 36 seconds per hour for 1% duty cycle). This difference in regulatory requirements obliged SigFox to modify the air interface to accommodate FCC regulations for deployments in the United States.

TV Whitespaces (TVWS)

TVWS has been considered for IoT connectivity, but has received little traction because:

- TVWS transmission is currently allowed in four countries only: US, Canada, UK, and Singapore. This restricts the total addressable market.
- The requirement for geolocation-based service to avoid interference to incumbent users imposes an additional burden to register the device location with a database that looks up the availability of the band and provides permission to operate as well as revoke operation privileges.
- Broadcasts from high-power TV transmitters pose a challenge for adjacent channel interference isolation. Filtering adds to the expense of the solution. This is particularly critical for low-cost sensors wherefilter cost can be prohibitive.
- Uncertainty related to the regulatory framework deters investment. In the United States, the FCC will auction the part of the UHF band (470-698 MHz) for mobile services by migrating TV broadcasters to a lower part of the band. While this promises to free spectrum for TVWS in highly congested markets like New York and Los Angeles where no TVWS channels are available today, it is not expected in practice to result in many usable channels due to adjacent channel interference.

The above considerations have limited the interest in TVWS for massive IoT applications.

Licensed Spectrum

Mobile network operators own significant spectrum especially in the sub 1 GHz band. Licensed spectrum provides advantages over licensed-exempt spectrum in terms of performance, but is more restrictive from a business and operational perspectives as access to this spectrum is constrained through MNOs.

Table 6 Comparative analysis of licensed and licensed-exempt spectrum.

	Pros	Cons
Licensed-exempt spectrum	• Allows private and public networks • Allows fast time to market • Enables variety of technologies supporting different application requirements	• Non-harmonized regulations across different regions • Variety of spectrum bands limits harmonization • Regulations limit operating performance specifically related to coverage and capacity • Reliability cannot be predicted and interference cannot be managed
Licensed spectrum	• Allows greater capacity and coverage performance • Leverages existing mobile network infrastructure to enable quick coverage • Reliability can be better controlled as all interference is generated by users of the network • Better harmonization of spectrum across countries and regions	• Controlled by mobile network operators • High cost to acquire: return on investment will be viable for very large number of devices

Key Takeaways Based on Spectrum Regulatory Framework

1- There is a lack of global harmonization for license-exempt spectrum for IoT applications: different frequency bands and regulatory requirements make LPWA networks susceptible to local regulatory framework which impacts performance and cost effectiveness of the networks.

2- Lack of harmonization precludes a single global framework for certification and compliance of devices to regulatory requirements: devices in one region will not work in another region.

3- Global roaming capability will require devices to support multiple radios and protocol stacks for the same technology in order to comply with regional regulatory framework. This will impact the viability of LPWA in certain applications that involve traversing regional boundaries such as asset tracking.

4- Regulations in license-exempt bands treat all emitters equally; hence, there is no distinction between a base station and an end device. This limits operating parameters and leads to constraints in wide area network deployments.

5- TVWS bands are not expected to factor heavily into IoT deployments in the foreseeable future due to the complexities of filtering and harmonized spectrum.

The United States and Americas market offers a more favorable regulatory framework for LPWA deployments the European market, as characterized by a higher transmit RF output power which impacts the business case positively by reducing cell count and investment in infrastructure.

Wide-Area IoT Connectivity Technologies

Three classes of technologies compete for wide area connectivity:

1- Low-power wide-area technologies: LPWA provide wide area connectivity and low bit rate, ranging from order of a few bytes per hour to 30 kbps, with optional operating modes reaching to 100 kbps. The key use case is in low-power consumption applications where devices operate on battery over a long period of time reaching several years (e.g. 5 – 10 years). LPWA technologies are based on point-to-multipoint topology and operate in license-exempt spectrum.
2- Cellular technologies: The 3GPP roadmap for LTE includes support for battery-power operation over a period of time stretching into several years. This is achieved by reducing the transmission bandwidth, adding power saving features, reducing control signaling to a minimum in addition to other features. We include in the group the evolution of EGPRS which is being standardized in GERAN. Collectively, we call these 3GPP technologies. They all operate in licensed spectrum.
3- Short-range wide area: these protocols are based on open or proprietary standards which are deployed in many industrial applications. They typically fall under two topologies: short range point-to-multipoint connectivity (e.g. Wi-Fi, Bluetooth) and mesh or multi-hop topology (e.g. ZigBee) (Figure 4).

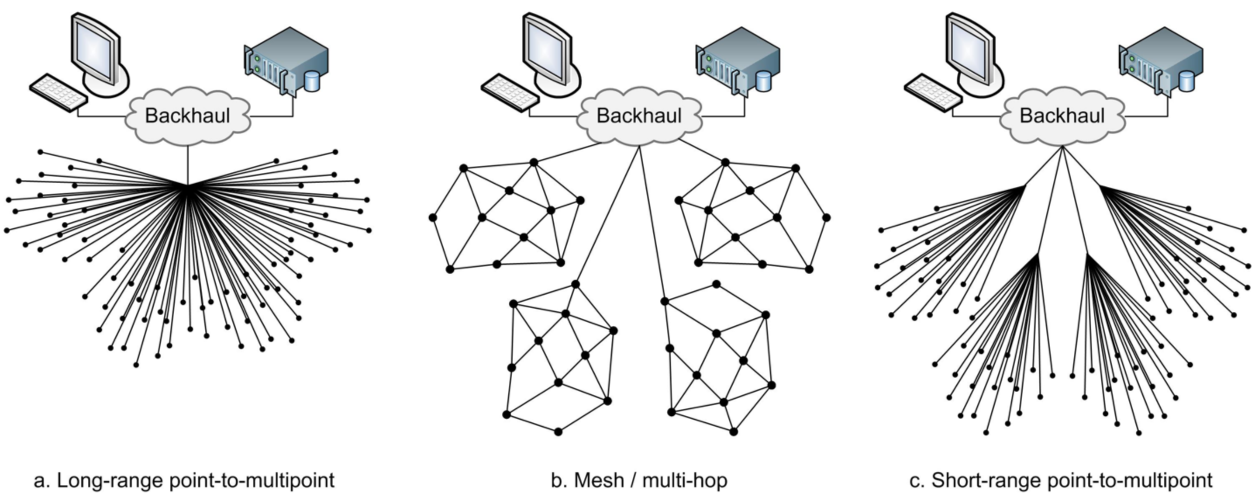

Figure 4 Network topologies for area connectivity.

We provide an overview of all three categories to provide the context for LPWA technologies; all three categories of technology compete in many market segments for the same application.

Low-Power Wide Area Technologies

LPWA concepts are not new to the market despite the recent flurry of investment activities and press releases. The technologies have been available for short range use, but their extension for wide-area coverage began to develop within the last 5 years. They can be broadly divided into three classes of technologies:

1- Ultra-narrowband (UNB): these technologies operate in very narrow channels ranging between 100 – 1000 Hz. They include protocols such as SigFox, Qowisio, Telensa and Weightless-N. These technologies offer low bit rate – on the order of a few bytes per hour in order to comply with emission regulations.
2- Spread-spectrum: technologies based on direct-sequence spread spectrum (RPMA) or Chirp SS (CSS) (LoRa). They typically operate over a channel bandwidth ranging from 125 kHz to 1 MHz and offer data rate on the order of a few tens of kbps.
3- Narrowband: technologies best exemplified by Weightless-P which combines time division multiple access (TDMA) and frequency hopping spread spectrum protocol over a 12.5 kHz channel.

The first two categories are more popular today in terms of ecosystem support. However, narrowband technologies are relatively new and they account for some of the shortcomings of UNB and DSSS/CSS technologies.

LPWA network architecture is relatively simple (Figure 5). It consists of a base station or a gateway (we will use the term base station in this report) with which field devices communicate. A network controller manages multiple base stations and processes data from devices. The base station is connected to the network controller over an Ethernet backhaul link. Multiple backhaul technologies can be used including cellular technologies[1] depending on application. Finally, an application server which can be hosted in the cloud provides clients the ability to manage the field devices and access the collected data.

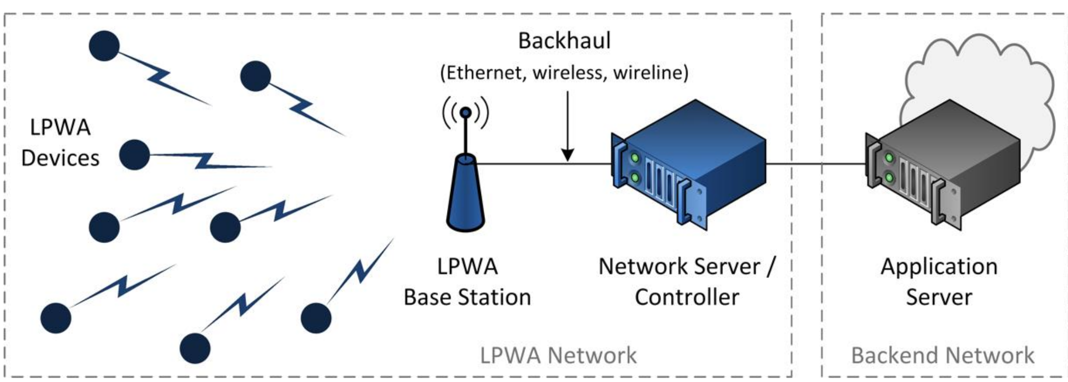

Figure 5 LPWA General network architecture.

[1] The low data rate in IoT applications allows using cellular technologies to backhaul data from IoT base stations. The latency in such architecture is typically too high to be acceptable for control applications, but is perfectly suitable for latency tolerant applications.

LPWA networks are deployed in a cellular architecture by leveraging tower assets and tall buildings in urban areas. Different configurations can be possible when deployed in private networks to serve a specific application and use case.

SigFox

SigFox technology is based on ultra-narrowband transmissions (100 Hz in Europe, 600 Hz in US) modulated with DBPSK on the uplink (100bps and 600bps data rate in Europe and the US, respectively[2]) and GFSK on the downlink (600 Hz, 500 bps) (Table 7). An uplink transmission delivers 12 bytes in payload data and lasts up to 6 seconds. The transmission is repeated three times on different frequencies for robustness against interference (2 seconds per frequency for a total of 6 seconds). Transmissions could be received by multiple base stations and a central server selects the most appropriate transmission (Figure 6). The total uplink packet size is 26 bytes and includes the unique device ID and a message authentication hash and CRC bits. The ultra-narrow channel bandwidth requires good quality crystal oscillator which adds to the cost of the end device.

Transmissions in the downlink are based on 'time-delayed piggy-back' technique where downlink packets are stored in the core network and forwarded to the device after an uplink transmission. This provides a limited transmission acknowledgement mode. To accommodate this mode, the device remains 'awake' for 14 seconds after the conclusion of an uplink transmission instead of going into sleep mode. The downlink is limited to a payload of 8 bytes so it is not suitable for firmware updates. A SigFox service package provides for up to 4 x 8 bytes downlink messages per day.

To meet regulatory requirements, SigFox only transmits 6 messages per hour to comply with the 1% duty cycle requirements (868 – 868.6 MHz in Europe), hence a limit to transmit 140 messages per day. In the United States, FCC regulations allow much higher message count in the 915 MHz band - up to 450 messages - but the transmission time is limited to 0.4 seconds.

Table 7. SigFox duration of transmissions.

	Data rate (bps)	Duration (seconds)
CEPT/ETSI	100	2.1
FCC	600	0.35

[2] SigFox bandwidth and data rate for US deployments complies with the 0.4 second transmission duration limit.

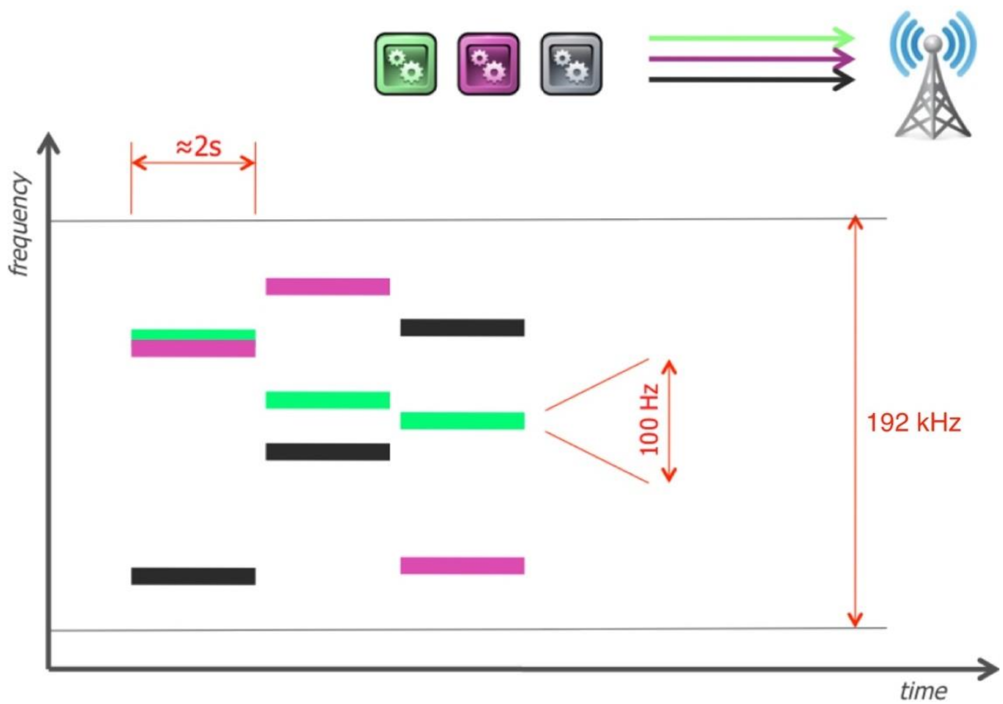

Figure 6 Macro diversity in SigFox UNB. [Source: SigFox]

SigFox does not support paging mode so there is no mean to wake up a device to push downlink packets towards it, nor does SigFox support broadcast or multicast services. While every message is signed with the device 16-bit private key, SigFox does not encrypt messages as it expects the device generating the data to perform this task.

Power consumption of SigFox compliant modules is low – current draw of about 50 mA during transmit mode at maximum allowed power (ERP of 14 dBm per European regulations).

Figure 7 SigFox base station. [Source: SigFox]

Technology Characteristics and Applications

SigFox is best suited for stationary applications. It does not enable mobile applications because its narrowband characteristics makes it susceptible to Doppler spread. In stationary applications, SigFox is ideal for digital on/off messaging (e.g. full/empty, available/occupied, functional/out-of-order, etc.). It can also be used in applications with short messages and low report duty cycle such as sensors (e.g. environmental sensors). SigFox applications are latency-tolerant.

LoRa

LoRa, which stands for Long Range, is a technology first developed by Cycleo of Grenoble, France which was acquired by Semtech in 2012 for $5 million. LoRa defines a physical layer technology based on chirp spread spectrum signals that spread transmitted data over a channel bandwidth of 125 kHz, 250 kHz, or 500 kHz (US only) with multiple spreading factors (SF) which define data rate and range (Table 8). In the US, the data rate varies between 980 bps and 21.9 kbps. In Europe, the data rate varies between 250 bps and 11 kbps in addition to a single non-LoRa (not spread) GFSK signal at 50 kbps. LoRa complies with duty-cycle regulatory requirements and does not implement the alternative listen-before-talk (LBT) option available in European regulations. The maximum packet size in LoRa mode is 256 bytes.

Table 8 LoRa regional operating parameters. [Source: LoRa Alliance]

	Europe	North America	China	Korea	Japan	India
Frequency Band	867 – 896 MHz	902 – 928 MHz	470 – 510 MHz	920 – 925 MHz	920 – 925 MHz	865 – 867 MHz
Channels	10	64 + 8 + 8	Under definition	Under definition	Under definition	Under definition
Channel BW - UL	125 / 250 kHz	125 / 500 kHz				
Channel BW - DL	125 kHz	500 kHz				
Spreading factor - UL	7 - 12	7 - 10				
Bit rate	250 bps – 50 kbps	980 bps – 21.9 kbps				

Different Layer 2/MAC solutions are available for LoRa. The LoRa Alliance[3] is in process of standardizing a Layer 2 / MAC protocol: LoRaWAN. LoRaWAN includes specifications to meet requirements of FCC 915 MHz ISM rules, European SRD 860 and 433 MHz requirements and China's 779 MHz rules. LoRaWAN allows for different classes of devices which makes it suitable for different application requirements:

- Class A – Bi-directional devices: This mode allows for uplink and downlink transmissions whereby uplink transmission is followed by two open windows for downlink transmissions. This mode is the most energy efficient but results in the longest latency for downlink transmissions which are limited. This mode is most suitable for uplink dominated applications without requirements for firmware upgrade.

- Class B – Bi-directional with scheduled receive slots: This mode allows for downlink transmissions to be scheduled at a specific time. The end device would have to synchronize to a beacon signal from the LoRa gateway. This mode allows for multicast messages and makes it more suitable for device firmware upgrade.

- Class C – Bi-directional with maximal receive slots: This mode allows for nearly continuous open receive window that are closed only when the device is transmitting. Power consumption is highest in this mode but provides the lowest downlink latency. This mode requires power and would not be considered where long battery life is expected.

[3] The LoRa Alliance formed in February 2015 and counts over 130 member companies as of the time of writing this report.

LoRaWAN manages data rate and RF output for each end-device individually by means of an adaptive data rate (ADR) algorithm. Devices close to the LoRa gateway can transmit at high data rate and at lower RF output power to optimize the longevity of the device battery.

LoRaWAN incorporates AES CCM 128 key message encryption (Figure 8). It also allows for network antenna diversity as different gateways listen to the same uplink channel. LoRa gateways operate multiple channels and scale to support tens of thousands of devices. Additionally, the CSS technology enables geo-positioning through difference time of arrival techniques (DTOA).

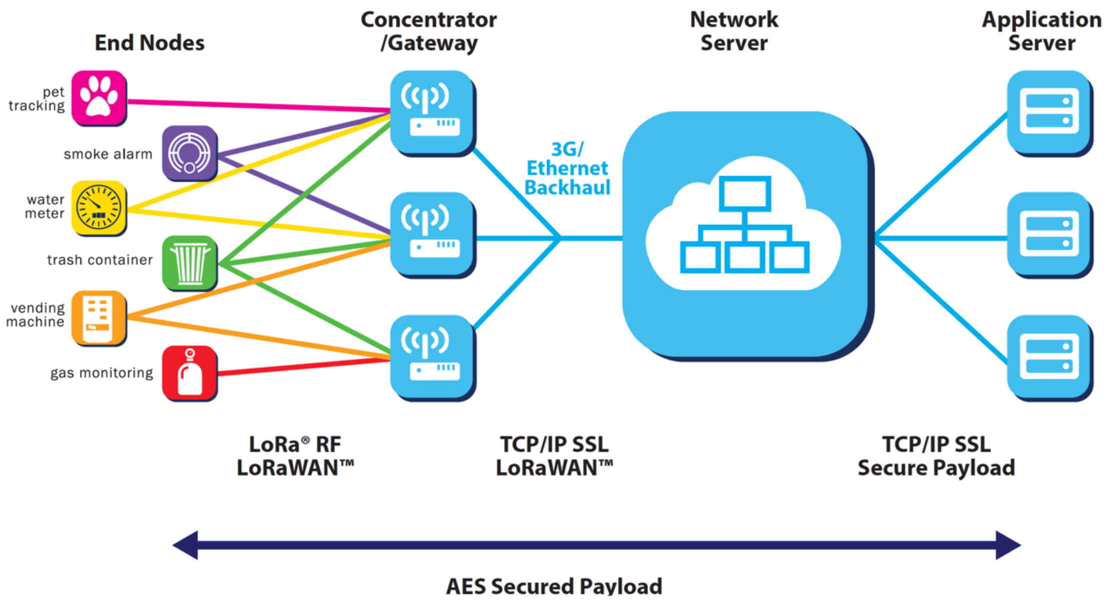

Figure 8 LoRa network architecture. [Source: LoRa Alliance]

Aside from LoRaWAN, there are specialist implementations that target specific enhancements. For example, Link Labs' Symphony Link is geared towards synchronous network with features for QoS, over-the-air firmware upgrades, message acknowledgment, and broadcast services. Symphony Link targets the North American market as it is designed for compliance with ISM 915 MHz band rules.

Technology Characteristics and Applications

LoRa enables certain features prized by certain applications such as:

- Mobility due to relatively wide channel bandwidth (125 kHz).
- Multicast services which enable firmware upgrade over the air.
- Multiple options for downlink service quality.
- Geolocation services, as devices can be located in the network.

LoRa spreads the signal over relatively narrow bandwidth using a small number of spreading factors (6). This impacts the capacity, especially for indoor applications where there is high signal attenuation and only low bit rate (high spreading factor) can be used.

Weightless SIG

The Weightless SIG is a non-profit organization setup to standardize LPWA wireless connectivity protocols for machine-type communication. The organization, which was initially spearheaded by Neul, opened to the public in late 2012. Weightless standards are open to members on a royalty-free non-assert basis (FRAND-Z). The organization provides a test and certification program to verify compliance and interoperability.

Weightless counts three standards among its portfolio (Table 9). These standards offer different capabilities suitable for different IoT applications and services. Among the three standards, Weightless-P (W-P) is the most differentiated.

Table 9 Overview of Weightless series of IoT connectivity standards. [Source: Weightless SIG]

	Weightless-N	Weightless-P	Weightless-W
Directionality	1-way	2-way	2-way
Feature set	Simple	Full	Extensive
Range	5 km+	2 km+	5km+
Battery life	10 years	3-8 years	3-5 years
Spectrum	ISM	ISM	TVWS
Terminal cost	Very low	Low	Low-medium
Network cost	Very low	Medium	Medium

Weightless-P

W-P operates over a channel bandwidth of 12.5 kHz and offers full bi-directional, acknowledged traffic to provide a level of QoS that is not designed into ultra-narrow band technologies. The protocol is based on TDMA and FDMA frequency hopping technologies. It's capable of scalable data rate ranging between 0.625 bps to 100 kbps using GMSK and O-QPSK modulation. W-P supports the following features (a longer list is provided in Appendix 1 – Abridged Weightless-P Features List.):

- Power control on both uplink and downlink to reduce interference.
- Paging of devices.
- Radio resource scheduling which necessitate time-synchronization of the base stations.
- Forward error correction and automatic retransmission request (ARQ).
- Mobility features such as cell reselection, handover and roaming.
- CCM (RFC 3610 Counter with CBC-MAC) with AES-128 block cipher.
- RFC 5433 EAP-GFSK device authentication.

W-P offers features similar to cellular IoT technologies in the GERAN and 3GPP roadmap, but it offers lower data rate and operates in a narrower bandwidth. It is in a class of protocols that compares with 3GPP protocols in terms of capabilities. One feature that may play well in future IoT networks is that W-P allows multiple service providers to share a common infrastructure enabling the possibility for different business models that leverage network sharing for cost reduction.

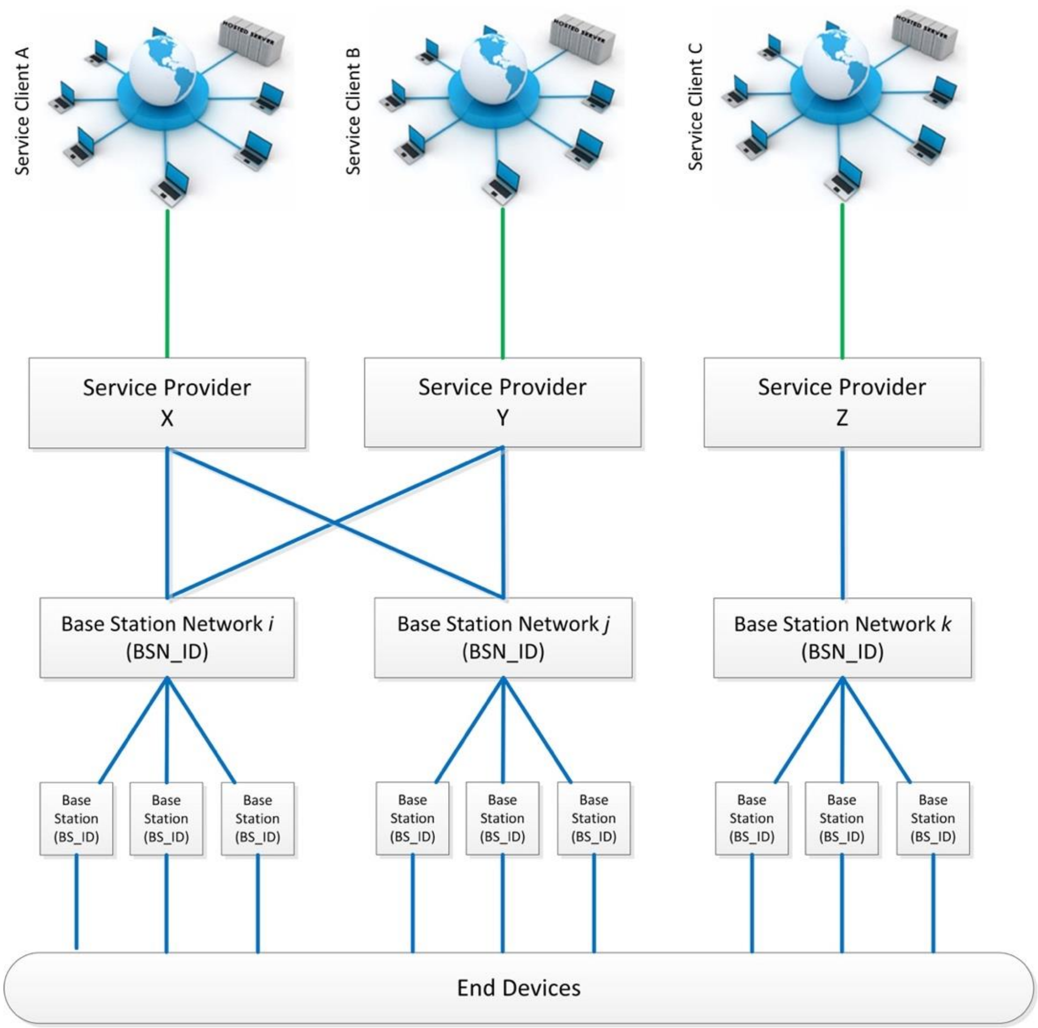

Figure 9 Network infrastructure sharing among several service providers. [Source: Weightless SIG]

The standard was completed and adopted by the Weightless SIG in November 2015 and equipment are expected on market in 2016. Given these timelines, W-P will have about 2-year head start on 3GPP technologies.

Weightless-N

Weightless-N is an ultra-narrowband protocol based almost wholly on the contributions by NWave (UK-based). The protocol implements frequency hopping technology in sub-1 GHz ISM bands. Weightless-N is primarily an uplink protocol, similar to SigFox. It offers 100 bps data rate with D-BPSK modulation. It differs from Sigfox by having a 2 MHz spectrum monitoring window instead of 192 kHz used by SigFox which results in higher number of devices supported per channel (i.e. spectrum monitoring window). Data is encrypted with AES-128. The protocol allows operating multiple private networks on common access infrastructure. The base station queries a central data base to determine which network the device is registered in order to decode and route the data. The standard was published in May 2015. We expect this standard to have limited (and dwindling) following, especially in light of W-P which allows for greater capability.

Weightless-W

Weightless-W is the original protocol in this series designed by Neul (UK-based) to operate in TVWS spectrum between 470 MHz – 790 MHz using 6 MHz channels in the US and Canada, and 8 MHz channels in the UK.

Weightless-W offers a scalable technology to provide data rate ranging between 1 kbps and 10 Mbps. It supports small packet size starting from 10 bytes. Both acknowledged and unacknowledged transmission modes are available. The downlink is based on 1024-factor spreading code with D-BPSK to 16 QAM scalable modulation. The uplink is based on FDMA with 24 parallel channels (outside North America) and 16 interleaved channels (for US and Canada markets). Each channel offers 125 kbps. Weightless-W supports multicast and 128-bit AES encryption for data traffic.

The protocol has not been commercially successful due to the limited availability of TVWS spectrum. Huawei's acquisition of Neul changed priorities away from this standard.

Telensa UNB

Telensa developed and deployed an ultra-narrow band technology in sub 1 GHz license-exempt bands compliant with SRD 868 MHz and FCC 915 MHz regulations, in addition to 470 MHz (China), 868 MHz in Russia, and licensed bands at 60 MHz and 200 MHz. Telensa UNB protocol supports symmetric bi-directional traffic required for device control and management applications, software downloads and low-power location tracking. It also supports paging of devices which allows tracking applications and geo-location services. Telensa implements a star topology and is widely deployed in street lighting systems in addition to other applications including smart parking and gas monitoring[4]. Telensa claims high power efficiency allowing up to 7 years of operation for parking devices and 10 years of operation for gas monitoring. A base station scales to support between 5,000 and 10,000 Telensa devices in street lighting applications. Telensa implements TALQ which is an application-layer protocol between a central management system (CMS) and outdoor lighting networks (OLNs) to enable configuration management, lighting control and monitoring of outdoor lighting systems. TALQ specifies message types, data format, parameters and behavior of the application end-points at the OLN side. Application data is encoded in XML and transported over an application messaging layer based on HTTP.

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[4] Telensa has shipped over 9 million devices, of which one million are for street lighting.

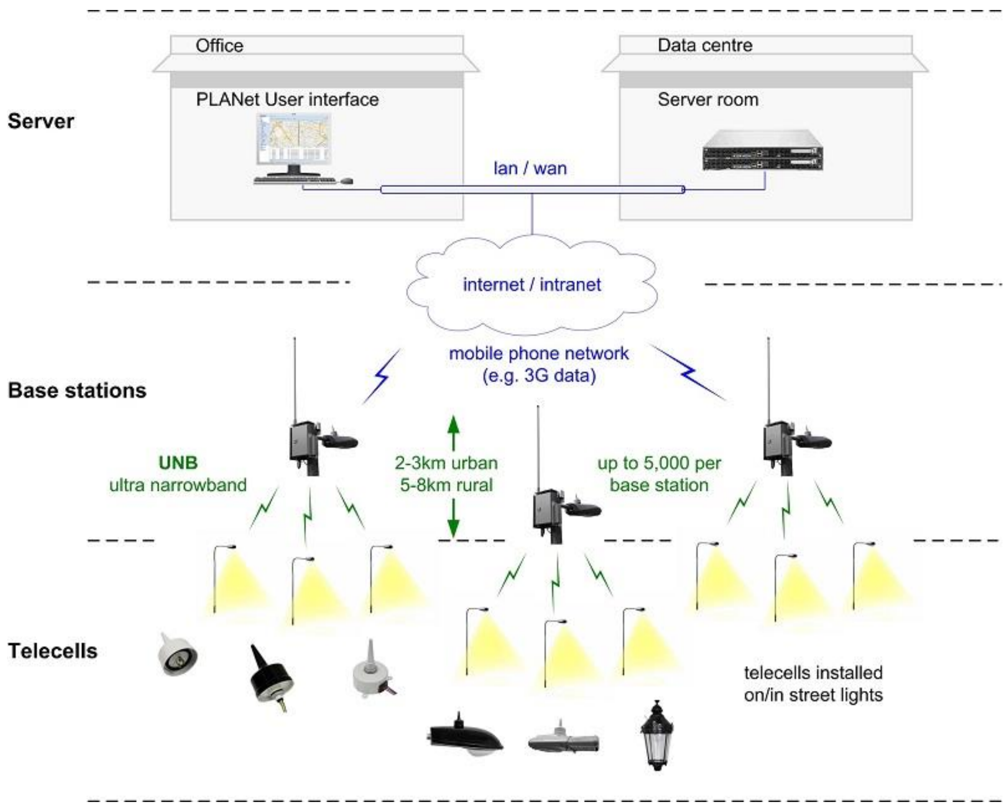

Figure 10 Telensa UNB in smart lighting application. [Source: Telensa]

Random Phase Multiple Access (RPMA)

RPMA is a technology developed by On-Ramp Wireless, which recently rebranded as Ingenu (September 2015). RPMA implements DSSS in the ISM 2400 MHz band which is harmonized globally. It uses 1 MHz-wide channels with up to a maximum reuse of 40 channels, and a spreading factor of 8,192 and D-BPSK modulation. It achieves data throughput up to 41 kbps in countries that follow the FCC, and 20.5 kbps in Europe. RPMA implements power control which is essential for minimizing interference between devices and consequently allows RPMA to support higher capacity than other DSSS or CSS-based technologies such as LoRa which does not implement power control. RPMA supports bidirectional communications and acknowledges every device message unlike SigFox or LoRa which have the capability to acknowledge a small percentage of messages.

One of the key aspects of RPMA is that it features higher system gain and capacity (i.e. number of devices per base station) than other LPWA technologies. The high system gain is favorable for long-range operation in open areas. However, because RPMA operates in 2400 MHz, performance in urban areas is liable to significant reduction in range due to higher wall penetration losses in 2400 MHz than sub 1 GHz frequencies.

Ingenu has traditionally focused on applications in the energy sector (oil and gas). It has since expanded to target wider applications such as asset tracking, connected car and smart city applications. RPMA is deployed in 38 private networks in 20 countries.

Qowisio

Qowisio, an Agers, France-based company, is taking a unique path to IoT connectivity. The company developed its own UNB protocol but is also a member of the LoRa Alliance. Qowisio's strategy is to be a full one-stop shop for IoT services, that is to provide connectivity services in addition to developing technology. Unlike SigFox, Qowisio seeks to support multiple modes, hence, LoRa is one of many connectivity techniques in the "Qowisio box" as the base station is called. Qowisio has deployed over 1,000 sites in France. Qowisio's roots are in energy management for cellular sites which are deployed in private networks in 18 countries.

The Qowisio UNB protocol offers similar characteristics to other UNB protocols as it is bound heavily by regulatory requirements. It offers low bit rate (12 bps) and limited number of messages per device (36 messages per hour in 1% duty cycle SRD 869 MHz band). The protocol is bidirectional and includes improvements for interference and noise management. It supports 500 msec latency end-to-end.

DART

DART (Dynamic Automatic Radio Transceiver) is Raveon Technologies' wide-area wireless networking system which will be deployed by M2M Networks in 850 MHz trunked radio band in the United States. The protocol operates in 12.5 kHz channel bandwidth. DART is optimized for data, telemetry, GPS tracking, and meter reading instead of two-way land-mobile voice. It supports different devices classes to offer performance characteristics optimized for different applications (Table 10). DART is optimized to support a high number of devices per base station. The encryption technology is based on AES-256 but only half that many bits are sent over the air. DART implements a proprietary forward error correction scheme (HYPER) which results in only 25% overhead. Device addressing is through unique 42-bit device IDs that only consumes 8 bits during over-the-air transmissions to save bandwidth.

Table 10 DART device classes and performance capabilities. [Source: Raveon Technologies]

	Data Modem	GPS Tracker	Meter Reading /SCADA
Dynamic configuration of groups, frequencies, power management, report rate, and authorization	✓	✓	✓
Dynamic data bandwidth	✓		
Roaming and base handoff	✓	✓	
Autonomous reporting		✓	✓
Bandwidth priority by net, group	✓		
Reporting rate priority by net, group		✓	
Local communication without base	✓	✓	✓
Group, net, and ID data broadcasts	✓	✓	✓
Group, net, and ID range mass-poll		✓	✓
Small-slot compression using slot assignments by ID and delta position reporting		✓	

LPWA Technologies Summary

Table 11 Technical parameters for LPWA technologies.

	LoRa	SigFox UNB	Weightless-P	RPMA	Telensa	Qowisio
Frequency of operation	ISM 433 / 915 MHz SRD 868 MHz	ISM 433 / 915 MHz SRD 868 MHz	ISM 433 / 915 MHz SRD 868 MHz	2402 - 2476 MHz (FCC) 2402 - 2481 MHz (EU)	ISM 433 / 915 MHz SRD 868 MHz	SRD 868 MHz
Channel bandwidth	125 kHz (typical), 250 kHz, 500 kHz (FCC)	100 Hz (EU) 600 Hz (FCC)	12.5 kHz / 100 kHz	1 MHz	100 Hz	100 Hz
Physical layer	CSS	FHSS	TDMA/FHSS	DSSS	FHSS	FHSS
Modulation schemes	LoRa SF 6-12 FSK GFSK	D-BPSK (UL) GFSK (DL)	GMSK; O-QPSK	D-BPSK	D-BPSK	BPSK
Data rate - uplink	0.25 - 37.5 kbps (UL) 12 kbps (DL)	100 bps (EU) 600 bps (FCC)	0.625 bps - 100 kbps	41 kbps (FCC) 20.5 kbps (EU	100 bps	100 bps (EU)
Data rate - downlink	Low, except class C	Very low	100 kbps	20.4 kbps (FCC) 10.2 kbps (EU)	100 bps	
Max. RF power - EiRP	+36 dBm (FCC) +16 dBm (EU)	+36 dBm (FCC) +16 dBm (EU)	+36 dBm (FCC) +16 dBm (EU)	+36 dBm (FCC) +30 dBm (EU)	+36 dBm (FCC) +16 dBm (EU)	27 dBm
Data payload (Bytes)	50	12 fixed	1 - 65,535 (~250 byte fragmentation)	6 – 10,000 with fragmentation		12
Power consumption - active	117 mW	165 mW				130 mW
Power consumption – sleep/idle	Sleep mode current draw is hardware dependent; idle mode is dependent on hardware and application/device behavior – typically ranging between 0.007 mW to 0.1 mW.					
Data encryption	AES-128	16-bit signed key	CCM/AES-128	AES-256		
Topology	Star/PMP	Star/PMP	Star/PMP	Star/PMP	Star/PMP	Star/PMP

3GPP IoT Technologies

Early LTE specifications defined in 3GPP Release 8 and 9 are focused on meeting requirements for mobile broadband connectivity in macro cellular network topology. Neither devices nor network included the required features to support machine connectivity. 3GPP Release 10 first introduced low access priority indicator (LAPI) to enable congestion and overload control mechanisms where the network can reject or delay connection request from low-priority devices in a congestion scenario. This was followed in Release 11 which incorporated architectural improvements such as introducing new functional entities for device connectivity (M2M-IWF and M2M-AAA) and eliminating the requirement for a phone number (MSISDN) in favor of IPv6 identifier (Figure 11).

LTE Release 8 through 11 presents several challenges for device connectivity:

- Range: insufficient system gain, typically at 140 dB maximum coupled loss (MCL), cannot reach deep into buildings and basements for stationary devices.
- Complexity: multiple transceivers due to multiple transmit and receive antenna configurations are costly for IoT applications.
- Scalability: cannot support high number of devices which adversely impacts the business case.
- Power: high power consumption does not allow operating on battery for extended time.
- Inefficiency: high signaling overhead in relationship to the amount of transmitted data for many applications.

3GPP Release 12 begins to address LTE's machine connectivity in a comprehensive manner on the device and network sides. It defines a new category of devices termed Category 0 (Cat-0) and introduces a number of features such as:

- One receive (Rx) antenna compared to a minimum of 2 Rx antennas for other device categories which reduces cost and complexity at the expense of losing diversity reception.
- Limited peak data rate to 1 Mbps in downlink (DL) and uplink (UL) in comparison with peak rate of 10 Mbps/5 Mbps in DL/UL for Cat1 device which is the lowest category of non-M2M LTE device. This is accomplished by reducing the transport block size.
- Optional half-duplex FDD mode that reduces the cost of the modem by eliminating a few hardware components (e.g. duplexer, switches). This mode would not have a large impact on power consumption if devices are idle for most of the time.
- Enhanced Power Saving Mode (PSM). A device remains registered on the network but not reachable in PSM mode which eliminates registration setup and connection signaling. This optimizes modem turn-on for device-originated data or scheduled transmissions. It improves battery life and reduces overhead signaling.
- Extended Discontinuous Reception (DRX). DRX is designed for paging mobile user devices accounts for large amount of device power consumption. Increasing the

DRX/paging cycle reduces energy consumptions by increasing the length of the sleep cycle but lowers device responsiveness which is acceptable in many IoT applications.

- Reduced Tracking Area Updates (TAU) and measurements for stationary devices.

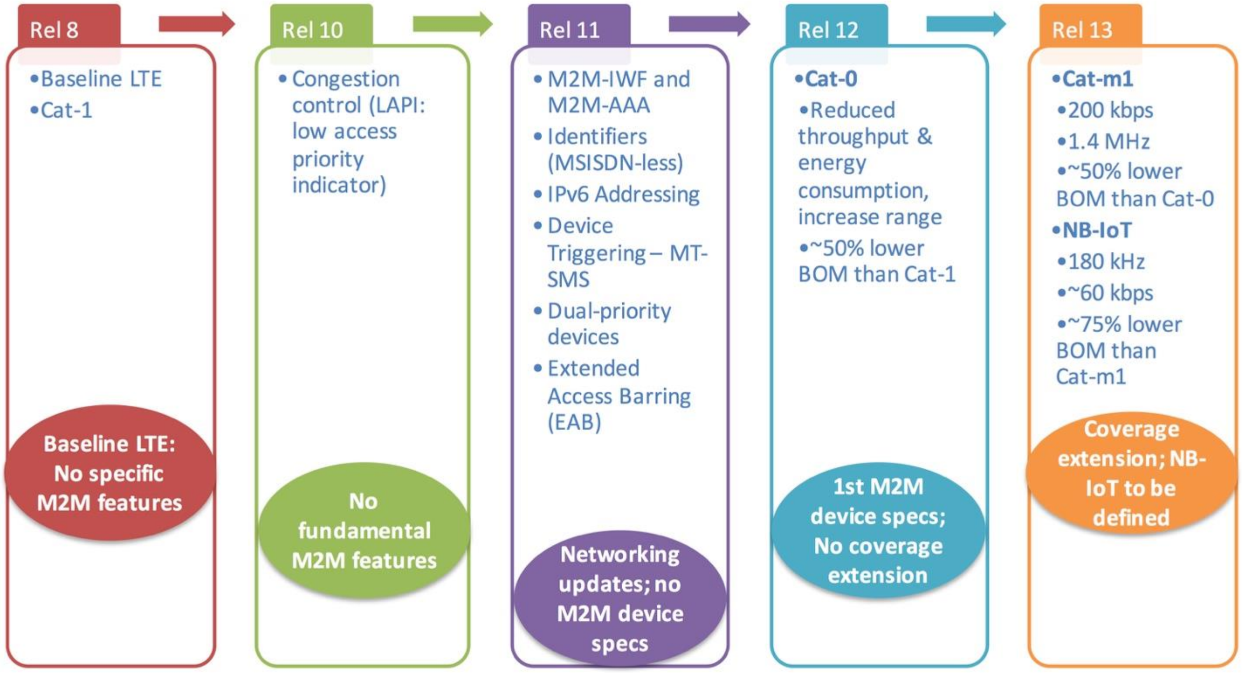

Figure 11 LTE roadmap to support machine-type communications.

While Rel-12 Cat-0 device brings performance improvements for IoT applications, it is considered as a stepping stone for further improvements planned in Rel-13. Operators are indicating they would bypass the implementation of Cat-0 in favor of Rel-13 devices. Cat-0 features like PSM and half-duplex FDD require network software upgrade that can be complex and involves rigorous testing and regulatory compliance processes. PSM which is an important feature, was demonstrated by Altair and Ericsson on a modified Cat-1 device and featured by Qualcomm in their recent Cat-1 SoC. MNOs largely accept a one antenna Cat-1 device even as it results in a hit to system gain and coverage range by 3 dB. Cat-0 requires a ground-up SoC development which makes silicon vendor particularly cautious on investment in light of future roadmap.

Release 13 defines a new device category (Cat-m1) that promises further reduction in complexity and cost (Table 12). It reduces the channel bandwidth, lowers the data rate and reduces transmit power among other modifications to the protocol stack. It also targets improving the system gain by 20 dB over that for current device categories to MCL over 160 dB. The full features of this solution are currently under discussion which would close with Rel-13 freeze date on March 11, 2016.

Table 12 Feature list comparison for different UE categories. [Adapted from RP140845]

	Rel-8 Cat-4	Rel-8 Cat-1	Rel-12 Cat-0	Rel-13 Cat-m1
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	~200 kbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	~200 kbps
Max number of DL spatial layers	2	1	1	1
Number of antennas and device RF receiver chains	2	2	1	1
Modulation DL/UL	64 / 16 QAM	64 / 16 QAM	64 / 16 QAM	
Transport block size DL/UL (bits)	150752/51024	10296/5160	1000/1000	
Duplex mode	Full duplex	Full duplex	Half duplex (optional)	Half duplex (optional)
Device receive bandwidth	20 MHz	20 MHz	20 MHz	1.4 MHz
Maximum device transmit power	23 dBm	23 dBm	23 dBm	20 dBm

Narrowband IoT

In parallel to developing an LTE roadmap for machine connectivity, efforts began in early 2015 to establish a narrowband standard compatible with cellular technologies and operating in licensed mobile spectrum. The roots of this effort are traced to the acquisition of Neul by Huawei who then made proposal at GERAN (the standard organization for GSM) for a clean-slate narrowband technology. Qualcomm, Semtech, and SigFox followed with their own proposals. This track continues as Extended Coverage GSM (EC-GSM) which offers operators with EGPRS install-base a roadmap for migration. But it was more important to get narrowband technologies under 3GPP as it represent the current and future roadmap for operators. Today, 3GPP is in process of streamlining two proposals to converge on a single clean-slate Narrowband-IoT (NB-IoT) standard in 3GPP Release 13 (Table 13). The proposals under considerations include:

- Narrowband-LTE (NB-LTE): Led by Ericsson and includes Nokia, Alcatel-Lucent, AT&T, Verizon, Sprint, NTT Docomo, Samsung and others. This group includes most of the equipment vendors who are keen on preserving the investment made in technology, patents and install base.
- Cellular-IoT (C-IoT): Led by Huawei and Qualcomm and includes Vodafone, Deutsche Telekom, China Mobile and others.

Harmonization of these two proposals is known as Narrowband IoT (NB-IoT) which has features close to Cat-m1. But whereas Cat-m1 adheres to the standard LTE channel bandwidth and is implemented within a regular LTE carrier (1.4 – 20 MHz bandwidth and 15 kHz sub-carrier spacing), NB-IoT operates in three modes:

1. Standalone carrier in GSM spectrum as a replacement of one or more GSM carriers, or in another spectrum allocation (Table 14).
2. The guard-band of the LTE carrier by utilizing the unused resource blocks.

3. In-band operation LTE by utilizing resource blocks within a normal LTE carrier.

Table 13 Key parameters of 3GPP narrowband IoT technologies.

	EC-GSM	NB-LTE[5]	C-IoT[5]	NB-IoT[5]
Spectrum	GSM Inband; Greenfield			GSM or LTE Inband, Greenfield
Release Date	2016	2016	2016	2016
Commercialization	2017	2018/2019	2018/2019	2019
3GPP Release	Rel-13	Rel-13/14	Rel-13/14	Rel-13/14
Peak DL Data Rate	74 kbps	128 kbps	32 kbps	TBD
Peak UL Data Rate	74 kbps	64 kbps	48/14.7 kbps	TBD
Channel Bandwidth	200 kHz	200 kHz	200 kHz	180 kHz
Battery Operation	Yes	Yes	Yes	Yes
System Gain Target	164 dB	164 dB	164 dB	164 dB
Network Upgrade	SW: Yes HW: TBD	Yes (HW/SW)	Clean slate overlay network	Yes (HW/SW)

According to the latest information from 3GPP available at the time of writing this report, NB-IoT will be based on OFDMA technology in the downlink with 15 kHz sub-carriers for all modes of operation. For the uplink, there is a choice between:

1. Single tone transmission: 3.75 and 15 kHz
2. Multi-tone transmission: based on SC-FDMA with 15 kHz uplink subcarriers

NB-IoT features lower mobility support than LTE Cat-m1. Both technologies operate in FDD mode. A TDD mode of NB-IoT will be standardized in Release 14, which does not have a defined end-date as per the writing on this report.

3GPP is in process of harmonizing the different proposals as of the time of writing this report, hence, not all aspects of NB-IoT are known at this time, but the broad lines for the technology have been outlined.

[5] These are the original parameters which are subject to change due to on-going work at 3GPP to harmonize NB-LTE and C-IoT into a single NB-IoT standard.

Table 14 Frequency bands for 3GPP NB-IoT.

Band	Uplink (MHz)	Downlink (MHz)
1	1920 – 1980	2110 – 2170
3	1710 – 1785	1805 – 1880
5	824 – 849	869 – 894
8	880 – 915	925 – 960
12	699 – 716	729 – 746
13	777 – 787	746 – 756
17	704 – 716	734 – 746
19	830 – 845	875 – 890
20	832 – 862	791 – 821
26	814 – 849	859 – 894
28	703 – 748	758 – 803

3GPP IoT Roadmap and Likely Outcomes

The landscape for licensed-band wide area protocols is crowded with options, but we believe these options will converge to fewer choices in the coming year. Today's workhorse which accounts for over 75% of operators' M2M connections, EGPRS, is expensive with modules costing typically $10/unit. Moreover, operators in many markets have either turned off GSM networks (e.g. SK Telecom in Korea) or announced plans that they will (e.g. AT&T in the US). 3G is not successful in IoT connectivity applications and a few European operators have announced they will turn off 3G networks. Hence, the strategy for IoT connectivity for wireless operators will include a flavor of LTE.

The question revolves on which modes of LTE will be dominant, and which will die out. At this stage, we can make the following observations (Table 13):

- In the short term, between today and 2018, the market will focus on Cat-1 devices as Cat-0 is deemed to have few benefits and performance improvement over Cat-1 in addition to network upgrade costs. The timing between Cat-0 availability (mid-2016) and Cat-m1 (early 2018) availability does not warrant the implementation of Cat-0 (Figure 12).

- Cat-m1 will arrive on market before NB-IoT by about 9 – 12 months. NB-IoT provides operators flexibility in deploying dedicated IoT carrier in GSM spectrum or in other bands but also requires a hardware upgrade. It features a slightly lower cost per device (about 75% the cost of LTE Cat-m1). Both technologies are similar in allowing extended battery operation. As LTE Cat-m1 offers a quicker path to market, it is expected to lead in initial deployments with uptake in NB-IoT pending market performance in 2018 – 2019 timeframe and operator spectrum strategies to support IoT services. These are important issues to watch.

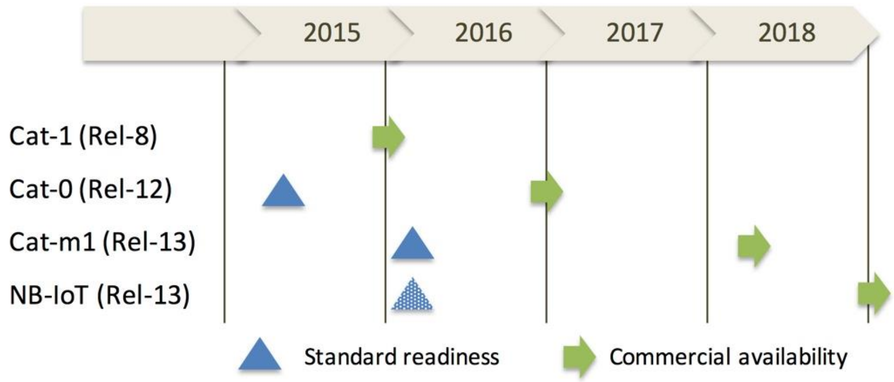

Figure 12 Roadmap and projected availability of 3GPP IoT technologies.

Table 15 Comparison between LTE Cat-m1 and NB-IoT.

Technology	Benefits and advantages	Drawbacks
LTE Cat-m1	▪ Full spectrum compatibility with current LTE releases ▪ No hardware requirements to existing LTE base stations ▪ Operation on a normal LTE carrier with system bandwidth 1.4-20 MHz and 15 kHz sub-carrier spacing ▪ Allows for dedicated m2m carrier as well as overlay with mobile broadband services on same carrier ▪ Low power consumption to allow battery-powered applications ▪ Low modem cost – approximately 25% the cost of LTE-Cat-1	▪ Less smooth migration of GSM spectrum ▪ Not as optimized for low-cost/low-energy in comparison with NB-IoT
NB-IoT	▪ Fully optimized for low-energy use case ▪ Operation in new narrowband carrier (180 kHz) compatible with GSM and LTE spectrum as well as greenfield deployments ▪ Allows dedicated M2M carriers as well as overlay with mobile broadband services on same carrier ▪ Further performance enhancements compared to LTE Rel 13 roadmap with primary advantage of longer range and in-building penetration ▪ Approximately 25% reduction in modem cost over LTE Cat-m1 ▪ Allows for greater density or number of devices supported by one base station over Cat-m1	▪ Hardware upgrade to base station ▪ Limited data rate scalability

For the time being, MNOs don't have a technology answer for LPWA technologies. The 3GPP roadmap will require at least 3 years in order to provide specifications comparable to LPWA technologies. For this reason, many operators are hedging their bets in the IoT connectivity market through two approaches:

1- Investing in LPWA networks: this is happening in Europe. For example, T-Mobile in the Czech Republic intends to roll out SigFox network while Orange, KPN and Bouygues opted to deploy LoRa. AT&T is also considering an investment in the USA.
2- Investing in companies that run LPWA networks: An example of this is the investment by Telefonica, SK Telecom and NTT Docomo in SigFox in late 2014 (€100 m).

Short-Range Wide Area Technologies

A number of short-range wireless connectivity protocols have been adapted to serve wide areas in industrial and commercial applications as well as consumer applications such as connected home. These protocols can have star or PMP topology similar to LPWA or 3GPP technologies. But more applicable is the mesh topology that enables device-to-device connectivity. This allows extending connectivity service over a wide area over multiple hops (devices). A gateway connects to the wide area network for backhaul to a central office. Most of these protocols operate in the licensed-exempt bands. We will refer to them collectively in this report as short-range wide-area technologies (SRWA).

IEEE 802.15.4

This WPAN standard defines a physical (PHY) and medium access control (MAC) layer for low-data rate (typically 20 – 40 kbps; up to 240 kbps), low-cost communication between devices with minimal infrastructure. Protocols used in industrial IoT such as ZigBee, ISA100.11a and WirelessHART, as well as those used in home automation such as Thread, are extensions of 802.15.4 to upper layers of the protocol stack. Devices based on 802.15.4 can use 868, 915, and 2400 MHz bands. Additional bands were defined for China (300/400 MHz) and Japan (950 MHz). 802.15.4 supports multiple types of physical layers including DSSS, CSS, and UNB. A key feature of the standard is support for peer-to-peer communication which forms the basis for ad-hoc mesh networks, in addition to a star configuration. This protocol is heavily used in private industrial and commercial networks including smart grids (especially in North America where it is heavily used in electric smart metering), smart parking and street lighting. The advantage of LPWA solutions over 802.15.4 are two fold:

1. 802.15.4 is relatively high on power consumption compared to some LPWA technologies and typically used where a power supply from the electricity supply is available.
2. LPWA provides on-demand spot connectivity, unlike 802.15.4 which requires device area coverage to form the mesh network.

WirelessHART

WirelessHART is a protocol for industrial applications that operates in the 2.4 GHz ISM band using DSSS physical layer. It is an extension of the HART protocol used in industrial automation systems over legacy analog instrumentation wiring. WirelessHART is based on IEEE 802.15.4 and implements a self-organizing, self-healing mesh topology. It is designed for reliability, security, interoperability, and a fit in industrial environments. The protocol allows new wireless networks and devices integrate into HART-compatible control and configuration systems which allows the user to maintain proven processes (HART 7 application layer). This is a critical aspect when considering the competitive landscape among technologies as wireless extensions of existing wireline industrial standards present a lower barrier for adoption than new wireless technologies. WirelessHART networks are limited to about 30,000 devices due to the manner in which device addressing is handled.

ISA100.11a

The International Society of Automation is a US organization that developed ISA100.11a for industrial wireless applications, including wireless industrial plant needs, including process automation, factory automation and RFID. It is designed to provide flexibility by allowing multiple build and run-time options for customized operation. The standard bears many similarities to WirelessHART but does not specify a process automation protocol application layer or an interface to an existing protocol. ISA100.11a is based on IEEE 802.15.4 and operates in the 2.4 GHz ISM band using DSSS physical layer, but it does not include a standard compliant MAC. It supports mesh and star topologies and leverages IPv6 and 6LoWPAN for routing and addressing. ISA100.11a is capable of 100 ms latency. More than 250 organizations participated in the drafting of this standard. The SA100 Wireless Compliance Institute provides assurances of interoperability of device. ISA100.11a is implemented in applications that include machine health monitoring, remote process monitoring, leak detection, environmental and tank monitoring, and gas detection.

ZigBee

ZigBee is a low-power mesh protocol based on IEEE 802.15.4. It is used extensively in home automation applications but also in smart metering applications. Because 802.15.4 does not specify the upper layers, interoperability of ZigBee solutions is less than seamless as differences between vendors arise. In the home automation application, the Thread Group is developing a Layer 3 networking framework for interoperability to address this drawback. ZigBee networks can scale to support up to 65,000 nodes.

IEEE 802.11ah and 802.11af

IEEE 802.11ah (low-power Wi-Fi) targets the 755 – 928 ISM bands with data rate over 150 kbps. While indoor applications, especially home automation applications, are a key target of this standard, it can support a range of 1 km which makes it suitable for outdoor service. 802.11ah is based on OFDM physical layer with 1/2/4/8/16 MHz channel bandwidth and modulation schemes up to 256QAM. In fact, the standard is a clocked-down version of 802.11ac by a factor of 10: this would indicate a relatively quick time to market once the standard is completed in 2016. The standard incorporates features for long-life batter operation reaching up to 10 years: for example, the transceiver is deactivated when the device is not active to save power. An 802.11ah access point can support up to 8,191 devices. This standard does not need to maintain backward compatibility with the other 802.11 standards.

The IEEE 802.11af standard specifies radio and access control mechanisms for TVWS operation. It is also based on 802.11ac and supports multiple concurrent downlink transmissions utilizing multi-user MIMO (MU-MIMO). 802.11af is designed to improve spectrum efficiency with smart antenna technology. It reduces latency by supporting up to four simultaneous user transmissions.

Technology Comparative Analysis

This section compares LPWA and 3GPP technologies on quantitative (range, capacity) and qualitative levels. Range and capacity are important parameters that impact the cost of the infrastructure and consequently profitability. Qualitative parameters, such as open standards and time-to-market, factor into service providers' strategies and impact market competitive dynamics.

Operating Features

LPWA and 3GPP technologies perform differently on a number of parameters that would determine the fit with user applications (Table 16). Today, 3GPP technologies represented by EGPRS, 3G or Cat-1 modules are not suitable for extended battery operation. This landscape will change in 2018 when Cat-m1 and NB-IoT become available. Until then, SigFox, LoRa, RPMA and Weightless have a head start. We expect the lead in attention that SigFox and LoRa have built over 2015 to extend well into 2016. However, LoRa and SigFox/UNB are most suitable for sensor applications due to their one-way communications nature (LoRa does include a mode for bi-directional communication, but it limits capacity and scalability of the network). There are many applications that require multicast/broadcast, paging, or firmware upgrade capabilities for which SigFox and LoRa are not well equipped to handle. RPMA or Weightless-P is an option in this case, but that ecosystem has not yet developed.

Table 16 Comparative analysis of key LPWA and 3GPP technology parameters.

	Symmetric DL/UL	Multicast / Broadcast	Message Ack	Battery operation	Power control	Location services*	Handover support	Firmware upgrade
LoRa	◐	◐	◐	○	●	◐	●	◐
UNB/SigFox	●	●	●	○	O	●	●	●
Weightless-P	○	○	○	○	○	○	○	○
RPMA	○	○	○	○	○	◐	○	○
Telensa UNB	○	○	○	○	O	○	●	○
LTE Cat-1	○	○	○	●	○	○	○	○
LTE Cat-m1	○	○	○	○	○	○	○	○
LTE NB-IoT	○	○	○	○	○	○	◐	○

Legend:
○: Supported | ●: Not supported | ◐: Partial support; optional support | O: Not required
*** Location services include paging capability.**

Range performance

Coverage or range is a key parameter that impacts the capital and operational expenses of the wireless network. We developed and compared link budgets to gain insights into the performance of LPWA and 3GPP IoT technologies which we will use in the financial analysis in the next chapter. The comparison is based on practical strategies service providers would adopt as outlined in the assumptions (Table 17) and detailed calculations (Appendix 2 –Link Budget Calculations).

Table 17 Network parameters for LPWA and 3GPP IoT technologies.

	LPWA	3GPP IoT
Frequency of operation (MHz)	868 (EU) 915 (FCC) 2450 (RPMA)	900
Base station antenna height (m)	60	60
Device antenna height (m)	1	1
Interference margin (dB)	DL: 6 UL: 3	DL: 3 UL: 1
Shadow fade margin* (dB)	8.8	8.8
Wall penetration loss (dB)	25 (< 1 GHz) 35 (ISM2400)	25
***Shadow fade margin for 95% area coverage reliability based on path decay exponent n = 3.5, and shadow fade standard deviation of 8 dB.**		

Note that because LPWAN devices operate in unlicensed spectrum, we anticipate a higher level of interference than licensed-spectrum devices, because the interference is external to the network and is unpredictable. Therefore, we provision for higher interference margin for LPWA than for 3GPP technologies. We also took 25 dB and 35 dB wall penetration loss in 900 MHz and 2400 MHz, respectively, which is typical for multilayer concrete walls as the intent is to penetrate deep into buildings where many devices are typically placed. This assumption adversely impacts the performance of RPMA which operates in 2400 MHz in comparison with other technologies which operate in sub 1 GHz spectrum.

We analyze deployments under both FCC and CEPT/ETSI requirements using actual product parameters from equipment vendors for both base stations and devices[6]. The parameters are used to calculate practical system gain for each technology. We balanced the uplink and downlink in a manner that maximizes system gain. This generally involved using high gain omni-directional antennas on LPWA base stations (9 – 12 dBi) which is representative of existing deployments. The antennas on the devices have low gain (typically 0 dBi). Under FCC rules, LPWA technologies are generally uplink limited, therefore, using a high-gain antenna on the base station improves the maximum allowable path loss used in range calculations. We generally consider the base station to be mounted on top of the tower. Where this is not the case, as in SigFox's case, a tower-top low-noise power amplifier is used to compensate for uplink losses. We therefore estimate cable losses to be 1 dB or less.

[6] For technologies with no products on market such as Cat-m1, NB-IoT and Weightless-P, we used parameters provided by the respective standards organizations modified to reflect actual deployment scenarios.

3GPP IoT technologies benefit from sectored antennas on existing base station which typically have high gain (11 - 13 dBi), but the main advantage come ability to support higher transmit power than LPWA technologies.

We calculated the cell radius using the Hata model for sub 1 GHz bands and modified COST-231 for the ISM2400 band (Table 18, Figure 13). The clear advantage in range goes to NB-IoT due to low receive sensitivity and high transmit power. LTE Cat-m1 on the other hand features high transmit power, but its receiver sensitivity is lower than NB-IoT which limits its range.

Table 18 Coverage performance of LPWAN and 3GPP IoT systems.

	EU – CEPT/ETSI				FCC				3GPP IoT	
	LoRa	SigFox	W-P	RPMA	LoRa	SigFox	W-P	RPMA	Cat-m1	NB-IoT
System Gain (dB)	150	144	148	166	161	158	156	172	159	173
MAPL – Outdoor (dB)	135	129	133	151	149	146	141	157	147	163
MAPL – Indoor (dB)	110	104	108	116	124	121	116	122	122	138
Outdoor range (km)	2.3	1.5	2.0	2.7	5.8	4.7	4.1	4.1	5.2	15.6
Indoor range (km)	0.41	0.27	0.36	0.24	1.03	0.84	0.73	0.36	0.91	2.76

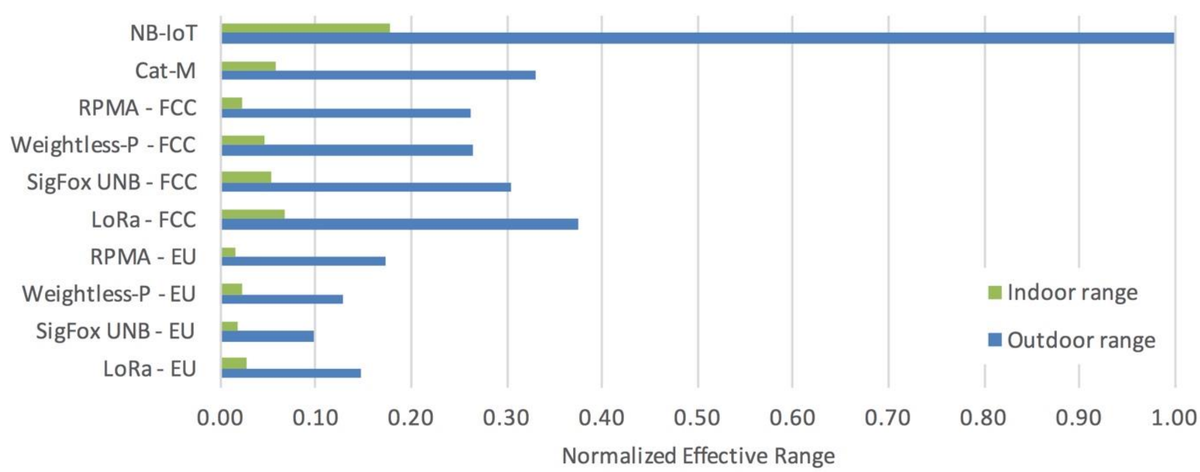

Figure 13 Normalized effective range (km) for IoT connectivity technologies.

Regulatory requirements in license-exempt spectrum impact on the coverage performance of LPWA systems. The analysis points towards the following:

1- European regulations limit the range of LPWA networks by restricting transmit power. Cells are larger under FCC rules, where transmit power can be higher. Consequently, lower site count is required in the US to meet similar coverage objectives as in Europe where more capital investment would be required to reach a comparable grade of service to that in the United States.

2- DSSS/CSS (LoRa) has the longest effective range among LPWAN technologies for indoor coverage surpassing SigFox and Weightless-P, and RPMA.
3- RPMA provides highest system gain among LPWA technologies and result in competitive range for outdoor applications even as it operates in 2400 MHz. However, high wall penetration losses at 2400 MHz result in disproportional reduction in range in comparison with other LPWA technologies.
4- 3GPP NB-IoT benefits from favorable spectrum regulations and narrow channel bandwidth to exceed the range of LPWA and other 3GPP technologies by a significant margin – up to 167%.
5- Under FCC rules, the uplink is the limiting path for LPWA technologies (except RPMA). Greater range could be achieved with higher device transmit power than what is typically available on market (16 dBm) or by implementing receive diversity systems on the LPWA base stations.
6- Under CEPT/ETSI rules, the downlink is the limited path due to limited transmit power. This places a ceiling on coverage range that cannot be extended farther.

To illustrate the potential impact on the business case, we calculated the number of sites required to achieve contiguous indoor coverage in San Francisco (121.4 sq. km) and Paris (105.4 sq. km) (Figure 14). These sites cover the city boundaries only and not the entire metro area. We note that LPWA networks built to date do not provide contiguous coverage in cities in part because these networks are still new and would require more time and investment to mature. Consequently, reports of service holes are well explained by our findings and the need to increase coverage in the future.

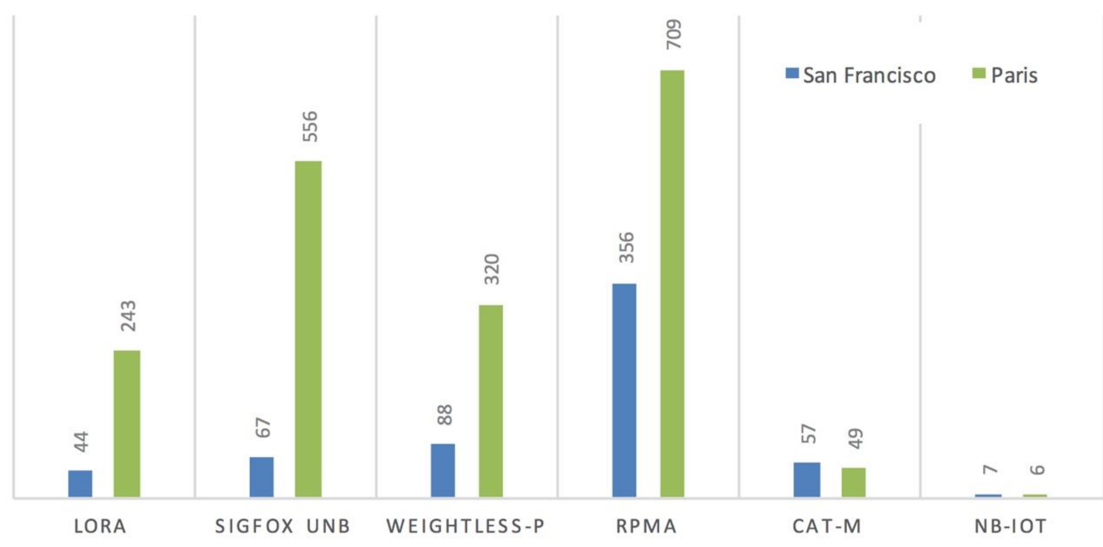

Figure 14 Number of sites required for contiguous indoor coverage in Paris and San Francisco.

Capacity Performance

In reviewing the capacity of LPWA technologies, we came across numbers around a million of devices per base station. These parameters are based on theoretic maximum capacity of the system without consideration for a number of factors that will reduce the actual capacity to a smaller number, typically below the 100,000 devices per base station (Table 19). The actual number of supported devices will depend on a number of factors including the characteristics of the technology and the frequency of device transmissions in addition to regulatory requirements.

Table 19 Theoretical capacity of SigFox UNB channel.

	US/FCC	Europe/CEPT-ETSI
Monitored spectrum (kHz)	192	192
Channel bandwidth (Hz)	600	100
Number of channels	320	1,920
Duration of transmission (Sec)	0.4	2
Time slots per hour	9,000	1,800
Frequency-time slots per hour	2,880,000	3,456,000
Theoretical number of devices per base station (one message per hour)	960,000	288,000

Regulatory duty cycle requirements have a major impact on the capacity performance of LPWA networks as they define the duration and frequency of transmissions. As a result, the capacity of a LPWA technology in the US is different from Europe or other parts of the world. This regulatory impact on performance leads to a financial impact as more cell sites will be required to support a fixed number of devices. Capacity of LPWA could be much greater, perhaps by at least 10x, if they were not subject to duty cycle limits. 3GPP technologies, on the other hand, do not have such restrictions and their capacity is determined by the interworking of the access protocol, the deployment scenarios, and the application uses cases. Unlike LPWA networks, the capacity of 3GPP networks does not depend on on the region where the network is deployed.

UNB and CSS-based LPWA network elements are not time-synchronized. Transmissions from multiple devices can collide at the base station leading to errors. Technologies like SigFox and LoRa do not implement error correction codes, to save bandwidth, and are especially susceptible to errors. To compensate, these technologies implement other techniques to improve performance in noisy channel, such as packet repetition and or diversity reception at multiple base stations--after which a network controller chooses the best data packet. The likelihood of collision increases with the density of devices, the data rate, and the duration of transmission. For example, under European rules, SigFox transmits a 12-byte information packet during 2 seconds while LoRaWAN needs 2.8 seconds to transmit a 32-byte packet at the lowest bit rate (SF12, 250 bps). Additionally, in the case of LoRa CSS access technique, there is a potential of interference between transmissions using low and high spreading factors resulting from a large difference in received power level at the base station. Based on their own field deployment with RPMA, Ingenu estimates that only 14.6% and 26.2% of devices operating on DSSS have transmissions received below the noise floor in FCC and ETSI domains, respectively. The remainder of devices, 85% in FCC and 74% in ETSI domains, run a risk of interference due to loss of orthogonality between spreading factors. This reduces the capacity of DSSS/CSS systems that don't implement power control to ensure all signals are received at the base station at equal power level, as with CDMA-based mobile communication systems (e.g. 3G/UMTS). Large variance in power rises in large cells and for indoor devices where low data rate is used to reach the base station.

Capacity for LPWA networks is therefore a statistical number: the number of devices will vary depending on the deployment scenario in each regulatory domain. Calculations published by Ingenu[7] show a rather dim view of LoRaWAN and SigFox performance under CEPT/ETSI rules in Europe – the fact the data is being published by a competitor under simplifying assumptions would have to be taken into consideration (Table 20). We believe that under different assumptions and factoring some of the techniques which LoRaWAN and SigFox implement would lead to different, more optimistic numbers in real deployments[8]. Nevertheless, practical capacity is less than the theoretical 1 million devices advertised by LoRa, SigFox, and many others in the LPWA camp (which is based on a limited number of transmitted messages per day).

Table 20 Capacity of LPWAN networks. [Source: Ingenu]

	FCC (US)			CEPT/ETSI (Europe)		
	LoRa	SigFox	RPMA	LoRa	SigFox	RPMA
200 Bytes per 15 min	287	1,116	23,077	17	N/A	11,539
100 Bytes per hour	2,295	8,928	184,617	135	225	92,306
140 12-Byte messages per day	3,279	12,754	263,739	193	321	131,869

Notes:
1- SigFox operates over 8 MHz and 200 kHz under FCC and CEPT/ETSI rules, respectively.
2- LoRa operates over 64 and 8 x 125 kHz channels under FCC and CEPT/ETSI rules, respectively.
3- RPMA operates over 8 and 4 x 1 MHz channels under FCC and CEPT/ETSI rules, respectively.

For a feel for actual capacity, we consider Telensa's UNB protocol which based on field deployments can support between 5,000 – 10,000 devices. We also consider simulations provided by Semtech for a version of CCS in licensed spectrum where there are no duty cycle restrictions. They indicate that LoRa can achieve capacity between 20,000 and 90,000 devices per 3-sectored base station, for large and small cell, respectively[9]. These figures serve as a proxy for a ceiling on device capacity for LoRa.

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[7] Ingenu, "RPMA to LPWA Tech Comparison," http://www.scoop.it/t/the-french-wireless-connection/p/4055199441/2015/11/14/ingenu-rpma-to-lpwa-comparison, last accessed on December 8, 2015.
[8] For example, the Ingenu calculations do not take into consideration that multiple base stations can receive a transmission from cell-edge devices which would improve capacity at network level.
[9] Semtech, Combined narrow-band and Spread Spectrum physical layer coverage and capacity simulations, GP-150076, 3GPP TSG GERAN meeting #65, Shanghai, March, 2015.

The available data leads us to conclude that SigFox/UNB protocols have higher capacity than LoRaWAN. We expect the difference to range between 2x – 3x in favor of SigFox. This should play in favor of SigFox in its pursuit of a service provider business model where scalability is key to reducing expenditures.

The wide channel bandwidth and high spreading factor helps RPMA to achieve greater capacity than SigFox and LoRaWAN. We had no information on the capacity of Weightless-P as the standard has not been published at the time of writing this report. However, the protocol is designed to address high capacity networks with target over 50,000 devices in smart meter applications.

The capacity of LPWA in the ISM band is ironically adversely impacted by the success of LPWA networks. This is because multiple LPWA networks would share the same spectrum and compete for the same air interface resources resulting in proportional decrease in capacity. As there is more ISM spectrum in the US than there is SRD spectrum in Europe, the degradation due to multiple networks will be felt more acutely in Europe where, for example, only 8 x 125 kHz channels are available for LoRa networks.

Capacity capabilities have an impact on product design as well as network design, and LPWA equipment vendors are differentiating on features and capabilities to serve different market segments. In public networks, base stations supporting multiple channels are used to provision for high capacity while private networks would have to dimension the base station according to their projected requirements. For example, SigFox base stations support up to 8 MHz of spectrum (40 channels) through SDR technology. LoRa vendors implement one or two channels for private networks and 8 channels for public networks.

Capacity in conjunction with coverage can be used to derive a measure of capital effectiveness for a technology. Our conclusion predicts that RPMA has higher effectiveness than SigFox whose effectiveness exceeds LoRaWAN. The effectiveness is mainly due to the ability to provide connectivity for high number of devices which is contingent on IoT connectivity market size and success in penetrating different applications. However, to achieve high capital effectiveness, the investment required for RPMA is higher than both SigFox and LoRa, by an order of 5x as we explore later in the report. This leads to higher barrier of entry for RPMA technology. SigFox on the other hand provides a more balanced mix with expenditure still higher than LoRaWAN but better cost effectiveness.

Power Consumption

LPWA protocols are designed to enable low power consumption (Figure 15). This is achieved through:

1. Simple waveforms: LPWA networks are based on relatively simple waveforms that are computationally light. The baseband protocols are implemented on low-cost off-the shelf microcontrollers. This contrasts with 3GPP technologies, which have complex waveforms and are implemented on silicon as a system-on-chip (SoC). A

large part of the effort in 3GPP focuses on simplifying the waveform and computational complexity to reduce the cost of silicon. Compatibility with existing networks limits the option available to achieve this objective as manifested in the debate to harmonize C-IoT (simpler waveform) and NB-LTE (OFDM-waveform compatible with LTE infrastructure).

2. Protocol design: LPWA protocols eliminate or limit the use of functions that increase power consumption such as device paging, location update, message acknowledgement and downlink communication. They use simple forward error correction codes, if any. The protocols are designed for miniscule current draw in sleep or idle mode. Moreover, some protocols are limited in using encryption (e.g. SigFox). They also may implement non-standard addressing techniques to save bandwidth. This is a critical issue to watch for in the future as end-to-end data management is a critical issue and security needs to be addressed across the entire network. Security plays a large role in technology selection, so we expect that LPWA networks to come under close scrutiny for compliance with client requirements.
3. Limited transmit power: the emitted power limit under SRD rules is relatively low (16 dBm). 3GPP technologies which do not have this restriction are designed to operate at higher power: 20 dBm for NB-IoT and Cat-m1 (23 dBm used in Cat-1 devices).
4. Limited communication: LPWA devices transmit packets of a few bytes in intermittent bursts with long periods of quiet time between transmission. To achieve battery life on the order of 5-10 years, the amount of data is limited to tens of bytes per hour. The active period of a device consumes most of its power. The simpler waveform and lower protocol complexity of LPWA systems together with lower transmit power conserves energy. Minimization of sleep or idle mode current draw is critical to achieving long battery life. LPWA devices achieve very low current draw ranging on the order of a few micro amps in sleep or idle mode. 3GPP technologies aim to achieve levels close to this with NB-IoT.

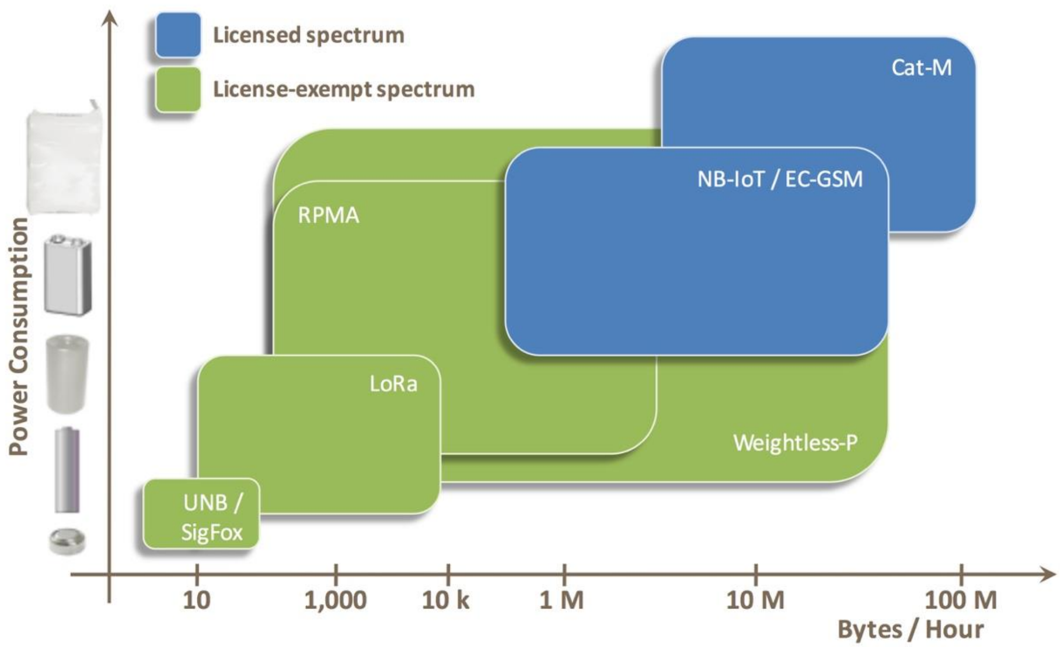

Figure 15 Information rate and power consumption performance of wide area connectivity protocols.

Qualitative Assessment

A few key areas come to the forefront when looking at IoT connectivity strategies that impact adoption: Standards and interoperability, and time-to-market.

Standards and Interoperability

LPWA systems are proprietary solutions with the exception of the Weightless SIG which is an open standard with royalty-free structure that's similar to Bluetooth SIG. SigFox operates as a service provider in the US and works partners with third parties in Europe and the rest of the world: SigFox Network Operators. The LoRa Alliance is defining Layer 2 and higher protocol on top of Semtech's Layer 1 and RF technologies which essentially locks the ecosystem to Semtech's technology though this is available from third parties under license from Semtech.

Mobile network operators prefer to deploy standard-based technologies in keeping with the mobile service business model they offer. Standards allow operators flexibility in choosing system vendors and reduces the potential of vendor lock. It enables defining end-to-end interoperable technologies and interfaces. It becomes possible to provide global services with partners in different geographic markets. Standards also work in favor of a security framework that MNOs will demand.

This is one reason that leads us to believe that MNOs will largely wait for 3GPP IoT technologies to mature before investing heavily in IoT connectivity solutions.

Time to Market

The advantage of LPWA is time-to-market. The technologies are available today and some have been deployed for several years already, so they are not new technologies. EC-GSM, NB-IoT and Cat-m1 are at least two years away from commercial launch. Additionally, they require another 1 to 2 years before scale is achieved to secure low cost devices. Hence, the window for LPWA can stretch for up to 4 years in which to establish market share.

MNOs who are not involved in sensor and low-bit rate IoT connectivity applications see LPWA as a threat to future growth in light of the lack of a ready competitive response. In our conversation with MNOs, the bias is towards standard-based technologies. MNOs see service level agreements (SLAs) as a competitive advantage they can secure by operating in licensed spectrum to serve high-reliability applications. Hence, the MNOs investing in LPWA are doing so as a proactive defensive tactic as there is not immediate comparable technology. These investments are a way to ensure that the operator doesn't miss out on potential market uptake. But the key issue remains whether new business models and investments flowing into LPWA will lead to an uptake in market adoption. The answer will lie in the specific applications and markets because cost alone is not the main driver for IoT service adoption.

Speed of Deployment

There are alternative technologies to both LPWA and 3GPP technologies as we already explored - ISA100.11a or WirelessHART in industrial applications are examples. These technologies are used by vendors and system integrators in an entrenched supply chain catering to vertical markets. This is an area where LPWA technologies need to make a breakthrough and win over incumbent solution vendors to increase market share. The threat of incumbents is often underestimated as solution vendors have significant market power with end users who often rely on turn-key solutions. LPWA make a compelling case in enabling on-demand deployment scenario, as opposed to costly incremental growth of service areas associated with mesh technologies. This aspect of the market is best addressed by the go-to-market approach which is critical to success.

Existing mobile networks, in many countries, are now based on software-definable radios, so speed of deployment could be very rapid for 3GPP-based solutions. A mobile operator could upgrade 50,000 base stations via software, to add LTE Category 0 or Category 1 functionality. Similarly, to the extent that NB-IOT or Cat-m1 operation takes place within existing frequency bands, the operator may already have excellent radio coverage and the ability to instantly deploy the network through software. Despite a 2-year wait for standards to be finished, 3GPP options may be quickly rolled out eventually.

Global Roaming

3GPP standards are the same worldwide, and to the extent that mobile operators can agree on a common frequency band for operation (e.g. the 900 MHz GSM band), LTE-m1 devices can roam worldwide easily. Applications such as tracking of large shipping containers will benefit from this kind of global service. LPWA devices will need to support multiple frequency bands to roam internationally, with intelligence to recognize the country of operation so that the device can adjust power levels and frequency band to the local network.

Summary Observations

LPWA technologies open a market under-served by both 3GPP and SRWA technologies based on meeting key parameters related to low power consumption and on-demand spot connectivity (Figure 16). They target low bit-rate applications and intermittent transmit applications and are designed for power efficiency. They would excel at serving the 'low' end of the market consisting of sensors applications with penetration into control applications where the associated overhead is low.

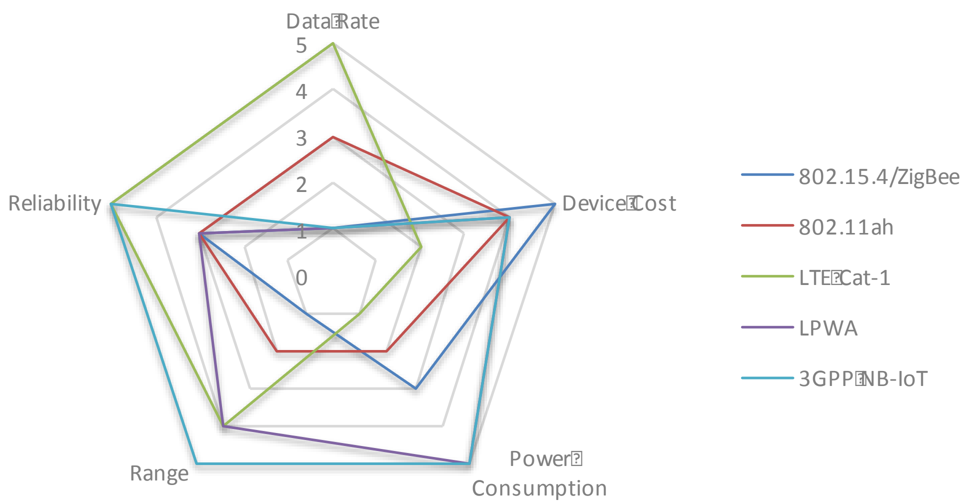

Figure 16 Characteristics of wide area IoT connectivity technologies.

In the short term, LPWA is considered complementary to current MNO IoT services based on GRPS and LTE Cat-1 services. However, with the advent of EC-GSM, LTE Cat-m1 and NB-IoT in the 2018+ timeframe, LPWA will have stronger competition in the middle market where applications require higher service level associated with control applications that require bidirectional traffic and high reliability (Table 21).

Table 21 Comparative analysis between 3GPP and LPWAN.

	PRO	CON
3GPP / Cellular	▪ Licensed spectrum provides higher assurance on reliability ▪ Standard-based technologies ▪ Interoperable networks and devices ▪ Existing infrastructure: towers/physical assets, backhaul, network centers reduces build out costs for incumbent service providers ▪ Long coverage range (exceeds LPWA) ▪ Longevity: MNOs are stable entities providing high assurance on business continuity over the life of device (years) ▪ Downlink and bi-directional communications unaffected by regulatory duty cycle requirements ▪ Potential for global roaming	▪ Time-to-market: NB-IoT/Cat-m1 available in 2018 ▪ Legacy core networks designed for consumer broadband: requires new core infrastructure ▪ Operator business model and market approach may leads to higher cost base than the more nimble LPWA players ▪
LPWA	▪ Technology is available now ▪ Agility: nimble entities can cater to different requirements and business models ▪ Enables private networks – can be deployed anywhere ▪ Optimized for sensor applications; excel in low-power applications dominated by long idle cycles ▪ Quick to deploy: light infrastructure with on-demand spot service	▪ Proprietary technologies (except for Weightless SIG) ▪ Unproven scalability (devices / base station) ▪ Licensed-exempt spectrum may preclude high-reliability applications ▪ Limited performance and applicability in control application ▪ Regulatory restrictions limit range and capacity performance ▪ Lack of global harmonization on spectrum means that LPWA limits roaming across different markets
SRWA	▪ Optimized for specific applications to meet user-defined requirements ▪ Wide and established ecosystem ▪ Incumbency advantage ▪ Integration with existing systems and networks	▪ Limited performance when operated on battery – capacity and range or link robustness are significantly reduced ▪ Cannot provide on-demand spot connectivity; coverage is through area buildout which adds to cost ▪ Not available for public networks ▪ Requires more planning than long-range technologies

Techno-Economic Analysis of LPWA vs. LTE

Connectivity in the IoT value chain is a commodity; high prices will impede adoption while low prices could spark higher adoption. In this section we explore the cost structure of LPWA and 3GPP networks.

Device Costs

Successive generation of 3GPP technologies reduce modem complexity to reduce the cost of the baseband modem. Our survey of the cost of Cat-1 modules touched a low of $13 in high volume, but more typically unit price is in the $18 - $20 range (Table 22). We also found that device OEMs and operators expect Cat-0 modules to cost around $10. A more significant cost reduction would come from Cat-m1 with expected range between $5 - $7. NB-IoT is expected to break the $5 barrier. GPRS modules which make up the majority of existing cellular IoT connections are priced at about $10 per unit.

The modem constitutes a relatively large percentage of the cost of LTE module which includes additionally the RF subsystem. The typical ratio is about 40:60 in cost of RF to baseband (Figure 17). LTE baseband is implemented in silicon, with multiple processing cores and accelerators due to the complexity of the LTE stack. The development of SoCs is expensive and runs in the millions of dollars which requires stable standards. For access technologies such as NB-IoT, the aim is to ultimately develop a single RF and baseband SoC to reduce cost. This approach requires harmonization of spectrum for IoT to be economical.

Table 22 LTE modem complexity and projected module costs.

	Rel. 8 Cat-4	Rel. 8 Cat-1	Rel 12 Cat-0	Rel. 13 Cat-m1	Rel 13 NB-IoT
Modem complexity	100%	80%	40%	20%	15%
Module cost	> $25	$13-$20	$10	$5-$7	< $5

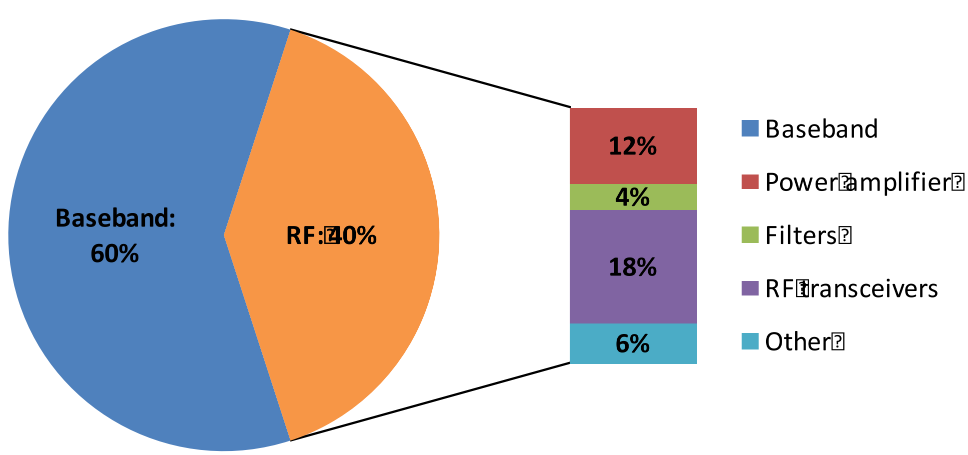

Figure 17 Cost structure for IoT connectivity device.

In contrast to 3GPP devices, LPWA modules are based on microcontrollers that are optimized for low power consumption. Hence, they draw upon a different ecosystem than 3GPP technologies. This is an important difference between the two ecosystems as technologies evolve into the future especially as the cost of elements account for about 60% of the total module cost (Table 23).

Table 23 IoT module cost structure to achieving sub $5 cost target.

Baseband and RF	Cost	% of Total
Baseband subsystem / microcontroller	$0.95	20%
Memory*	$0.45	9%
RF subsystem including filters & front-end	$0.65	14%
Oscillators	$0.30	6%
Discrete elements and connectors	$0.35	7%
Total Elements BOM	$2.70	57%
Mechanical, Assembly & Test		
PCB	$0.25	5%
Shield	$0.05	1%
Assembly	$0.45	9%
Test	$0.10	2%
Yield loss (2%)	$0.07	1%
Packaging/labelling	$0.10	2%
CM margin (5%)	$0.20	4%
Total ex-works price	$3.92	82%
OEM Value-add		
Freight/shipping	$0.20	4%
RMA allowance (2%)	$0.07	1%
OEM margin (10%)	$0.57	12%
Total expense to MNO or VAR+	**$4.76**	100%

* Memory could be combined with baseband to reduce cost
\+ IP licensing not factored – may be additional cost item

Within the LPWA camp, different technologies have specific requirements that impact the cost of modules. For example, ultra-narrowband technologies (100 Hz) require high frequency stability which is provided by a crystal oscillator (TCXO) that adds cost to the module as opposed to DSSS or CSS-based technologies where lower tolerances are acceptable. However, notwithstanding these differences, volume has the ultimate impact on cost.

The LPWA market advertises sub $5 module price points. Our analysis of the LPWA device market indicate that the industry is not yet at a stage to provide a sub-$5 device, mainly due to low volumes. In our survey, modules were quoted as high as $29, but were typically in the $10-$19 range in low volumes (1,000 – 5,000 units). For example, Microchip's RN2483 Class-A

LoRa module is priced at $10.90 in 5,000 unit volume[10]. We did, however, come across AXSEM[11] AX-Sigfox SoC and RFIC is priced at $1.91 in 2,000 unit volume (Figure 18) which is an outlier in our survey, but also represents an important proof of ecosystem support. We believe that LPWA semiconductor solutions can achieve sub $2 ASP in high volumes leading to about 60% cost advantage over NB-IoT (Figure 19). This is supported by simple LPWA waveforms, low protocol overhead and commodity-priced embedded processor architecture. Nevertheless, while the cost of the module is a first barrier to IoT adoption, it is not the most critical barrier, especially in industrial applications where the module cost often takes secondary priority over the total cost of ownership and/or the benefits of IoT. Hence, module cost alone is not a sufficient measure for the potential market uptake of a technology.

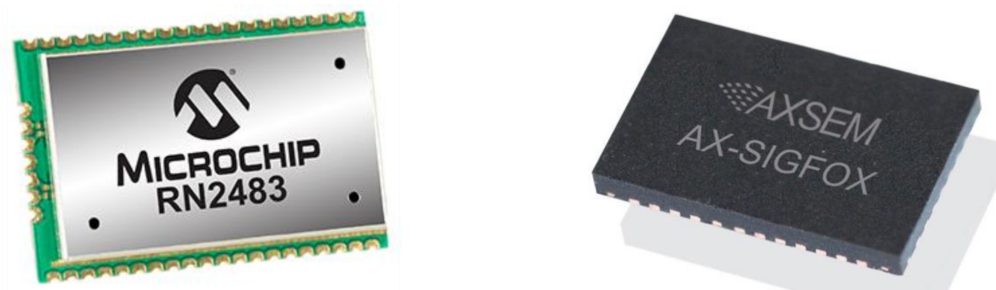

Figure 18 Microchip LoRa and AXSEM SigFox modules.

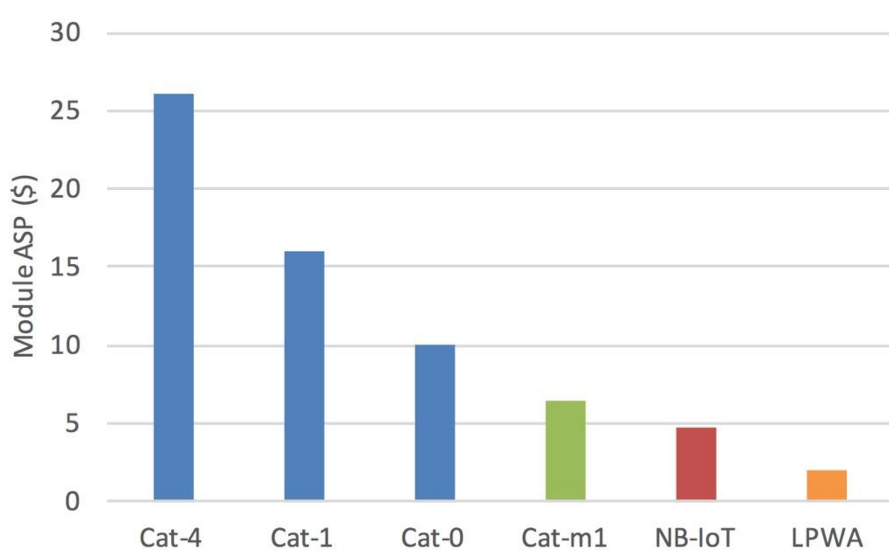

Figure 19 IoT Module average selling price in high volume.

[10] http://www.microchip.com/wwwproducts/Devices.aspx?product=RN2483, last accessed on 12/7/2015

[11] AXSEM was recently acquired by ON Semiconductor.

Network Costs

The network can be divided into three main elements: the radio access network, the core network, and the application layer (Figure 20). The core network in LPWA includes a network server that processes packets from multiple base stations and provides complementary services such as redundancy of packets in SigFox and LoRa networks. The application layer is important from an end-user perspective as it relates to device management and data processing and analytics.

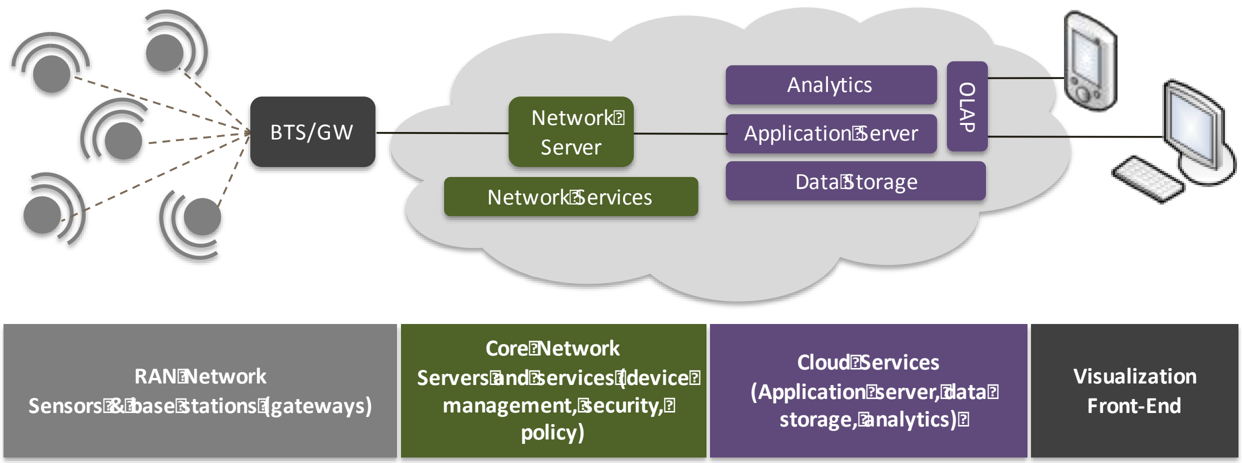

Figure 20 Reference model for LPWA IoT networks.

When LPWA is deployed as a private network, the end user owns all the elements of the network. However, where LPWA is deployed as a service, the service provider deploys and operates RAN and core networks and provides end users a platform to monitor and control devices. The end user may implement data analytics platforms to derive information from collected data or alternatively the service provider may choose to deliver such value added services (Figure 21). We focus our analysis on public networks and compare the cost of LPWA and 3GPP-based technologies.

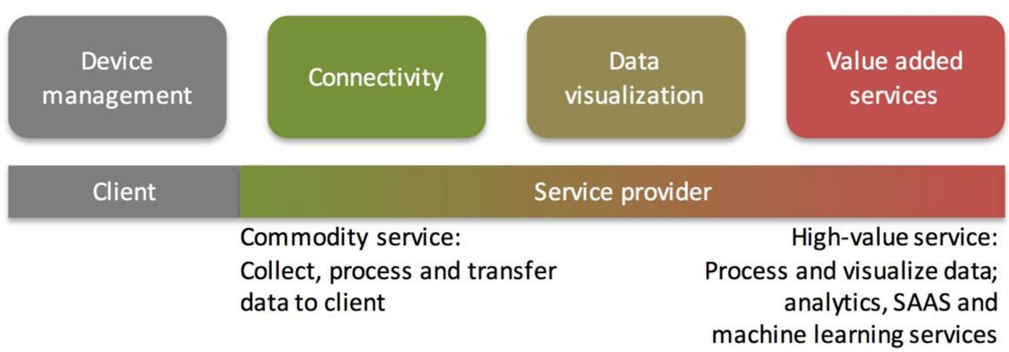

Figure 21 Network operator range of service offering.

The Radio Access Network

The main costs elements of the radio access network are as follows:

Capital expenditures: The cost of LPWA base stations is relatively low, typically ranging from a few hundred dollars to a few thousand dollars depending on the number of channels. Site acquisition and deployment cost more than the cost of LPWA base station equipment. Public networks require high capacity base stations supporting multiple channels while one or more channels can be sufficient in private networks. To reduce costs, LPWA service providers seek to collocate on existing towers, as in the case of M2M Spectrum and Crown Castle. Tower companies see an opportunity to become IoT service providers; for example, Arqiva (UK) has become a SigFox Network Operator.

In our market survey of equipment costs, we found a narrow range of difference among different technologies. Rather, volume and equipment features have more impact on pricing. Furthermore, the cost of LPWA base stations is relatively low ranging from $400, for a single channel LoRa gateway, to $3,500 for base stations designed to scale in large deployments.

LTE Cat-m1 requires no additional base station hardware; the capex includes software license to enable this feature. We made an estimate on the cost of SW license based on parallel cases we encountered in the industry; however the estimates given by OEMs and by mobile operators differ widely. The final cost of software currently has a high uncertainty as the technology will not be available commercially until 2018.

NB-IoT will not require hardware upgrade if deployed within the same channel as LTE, but it would require new hardware if deployed in a separate band. In our analysis, we will assume that no additional hardware is required, therefore, its economics will track Cat-m1 but would result in improved cost effectiveness[12].

[12] The C-IoT proposal requires a new radio, whereas NB-LTE aims to preserve the operator investment in existing hardware assets. The final outcome will depend on the harmonization between the two technologies which would result in multiple options which operators can pursue.

Table 24 Capital expenditures for wide-area IoT connectivity networks.

	LoRa	SigFox UNB	Weightless-P	RPMA	Cat-m1
Base station	2,500	3,500	3,000	2,500	-
Antenna & ancillary	500	500	500	500	-
SW Licensing	-	-	-	-	5,000
Site acquisition, A&E, civil works	2,000	2,000	2,000	2,000	-
Installation, test & commissioning	1,100	1,100	1,100	1,100	500
RF Planning & design	591	591	591	591	148
Project management	1,875	1,875	1,875	1,875	469
Total Capex	$ 6,100	$ 7,100	$ 6,600	$ 6,100	$ 6,116

Operational expenditures: Site-lease, support and maintenance expenses are the major expenditures. Most LPWA base stations are full outdoor modules [13] that combine baseband and RF subsystems. Hence, these costs are relatively low. Maintenance involves replacing failed equipment which requires a tower climb as typical LPWA base stations are mounted on tower top. Power is not a major cost item as public network LPWA base stations typically consume under 50 W, while private network solutions typically consume under 15 W.

Backhaul costs are relatively low, mainly due to the low data rate of LPWA technologies. UNB networks in Europe provide a floor on the cost of backhaul as it is not expected practically to exceed 100 kbps. This increases in North American markets as well as for other technologies, but nevertheless, required backhaul capacity remains low even under loaded conditions (as limited by the channel bandwidth and spectral efficiency of LPWA systems). Cellular technologies are often used in IoT backhaul applications. However, in private networks, it would be desired to implement low latency backhaul, hence, LPWA service providers would have to pay for latency performance instead of throughput performance. Note that unlike wireless broadband networks where backhaul is a key cost item and data management is not critical, in IoT applications data management including storage takes an important role that is still in early stages of evolution.

[13] SigFox is an all indoor base station unit. Deployment in the US include a tower-top low noise amplifier.

Table 25 Data storage requirements in UNB networks.

Devices per site	UNB (kbps)	Storage (MB/Day)
1,000	0.9	1.6
10,000	8.6	16.5
100,000	86.4	164.8
1,000,000	864	1647.9

The RAN operating expenses for 3GPP IoT technologies are small as they are incremental to the wireless network, especially when no additional hardware is required.

Table 26 Annual operational expenditures for wide-area IoT connectivity networks.

	LoRa	SigFox UNB	Weightless-P	RPMA	NB-IoT
Site lease	3,600	3,600	3,600	3,600	-
Backhaul	900	900	900	900	-
Power	25	25	25	25	-
Operation & maintenance	1,445	1,615	1,530	1,445	750
Total annual opex	$ 5,970	$ 6,140	$ 6,055	$ 5,970	$ 750

The Core Network

While LPWA resembles cellular networks on the radio access side, there are major differences in the core network. The nature of IoT requires highly scalable systems to support high volume of low-bit rate devices. In contrast, mobile networks are designed to support a lower number of users but much higher throughput. Virtualization is the mean to cost effective IoT core networks. LPWA service providers can choose to architect the core network in a number of different ways including leveraging data centers for compute, storage and networking resources. Virtualization in mobile networks is a nascent field which despite much hype in the last few years, it has yet to come to full commercial service; its market penetration limited to certain OSS/BSS functions. As such, IoT networks would be breaking new technology grounds in implementing comprehensive scalable networks based on Network Function Virtualization (NFV) techniques. NFV allows LPWA service providers to scale core network functions on per-demand basis by decoupling software from hardware which would be based on commercial off-the shelf servers. This is a major difference from mobile networks.

Mobile network operators have well architected core networks and support systems. Some MNOs have implemented their own IoT platforms while others rely on third parties. However, not all elements of the existing platforms can be used in supporting LPWA IoT services. The scale of LPWA would require re-architecting of certain network functions. This is an area where MNOs will have to invest in; it includes data management and IT support services.

The costs of the core network will vary depending on the scale of connected devices, technology and offered services. Hence, it includes a price structure that greatly varies depending on the size and scope of the network. We chose to assign costs associated with typical compute, storage and networking capable of supporting a minimum 1 million devices as they would be incurred if the operator chooses on premise operations. Lower costs are possible if certain functions are moved to a data center to be hosted in the cloud. It is such architectural designs that make a difference in the final cost of network. In 3GPP core networks, the cost is on the order of a few dollars per subscriber. This does not scale for IoT devices - this cost will need to drop significantly to a fraction of a penny per device to support IoT business models.

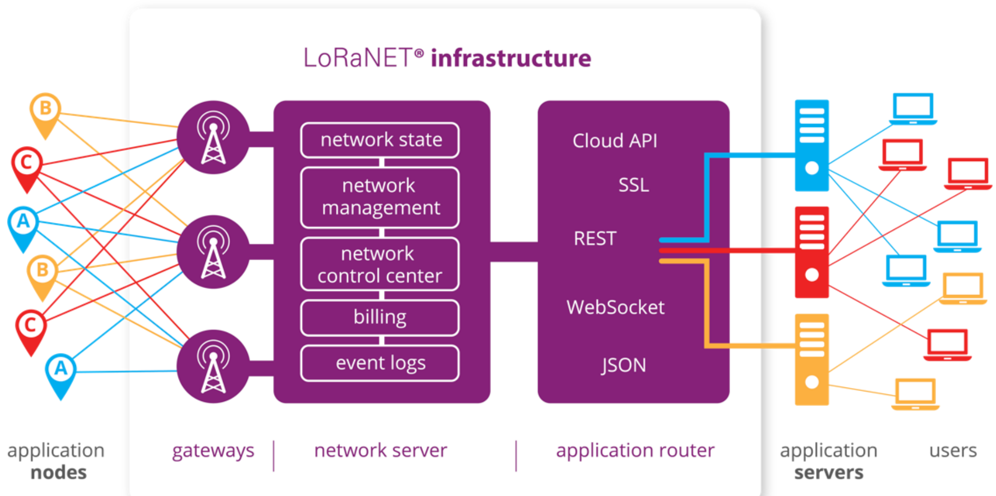

Figure 22 Overview of LoRaNet end-to-end network. [Source: FlashNet]

Table 27 Annualized capex and opex expenditure amortized per cell site (US Dollars).

	LoRa	SigFox UNB	Weightless-P	RPMA	NB-IoT
Core network	336	331	397	336	596

Total Cost of Ownership

Operating expenses for LPWA make for the bulk of total cost of ownership (89%) while CAPEX stands at 11%. This stands in contrast with mobile networks where CAPEX to OPEX ratio of TCO is about 30:70 (Table 28).

Table 28 Total cost of ownership for wide-area connectivity networks per cell site. (US Dollars)

	LoRa	SigFox UNB	Weightless-P	RPMA	NB-IoT
RAN Capex	6,100	7,100	6,600	6,100	6,116
RAN Opex	53,860	56,220	55,040	53,860	12,116
Core Capex & Opex	2,685	2,648	3,178	2,685	4,766
Network TCO – 8 Years	**$56,545**	**$58,868**	**$58,218**	**$56,545**	**$ 16,883**

MNO Strategy for LPWA

MNOs who already own infrastructure assets would find the cost of deploying LPWA incrementally small. This helps explain some of the recent investments by MNOs in LPWA networks. The investments provide MNOs a foothold in an emerging IoT market that is still limited in scale but has a large potential. With 3GPP technologies 2-4 years away from providing a competitive technology, LPWA networks provide a relatively low-cost interim solution to guard a greater prize in the future. In essence, LPWA deployments by MNOs are an insurance policy on the potential of LPWA.

Impact of Regulatory Framework on TCO

Regulatory requirements have a high impact on the cost of deploying LPWA networks. Emission and duty cycle requirements lead to higher site count in Europe and consequently higher expenditures. The difference is significant: between double to quintuple the number of sites and investments depending on technology (Figure 23).

The results we present are coverage-based and therefore indicative for the initial network buildouts. To support longer term network evolution, capacity is the dominant metric. Therefore, while we show LoRa has the lowest deployment cost, the result would be different should capacity drive network sizing as is the case in loaded networks. Nevertheless, the duty cycle requirements in Europe lead to higher site to support the same number of devices as would be in a US-based network.

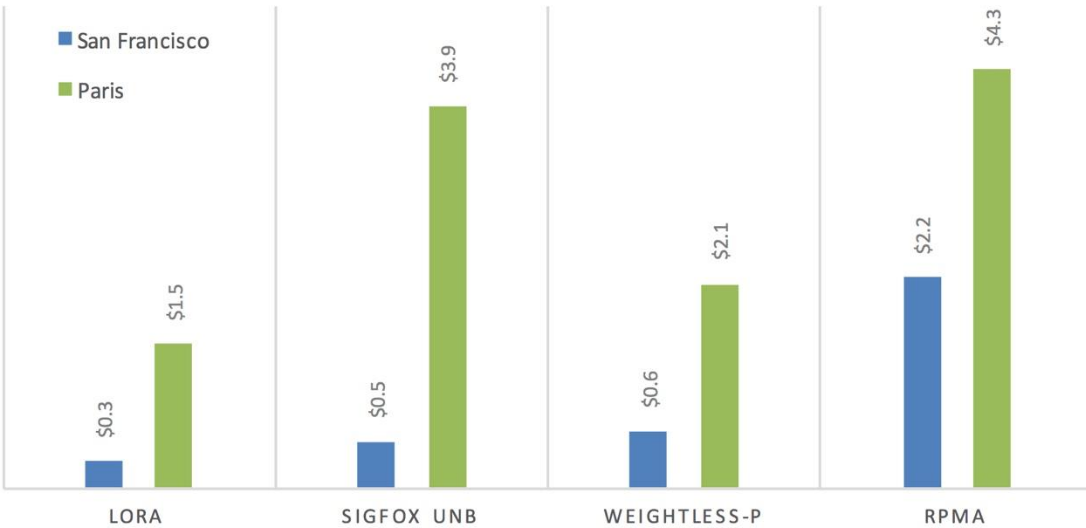

Figure 23 Capex requirements for LPWA radio access networks buildout. ($ Millions)

Revenue Model and Profitability

From a revenue perspective, we can use the example of SigFox service and pricing structure as a floor (Table 29). SigFox advertises pricing in the range between $6-8 per device per year for a basic plan with additional volume price discounts. Using $6 per device-annum and $7,250 annual operating cost and amortized capex based on 8-year lifecycle leads to 1,200 devices per cell to breakeven on network operating costs in one year. This number is the low limit as we need to consider additional costs incurred in the network, the cost of sales and marketing, as well as SG&A.

Table 29 SigFox service packages. [Source: SigFox]

Platinum	101 to 140 messages + 4 downlink
Gold	51 to 100 messages + 2 downlink
Silver	3 to 50 messages + 1 downlink
One	1 to 2 messages + no downlink

If we take the city of San Francisco as an example, the required penetration would be equivalent to roughly one device per person to breakeven on RAN operations (Table 30).

The analysis raises an important issue in wide-area LPWA deployments. The density of devices is directly correlated to revenue and profitability: the higher the density the faster time to breakeven. Wide-area indoor applications require many cells to provide contiguous coverage which reduces profitability unless there is sufficient volume. This is unlikely to be achieved in the early stages of deployments. As a result, LPWA service providers will have to be selective on where indoor coverage is provided and proactively work with clients to fill coverage gaps.

Table 30 RAN breakeven parameters for urban LPWAN deployments.

San Francisco, CA	
Population	776,733
Metro area (sq. km)	120.9
House density (houses / sq. km)	2,865
Person/house (average)	2.2
Cell area (indoor coverage, sq. km)	0.20
Houses per cell site	585
Persons per cell site	1,311

Additional Observations from the TCO Model

The following are a few key observations derived from the LPWA TCO Model:

1- Weightless-P provides the lowest cost per bit and enables the widest range of applications and feature set which makes it the most compelling threat to 3GPP technologies.

2- NB-IoT provides the lowest site count even at lower tower height. This is because of higher system gain than LPWA technologies. The longer range is not only due to higher allowed transmit power, but also in due to the quality of the spectrum and network planning.

3- Mobile network operators are endowed with strategic spectrum and infrastructure assets that gives them an advantage over LPWA service providers in the radio access network and to some, but lesser extent, in the core network. This advantage is translated into a lower cost of building IoT networks provided the evolution roadmap does not require hardware upgrade. The cost advantage would be eliminated should upgrade to NB-IoT require new equipment.

4- Cat-m1 and NB-IoT will not be commercially available before the start of 2018 and in volume for 1 to 2 years after that. MNOs will not have a technology in hand to compete with LPWA on range, cost, and performance until that time. This provides LPWA proponents a minimum 3 – 4-year window of opportunity to establish and solidify market presence.

5- LPWA service providers have to differentiate on business models and services in order to compete effectively. Data management, analytics and other services are key areas where service providers can differentiate.

The Business Model

The cost distinctions between technologies are actually small in comparison with the expected size of the long-term opportunity, so in this case the go-to-market strategy could determine the prospects of each technology. LPWA system vendors and technology developers have taken different paths to market (Table 31). This can be summarized in the following categories:

1- Network operator
2- Ecosystem-centric based on standards
3- Vertical focus

Table 31 Approach to market and its context.

Technology	Characteristic and market approach
LoRa	▪ Standardized Layer 2 built above Semtech's proprietary Layer 1/RF technology. ▪ Semtech licenses its technology to partners. ▪ LoRa Alliance develops and maintains the standard and ensures interoperability of devices through a testing and certification process. ▪ Member companies have their own market strategy.
SigFox UNB	▪ SigFox operates as a service provider in the US and partners on revenue-share basis with service providers in Europe and other markets. ▪ Technology is proprietary to SigFox modems are developed under license by different vendors. ▪ SigFox makes its protocol stack available to application developers.
Weightless	▪ Special interest group developing open connectivity standards. ▪ Open standards encourage adoption of technology to leverage economies of scale associated with large volumes. ▪ Royalty-free IP policy based on FRAND-Z. ▪ Member companies have their own market strategy.
3GPP	▪ Open standards with well defined interfaces and certification and acceptance process. ▪ IP policy is the domain of the contributing member and royalties may be charged. ▪ MNOs are members of the standardization body alongside vendors; both actively contribute in shaping standards and technologies.

The Network Operator Model

This model is best exemplified by SigFox, whose strategy in the United States involves building and operating its own network. This diverges from the revenue-share model SigFox pursues in Europe through its SigFox Network Operator program. This network operator approach aims to kick-start a market by providing ready access to a network. Execution, coverage and pervasiveness of service become a critical aspect. SigFox has to be first to market in scale and needs to time the market correctly. The SigFox approach has the advantage of simplicity as it lowers the barriers to entry for end users, who find a readily available network to integrate into. Scale and ubiquitous service attracts certain IoT use cases, for example, a multi-national SigFox network allows asset tracking across multiple countries provided they fall within the same regulatory domain.

The disadvantage of this model is vendor-lock related to both technology and operator. Users of the SigFox network have to embed SigFox modems and subscribe to a service from SigFox. The long-term prospect of a technology and service provider will weigh heavily in the mind of end users. This is a critical factor for in sectors such as utilities and smart city applications which are dominated by municipalities and government organizations with long-term plans.

This network operator market approach has to attract developers into the technology: SigFox makes the protocol stack readily available to application developers. Achieving a price advantage comes from competition which the operator needs to garner among its partners and suppliers. The network operator model requires heavy capital expenditures and presents a high-level of risk in conjunction with a high-level of reward should it succeed.

The Ecosystem Model

This model is exemplified by Semtech, whose LoRa technology forms a platform for a wide ecosystem of service providers, module designers, application developers, system integrators, and equipment vendors. The ecosystem comes under the umbrella of the LoRa Alliance which, in 10 months since inception, counted over 130 member companies. Another example of the ecosystem approach is the Weightless SIG.

The ecosystem approach is based on developing a technology standard. The advantages are many: competition between ecosystem partners lowers prices; interoperability of equipment and devices limits the risk of vendor lock; openness of the specifications encourage adoption and innovation. It is critical for proponents of a technology to establish a well defined standard and means to certify equipment for compliance with the standard and interoperability, and to increase the profile of the technology to grow the size of the ecosystem.

Agility is a key aspect to the ecosystem approach, but this is where the risk lies as different parties bring differing views that needs to be reconciled and harmonized. Time-to-market may suffer in comparison to a proprietary approach. However, once a technology baseline is established, its prospects of taking hold in the market improves.

The ecosystem approach has to provide flexibility to support different applications. This allows member companies to tailor solution to specific market segments. LoRa, for example, specifies different device classes to target different applications.

The Vertical Approach

The IoT marketplace is fragmented as a result of a large number of applications, each with unique technical, operational, and economic requirements. Fragmentation supports a vertical approach to market which focuses on a market segment or an application. Incumbent players have an advantage in vertical markets, that is often underestimated in the LPWA connectivity market place. Incumbents have either developed proprietary technologies, or adopted standard technologies to service a vertical. More critically, incumbents are well established in a market segment which poses a challenge for new entrants.

An example of an incumbent with its own LPWA technology is Telensa which has its roots in smart street-lighting control systems, but also offers solutions in other segments such as smart parking and metering applications. Telensa's UNB technology is designed with specific features to allow remote control of lighting systems which requires bidirectional link to the device and broadcast service to control multiple devices at once. In addition to the optimized connectivity layers, Telensa implements TALQ application-layer protocol for interoperability with existing city CMS solutions. Telensa provides a complete backend system for management and control which is critical. In this example, Telensa would be in direct competition with a company like FlashNet which has its own lighting control systems based on the LoRa technology. Both companies are also in competition with solution vendors implementing a non-LPWA technologies.

Recent trends show that LPWA companies pursuing a vertical market approach diversifying into other sectors. Telensa expanded market scope following its acquisition of Senaptic. OnRamp, which traditionally focused on serving the oil and gas market, recently rebranded as Ingenu and expanded the scope of its market outreach into other applications.

The Threat of Incumbents

The threat of incumbents to the nascent LPWA market is often overlooked and underestimated. Incumbents include companies and ecosystems in specific verticals that offer complete connected solutions including management and control, especially in industrial applications. While incumbents may partner with LPWA technology and service providers, they also represent a threat. The success of LPWA technologies will depend on the dynamics between the incumbents and the LPWA proponents. We explore a few examples to illustrate these dynamics in specific verticals.

Home Automation Applications

Fire and smoke detection, water leakage, intrusion detection are example of applications that LPWA technologies seek to penetrate[14]. The home automation ecosystem is actively pursuing these applications along a separate path that involves short-range technologies

[14] SigFox through its SNO Abertis Telecom signed Securitas Direct to service home alarm applications.

(e.g. Bluetooth, ZigBee, Z-Wave) and an Internet-connected home hub. The gateway approach decouples the short-range network from the connectivity of the Internet and provides a lower product and service cost than LPWA technologies.

In the home automation, LPWA service providers are pitted against a host of players who form a diverse ecosystem that's currently in a state of flux as multiple entities are battling for the ownership of the home hub. Some of these players include Honeywell, Schneider, Phillips and GE (industrial conglomerates who are considered incumbents in this market), Google Nest, Microsoft, and Apple (technology giants), Samsung SmartThings, Sony, LG, Panasonic (consumer electronics), Vivint and ADT (service providers), Intel and Qualcomm through its AllJoyn initiative that morphed into the AllSeen Alliance, and Comcast as an example of a traditional service provider leveraging home automation to provide complementary services. Alliances and interoperability initiatives to expand the utility of connected solutions are key for penetrating this market where network effect plays a large role in market penetration.

The scope of applications for LPWA in the home automation centers on sensor applications where direct network connectivity is needed. Manufacturers who integrate LPWA into their products need to convince home owners and commercial or industrial property managers to subscribe to the service. This will limit traction to special cases where direct connectivity is a requirement and not an option given that there are lower cost solutions providing similar benefits.

Smart City Lighting Applications

There is a strong drive by municipalities to upgrade city lighting to LED from a wide variety of lamps such as high-pressure sodium (HPS) (100 lumens/W), metal-halide (75-100 lm/W), and mercury vapor (35-65 lm/W) which are almost extinct. LED (70 – 150 lm/W) consumes on average 35% less energy than equivalent HPS lamps and result in 25% reduction in annual energy expenditure. LED lamps have better longevity than high-intensity discharge lamps and lower failure rate. With RoI breakeven ranging between 5-8 years, the change to LED has a tangible business case for some municipalities, especially those who still use older, less efficient technologies. For example, the city of Boston operated 64,000 street lights, 42,000 of which used mercury vapor and 22,000 used HPS before embarking on a process to change to LED, a project that paid for itself in less than 1.5 years.

Connected lighting provides municipalities with additional benefits such as instant identification of failed lights and ability to dim LEDs to increase longevity and improve efficiency. The incremental savings in operation and management costs are in the range between 5% – 20%. Implementing connected lighting at the time of LED switchover is most economical to eliminate multiple truck-rolls.

An example of incumbent player is GE which offers LightGrid Node a connected solution based on IEEE 802.15.4 mesh technology operating in the ISM 915 MHz band. Each light node connects to a gateway where wireline or cellular wireless connection will backhaul the data to the the operation center (Figure 24). The system which is deployed in downtown San Diego is considered as the first deployment of intelligent lighting in the United States. The deployment in 3,000 streetlights is expected to provide $350,000 in annual energy and maintenance costs savings.

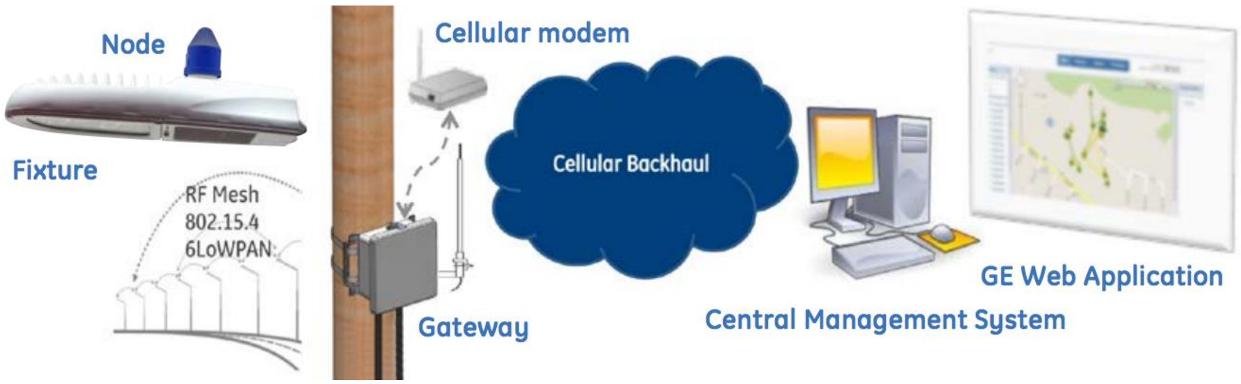

Figure 24 Application of 802.15.4 in street lighting deployment. [Source: GE]

An example of LPWA specialist is UK-based Telensa whose UNB technology claims wider deployments than GE and Phillips combined, with 1 million connected streetlights shipped. Telensa is deployed in 10% of the UK's 7 million streetlights. Part of Telensa's value proposition is a technology optimized for control and management of lighting systems – bidirectional communications with device paging and multicast capability. But more importantly, it is the financial incentives and the business case that drives municipalities to roll out smart lighting. Municipalities operate on very tight budgets and require dependable suppliers over a long term. Incumbents have the longevity and brand-power to impact technology selection decisions.

Romania-based Flashnet is an example of a company that optimized the LoRaWAN protocol with extensions necessary for street lighting applications such as multicast/broadcast. FlashNet draws on the strength of the ecosystem to supply critical infrastructure solutions such as base stations from Cisco or Kirlink while it focuses on enabling the street lighting application with a comprehensive solution to manage and control lighting devices. FlashNet goes even a step further by working with the ecosystem on transforming the streetlight network into a smart grid of connected sensors and electric vehicle charging stations (Figure 25). In this example, a stable and vibrant ecosystem around a solution provider is critical in sustaining business activity.

In the battle for smart lighting applications, LPWA technologies will have to compete against the market strength of incumbents not only through technology innovations but more critically through a go-to-market approach that de-risks uncertainty, for example, through partnerships. Mobile network operators, particularly in Europe are showing high-interest in this market segment. This opens the door for potential collaboration with the LPWA ecosystem in areas where current cellular technology is inefficient or future 3GPP IoT technologies are deemed too late to market.

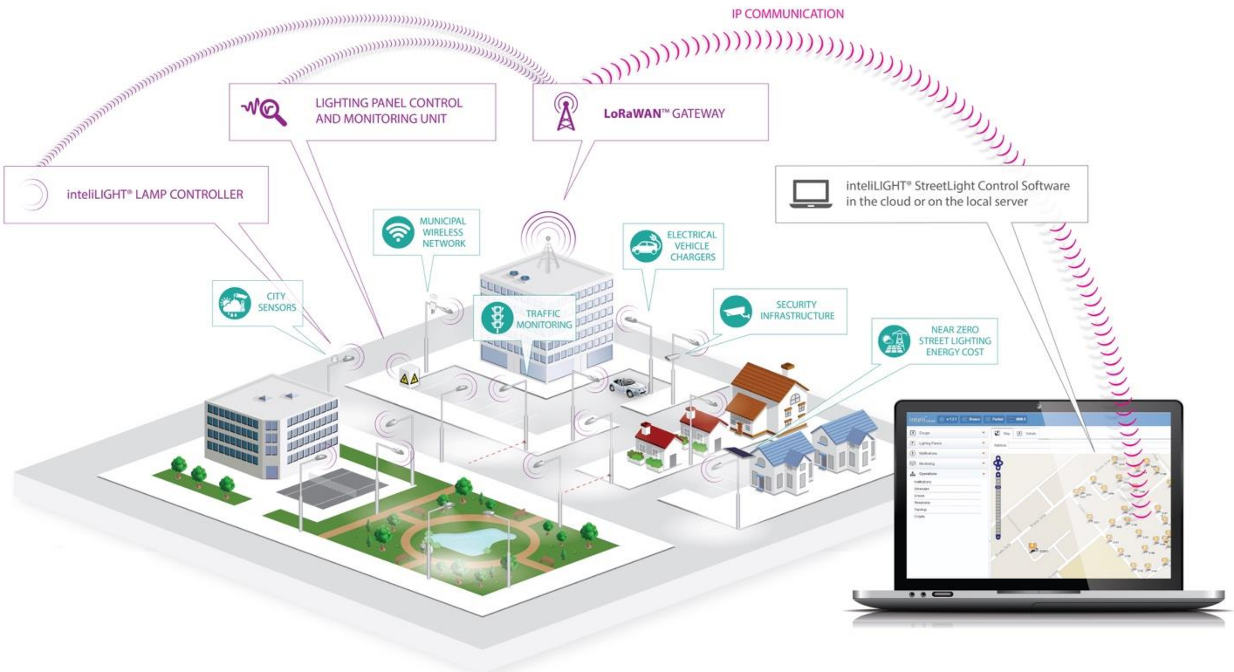

Figure 25 Leveraging the street lighting grid for smart city applications. [Source: FlashNet]

Industrial Automation

Industrial automation encompasses applications in different sectors including energy, chemicals, life sciences, marine, mining, oil and gas, and water among other industries. This breadth provides opportunities for LPWA players but also presents challenges. One challenge is the fragmentation of applications and their corresponding connectivity requirements which prompted industry players to develop their own connectivity solutions. For example, electric smart metering uses variants of IEEE 802.15.4 in North America or PLC in Europe which are designed to cater to the unique architecture and characteristics of the electric distribution networks. The connectivity networks are deployed and managed by the electric utility distributor who often are under certain regulatory requirements to compel the deployment of these meters, or in a few cases, delay such deployments (e.g. security and encryption requirements in Germany necessitate broadband capability that makes smart metering cost ineffective). Metering solution vendors integrate connectivity into their product portfolio and provide management and control systems. Therefore, incumbents are well entrenched into an ecosystem with unique value chain characteristics including purchasing, deploying and using connectivity technologies.

LPWA technologies have to provide a compelling proposition in this market that center first on meeting stringent application requirements better than existing solutions. Second comes meeting the financial objectives. LPWA provides a number of benefits over current industrial solutions, including:

- Battery operation: LPWA operates on battery which makes it safe in applications where power mains cannot be used – for example in water and gas metering.

- Speed of deployment: LPWA allows rapid, ‘on-demand’ deployment where and when needed as opposed to existing industrial connectivity techniques based on mesh-networking.
- Wide-area service: LPWA covers wide area which makes it suitable for tracking applications.

Senet is a service provider of propane tank monitoring and heating services that found in LPWA a potential to broaden services into other applications. The company has been operating its proprietary technology in 400 MHz, but chose to switch to LoRa where it currently operates sites in parts of the Northeast, Midwest and West Coast regions of the United States. LoRa allowed the company to improve the propane monitoring service by implementing an industrial automation platform to improve the delivery process culminating in 30% savings in fuel delivery costs. Additionally, Senet plans to leverage the network to service different applications. It cites tracking groundwater pumping data from an aquifer in California as an example. To reach into diverse markets, Senet’s business model centers on partnering with sensor developers as a market channel. It also stresses aspects of security which are of prime concern in industrial applications.

On the other hand, an example of in incumbent vendor in the same market is Emerson Process Management which provides many solutions in various industrial sectors including tank monitoring solutions. From an end-user perspective, especially industrial enterprises, security is a major priority. Other high priorities include integration into existing monitoring systems and interoperability with backend support systems. These aspects have led enterprises to deploy their own private networks that solved specific challenges. Thus, LPWA needs to assure clients of meeting the application requirement in the first order to justify capital expenditure for implementing remote connectivity and achieving subsequent operational cost savings.

In summary, incumbents are often an underestimated threat to LPWA service providers. While incumbents can be partners in the LPWA ecosystem, they have made investments in competing technologies and are in process of evaluating their position on LPWA. The success for LPWA will center on meeting application requirements, integrating into well established ecosystems and overcoming certain regulatory constraints that affect the commercial viability of applications.

LPWA Applications and Markets

The adoption of LPWA technologies hinges on achieving an economic threshold that makes the business case viable and compelling after meeting the functional requirements of applications. In this section, we explore applications where LPWA can make inroads by exploring the requirements of potential applications.

LPWA Early Adopters

A survey of current LPWA IoT applications shows that in this initial phase, LPWA is competing primarily with proprietary and industrial technologies, in commercial applications (Table 32). LPWA provides a good fit for the requirements of these applications (Table 33). 3GPP seeks to attract that same segment of applications, hence, the impending collision between LPWA and 3GPP technologies.

The overlap in applications between LPWA and 3GPP is limited today, which is explained by the current divide between LPWA and 3GPP technology characteristics:

- LPWA has limited coverage and has yet to achieve high-scale deployment;
- 3GPP technologies leverage mobility and roaming features that are unavailable in LPWA, in addition to high data rate and control capabilities which have high value to end users.

This landscape is expected to change as cellular technologies 'scale down' to better meet requirements for low power consumption, but the process will take 2-4 years to unfold as we outlined.

Table 32 Qualifications of prominent LPWA applications.

Application	Competing technologies	LPWA Advantage*	Qualifications
Street lighting	Proprietary, 802.15.4	~	802.15.4 devices on light poles are used to create a mesh network connecting to an aggregation point. Power at the pole eliminates the need for battery.
Smart parking	Proprietary, 802.15.4	+	802.15.4 devices can be used, especially in garage complexes where power is available; LPWA is a better fit for city streets where power is not available.
Environmental monitoring: water	Proprietary, 802.15.4	+	LPWA allows distributing devices across large terrain and is suitable for locations where power is not available.
Asset tracking: bicycles	Cellular	+	LPWA has an advantage due to low power consumption and ability to track over a long period of time without charging batteries. GPRS is used to track over a short time period due to limited battery power (e.g. as used by Vodafone).

Water metering	Proprietary, 802.15.4	+	Short-range technologies allow drive-by measurements or gateway configuration. Power availability makes this case particularly dependent on batteries. LPWA can penetrate deep into buildings and basements making it a suitable technology to kick start this market. Limited or no subsidies are a key reason for delays in water metering applications unlike electrical smart meters.
Gas pipeline monitoring	Proprietary, 802.15.4, Satellite, Cellular	+	Multiple technologies are used today depending on location of the gas facilities, gauges and pipeline. LPWA provides the advantage of battery-power operation. LPWA base station can be backhauled by satellite service in remote areas, or by cellular technologies in areas where cell coverage is available.
Pet tracking	GPRS, Satellite, A-GPS/WAAS-GPS	~	This market is saturated with many types of devices using different technologies. LPWA technologies with device paging can be used in addition to unidirectional technologies in conjunction with GPS receiver to report location. The ubiquitous cellular and satellite coverage is yet unmatched by LPWAN.
Smart buildings: Light & temperature monitoring; smoke / fire detection.	ZigBee, Z-Wave, Bluetooth	~/-	Well entrenched technologies serve this market where interoperability and network effect has a strong impact in addition to cost. LPWA allows direct access to devices without the need to connect through an on-site gateway over third-party networks. It enables monitoring service but offers limited control capability.
Waste management	Proprietary, 802.15.4	+	LPWA wide area connectivity and battery-powered operation makes it ideal for applications such as detecting trash level in garbage bins; it is also used in waste compactors. Low device and service costs make the business case more viable by lowering the barriers to entry.
Electricity meters	802.15.4, ZigBee, PLC	~/+	Most North American smart meter deployments use 802.15.4 or a hardened form of ZigBee (high power) while PLC is prevalent in Europe. LPWA provides spot connectivity and serves both dense and sparse areas where meters are located too far apart for mesh or PLC technologies.
Tank monitoring	Proprietary, WirelessHART, ISA100	~/+	LPWA provides advantages for mobile tanks and in large complexes where short-range mesh solutions are challenged to provide coverage.

Legend:
~ : Neutral advantage over existing technologies.
- : Does not provide material advantage over existing technologies.
+ : Provides material advantage over existing technologies.

Table 33 LPWA application characteristics and critical parameters.

Application	Data Rate	Latency Tolerance	Speed	Duty Cycle	Range	Battery	Security
Street lighting	bytes / hour	High	Fixed	2+ reports / day	100's of meters to km's	Power available	Standard
Smart parking	bytes / hour	High	Fixed	1+ report per hour	10's of meters to km's	10 Years	Standard
Environmental monitoring: water	bytes / hour	High	Fixed	1+ report per hour	Few km	2 - 10 Years	Standard
Asset tracking: bicycles	bytes / hour	High	Nomadic	Few reports per hour	Few km	1 - 2 Years	Standard
Water metering	bytes / hour	High	Fixed	1+ report per day	Few km	10 Years	Standard
Gas pipeline monitoring	bytes / hour	High	Fixed	1+ report per hour	Few km	2 - 5 Years	High
Pet tracking	bytes / hour	High	Nomadic	Few reports per hour	Few km	Days - weeks	Standard
Smart buildings: Light & temperature monitoring	Up to 100's of bps	High	Fixed	Few reports per day	Few km	Power available; 1-5 years otherwise	Standard
Waste management	bytes / hour	High	Fixed/Nomadic	1+ report per day	Few km	2 - 10 Years	Standard
Alarms: smoke/fire detection	bytes / hour	High	Fixed	1+ report per week	Few km	Power available	Standard
Electricity meters	Up to tens of kbps	High	Fixed	1+ report per day	Few km	Power available	High
Tank monitoring	bytes / hour	High	Fixed	1+ report per day	Few km	2 - 10 Years	Standard

LPWA deployments are relatively small so far, and they concentrate on private networks rather than public networks. Private networks cater to specific applications which indicate that LPWA networks address unfulfilled market requirements.

LPWA and 3GPP Mass Market Applications

High-volume adoption of LPWA technologies will hinge in large part on its success in public networks. In the public case, operating costs are shared among multiple users, reducing the cost of connectivity to a commodity level. Hence, the following factors need to be considered in addition to meeting application requirements:

1. Tolerance for unlicensed spectrum and related impact on service reliability: mission-critical applications that require high reliability are unlikely to use LPWA networks.
2. Availability of standard-based technologies to drive low connectivity cost and provide confidence to large adopters on avoiding vendor-lock and ensuring viable solution roadmap.
3. Ensuring end-to-end security which is critical for private corporations and public organizations alike.
4. Achieving a reasonable RoI and service longevity: IoT applications have a long lifetime which are at least equivalent to the life of the battery for that application.

To determine where LPWA fits within the application landscape (Table 34), we evaluated a number of applications according to the following parameters:

- Power consumption and battery requirement
- Real-time operation and tolerance to latency
- Reliability of transmission
- Wide-area fixed or mobile application and the requirement for roaming
- Bi-directional traffic support
- Value proposition and business case

Table 34 LPWA, 3GPP and SRWA technology applicability per market segment and application[15].

	Application	LPWA	LTE Cat-m1, NB-IoT	Cellular, LTE Cat-1	Short range, industrial, proprietary
Smart Agriculture	Water quality	[green]	[green]	[yellow]	[yellow]
	Water leakages	[green]	[green]	[red]	[green]
	River floods	[green]	[green]	[red]	[green]
	Water management	[green]	[green]	[red]	[yellow]
	Supply chain control	[green]	[green]	[yellow]	[yellow]
	Wine quality enhancing	[green]	[green]	[red]	[yellow]
	Green houses	[green]	[green]	[red]	[green]
	Golf courses	[green]	[green]	[red]	[yellow]
	In-field monitoring	[green]	[green]	[red]	[yellow]
Smart Health	Fall detection	[red]	[red]	[yellow]	[green]
	Physical activity monitoring for aging people	[red]	[yellow]	[red]	[green]
	Medical fridges	[red]	[yellow]	[red]	[green]
	Sportsmen care	[red]	[red]	[yellow]	[green]

[15] See Appendix 2 for description of IoT applications. Adopted from Ovidiu Vermesan and Peter Friess, "*Internet of Things – From research and Innovation to Market Deployment*," River Publishers, 2014.

	Patients surveillance				
	Chronic disease management				
	Ultraviolet radiation				
	Hygienic hand control				
	Sleep control				
	Dental health				
Smart Living	Intelligent shopping applications				
	Energy and water use				
	Remote control appliances				
	Weather station				
	Smart home appliances				
	Gas monitoring				
	Safety monitoring				
	Smart jewelry				
Smart Environment Monitoring	Forest fire detection				
	Air pollution				
	Landslide and avalanche prevention				
	Earthquake early detection				
	Protecting wildlife				
	Meteorological station network				
	Marine and coastal surveillance				
Smart Manufacturing	Smart product management				
	Compost				
	Offspring care				
	Animal tracking				
	Toxic gas levels				
	Production line				
	Telework				
Smart Energy	Smart grid				
	Photovoltaic installations				
	Wind turbines				
	Water flow				
	Radiation levels				
	Power supply controllers				
Smart Buildings	Perimeter access control				
	Liquid presence				
	Indoor climate control				
	Intelligent thermostat				
	Intelligent fire alarm				
	Intrusion detection systems				
	Motion detection				

	Art and goods preservation	Red	Red	Red	Green
	Residential irrigation	Red	Red	Red	Green
Smart Transport	NFC payment	Red	Red	Red	Green
	Quality of Shipment Conditions	Green	Green	Green	Red
	Item location	Yellow	Yellow	Yellow	Green
	Storage incompatibility detection	Green	Green	Yellow	Yellow
	Fleet tracking	Green	Green	Green	Red
	Electric vehicle charging stations reservation	Red	Red	Green	Red
	Vehicle auto-diagnosis	Green	Green	Green	Red
	Management of cars	Yellow	Yellow	Green	Red
	Road pricing	Red	Red	Red	Green
	Connected militarized defense	Red	Red	Red	Green
Smart Industry	Tank level	Green	Green	Red	Green
	Silos stock calculation	Green	Green	Yellow	Green
	Explosive and hazardous gases	Green	Green	Red	Green
	Machine auto-diagnosis and assets control	Yellow	Yellow	Yellow	Green
	Maintenance and repair	Yellow	Yellow	Yellow	Green
	Indoor air quality	Yellow	Yellow	Yellow	Green
	Temperature monitoring	Yellow	Yellow	Yellow	Green
	Ozone presence	Yellow	Yellow	Yellow	Green
	Indoor location	Red	Red	Red	Green
	Aquaculture industry monitoring	Red	Red	Green	Green
Smart City	Smart parking	Green	Green	Red	Green
	Structural health	Green	Green	Red	Green
	Noise urban maps	Green	Green	Red	Green
	Traffic congestion	Green	Green	Red	Green
	Smart lightning	Green	Green	Red	Green
	Waste management	Green	Green	Red	Yellow
	Intelligent transportation systems	Green	Green	Red	Green
	Safe city	Red	Red	Green	Green
	Connected learning	Red	Red	Green	Green
	Smart irrigation of public spaces	Green	Green	Red	Green

Legend:
Green: technology is generally a good fit for the application
Red: technology is generally not a good fit for the application.
Yellow: technology meets certain but not all requirements; the technology is an acceptable option under certain conditions.

We can divide the connectivity market into three segments depending on the likelihood of LPWA adoption:

1. Prime segments: LPWA is prime connectivity technology in agriculture, smart city, smart transport, and environmental monitoring applications (Table 35).
2. Segments where LPWA has the lowest adoption rate: Short range, industrial, mesh and proprietary technologies are prime in smart health and smart building applications largely on cost considerations (Table 36).
3. Mixed segments: LPWA will compete with other technologies in serving applications in smart living, smart manufacturing, smart industry, and smart energy (

4. Table 37).

Table 35 Prime IoT Segments for LPWA deployments.

Sector/Application	Qualification
Agriculture	Applications focused on reporting sensor data with limited to no control applications. Wide area coverage and low power consumption in addition to on-demand spot connectivity are key requirements. Tolerance to latency is high.
Smart city	Applications focused on reporting sensor activities with limited control capability (digital on/off). Spot connectivity over a wide area allows for a better business case metrics than SRWA technologies. This market is tied to municipal spending which is limited. Smart city applications require low cost points and often result in low profit margins; strong RoI is critical.
Smart transport	Reporting sensor data and limited control capability. Often in transport applications, power is available (e.g. on buses or trains). This expands LPWA scope to control applications beyond simple reporting of sensor data.
Environmental monitoring	Monitoring and reporting sensor data is key strength of LPWA technologies. This is a prime market where spot connectivity is of high value as it allows rapid deployment and takedown of sensors over a wide area.

Table 36 IoT Segments where LPWA would have least penetration.

Sector/Application	Qualification
Smart health	Technologies based on short range PMP (Bluetooth, Wi-Fi) and cellular (3G, LTE) are more adept at meeting the requirements for this market which include high-bit rate and data streaming connectivity.
Smart buildings	Technologies based on short range PMP (Bluetooth, Wi-Fi) and mesh (Thread, ZigBee) are better positioned to take advantage of this market. Interoperability of systems and integration with home and building automation systems are critical requirements.

Table 37 IoT market segments where LPWA will have mixed impact.

Sector/Application	Qualification
Smart living	LPWA is restricted to monitoring applications. However, most applications in this segment require bidirectional traffic for control. Short range communications over Bluetooth, ZigBee and Wi-Fi are expected to dominate this market segment. These technologies can be integrated with cellular connectivity to enable remote applications.
Smart manufacturing	Many applications require bidirectional traffic and are latency intolerant. Therefore, industrial standards optimized for remote control and fast response time are better suited than LPWA.
Smart energy	LPWA is restricted to monitoring applications, which is most prevalent on consumer premises at the edge of the energy network. This market segment is significant in size. However, we anticipate lower adoption of LPWA in the energy generation and distribution networks where proprietary and industrial solutions are optimized for specific use cases.
Smart industry	LPWA is restricted to monitoring applications. Where remote control is required, industrial technologies optimized for specific use cases are preferred and would be adopted in place of LPWA. Security is important in many industrial applications and private networks are valued by large enterprises.

Market Penetration and Market Size

For a perspective on market penetration, connectivity using 3GPP technologies made a relatively small fraction of total connected devices – an installed base of 243 million in 2014[16], or about 3.2% of total connected devices based on total of 7.5 billion connected devices. 77% of 3GPP connected devices use 2G (GPRS). The number of 3GPP connected devices is projected to reach 1 billion by 2020 with 2G accounting for 44% of connectivity while 3G and LTE will account for 33% and 23%, respectively[17]. The relatively low penetration of cellular technologies in IoT connectivity is due to a number of factors including high cost thresholds and mismatch in performance requirements with potential applications.

LPWA opens a new market opportunity in competition with short-range wide area devices primarily and with cellular technologies secondarily in many applications. We estimate the LPWA market at the end of 2015 at 2.6 million devices, of which under 400,000 units, or 11% of total installed base are on public networks. The potential LPWA market is estimated by Cisco VNI to reach 933 million connections by 2019.

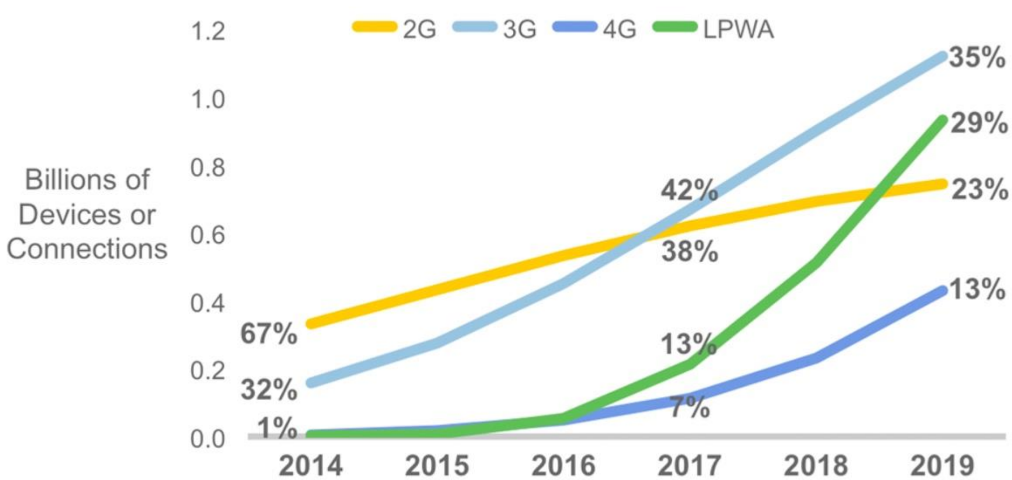

Figure 26 Global Mobile Devices and Connections by 2G, 3G, and 4G. [Source: Cisco VNI Mobile, 2015]

In the short term (2016 – 2018), the market penetration of LPWA will be highly dependent on:

1- The ability to compete effectively with SWRA technologies by enhancing the value proposition for IoT connectivity.
2- Success of the public network business model to scale deployments.

[16] GSMA Intelligence, "Global cellular M2M technology forecasts and assumptions," March 2015.
[17] Ibid.

3- Penetrating industrial applications including energy and manufacturing where LPWA has significant competition from established incumbents.
4- Investments in smart city and transport applications where LPWA provides a good match in performance requirements.

After 2018, the market dynamics will be altered due to the emergence of LTE Cat-m1 and NB-IoT technologies. The long term forecast for LPWA is contingent on providing a credible, secure and reliable IoT connectivity that provides a viable alternative to 3GPP technologies taking into account the ability of MNOs to provide a suitable business model which will differ from existing models for many carriers.

Based on our analysis, Mobile Experts expects new applications for LPWA to grow relatively slowly. The market is still fragmented with a crazy selection of technology options. If LPWA must rely on its own new business cases, we would not expect the LPWA market to reach the 1B unit level before 2020. A more likely outcome, in our view, involves shipments of about 200 million in 2020. There are three primary reasons for this conservative outlook:

1. Most industry forecasts (including the Cisco forecast) place high volumes of LPWA in consumer application, smart cities, and smart buildings. We view the consumer and smart building sectors as prime for short-range connectivity solutions where LPWA will play a secondary supportive role. LPWA is competitive in smart city applications, but that market is gated by municipal spending which operates on very tight budgets and is takes longer time to evolve than applications in the private sector. Therefore, the pull for LPWA will come from multiple markets and will be fragmented in nature. This pull will include applications in utilities, agriculture, and environmental monitoring as outlined earlier.
2. High LPWA volumes are driven by fledgling public networks which require time to provide the required coverage and density to support volume deployments. Public networks need more time for standardization and ecosystem development, before rapid growth can take off.
3. The market will be in a state of confusion, given a large number of available technology and business options. Fragmented choices will cause uncertainty for customers, investors, and module developers which can slow down big deployments. End users within the next 2 years will be concerned about making the 'right' technology decision given the expense associated with implementing IoT connectivity and the return on investment.

On the other hand, if these issues are resolved in the short term, then 2018-2020 could bring strong growth in LPWA. The low cost and widespread coverage of LPWA networks will create options that are not available with 2G/3G/LTE or with SWRA. If large enterprise applications (cars, trucking fleets, shipping companies) coalesce on a single LPWA format, then growth could accelerate during the 2019-2020 timeframe.

In addition, we believe that LPWA holds strong promise for "stealing" business from WI-Fi, Bluetooth, GPRS, and LTE. The existing market for wireless IoT devices includes an installed base of 7.5 billion devices today, with 100 million GPRS devices shipping per year. Over the next five years, we anticipate a strong likelihood that LPWA options will undercut the pricing of GPRS/LTE products, and offer better coverage than Wi-Fi or Bluetooth options. In short, we believe that LPWA can achieve up to 1 billion-device-per-year volume by 2020 by latching onto existing markets that are already underway.

In our forecast, we show the "organic growth" of LPWA as a relatively firm forecast, with strong potential upside in IoT business coming from applications in the short-range wireless area or the GPRS/LTE area today.

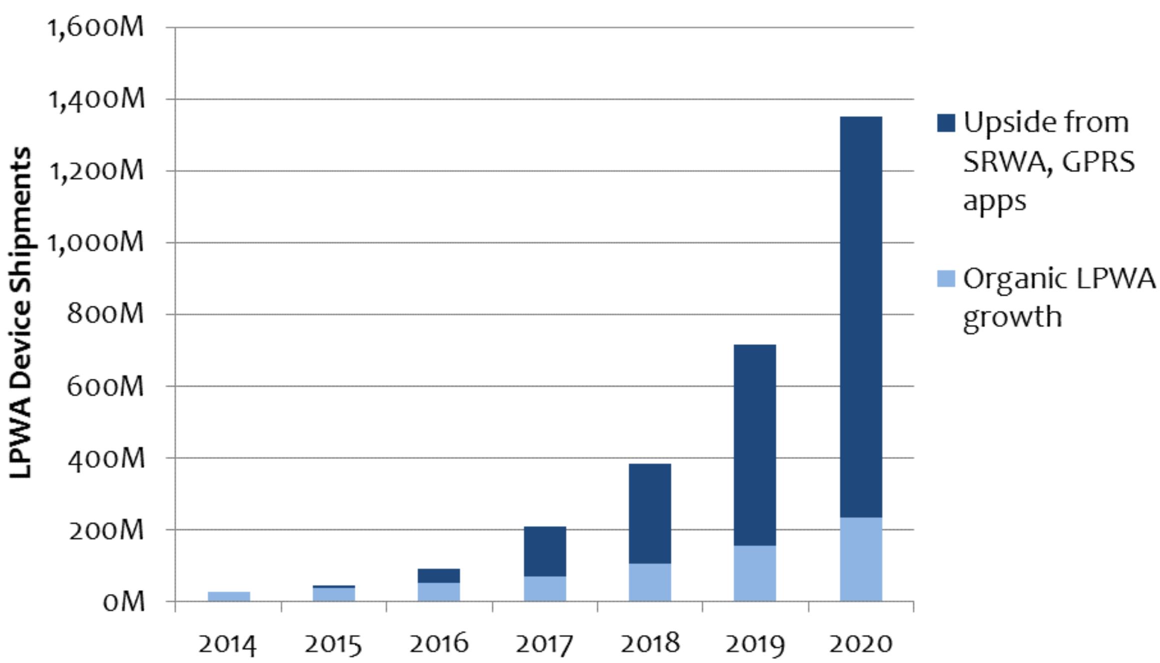

Figure 27 Global Forecast of LPWA device shipments

Concluding with a final observation that impacts the forecast for LPWA, we note that this market is dominated by enterprise and not consumer applications. While this market may be slow to evolve in the short term, it offers a large potential in the long term and provides much opportunities for growth. This new opportunity comes at a time that sees rapid changes in the consumer connectivity space with expanding use of short-range technologies (Bluetooth, Wi-Fi) and flattening growth in the smartphone market that is reaching saturation, but nevertheless providing the platforms for growth in short-range solutions.

Acronyms

3G	Third generation
3GPP	Third Generation Partnership Project
4G	Fourth generation
A-GPS	Assisted GPS
AAA	Authentication, authorization, and accounting
ACC	Adaptive channel coding
Ack	Acknowledgment
ADR	adaptive data rate
AES	Advanced encryption standard
ARQ	Automatic retransmission request
ASP	Average selling price
BPSK	Binary phase shift keying
BW	Bandwidth
C-UNB	Cooperative Ultra Narrowband
Cat	Category
Cat-m1	Category minus 1
CCM	Counter for cipher block chaining message authentication code
CEPT	Comite Europeen des Postes et Telecommunications
CFR	Code of Federal Regulations
CMS	Central management system
CRC	Cyclic redundancy check
CSS	Chirp spread spectrum
D-BPSK	Differential binary phase shift keying
D-QPSK	Differential quadrature phase shift keying
DART	Dynamic Automatic Radio Transceiver
DCXO	Digitally-compensated crystal oscillator
DL	Downlink
DRX	Discontinuous reception
DSSS	Direct sequence spread spectrum
DTOA	difference time of arrival techniques
EAB	Extended access barring
EAP	Extended authentication protocol
EC-GSM	Extended Coverage GSM
ECC	Electronic Communications Committee
EEA	EPS Encryption Algorithm
EGPRS	Enhanced general packet radio service
EiRP	Effective isotropic radiated power
EPDCCH	Enhanced physical downlink control channel
EPS	Evolved Packet System
ERP	Effective radiated power
ETSI	European Telecommunications Standards Institute
eUICC	embedded Universal Integrated Circuit Card
EV	Electric vehicle
FCC	Federal Communications Commission

FDD	Frequency division duplex
FDMA	Frequency division multiple access
FEC	Forward error correction
FHSS	Frequency hopping spread spectrum
FRAND-Z	Fair, reasonable and non-discriminatory with zero royalty
GERAN	GSM EDGE radio access network
GFSK	Gaussian frequency shift keying
GMSK	Gaussian minimum shift keying
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global System for Mobiles
HART	Highway Addressable Remote Transducer Protocol
HPS	high-pressure sodium
HPS	High-pressure sodium
HTTP	HyperText Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet protocol
ISA	International Society of Automation
ISM	Industrial, scientific, medical
IWF	Interworking function
LAPI	Low access priority indicator
LBT	Listen before talk
LCD	Liquid crystal display
LED	Light emitting diode
lm	Lumen
LoRa	Long Range
LoRaWAN	LoRa wide area network
LPWA	Low power wide area
LPWAN	Low power wide area network
LTE	Long Term Evolution
LTE-M	LTE Machine
M2M	Machine to machine
MAC	Medium access control
MNO	Mobile network operator
MSISDN	Mobile station international subscriber directory number
MTC	Machine Type Communications
MU-MIMO	multi-user multiple-input, multiple-output
NB-IoT	Narrowband IoT
NB-OFDMA	Narrow-band OFDMA
NFC	Near-field communications
O-QPSK	Offset quadrature phase shift keying
OFDMA	Orthogonal frequency division multiple access
OLN	Outdoor lighting networks
PBCH	Physical broadcast channel
PDSCH	Physical downlink shared channel

PDU	Packet data unit
PHY	Physical layer
PLC	Power line communications
PRACH	Physical random access channel
PSM	Enhanced power saving mode
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
QoS	Quality of service
QPSK	Quadrature phase shift keying
RAN	Radio access network
Rel	Release
RF	Radio frequency
RFC	Request for comments
RFIC	Radio frequency integrated circuit
RFID	Radio-frequency identification
RPMA	Random Phase Multiple Access
Rx	Receiver
SC-FDMA	Single carrier frequency domain multiple access
SC-FDMA	Single carrier frequency division multiple access
SCH	Shared channel
SDR	Software defined radio
SF	Spreading factor
SIG	Special interest group
SMS	Short message service
SNO	SigFox network operator
SoC	System on chip
SRD	Short range devices
SRWA	Short-range wide-area
SW	Software
TAU	Reduced tracking area update
TCXOs	Temperature-controlled crystal oscillator
TDMA	Time division multiple access
TDOA	time difference of arrival
TVWS	Television whitespace
Tx	Transmit
UL	Uplink
UNB	Ultra narrow band
UV	Ultraviolet
UWB	Ultra-wideband
W-P	Weightless-P
WAAS-GPS	Wide area augmentation system – GPS
WirelessHART	Wireless Highway Addressable Remote Transducer Protocol
XML	Extensible markup language
XO	Crystal oscillator

Appendix 1 – Abridged Weightless-P Features List.

- FDMA+TDMA in 12.5kHz narrow band channels to support uplink-dominated traffic from a very large number of devices with moderate payload sizes
- 12.5 kHz channels with frequency hopping for robustness to multi-path and narrowband interference
- Operates over the whole range of license-exempt sub-GHz ISM/SRD bands for global deployment: 169/433/470/780/868/915/923 MHz
- Flexible channel assignment for frequency re-use in large-scale deployments
- Adaptive data rate from 200 bps to 100 kbps with variable radio resource usage optimization depending on device link quality
- Transmit power control for both downlink and uplink to reduce interference and maximize network capacity
- Time-synchronized base stations for efficient radio resource scheduling and utilization
- Supports both network-originated and device-originated traffic
- Paging capability
- Low-latency in both uplink and downlink
- Fast network acquisition
- Forward Error Correction
- Automatic Retransmission Request
- Adaptive Channel Coding
- Handover
- Roaming
- Cell re-selection
- Fully acknowledged communications
- Auto-retransmission upon failure
- Frequency and time synchronization
- Supports licensed spectrum operation
- GMSK and offset-QPSK modulation
- Adaptive transmit power and data rate to maximize battery-life
- Power consumption in idle state when stationary below 100uW
- Authentication to the network
- AES-128/256 encryption
- Radio resource management and scheduling across the overall network to ensure quality-of-service to all devices
- Support for over-the-air firmware upgrade and security key negotiation or replacement
- Fast network acquisition and frequency/time synchronization
- Compared to UNB, narrowband operation is less sensitive to frequency offset and drift, allowing the use of lower cost, lower power XOs or DCXOs instead of TCXOs
- Royalty free IP (FRAND-Z) open standard

Appendix 2 –Link Budget Calculations

Table 38 Link budget for LTE-MTC Cat-m1 (3GPP Release 13).

		Uplink Channels			Downlink Channels			
	Physical layer channel	PUCCH	PRACH	PUSCH	PDSCH	SCH	PBCH	EPDCCH
1	Tx power (dBm)	23	23	23	46	46	46	46
2	Thermal noise density (dBm/Hz)	-174	-174	-174	-174	-174	-174	-174
3	Receiver noise figure (dB)	5	5	5	9	9	9	9
4	Interference margin (dB)	0	0	0	0	0	0	0
5	Occupied channel bandwidth (kHz)	180	1080	360	180	1080	1080	180
6	Effective noise power = (2)+(3)+(4)+10 log((5)) (dBm)	-116.4	-108.7	-113.4	-112.4	-104.7	-104.7	-112.4
7	Required SINR (dB)	-7.8	-10	-4.3	0	-3.8	-3.5	-0.7
8	Coverage enhancement techniques	13.8	19.3	20.3	2.6	6.5	6.8	1.9
9	Receiver sensitivity = (6) + (7) - (8) (dBm)	-138.0	-138.0	-138.0	-115.0	-115.0	-115.0	-115.0
10	MCL = (1) - (9) (dB)	161.0	161.0	161.0	161.0	161.0	161.0	161.0

Note:
1. Coverage enhancement techniques include repetition and/or PSD boosting and HARQ retransmission.
2. While the 3GPP calculations assume +23 dBm transmit power, in our Mobile Experts comparisons we assume +20 dBm because the lower power level is more likely in most devices.

Table 39 Link Budget for NB-IoT (3GPP Release 13).

		Uplink	Downlink
1	Tx power (per channel, dBm)	23	32.5
2	Thermal noise density (dBm/Hz)	-174	-174
3	Receiver noise figure (dB)	3	5
4	Interference margin (dB)	0	0
5	Occupied channel bandwidth (kHz)	3.75	15
6	Effective noise power = (2) + (3) + (4) + 10 log((5)) (dBm)	-135.3	-127.2
7	Required SINR (dB)	-6.3	-4.8
9	Receiver sensitivity = (6) + (7) (dBm)	-141.6	-132.0
10	MCL = (1) - (9) (dB)	164.6	164.5

Note:
1. While the 3GPP calculations assume +23 dBm transmit power, in our Mobile Experts comparisons we assume +20 dBm because the lower power level is more likely in most devices.

Table 40 Link budget for LPWA technologies per FCC regulations.

	SigFox		LoRa		Weightless-P		RPMA	
	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Tx power (dBm)	28	16	28	16	28	16	25	20
Tx antenna gain (dBi)	9	0	9	0	9	0	12	0
Cable loss (dB)	1	0	1	0	1	0	1	0
EiRP (dBm)	36	16	36	16	36	16	36	20
Rx antenna gain (dBi)	0	9	0	9	0	9	0	12
Ant diversity gain (dB)	0	0	0	0	0	0	3	3
Cable loss (dB)	0	1	0	1	0	1	0	1
Rx sensitivity (dBm)	-134	-134	-134	-137	-132	-132	-133	-142
Total (dB)	170	158	170	161	168	156	172	176
System gain (dB)	158		161		156		172	

Note:

1. RPMA implements two antennas for receive diversity. This is accounted for on both the base station and device sides.

Table 41 Link budget for LPWA technologies per CEPT/ETSI rules.

	SigFox		LoRa		Weightless-P		RPMA	
	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Tx power (dBm)	8	16	8	16	8	16	21	20
Tx antenna gain (dBi)	9	0	9	0	9	0	10	0
Cable loss (dB)	1	0	1	0	1	0	1	0
EiRP (dBm)	16	16	16	16	16	16	30	20
Rx antenna gain (dBi)	0	9	0	9	0	9	0	10
Ant diversity gain (dB)	0	0	0	0	0	0	3	3
Cable loss (dB)	0	1	0	1	0	1	0	1
Rx sensitivity (dBm)	-128	-131	-134	-137	-132	-132	-133	-142
Total (dB)	144	155	150	161	148	156	166	174
System gain (dB)	144		150		148		166	

Appendix 3 – Descriptions of IoT Applications

	Application	Description
Smart Agriculture	Water quality	Study of water suitability in rivers and the sea for fauna and eligibility for drinkable use.
	Water leakages	Detection of liquid presence outside tanks and pressure variations along pipes.
	River floods	Monitoring of water level variations in rivers, dams and reservoirs.
	Water management	Real-time information about water usage and the status of waterlines could be collected by connecting residential water meters to an Internet protocol (IP) network. As a consequence could be reductions in labor and maintenance costs, improved accuracy and lower costs in meter readings, and possibly water consumption reductions.
	Supply chain control	Monitoring of storage conditions along the supply chain and product tracking for traceability purposes.
	Wine quality enhancing	Monitoring soil moisture and trunk diameter in vineyards to control the amount of sugar in grapes and grapevine health.
	Green houses	Control micro-climate conditions to maximize the production of fruits and vegetables and its quality.
	Golf courses	Selective irrigation in dry zones to reduce the water resources required in the green.
	In-field monitoring	Reducing spoilage and food waste with better monitoring, statistic handling, accurate ongoing data obtaining, and management of the agriculture fields, including better control of fertilizing, electricity and watering.
Smart Health	Fall detection	Assistance for elderly or disabled people living independent.
	Physical activity monitoring for aging people	Body sensors network measures motion, vital signs, unobtrusiveness and a mobile unit collects, visualizes and records activity data.
	Medical fridges	Control of conditions inside freezers storing vaccines, medicines and organic elements.
	Sportsmen care	Vital signs monitoring in high performance centers and fields. Health and fitness products for these purposes exist, that measure exercise, steps, sleep, weight, blood pressure, and other statistics.
	Patients surveillance	Monitoring of conditions of patients inside hospitals and in old people's home.
	Chronic disease management	Patient-monitoring systems with comprehensive patient statistics could be available for remote residential monitoring of patients with chronic diseases such as pulmonary and heart diseases and diabetes. The reduced medical center admissions, lower costs, and shorter hospital stays would be some of the benefits.
	Ultraviolet radiation	Measurement of UV sun rays to warn people not to be exposed in certain hours.
	Hygienic hand control	RFID-based monitoring system of wrist bands in combination of Bluetooth LE tags on a patient's doorway controlling hand hygiene in hospitals, where vibration notifications is sent out to inform about

		time for hand wash; and all the data collected produce analytics which can be used to potentially trace patient infections to particular healthcare workers.
	Sleep control	Wireless sensors placed across the mattress sensing small motions, like breathing and heart rate and large motions caused by tossing and turning during sleep, providing data available through an app on the smartphone.
	Dental health	Bluetooth connected toothbrush with smartphone app analyzes the brushing uses and gives information on the brushing habits on the smartphone for private information or for showing statistics to the dentist.
Smart Living	Intelligent shopping applications	Getting advice at the point of sale according to customer habits, preferences, presence of allergic components for them, or expiring dates.
	Energy and water use	Energy and water supply consumption monitoring to obtain advice on how to save cost and resources. Maximizing energy efficiency by introducing lighting and heating products, such as bulbs, thermostats and air conditioners.
	Remote control appliances	Switching on and off remotely appliances to avoid accidents and save energy.
	Weather station	Displays outdoor weather conditions such as humidity, temperature, barometric pressure, wind speed and rain levels using meters with ability to transmit data over long distances.
	Smart home appliances	Refrigerators with LCD screen telling what's inside, food that's about to expire, ingredients you need to buy and with all the information available on a smartphone app. Washing machines allowing you to monitor the laundry remotely, and run automatically when electricity rates are lowest. Kitchen ranges with interface to a smartphone app allowing remotely adjustable temperature control and monitoring the oven's self-cleaning feature.
	Gas monitoring	Real-information about gas usage and the status of gas lines could be provided by connecting residential gas meters to an Internet protocol (IP) network. As for the water monitoring, the possible outcome could be reductions in labor and maintenance costs, improved accuracy and lower costs in meter readings, and possibly gas consumption reductions.
	Safety monitoring	Baby monitoring, cameras, and home alarm systems making people feel safe in their daily life at home.
	Smart jewelry	Increased personal safety by wearing a piece of jewelry inserted with Bluetooth enabled technology used in a way that a simple push establishes contact with your smartphone, which through an app will send alarms to selected people in your social circle with information that you need help and your location.
Smart Environme	Forest fire detection	Monitoring of combustion gases and preemptive fire conditions to define alert zones.
	Air pollution	Control of CO_2 emissions of factories, pollution emitted by cars and toxic gases generated in farms.

	Landslide and avalanche prevention	Monitoring of soil moisture, vibrations and earth density to detect dangerous patterns in land conditions.
	Earthquake early detection	Distributed control in specific places of tremors.
	Protecting wildlife	Tracking collars utilizing GPS modules to locate and track wild animals and communicate their coordinates via SMS.
	Meteorological station network	Study of weather conditions in fields to forecast ice formation, rain, drought, snow or wind changes.
	Marine and coastal surveillance	Using different kinds of sensors integrated in planes, unmanned aerial vehicles, satellites, ship etc. to control the maritime activities and traffic in important areas, keep track of fishing boats, supervise environmental conditions and dangerous oil cargo etc.
Smart Manufacturing	Smart product management	Control of rotation of products in shelves and warehouses to automate restocking processes.
	Compost	Control of humidity and temperature levels in alfalfa, hay, straw, etc. to prevent fungus and other microbial contaminants.
	Offspring care	Control of growing conditions of the offspring in animal farms to ensure its survival and health.
	Animal tracking	Location and identification of animals grazing in open pastures or location in big stables.
	Toxic gas levels	Study of ventilation and air quality in farms and detection of harmful gases from excrements.
	Production line	Monitoring and management of the production line using RFID, sensors, video monitoring, remote information distribution and cloud solutions enabling the production line data to be transferred to the enterprise-based systems. This may result in more quickly improvement of the entire product quality assurance process by decision makers, updated workflow charts, and inspection procedures delivered to the proper worker groups via digital displays in real time.
	Telework	Offering the employees technologies that enable home offices would reduce costs, improve productivity, and add employment opportunities at the same time as reducing real estate for employees, lower office maintenance and cleanings, and eliminating daily office commute.
Smart Energy	Smart grid	Energy consumption monitoring and management.
	Photovoltaic installations	Monitoring and optimization of performance in solar energy plants.
	Wind turbines	Monitoring and analyzing the flow of energy from wind turbines, and two-way communication with consumers' smart meters to analyze consumption patterns.
	Water flow	Measurement of water pressure in water transportation systems.
	Radiation levels	Distributed measurement of radiation levels in nuclear power stations surroundings to generate leakage alerts.
	Power supply controllers	Controller for AC-DC power supplies that determines required energy, and improve energy efficiency with less energy waste for power

		supplies related to computers, telecommunications, and consumer electronics applications.
Smart Buildings	Perimeter access control	Access control to restricted areas and detection of people in non-authorized areas.
	Liquid presence	Liquid detection in data centers, warehouses and sensitive building grounds to prevent break downs and corrosion.
	Indoor climate control	Measurement and control of temperature, lighting, CO2 fresh air in ppm etc.
	Intelligent thermostat	Thermostat that learns the users programming schedule after a few days, and from that programs itself. Can be used with an app to connect to the thermostat from a smart telephone, where control, watching the energy history, how much energy is saved and why can be displayed.
	Intelligent fire alarm	System with sensors measuring smoke and carbon monoxide, giving both early warnings, howling alarms and speaks with a human voice telling where the smoke is or when carbon monoxide levels are rising, in addition to giving a message on the smartphone or tablet if the smoke or CO alarm goes off.
	Intrusion detection systems	Detection of window and door openings and violations to prevent intruders.
	Motion detection	Infrared motion sensors which reliably sends alerts to alarm panel (or dialer) and with a system implementing reduced false alarms algorithms and adaption to environmental disturbances.
	Art and goods preservation	Monitoring of conditions inside museums and art warehouses.
	Residential irrigation	Monitoring and smart watering system.
Smart Transport	NFC payment	Payment processing based in location or activity duration for public transport, gyms, theme parks, etc.
	Quality of Shipment Conditions	Monitoring of vibrations, strokes, container openings or cold chain maintenance for insurance purposes.
	Item location	Searching of individual items in big surfaces like warehouses or harbors.
	Storage incompatibility detection	Warning emission on containers storing inflammable goods closed to others containing explosive material.
	Fleet tracking	Control of routes followed for delicate goods like medical drugs, jewels or dangerous merchandises.
	Electric vehicle charging stations reservation	Locates the nearest charging station and tell the user whether its in use. Drivers can ease their range anxiety by reserving charging stations ahead of time. Help the planning of extended EV road trips, so the EV drivers make the most of potential charging windows
	Vehicle auto-diagnosis	Information collection from CAN Bus to send real time alarms to emergencies or provide advice to drivers.
	Management of cars	Car sharing companies manages the use of vehicles using the Internet and mobile phones through connections installed in each car.

	Road pricing	Automatic vehicle payment systems would improve traffic conditions and generate steady revenues if such payments are introduced in busy traffic zones. Reductions in traffic congestions and reduced CO2 emissions would be some of the benefits.
	Connected militarized defense	By connecting command-center facilities, vehicles, tents, and Special Forces real-time situational awareness for combat personnel in war areas and visualization of the location of allied/enemy personnel and material would be provided.
Smart Industry	Tank level	Monitoring of water, oil and gas levels in storage tanks and cisterns.
	Silos stock calculation	Measurement of emptiness level and weight of the goods.
	Explosive and hazardous gases	Detection of gas levels and leakages in industrial environments, surroundings of chemical factories and inside mines. Meters can transmit data that will be reliably read over long distances.
	Machine auto-diagnosis and assets control	Machine auto-diagnosis and assets control.
	Maintenance and repair	Early predictions on equipment malfunctions and service maintenance can be automatically scheduled ahead of an actual part failure by installing sensors inside equipment to monitor and send reports.
	Indoor air quality	Monitoring of toxic gas and oxygen levels inside chemical plants to ensure workers and goods safety.
	Temperature monitoring	Control of temperature inside industrial and medical fridges with sensitive merchandise.
	Ozone presence	Monitoring of ozone levels during the drying meat process in food factories.
	Indoor location	Asset indoor location by using active (ZigBee, UWB) and passive tags (RFID/NFC).
	Aquaculture industry monitoring	Remotely operating and monitoring operational routines on the aquaculture site, using sensors, cameras, wireless communication infrastructure between sites and land base, winch systems etc. to perform site and environment surveillance, feeding and system operations.
Smart City	Smart parking	Real-time monitoring of parking spaces availability in the city making residents able to identify and reserve the closest available spaces. Reduction in traffic congestions and increased revenue from dynamic pricing could be some of the benefits as well as simpler responsibility for traffic wardens recognizing non-compliant usage.
	Structural health	Monitoring of vibrations and material conditions in buildings, bridges and historical monuments.
	Noise urban maps	Sound monitoring in bar areas and centric zones in real time.
	Traffic congestion	Monitoring of vehicles and pedestrian levels to optimize driving and walking routes.
	Smart lightning	Intelligent and weather adaptive lighting in street lights.
	Waste management	Detection of rubbish levels in containers to optimize the trash collection routes. Garbage cans and recycle bins with RFID tags allow

		the sanitation staff to see when garbage has been put out. Maybe "Pay as you throw"-programs would help to decrease garbage waste and increase recycling efforts.
	Intelligent transportation systems	Smart Roads and Intelligent Highways with warning messages and diversions according to climate conditions and unexpected events like accidents or traffic jams.
	Safe city	Digital video monitoring, fire control management, public announcement systems
	Connected learning	Improvements in teacher utilization, reduction in instructional supplies, productivity improvement, and lower costs are examples of benefits that may be gained from letting electronic resources deliver data-driven, authentic and collaborative learning experience to larger groups.
	Smart irrigation of public spaces	Maintenance of parks and lawns by burying park irrigation monitoring sensors in the ground wirelessly connected to repeaters and with a wireless gateway connection to Internet.