RPMA Technology for the Internet of Things

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010-0064-00 Rev. B

May 11, 2015

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Revision History

Revision	Release Date	Change Description
A	April 29, 2015	Initial release.
B	TBD	

1 Introduction

There will be billions of endpoints over the next 10 years that will require very low cost wireless networking to support the vision of the Internet of Things.

As a result, there is a massive opportunity to connect and unlock the value of data over an enormous number of devices. Many companies and analysts believe that a parallel, public, non-cellular, network is justified to reach these numerous devices. The primary set of technologies that address this market are generically referred to ***Low Power Wide Area*** (**LPWA**) networks. These solutions are gaining considerable attention (e.g., Sigfox most notably) and gaining some traction. These "***Other LPWA***" approaches (those not including ***RPMA***) are light on technology and have fundamental limitations on both ***Total Cost of Ownership (TCO)*** and ***Link Capability***. Of particular concern is the issue of ***Capacity*** and ***Lack of Capacity Scaling*** especially in the presence of interference. A network that may be functional today runs the risk of not being functional as ***Capacity*** is exhausted, particularly in the very limited amount of spectrum available in Europe's 868 MHz band. Worse, additional infrastructure deployed will not mitigate the problem. This looming problem undercuts a very important aspect of the LPWA networks: the ability to guarantee endpoints functioning on networks for the next 20+ years.

The ***Cellular*** approach, for very different reasons, is similarly incapable of guaranteeing longevity of their network for deployed endpoints due to the very real concern of spectrum sunsetting. Although the Cellular industry is addressing what they call Machine-Type-Communications (MTC) to better address the requirements of these endpoints, the one aspect that is not addressable will continue to be the specter of sunsetting. Additionally, approaches such as ***Mesh Networking*** and ***Local RF*** (Wi-Fi, Bluetooth, etc.) are mentioned as possible connectivity solutions as well.

RPMA (Random Phase Multiple Access), by contrast is a fundamentally new technology built from the ground up to dramatically minimize ***Total Cost of Ownership (TCO)*** while providing incredibly high ***Link Capability***. ***RPMA*** has leveraged the advancement in Silicon technology and key innovations to implement a fundamentally distinct communication link. ***RPMA*** has order(s) of magnitude advantages in the key performance metrics of *Coverage* and *Capacity*, which allows for much fewer Network Infrastructure points, with much higher capability than any other public network approach.

Today, there are more than 100 thousand ***RPMA*** endpoints deployed on dozens of privately owned networks. These networks are solving connectivity challenges that no other solutions come close to being able to solve See Table 14 for details on a few examples including large networks for Distribution Automation, Oil and Gas, Rural Smart Meters, International Large Utility, and Smart City.

Going forward, ***RPMA*** is the ideal technology to build a public network to connect many billions of devices for both ***Brown Field*** applications (e.g., the 95% of machines on today's cellular network that would be far better served by ***RPMA)***, and the even more exciting ***Green Field*** applications (the and vast set of endpoints that have no cost-effective solution without ***RPMA***).

2 Competitive Landscape

RPMA has been specifically designed to optimally connect billions of devices that require low-cost connectivity, yet at the same time, provides rich link capability for these devices. Other technologies are also addressing the billions of devices that are ideally suited for ***RPMA***. The ***Cellular*** roadmap technologies that address Machine Type Communications (MTC) (both the 2G and 4G camps) and the ***Other LPWA*** technologies (e.g., Sigfox and Lora) are also targeting these Billions of devices. We will show that ***RPMA*** has large advantages simultaneously in ***Total Cost of Ownership (TCO)*** as well as ***Link Capability*** as depicted in .[2]

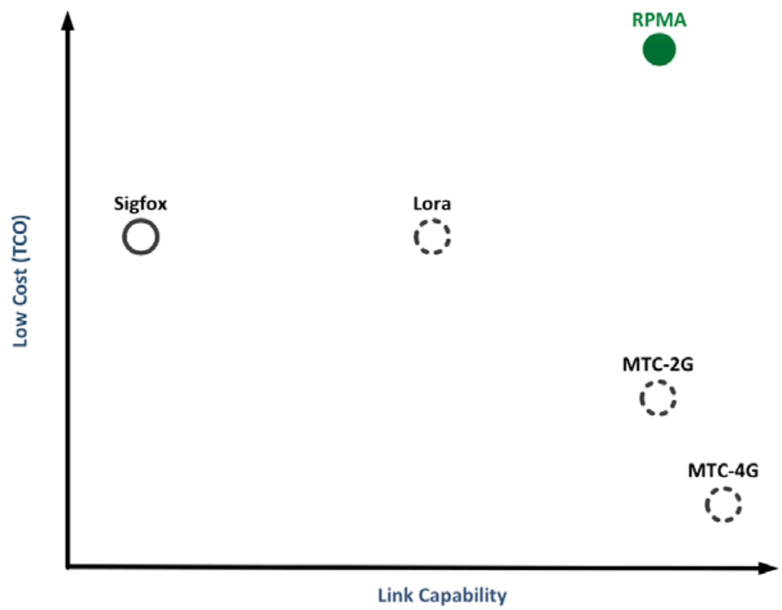

Figure 1. Competitive Landscape

Table 1 describes the requirements that must be met for a wireless network to address these endpoints and how well the competing approaches meet those requirements. For these devices, low-cost is critically important. There are several components of ***Total Cost of Ownership (TCO)*** and all of these components must be sufficiently low to feasibly connect these billions of relatively low value endpoints. Additionally, the communication link must have the best possible capability to address the needs of these endpoints; so several requirements are mapped to ***Link Capability*** in Table 1.

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[2] Dotted lines indicate that the details of these systems have yet to be worked out and are have no production networks currently deployed.

Note that the most significant **Primary Competitor** to ***RPMA*** is the existing ***Cellular*** systems, particularly the activities that are in the 3GPP standards body around Machine-Type-Connectivity (MTC). However, many companies, analysts, and thought leaders believe that for multiple reasons, ***Cellular*** has significant issues addressing these billions of endpoints. This paper also addresses the ***Other LPWA*** technologies that are gaining considerable mind-share into our list of **Primary Competitors** with Sigfox and Semtech's Lora being the primary examples of this group.

Local RF (e.g., Zigbee, Wi-Fi, Bluetooth) is a good connectivity solution for a large number of endpoints, but for a number of reasons, does not intrude on the billions of devices that require a Public Network and thus, is considered a **Secondary Competitor.**

Mesh Networking is considered a niche solution thus a **Secondary Competitor**, which have significant limitations that we'll discuss. The ***Wide Area Mesh*** is applicable to certain applications but has constraints that keep them from being widely available.

Table 1. System Requirements Summary

	System Requirement	Primary Solutions					Secondary Solutions	
		RPMA	Future Cellular		Other LPWA		Local RF	Wide-Area Mesh
			MTC 2G	MTC4G	Sigfox	Lora		
TCO: Cost to Provide Network Service	**Low Network Cost (Basic Coverage)**	✓	✓	✓	✓–	✓–	✓	×
	Low Network Cost (Deep Coverage)	✓✓	✓	×	×	×	×	×
	High Capacity per Network Infrastructure Point	✓	✓	✓	×	×	✓	✓–
	Cost Effective Capacity Scaling	✓	✓	✓	×	×	✓	×
	Low/Free Spectrum Cost	✓	×	×	✓	✓	✓	✓
TCO: Other Signficant Cost Drivers	**Low Endpoint Cost Radio**	✓	TBD	TBD	✓	✓	✓	✓
	Long Battery Life	✓	TBD	×	✓	✓	✓	×
	Network Longevity (e.g., No Sunsetting)	✓	×	✓–	✓	✓	×	✓
Link Capability	**Uplink Throughput**	✓	✓	✓	×	×	✓	✓
	Acknowledged Delivery	✓	✓	✓	×	✓	✓	✓
	Flexible Packet Sizes	✓	✓	✓	×	✓	✓	✓
	Downlink Capability	✓	✓	✓	×	TBD	✓	✓
	Broadcast/Multicast Capable (e.g., Firmware Download)	✓	✓–	✓–	×	TBD	✓	✓–
	Priority/Robustness	✓	×	×	×	TBD	×	×
	Security	✓	✓	✓	×	TBD	✓	✓
System Maturity	**Available Today**	✓	×	×	✓	×	✓	✓
	Proven Deployments at Scale	✓	×	×	×	×	NA	✓
Relevant Companies		On-Ramp Wireless	Nuel Huawei Qualcomm Ericson	Qualcomm Ericson Huawei Samsung	Sigfox <u>Other UNB:</u> NWave Taggle Senaptic	<u>Chip:</u> Semtech <u>MAC:</u> IBM Link Labs Thing Park	Zigbee Wi-Fi Bluetooth ANT	Silver Spring Cisco Itron Landis& Gyr Elster

The table above represents a description of the requirements for a networking technology to connect these billions of devices. Starting with the ***Total Cost of Ownership (TCO)*** components, we first explore the elements of ***Cost to Provide Network Service***. These include the costs that a public network operator will incur, which will typically be marked up and passed along to the application provider who in turn, mark up and pass along to the endpoint owner.

The following aspects of the technology determine the costs to the public network operator and ultimately, the cost to the endpoint owner:

- **Low Network Cost (Basic Coverage).** To build a Public Network business, with the exception of existing ***Cellular***, a new network must be built that has sufficient coverage for endpoints that will be deployed in the future. The capital investment required to build this network primarily depends on the amount of wireless infrastructure required. A technology that minimizes the amount of infrastructure to provide coverage is essential to make the initial capital investment feasible. ***Link Budget*** is an important figure of merit in understanding the initial cost of building these networks.
- **Low Network Cost (Deep Coverage).** One ubiquitous network that can reach everywhere is the stated vision of all the primary approaches: ***Cellular***, ***Other LPWA*** networks, and ***RPMA***. The ability to provide this depth of connectivity economically is challenging and a key performance criteria.
- **High Capacity per Network Infrastructure Point.** A successful business will involve maximizing the number of endpoints that use the network. At some point, the capacity of the network is exceeded. Two aspects that are critical to a successful and scalable business: how many endpoints can each piece of infrastructure support, and what happens when that number is exceeded? A figure of merit to understand the business result is ***Network Cost per Endpoint,*** and is explored in more depth in Section 4.2.
- **Cost Effective Capacity Scaling.** What happens when the capacity of a Network Infrastructure Point is exceeded? The answer depends on the technology whether this is an easily mitigated problem or a potentially disastrous scenario. Understanding Capacity Scalability is critical and is addressed in Section 4.2.4.
- **Low/Free Spectrum Cost.** The cost of spectrum is potentially very large – in the billions of dollars. Though voice and data subscription fees can justify the spectrum expense for public carriers, the lower value endpoints typically cannot. That is why the ability to use Free Spectrum is a critical attribute of a candidate approach if a parallel network is being built.

In addition to the ***Cost to Provide Network Service,*** there are the following additional costs:

- **Low Endpoint Cost.** Billions of communication modules certainly add up to significant cost. A networking technology to address billions of devices must be inexpensive. However, the rush to low endpoint cost at the expense of the other TCO items is not the optimal strategy. Moore’s law allows for a tremendous amount of processing in extremely cheap Silicon and the right technology will tend to take advantage of that fact if it dramatically minimizes other TCO components, most notably, Network Cost.
- **Long Battery Life.** The majority of the billions of endpoints benefiting from low-cost connectivity do not have access to electric power and certainty the option of wiring power to these devices is way too expensive. Needing to change batteries after a few years can be a considerable expense for devices that are extremely numerous. Technologies that are able to support 10-20+ years on small capacity advantages will represent a significant TCO savings relative to those technologies that cannot support such a battery life.
- **Network Longevity.** Putting billions of devices on a network is an expensive proposition. These devices may last several decades and it’s important that the wireless network is around that long. Requiring truck-rolls and endpoint module replacement would have catastrophic impact upon the Return on Investment (ROI) of the wireless connectivity.

The other questions to answer are: What is the ***Quality of Communication*** that the wireless technology provides? What ***Link Capability*** is achieved for the TCO? The following are attributes of ***Link Capability*** shown in Table 1:

- **Uplink Throughput**
- **Acknowledged Delivery**
- **Flexible Packet Sizes**
- **Downlink Capability**
- **Broadcast/Multi-Cast Capable (e.g., Firmware Download)**
- **Priority/Robustness**. The data from these billions of devices is very valuable. A wireless network that does not particularly value these endpoints is a problem (e.g., a cellular network giving preference to voice/data during on-peak times). Another problem that can impact the reliability of important data is lots of simultaneous communication from endpoints during an exception event. Without Congestion Management, there is the risk that data will not get through when it may be needed the most.
- **Security**. Security vulnerabilities could potentially be such a risk that wireless connectivity becomes net counter-productive. Security must be solid at all levels of the protocol.

Finally, it is important to consider the ***System Maturity*** of a given technology approach:

- Is it Available Today?
- Are there **Proven Deployments at Scale**? Sigfox, for example, claims significant amount of coverage but lacks large scale endpoint deployments. A subset of ***RPMA*** networks deployed today moves more data in a day than the entire multi-nation Sigfox network moves in a month.

2.1 RPMA

RPMA uniquely satisfies the requirements of billions of devices. Section 3 introduces ***RPMA*** technology.

Sections 1 and 1 delve deeply into ***Total Cost of Ownership (TCO)*** particularly in the aspects of:

- Low Network Cost (Basic Coverage),
- Low Network Cost (Deep Coverage)
- High Capacity Per Network Infrastructure Point
- Cost Effective Capacity Scaling
- Low/Free Spectrum Cost
- Long Battery Life
- Low Endpoint Cost
- Network Longevity (e.g., No Sunsetting)

RPMA also offers excellent ***Link Capability***:

- **Uplink Throughput.** ***RPMA*** provides sufficient uplink and downlink throughput for a wide range of devices. Currently, there are Commercial/Industrial electric meters that move >100 kbytes per day.
- **Acknowledged Delivery.** ***RPMA*** as an extremely spectrally efficient acknowledgement scheme so all data is sent from/to the network reliably.

- **Flexible Packet Sizes.** Different devices require different sized unit of transactions and even the same device will often need to efficiently communicate at a variety of packet sizes. ***RPMA*** supports this.
- **Downlink Capability.** ***RPMA*** provides downlink throughput for a wide range of devices. Downlink throughput to devices is required to update a configuration, actuate a critical function, or to transmit data that the device needs to perform its operation.
- **Broadcast/Multi-Cast Capable (e.g., Firmware Download).** Essential functions like Firmware Update and activation of group control (e.g., streetlights) are functions that ***RPMA*** provides. ***RPMA*** actually has reserved capacity for this purpose so steady-state operation is not affected by bandwidth intensive operations such as Firmware Downloads of multiple megabyte files.
- **Robustness/Priority.** The data from these billions of devices is very valuable. A wireless network that does not particularly value these endpoints is a problem.

Professionally Managed. ***RPMA*** (similar to Cellular and the Other LPWA approaches) offers "Out of the box" connectivity allows for a wide array of "things" to be connected as well as IT robustness essential for "machines".

Machine Priority. Having a communication link that will not be taken over by other applications (e.g., high speed voice or data during on-peak times) is essential and ***RPMA*** provides this since it is dedicated to these billions of devices.

Congestion Management. Especially in times of crisis, it is essential the communication system "does not fall over" when a large number of devices are urgently attempting to communicate at once. ***RPMA*** has "cellular-quality" Congestion Management capabilities to insure that they system does not get swamped during flurries of communications when that data is needed the most.

- **Security** . ***RPMA*** employs enterprise grade security guarantees (including strong authentication) using standard protocols including over the wireless link.

2.2 Cellular – MTC (Machine-Type-Communication)

The fundamental issue with Cellular is that it is very difficult to patch an extremely complicated system like Cellular into servicing requirements for which it was not designed as shown in Table 2. Though the Cellular industry is attempting to address some of the shortcomings, fundamentally the system was designed for a very particular set of requirements that are distinct from those required to address these billions of devices.

Table 2. Cellular Requirements

Voice and High Speed Data	LPWA Requirements
Very low latency (ms)	Latency tolerant (seconds)
Very high device throughput	Moderate device throughput
Relatively few devices	Very numerous devices
Relatively fast technology upgrade	20 Year Life of Technology
Battery life of days	Battery life of 10-20 years
Cost tolerant endpoint	Cost sensitive endpoint

Referring back to Table 1, ***MTC Cellular*** refers to the Machine-Type-Communication (MTC) activity within the 3GPP Standardization Body. MTC/Cellular proposals are in the fairly early stages of evaluation. As such, there are some open questions about how well these approaches will work particularly in regards to **Low Endpoint Cost** and **Long Battery Life**. We score **Robustness/Priority** low due to the cellular industry goal of taking advantage of "off-peak" capacity. At peak, the MTC endpoints will likely give priority to the big revenue voice and data endpoints.

MTC Cellular may be grouped into two families of approaches:

- ***MTC/2G*** refers to the various approaches using 2G (GSM) infrastructure. The most prominent of these approaches is Nuel/Huawei's Clean Slate, but other companies such as Qualcomm and Ericson have submitted proposals as well. The 2G proposals repurpose a single 200 kHz GSM voice channel into multiple MTC channels. Given the existence of infrastructure and the additional Link Budget proposed, **Deep Coverage** seems achievable. However, sun-setting of the 2G spectrum is of major concern and makes **Network Longevity** a significant risk. The sun-setting of AT&T's 2G spectrum in the US orphaned millions of devices. The cost of replacing the obsolete 2G modules with high cost LTE devices is very high.[3] Application providers are skeptical of a forward path that involves 2G spectrum. Because the proposals are in the early stage, it is unclear whether **Long Battery Life** and **Low Endpoint Cost** will be achieved.
- ***MTC/LTE*** is the forward path, which attempts to allow the MTC devices on 4G LTE spectrum with some optimizations to help coverage, cost, and battery life. There are proposals from the usual players in the cellular industry: Qualcomm, Huawei, Ericson, Samsung, etc. The fundamental issue is that it is very difficult to patch an extremely complicated system like LTE into servicing requirements it was not initially designed for and, at the same time, not affecting the capacity of the big revenue voice and data services. Though there are some proposed enhancements to Link Budget at a high level, there are acknowledged technical obstacles, which make many experts skeptical of the viability of this additional ***Link Budget***. Therefore, the cost of scaling the cellular network for **Deep Coverage** is still expected to be prohibitively expensive. Note that even though LTE spectrum is the forward path, the **Network Longevity** is still at risk based on the rate at which cellular technology advances without backward compatibility. 5G is a standardization effort in progress hence the check minus rating.

2.3 Other LPWA (Low Power Wireless Area) Networks

Referring back to Table 1, ***Other LPWA*** approaches include participation by a number of companies, but the Sigfox, and Lora solutions have the greatest amount of traction. The industry sees a need for a non-cellular solution given the known limitations of cellular. All of these approaches have not done the technology development with capacity in mind. Thus, these systems are expected to be capacity limited. The red x in the **Low Network Cost (Capacity Limit)** reflects this predicted inability to create a sustainable business. Also, due to the significantly lower link budgets of these approaches relative to

[3] As an example: *"The GSM sunset is a major issue for the alarm industry because it has deployed such large numbers of GSM devices. An estimated 4 to 5 million 2G GSM alarm devices must be replaced within four years (or less in major markets). Assuming 200 working days a year, the alarm industry must start replacing more than 5,000 devices per day, starting immediately. To accomplish that, the alarm industry must rapidly develop and execute a comprehensive plan, including new products from suppliers, detailed schedules, customer notifications, installer training, etc."*

RPMA, **Deep Coverage** is not a value proposition that these technologies are in a position to offer. Additionally, the **Communication Capability** is very limited for these approaches primarily due to the lack of capacity of the network. Finally, important robustness measures such as congestion management significantly impacts the robustness in the **Robustness/Priority**. Drilling a bit deeper into the two main successful approaches:

- **Sigfox** seems to have the most commercial traction with large countrywide networks covering France, Spain, and other locations in Europe. Though networks have been deployed, the endpoint rollouts are in early stages. Sigfox has additional **Communication Capability** limitations based on its one way, unacknowledged very weakly authenticated (2 byte hash)[4], fixed 12-byte packet data model. Additionally, **Security** is a concern based upon the lack of proper authentication in the messages.
- **Lora** is a radio solution created by the silicon provider Semtech. There are a number of companies that develop the MAC and higher layer software including IBM and Link Labs. The performance and capabilities of these systems will be determined by the quality of the MAC implementations performed by companies other than Semtech. However, even making "ideal" MAC assumptions indicates a significant capacity limit since the multiple access scheme supported by the Lora physical layer is extremely limited.

2.4 Secondary Competitors

2.4.1 Mesh

Mesh RF links are very short-range links. The only way to scale such a system to wide-areas is for the density of endpoints to be extremely high. Also, the endpoints must be powered (to repeat signals) which eliminates much of the low-cost endpoints. As a result, ***wide area mesh*** only has narrow applicability (e.g., Smart Electric Meters, possibly streetlights) though even these applications have a range of problems. Cisco makes "marketing claims" that defy physics and with no proof points.

There is a lot of marketing effort around this approach particularly with Cisco. There are very limited deployments of this technology for a number of fundamental reasons:

- Has a link range that is off by several orders of magnitude to scale a ***mesh***. Additionally, there are requirements for 10+ year battery life.
- Has limited traction in this space due to need off a tremendous number of repeaters, a notorious hard-to-reach problem,
- Has poor at-scale performance,
- Often lacks suitable spectrum internationally.

As an example, **Wide-Area Mesh** (the Itron ***Mesh***), which was deployed at SDG&E before ***RPMA*** was around, and was not able to address these requirements based on the 15 year battery life and the impossibility of scaling a ***Mesh*** away from the electric meter

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[4] https://www.dropbox.com/s/78vfabb0sjxocgz/One day at SigFox » disk91.com – technology blog.html?dl=0 *"The protocol overhead contains : Unique device ID (32b) and a Hash for authentication of the sigfox message. The total size is 26 bytes. The other bytes are used for security and to certify the content of the message (crc and stuff like this)."* Piecing the above relative to frame structure implies a 2-byte authentication.

As a result, ***Wide Area Mesh*** has never been able to connect anything other than Smart Meter deployments and utility feedback is that these systems have a tremendous number of issues.

2.4.2 Local RF

Local RF is a general term to describe short-range connectivity to a home gateway. Technologies such as Zigbee, Low-Power Wi-Fi and Bluetooth fall into this category. One thing that the ***Wide Area Mesh***, Cellular, and ***LPWA*** players agree on is that Local RF connectivity will not be connecting these billions of devices.

Per the 3GPP/MTC charter:
Many of these will use short-range wireless systems such as Bluetooth Smart, Wi-Fi or Zigbee, but, if so, they will depend on some private infrastructure being in-place, accessible and reliable. A ubiquitous public cellular network that was easy to use would be of enormous benefit.[5]

[5] http://www.cambridgewireless.co.uk/docs/Cellular%20IoT%20White%20Paper.pdf

3 RPMA Technology

3.1 RPMA Overview

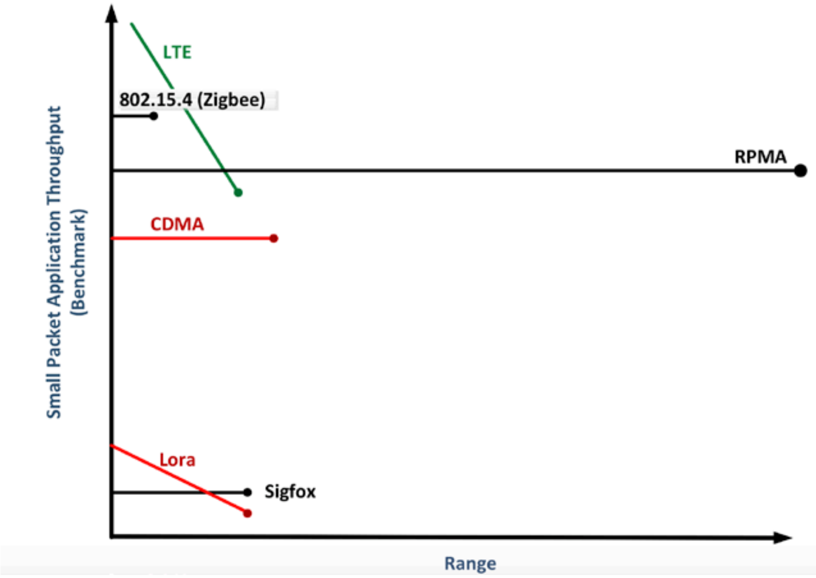

Figure 2. Air Interface Comparison

As shown in Figure 2, ***RPMA*** was designed to address both Range and Capacity simultaneously for these billions of devices. Whereas some of the other technologies (such as LTE and CDMA Cellular) do well for high throughput and large packet sizes, they tend to break down for the smaller, more numerous packets that are more common for these devices. Approaches such as Sigfox and Lora, even though designed for smaller packet sizes, fail to have sufficient Capacity or Range to build a cost effective wireless network.[6]

RPMA (Random Phase Multiple Access), as is shown, is a high technology communication system employing Direct Sequence Spread Spectrum (DSSS) multiple access. ***RPMA*** technology employs tight transmit power control and orders of magnitude more processing gain than ever has been achieved (39 dB) and allows for hundreds of square miles covered per low cost access point simultaneous with extreme capacity while optimized for long battery life and enterprises grade security. ***RPMA*** was designed to make optimal use of the 2.4 GHz band - globally available free spectrum.

RPMA took the approach of a clean sheet of paper design including taking a fresh look at the approach and the spectrum that would be used for such a system. There is no attempt to leverage existing approaches or components and as such, no baggage or constraints of this nature introduced. Additionally, the notion of how much processing is cost effective on the endpoint and network side was re-examined in light of modern technology particularly Moore's law.

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[6] Small Packet Capacity Benchmark is based on small 32 byte packets from numerous non-scheduled endpoints.

RPMA uniquely satisfies the critical, enabling Low Network Cost based on the following fundamental aspects of the technology:

- **Extreme Coverage**. Based on key fundamental innovations and the advancement of silicon technology, ***RPMA*** has the highest industry link budget in all global regions, which minimizes density of infrastructure by orders of magnitude relative to any other approach. An inexpensive, shoe-box sized ***RPMA*** Access Point can cover up to 500 square miles with 100% connectivity and non-line-of site (NLOS) conditions.
- **Extreme Capacity**. ***RPMA*** has extremely high capacity, which allows for hundreds of thousands of endpoints supported per infrastructure location with each endpoint able to participate in far richer data models than competing LPWA approaches.
- **Use of Global Free Spectrum**. **RPMA** uses global 2.4 GHz free-spectrum, which means no spectrum costs.
- **High Link Capability**. Low-value endpoints may not require streaming video data rates, but that doesn't mean the offered Link Capability should be short-changed. (See Section 5). Even relatively low value endpoints require reliable delivery, strong authentication, flexible frame sizes, 2-way data flow, and potentially firmware download.
- **Low Endpoint Power Consumption**. Endpoint power consumption can be a significant cost driver for battery-powered devices. Though ***RPMA*** has significant more digital processing than the Other ***LPWA*** approaches, this actually allows for large power consumption savings in that the endpoint minimizes transmit time (a big driver in battery consumption) to the minimal amount to be able to close the link. This is in contrast to low-technology open loop systems that must always transmit at the worst-case data rate.

3.2 RPMA – Do We Really Need Another Air Interface?

There are fundamentally two approaches to increase the robustness at the expense of link throughput: Direct Sequence Spread Spectrum (DSSS) and Narrowband. There are several existing approaches in each category, so a natural question is whether any of the existing air interfaces are suitable. Table 3 compares key performance metrics of the existing air interfaces with RPMA.

Table 3. RPMA Comparison with Other Air Interfaces

	Link Requirement	Direct Sequence Spread Spectrum			Narrowband		
		RPMA	CDMA Cellular	802.15 (Zigbee/ ISA-100)	LTE Cellular	UNB (Sigfox)	Lora[7]
Coverage	Receiver Sensitivity (US)	-142 dBm (UL) -133 dBm (DL)	-121 dBm (UL/DL)	-102 dBm (UL/DL)	-118 dBm (UL) -103 dBm (DL)	-135 dBm (UL) -119 dBm (DL)	-132 dBm (UL/DL)
	Receiver Sensitivity (Europe)	-142 dBm (UL) -133 dBm (DL)	-121 dBm (UL/DL)	-102 dBm (UL/DL)	-118 dBm (UL) -103 dBm (DL)	-142 dBm (UL) -126 dBm (DL)	-137 dBm (UL/DL)
	Interference Robustness	Excellent	Not Needed	Fair	Not Needed	Very Poor	Fair
	Coverage Scaling	Inexpensive with Extender	Expensive	Inexpensive	Expensive	Inexpensive	?
Capacity	Uplink Spectral Efficiency (bps/Hz/Sector)	0.10	0.17 to 0.5	0.1	0.65 to 1.3	0.001	0.0001 to 0.001
	Short Asynchronous Message Throughput [8]	15	Less Than RPMA	~20	Similar to RPMA	1	0.1 to 1
	Downlink Capacity	High	Very High	High	Extreme	Very Low	Low
	Scalable Capacity	Inexpensive	Inexpensive	Not Possible	Inexpensive	Not Possible	Not Possible
	Adaptable Data Rates	Yes	Yes	No	Yes	No	Yes
Throughput/ Latency	Throughput Limit Per Endpoint	100 Kbytes per day	~100 MBytes per day	~100 MBytes per day	~1 GByte per day	1.7 Kbytes per day	~Few Kbytes per day
	Latency	10s of seconds	100 ms	100 ms	5 ms	10s of seconds	10s of seconds

Receiver Sensitivity is the prime differentiator in establishing ***Link Budget*** as shown in Section 4.1.1. ***Link Budget*** in turn significantly drives the density of network infrastructure (hence Network Cost) and the ability to reach challenging environments. ***RPMA*** has significant Receiver Sensitivity advantages relative to the other existing air interfaces. Section 4.1.2 shows the real-world implication as to what this ***RPMA*** benefit means in a practical network.

Coverage Scaling is the ability to preferably provide economical connectivity to endpoints that may be terrain obstructed, located in deep basements, or even underground. ***RPMA*** has network infrastructure (called an Extender) as well as sufficient frequency in the 2.4 GHz band that allows for operation of this low-cost device.

Interference Robustness is critical for operation in the ISM band. Channel coding and a robust retransmission scheme are a couple of key attributes that are critical to withstand interference from other users of the ISM band. RPMA has these measures of protection whereas Sigfox, for example, does not. Ultra Narrow Band (UNB) waveforms have the additional problem of being very adversely effected

[7] Lora considers themselves a "wideband" modulation but the attributes indicates a more narrowband approach – most notably a very limited multiple access scheme.

[8] Number of 32 byte application messages per MHz per Sector.

by wideband signals since a wideband signal is capable of destroying the entire band while wiping out thousands of narrowband channels

Uplink Spectral Efficiency is an extremely standard figure of merit for a communication technology[9]. The following statements are true regarding ***RPMA***:

- Has a tremendous **Uplink Spectral Efficiency** advantage over the other LPWA technologies of Sigfox and Semtech. This relatively poor performance is compounded especially in Europe by the very limited amount of spectrum (only ~200 kHz) available.
- Slightly less performance compared to CDMA, the older 3G technology
- Significantly less than the advanced LTE technology, which uses cutting edge techniques such as MIMO, Interference Cancellation, and increasing infrastructure density to fully take advantage of higher order modulations.

As will be shown, **Uplink Spectral Efficiency** is a big part of the story, but not the whole story. This metric is most interesting in regards to relatively large data transactions, but fails to give a complete figure-of-merit if the data is smaller, more frequent transactions across a very large number of users/endpoints.

Short Asynchronous Message Throughput is a measure of ultimately, how suitable the technology approach is to the type of traffic that dominates IOT/MTC. The cellular systems were designed with the expectation that overhead associated with initiating a transaction was only a few percent of the large subsequent file size – typically 100s of kbytes on average of web-page or voice conversations. If you take the limit of small, unpredictable 32 byte payloads, then the "call-setup" type of overhead dominates considerably. Again, this is a figure-of-merit normalized by the amount of frequency available so the other LPWA approaches (Sigfox and Lora) that only have 200 kHz of spectrum available have a multiplier of 0.2 to yield an actual message rate. The LPWA calculations are described in more detail in Section 4.2.

Downlink Capacity may not be as important as uplink capacity based on the fact that most endpoints are transmitting more application data than receiving. However, it is still a parameter of interest in many application data models. It is not only important for data flow that occurs in the downlink direction, but for the capacity required to acknowledge uplink data flows. ***RPMA*** has high downlink capacity because the spreading factor used is tightly controlled by a closed loop signaling method. Sigfox, for example, operates at a fixed worst-case data rate which has very adverse effect on downlink capacity.

Adaptable Data Rates not only contribute to optimizing downlink capacity as explained above, it also contributes to optimizing battery life. The transmit operation is a big factor in battery life. Minimizing the duration of the transmit operation is important for long battery life. Whereas Sigfox transmits at the lowest data rate (maximum on-time), ***RPMA*** will minimize the spreading factor based on link conditions and thus will maximize battery life.

Throughput Limit per Endpoint tends to be a hard limit based upon a node that is operating without regard to the capacity that is being consumed. Cellular technology evolves to provide tremendous data rates for high-speed data applications; for example, LTE is easily able to provide GBytes per day if

[9] See the following link for a paper describing the cellular technology's Uplink Spectral Efficiency on page 7 of https://www.dropbox.com/s/ktpmfe0tnb3mpql/2013-08-4g-americas-spectral-efficiency.pdf?dl=0.

needed. ***RPMA*** strikes a balance being able to provide 100 Kbytes per day even at worst case link conditions which is typically more than enough for LPWA/MTC applications.

Latency is the other trade-off that RPMA (and the other LPWA approaches) have made relative to the Cellular evolution. LTE has dominated CDMA largely due to its extremely low 5 ms latency[10]. Eliminating the Throughput per Endpoint and Latency requirements allows for optimization of what is really important to these billions of devices.

3.3 RPMA Description

RPMA (Random Phase Multiple Access) is optimally suited for the requirements of IOT/MTC and is capable of supporting demodulation of typically 1200 fully overlapping signals. As shown in Figure 3, the endpoint node randomly chooses a number of chips to intentionally delay communication to the Access Point (AP). The range of selection that the node may choose can be quite large – e.g., a node can choose in the range thousands of chips to delay communication. This results in a time-of-arrival of all the signals that are received at the AP as depicted in the figure below.

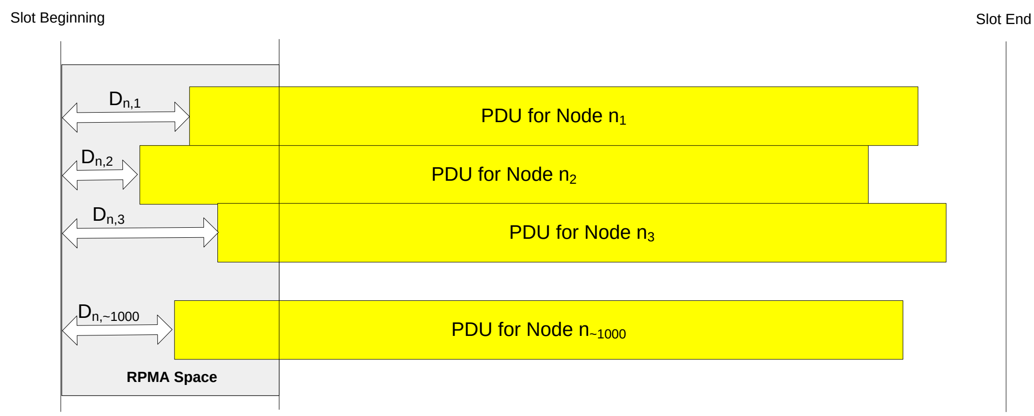


Figure 3. RPMA Scheme

The result is that as long as the sum of the intentional chip delay of each node, plus the number of chips required for propagation results in unique values, the link can be demodulated by virtue of the very large processing gain that exists. Of those links that do collide from the APs reference, these cannot be demodulated. In this case, a closed loop Forward Error Correction (FEC) allows for any data loss to be reconstructed.

The coupling of this air interface to a scheme that is capable of efficiently demodulating this waveform is extremely important. Remember, that the AP has no knowledge of the intentional delays that the individual nodes are adding, so the only viable strategy is the demodulation of *all* of the chip arrival hypothesis. In other words, each chip arrival hypothesis must be treated as a conventional modem treats any arriving signal – like a successful demodulation is expected. Each chip hypothesis must be de-

[10] The extremely low LTE latency allows for TCP/IP to operate seamlessly over wireless. Prior generations of cellular needed an additional adaptation protocol or confusion results on whether packet loss is based on wireless channel or based on network congestion.

spread, de-interleaved, Viterbi decoded, and then checked via a Cyclic Redundancy Check (CRC). The difference of this scheme to a more conventional scheme is that more often than not, the CRC will indicate failure. In a conventional scheme, that usually means that the attempted transmission was received in error. In our system, it usually means that there actually was no attempted transmission at that particular chip offset and it's time to give the next one a try.

Not shown in Figure 3 is an additional outer loop where multiple spreading factors are attempted: in powers of 2 from 512 to 8192. The endpoint unilaterally decides the optimal (minimum) spreading factor to transmit at based on measurement of the downlink signal strength. The Access Point need not know a priori which spreading factor the node will select because the Access Point brute-forces its way through all spreading factors at all chip x 2 arrival hypothesis.

The identity of each signal is only known after decoding by having it in the payload of the frame. This "Blind Demodulation" yields protocol efficiency and simplicity for the entire communication system.

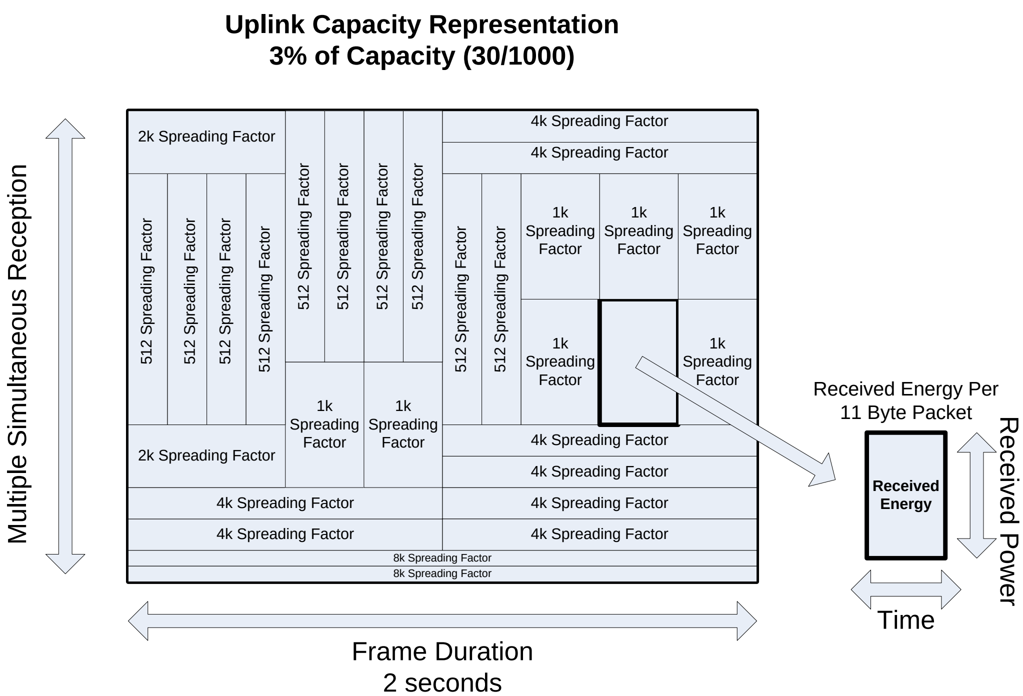


Figure 4. Depiction of RPMA Capacity Model

Figure 4 shows multiple signals from various users at a variety of spreading factors all being received simultaneously by the Access Point. The result is a Simple capacity model: ~1200 PDUs (>10Kbps) received per frame regardless of:

- Spreading Factor Distribution of Users
- Number of PDUs per Spreading Factor
- Uplink Frame-Erasure-Rate (FER)

3.4 Leveraging the 2.4 GHz Band

As shown in the previous section (Section 3.2), ***RPMA*** has tremendous advantages in a system that is dedicated to sending an enormous number of small payload transactions over a huge number of devices. ***RPMA***, however, also has a number of benefits in free-spectrum. Imagine the value proposition of being able to take advantage of a very large amount of this spectrum, and not consume the licensed spectrum, which is increasingly valuable for the higher data rate endpoints like cell-phone and tablets. The 2.4 GHz band is even more appealing in that it is not just unlicensed free-spectrum, and a vast 80 MHz of spectrum, but this exists worldwide. We are talking about a single radio that can service endpoints ubiquitously across the entire globe. If the specific regulations of that spectrum do not preclude ***RPMA***, then we have an amazing confluence: the best optimized air interface in ***RPMA*** being employed in the best possible free-spectrum of 2.4 GHz.

There are only 2 viable bands that have sufficient capacity to build a license-free network parallel to the existing cellular network, the 900 MHz band and the 2.4 GHz band. Table 4 below shows the comparison between these 2 frequency bands. 2.4 GHz has tremendous advantages, but does pose limitations for NB approaches but not for DSSS. Thus, based on the particulars of the frequency regulations, the combination of 2.4 GHz and DSSS is fundamentally the superior approach.

Other key features of ***RPMA*** to optimally operate in the 2.4 GHz band include:

- Reliable operation even in high interference high packet loss environment. System can gracefully tolerate a 50% PER and not lose any data.
- Receive antenna diversity, which yields an 8 dB effective link budget improvement for outage intolerant applications.
- Signaling of asymmetric noise floor, which occurs in the ISM band.
- Robustness to making closed-loop measurements during short, high-intensity bursts of data (e.g., Wi-Fi, Bluetooth). Note that the ***RPMA*** waveform is innately robust to these events based on the very long symbol duration (up to 8 ms).
- Small spectral footprint to be a good neighbor to other 2.4 GHz traffic. An entire ***RPMA*** Network can be deployed as a SFN (Single Frequency Network) using only 1 MHz of the available 80 MHz of the 2.4 GHz band.
- Frequency agility to avoid particularly jammed portions of the ISM band.
- Support for 4 uncoordinated ***RPMA*** systems with absolutely no adverse interactions.
- Dedicated spectrum for Extenders such than these infrastructure devices has no capacity impact on the ***RPMA*** Access Points.

Table 4. Comparing 2.4 GHz vs. 900 MHz

	2.4 GHz	900 MHz
EIRP	The transmit powers and antenna gain are better in 2.4 GHz than 900 MHz in Europe (868 MHz band), similar in Asia, and in the US, additional sectorization can uniquely be used to exceed 36 dBm EIRP (44 dBm can be achieved).	Allowable transmit powers are significantly worse at 900 MHz than 2.4 GHz in Europe (868 MHz band), similar in Asia, and in the US, sectorization is not allowed to improve Link Budget.
Global Availability	2.4 GHz is worldwide spectrum with very similar rules everywhere.	900 MHz is not globally available and, where available, rules are often country specific.

	2.4 GHz	900 MHz
Propagation	Propagation at 2.4 GHz is worse but offset by RX Antenna diversity that is uniquely supportable in 2.4 Ghz in a small form factor.[11]	Propagation at 900 MHz is better than at 2.4 GHz but RX Antenna diversity is not typically feasible in a small form factor.
DSSS and Narrowband Restrictions	No 2.4 GHz regulation that limits the amount of processing gain for DSSS ONLY FOR NARROWBAND: In US, there are 2.4 GHz regulations that limit the ability to go narrowband due to 400 ms transmit time limit.	No 900 MHz regulation that limits the amount of processing gain for DSSS In Europe, there is no limit to how narrowband. In US, there are 900 MHz regulations that limit the ability to go narrowband due to 400 ms transmit time limit.
Duty Cycle Limitations	No duty cycle limitations affecting throughput or capacity.	Severe duty cycle restrictions limit both link throughput and severely limit downlink capacity in Europe including the ability to acknowledge uplinks. In Europe, a 1% duty cycle limitation means an inability to accurately track the downlink channel in support of closed-loop power control. US has no such limitations.
Amount of Spectrum Available	80 MHz of worldwide spectrum for high capacity, uncoordinated networks, channel agility to avoid interference, and Extender.	20 MHz of spectrum in US available. Only 500 kHz of spectrum available in Europe severely limiting capacity.

Figure 5 shows the 80 MHz available in the 2.4 GHz band. The RPMA waveform is contained in within 1 MHz with channels separated by 2 MHz. To ensure that RPMA does not interfere with Wi-Fi, the primary channels used are the solid lines where Wi-Fi is not typically deployed. A single common RPMA channel can be used for an entire network. As an example, the entire 4100 square miles network for SDG&E has all Access Points at the far left frequency of 2402 MHz.

With the 4 Frequency Assignments shown below, 4 overlapping non-coordinated networks can exist in a given regions.

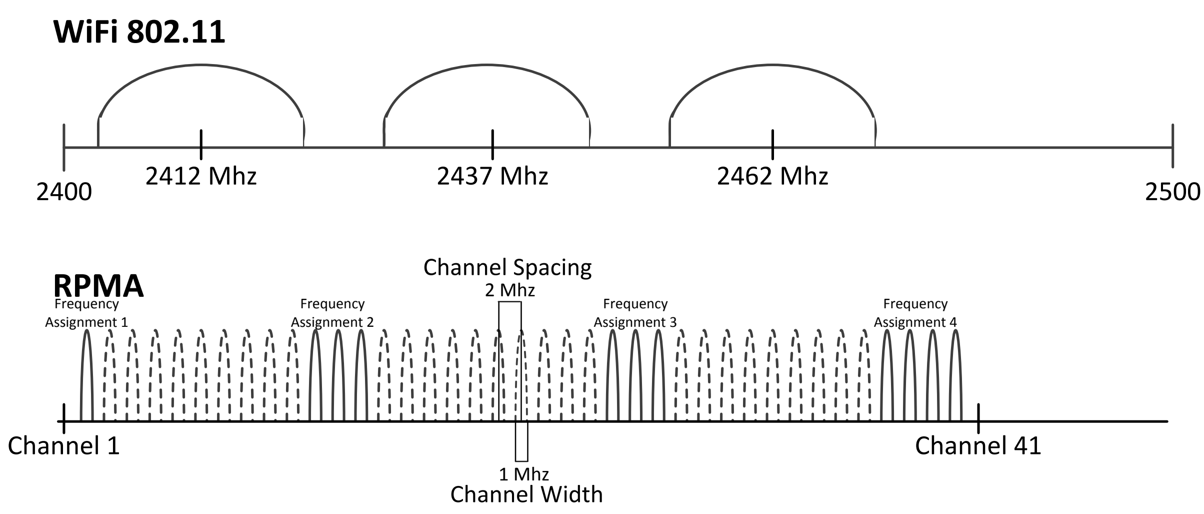


Figure 5. RPMA Frequency Plan

[11] 1/4 wave antenna separation requirement is much more feasible at the 2.4 GHz wavelength

3.5 Employing Advanced System Functions

Given, the current state of technology and Moore's law yielding gates that are essentially free, the optimal amount of endpoint processing is very high. Take cellular as an example, the evolution of the cellular endpoint, where the communication processing of modern handsets is vastly more complicated than in the past.   This trend is imperative to continue to increase the fundamental capacity of the network. ***RPMA*** has a similar philosophy: More endpoint complexity allows for a dramatic reduction in the amount of network infrastructure both for coverage and capacity reasons. Even given the fact that ***LPWA*** endpoint cost must be much lower than a cellular modem endpoint cost, processing is so much less expensive that making the endpoint infinitesimally larger is well worth the reduction in the amount of infrastructure by multiple orders of magnitude. This argument is made very strongly in Section 4. Stated another way, the optimal amount of processing on an endpoint is far greater than say, a low-tech garage door opener. You are not going to be able to build a cost effective and high performing system based on endpoints using such antiquated technology, yet that is exactly what the ***Other LPWA*** players are attempting to do.

Extending the cellular analogy, the one common theme of the progression from 2G to 3G to 4G is the progression of technology by leveraging Moore's Law and the most modern modem techniques on both the endpoint modem and the base stations. Only this way, can the cost of the network for delivering large amounts of aggregate data be optimized. Building this parallel network to cellular is not different; high technology is required to dramatically minimize the TCO. Development and cost optimizing of high technology modems is difficult and takes significant development expense including design of ASICs to perform this processing in a cost and power optimized manner.

The advanced technology features of ***RPMA*** include the following:

Time/Frequency Synchronization

- Reducing the processing complexity (acquisition and demodulation) of a 39 dB DSSS system by a factor of 1,000+ so it can be implemented cost and power effectively on today's silicon technology

Uplink Power Control

- Creating a very tightly power controlled system in free-spectrum and presence of interference which reduces the amount of required endpoint transmit power by a factor of >50,000 and mitigates the near-far effect.
- Frame structure to allow continuous channel tracking.
- Adaptive spreading factor on uplink to optimize battery consumption.

Downlink Data Rate Optimization

- Very high Downlink capacity by use of adaptive downlink spreading factors
- Open loop Forward Error Correction for extremely reliable Firmware Download.
- Open loop Forward Error Correction to optimize ARQ signaling. Signaling only needs to indicate completion, not which particular PDUs are lost.

Handover

- Configurable Gold Codes per Access Point to eliminate ambiguity of link communication.
- Frequency reuse of 3 to eliminate any inter-cell interference degradation.
- Background scan with handover to allow continuous selection of the best Access Point

3.6 Technology Comparison: Sigfox and Semtech/Lora

To illustrate the importance of performing these processing intensive system functions, it is instructive to compare with "best-in-breed" approaches that tend to not perform these functions at all, or in a very limited fashion. Table 5 illustrates the importance of this system functions by comparing ***RPMA*** with Sigfox and Lora. Note that this is similar to the evolution of the Cellular systems: SIgfox/Lora represents simpler/older Cellular Systems with less capability (e.g., AMPS/GSM) while ***RPMA*** represents more complex/modern Cellular Systems (e.g., CDMA/LTE).

Table 5. Processing Intensive Communication System Functions

Comm System Function	RPMA	Sigfox	Lora
Multiple Access	RPMA supports simultaneous demodulation of up to 1200 fully overlapping signals per sector that are all in the same frequency.	Sigfox does allow for simultaneous demodulation of signals in its bandwidth. However, the very simplistic nature of the protocol means a highly spectrally inefficient protocol.	For a given data rate, there is only the ability to demodulate a single user at a given time. This results in a capacity model that becomes a single-threaded Aloha scheme.
Interference Robustness	RPMA has robust channel coding, and a robust retransmission scheme. Additionally, RPMA operates on relatively small fragment sizes which allow for predictable progress in building up larger frame sizes. An outer FEC code is used for efficient reconstruction of erasures caused by bursty interference in the ISM band. RPMA has a very fast data rate adaptation, which is able to track rapidly changing interference levels.	Sigfox does not have robust channel coding and only an open-loop retransmission scheme that fails to take interference into account. Ultra Narrow Band (UNB) waveforms like Sigfox have the additional problem of being very adversely effected by wideband signals since a wideband signal is capable of destroying the entire band while wiping out thousands of narrowband channels.	Lora does have channel coding and potentially retransmission schemes. Lack of fast data rate adaptation may be a problem when a Lora system is deployed in the real-world
Time/Frequency Synchronization	RPMA does this very carefully. The RPMA ASIC must acquire and track frequency to 10s of Hz to support 8192 spreading factor, and 0.5 us in time. Base stations are synchronized so nodes are aligned to entire network at all times. Lots of development to minimize power consumption.	Sigfox is not able to schedule transmissions in time/frequency and loses a significant amount of capacity since the system becomes unslotted Aloha	Lora is not able to schedule transmissions in time/frequency and loses a significant amount of capacity since the system becomes unslotted Aloha
Uplink Power Control	RPMA has on average 1.25 dB of Power Control error, which is essential for DSSS capacity.	Sigfox does not do this. 30 dB average Power Control error. Though not as essential as for NB systems, Sigfox loses a factor of 9 in capacity compared to if they did this because of all the repetitions.	Not clear how a Lora MAC could track potentially fast moving channels to support this. Additionally, the Lora chipset does not have the interface for full range transmit power control.

Comm System Function	RPMA	Sigfox	Lora
Downlink Data Rate Optimization	RPMA endpoint is constantly aware of channel conditions and local interference levels. This information is continuously signaled back to Access Point during any downlink transaction. In this way, the endpoint receives at maximum supported data rate and downlink capacity is increased by a factor of ~30 relative to always transmitting at worse case spreading factor.	Sigfox must always transmit at worst case data rate.	Not clear how a Lora MAC could track potentially fast moving channels to support this.
Handover	RPMA not only tracks the current Base station, but others to support handover as channel changes. This is necessary to optimize both uplink and downlink capacity. Note that even with a stationary endpoint, the RF channel is far from static.	Not relevant since Sigfox supports neither Uplink Power Control nor Downlink Data Rate Optimization so there doesn't exist the concept of an endpoint "joined" to a specific Access Point.	Not clear how a Lora MAC could track potentially fast moving channels to support this.

4 RPMA Coverage and Capacity

RPMA has many advantages relative to other technologies, but two advantages are so significant that we devote this chapter to explaining them: coverage and capacity. Section 4.1 (Coverage) and 4.2 (Capacity) has significant implications regarding the economics of the network. Section 4.1 represents the Coverage Driven scenario or the cost to get a useful depth of coverage to begin offering a public service. In the success case, there will be lots of endpoints connecting to the network. At some point, we enter the Capacity Driven scenario once the burgeoning number of endpoints demands more capacity than the infrastructure can deliver.

A useful way to understand the power of ***RPMA*** is in comparison with other technologies that are not as advanced. In particular, we contrast the dimensions of coverage and capacity to Sigfox and the Semtech Lora solution. Table 6 below compares the power of ***RPMA*** technology against the Other LPWA approaches. As will be discussed in the next sections, ***Link Budget*** and ***Total Application Throughput per Network Infrastructure*** significantly drive the ***TCO*** of the connectivity options.

RPMA has order(s) of magnitude in both Coverage (square miles per infrastructure) and Capacity (Total Uplink Application Throughput per Network Infrastructure). Coverage and Capacity are both critically important and potential bottlenecks. It makes little commercial sense to have a network with a big footprint, but insufficient capacity to serve the number of endpoint in that footprint; conversely it makes little sense to have good capacity but an insufficient coverage footprint to make use of that capacity. Sigfox and Lora have disadvantages in both of these performance metrics though depending on regulatory domain, different factors limit their performance. In Europe, there is a very small amount of 868 MHz band and therefore, Sigfox and Lora are more disadvantaged in capacity than in coverage – although coverage too is significantly inferior to ***RPMA***. In the US, the 900 MHz band is much wider and so the capacity limitation is far less in theory if these technologies choose to be a bad neighbor and use the entire 26 MHz of bandwidth. However, due to requirements of maximum narrowband transmit duration and more significantly, the large amount relatively wideband interference levels, coverage becomes the larger limiting factor particularly for Sigfox.

Table 6. LPWA Coverage and Capacity Comparison

Regulatory Domain	Technology	Link Budget (dB)	Area Covered per Network Infrastructure (Square Miles)	Total Uplink Application Throughput per Network Infrastructure (bps)
FCC	RPMA	180	300	19,000[12]
	Sigfox	149	1	9,000[13]
	Lora	157	4	260 to 3,250[14]
Europe	RPMA	168	33	19,000
	Sigfox	161	9	70[15]
	Lora	161	9	8 to 90[16] [17]

12 Usage of only a single 1 MHz channel. Best for coexistence.

13 Theoretically possible if using the entire 26 MHz – no product of that nature is currently specified however.

14 Theoretically possible if using the entire 26 MHz (15 MHz usable) band though may be a downlink control channel bottleneck.

15 Assumes g3 band for maximum link budget, which is 200 kHz of occupied bandwidth.

4.1 Coverage

How much area can a piece of infrastructure cover? A particular challenge of building a green-field network is cost. To be able to do this cost effectively means that each piece of network infrastructure must be able to cover large geographic areas very reliably. This tends to be much more challenging than is realized. The spec sheet ranges for radio links paint a misleadingly optimistic picture. In reality, the ranges are significantly lower once the effect of non-line-of-site (NLOS), local clutter, and fade margin for high probability coverage are taken into account. Stated another way: its relatively easy to find places where connectivity may be achieved at long distances, it is much more difficult to guarantee all locations are covered with a given distance. [18] That's why network cost winds up mattering much more than originally anticipated and why the figure of merit of ***Link Budget*** is incredibly important.

4.1.1 Link Budget

To make ***Link Budget*** the most descriptive figure of merit possible, we give it the following definition: Link Budget, along with assumptions on Path Loss[19], is sufficient to give the area covered for a given probability of coverage and a given indoor/underground penetration value. Leveraging the empirically observed network performance based on many hundreds of thousands of ***RPMA*** measurements in real-world environment, the ***Link Budget*** figure of merit allows direct extrapolation to systems with different Link Budgets (typically much worse relative to ***RPMA***).

Table 5 shows the components that contribute to Link Budget (see https://www.dropbox.com/s/wbauy868e8v84np/Competitive_Link_Budget.xlsx?dl=0: for spreadsheet format including Table 7 calculations):

- **TX Power** – transmit power is heavily regulated in free-spectrum especially in Europe. These limits are essentially the rules of the game. However, notice that 2.4 GHz regulations tend to be less restrictive than the 868 or 900 MHz rules.
- **RX Sensitivity** – this is an extremely significant parameter of the modem design. However, when this is optimized at the expense of capacity (which is typical), then one problem is simply being traded for another. ***RPMA*** optimizes this value while maintaining tremendous capacity.
- **Antenna Gain** – similar to TX power, this is value that is tightly subjected to regulations. Note that only the antenna gain on the non-obstructed end of the link (e.g., the network infrastructure)

[16] Range is from the current specified MAC (low end) to what an "ideal" (potentially impractical MAC) could yield.

[17] Assumes g1,g2, g4 which yields 6 x 125 kHz channels for uplink (750 kHz total). See https://www.dropbox.com/s/41kiwbe975serz6/etsi-compliance-sx1272-lora-modem.pdf?dl=0 for details on Lora channelization and link budget calculation on page 6 of https://www.dropbox.com/s/2i9bktcz6egikom/ThingPark_Wireless PHY_and_MAC_layer_specifications_v1.pdf?dl=0.

[18] Many technologies quote their free-space range (RPMA happens to be 6000 miles) but for real-world high reliability, we would design for no endpoint being further than 15 miles from an AP. You must de-rate the best possible by a factor of 400 for a real network, which is the same for all technologies.

[19] For example, Path Loss for highly elevated locations has been empirically determined to be approximately 2.5.

contributes to Link Budget. The endpoint is usually in the clutter and hence, antenna gain is not of value.

- **Sub GHz Benefit** – the basic Friis equation shows that better "propagation" is achieved at lower frequency.[20] To keep the figure of merit of Link Budget consistent, we give advantage to the lower frequency technologies in this line item.
- **Antenna Diversity** – an ***RPMA*** endpoint employs antenna diversity which is more feasible at 2.4 GHz based on the small wavelength requiring minimal antenna separation.
- **Noise Floor** – the empirical results gathered with ***RPMA*** as the baseline are uplink limited results because of significant uplink interference (5 dB on average) where Access Points are sited. This 5 dB typically does not apply to the downlink, and so we add this 5 dB to the downlink link budget to indicate that a downlink can close over a longer distance than the uplink. We assume larger levels of interference impact particularly on Sigfox given its uncoded waveform without a closed loop retransmission scheme. See Section 4.1.2 for details.
- **Link Budget Calculation** – ultimately, a chain is only as strong as its weakest link. The weaker of the uplink or downlink Link Budget will determine the performance of the system.

Table 7. Calculation of Link Budget for Various Technologies in FCC and European regulatory domains.

Technology	RPMA				Sigfox				Lora				Cellular			
Regulatory	FCC 2.4 GHz		Europe 2.4 GHz		FCC 900 MHz		Europe 868 MHz		FCC 900 MHz		Europe 868 MHz		CDMA		LTE	
Uplink/Dowlink	UL	DL	UL	DL	UL	DL	UL	DL	UL	DL	UL	DL	PCS	Cell	PCS	Cell
TX Power	21	30	21	21	20	30	14	21	20	30	14	21	23	23	23	23
RX Sens.	142	133	142	133	134	129	142	137	132	132	137	137	121	121	118	118
Antenna Gain	17	17	9*	9*	9*	9*	9*	9*	9*	9*	9*	9*	14	14	14	14
SubGHz Benefit	0	0	0	0	+9	+9	+9	+9	+9	+9	+9	+9	0	+9	0	+9
Ant. Diversity[21]	0	0	0	0	-8	-8	-8	-8	-8	-8	-8	-8	0	0	0	0
Noise Floor	0	5	0	5	-15	5	-5	5	-5	5	0	5	0	0	0	0
TOTAL	180	185	172	168	149	164	161	173	157	177	161	173	158	167	155	164
Link Budget (Relative to RPMA)	180		168		149		161		157		161		158/167		155/164	
Square Miles Covered	300		33		1		9		4		9		5/27		3/16	

NOTES:

- TX Power + Antenna Gain exceeds EIRP regulations by 3 dB to compensate for cable loss. [Note that RX Antenna Gain is typically assumed to be 0 dBi.]

[20] What is actually occurring is the fact that larger physical antennas may be used for lower frequencies and these absorb more radiation.

[21] Consider at target outage probability of 1%. The amount of margin required for a single antenna is 17 dB to combat the Rayleigh fade. For two antennas each of which governed by independent Rayleigh fades, that number reduces to 7 dB. The difference in signal powers is thus 17-7 = 10 dB required for the 1% outage probability. For the Link Budget analysis, we reduce this to 8 dB based on real-world imperfections with the antenna diversity scheme.

- In Europe, RPMA is certified under Annex 11 of ERC-70-30 operated at 27 dBm EIRP. -142 dBm Sigfox UL Slide 26: https://www.dropbox.com/s/o3zikxm69p8yg7j/WaveRF-2014-SIGFOX.pdf?dl=0
- Sigfox US uplink is based on 600 bps relative to 100 bps (10log10(600/100) = 8 dB less
- Sigfox European transmit power is from module spec https://www.dropbox.com/s/qnv3lv0ilvv672r/AX-Sigfox.html?dl=0 which indicates TX power of 14 dBm and DL RX sensitivity of –129 dBm at 600 bps (-137 dBm can be extrapolated based on bandwidth scaling of 8 dB).
- We assume a 20 dBm TX power in US for both Sigfox and Lora to give benefit of doubt although we have not been able to find a module that supports these power levels.

Approaches that optimize coverage at the expense of capacity will not be economical in the success case of supporting lots of endpoints. ***RPMA*** is an approach that optimizes both Link Budget and Capacity simultaneously. Section 4.3 will drill deeper into the TCO economics associated with Capacity.

Link Budget is a figure-of-merit that can be used in a variety of ways. The 3 ways to conceptually "spend" this Link Budget is as follows:

- **Less Infrastructure**. A system with the higher Link Budget can deploy the same coverage with much less network infrastructure.
- **More Penetration**. A system with the higher Link Budget can penetrate more deeply into hard-to-reach locations like Indoors, Basements, or potentially even underground.
- **Higher Probability of Coverage**. A system with the higher Link Budget can provide much more reliable coverage. The probability of a location randomly chosen in the network will be significantly higher with the system with the larger Link Budget.

Table 7 also contains a square miles of coverage calculation. For tower deployments, the path loss exponent (n) is typically between 2 and 3. Using the equation for path loss (L)

$$L = 10n\log_{10}(d) + C,$$

the multiplicative area covered for a given path loss advantage can be shown to be

$$A_{rpma} = (10^{2P/n/10})A_{other} = F\,A_{other}$$

Specifically, Table 7 is that factor F which is a function of RPMA path loss benefit (P) and for a range of assumed path loss exponent (n).

4.1.2 Effects of Interference

In the US, for example, Sigfox is planning to deploy in the 900 MHz ISM band. This approach will face challenges with the existing interference in that band including Smart Meters, baby monitors, cordless phones, etc. The problem will be exacerbated due to the relatively wide signal bandwidth of these devices. Wideband and Narrowband (particularly Ultra Narrow Band like Sigfox) do not coexist well at all. A single wideband transmission (even a very brief few hundred microsecond transmission) will jam hundreds or thousands of UNB channels.

Table 8 shows measurements that were performed on the first two tower locations where ***RPMA*** Access Points were deployed. Figure 5 shows the jamming waveform of Mt. Woodson. Though it is true that this interference consumes 10 dB and 16 dB respectively Link Budget, the interference would much more adversely impact the already diminished Link Budget of Sigfox by an additional 18 dB on Mt. Woodson and 22 dB on Black Mountain. This is due to the lack of channel coding of the Sigfox waveform exacerbated by the wideband signals common in the US ISM band taking out 10s of thousands of narrowband channels at once. This observation is the justification for the additional 15 dB interference impact in Table 6 for Sigfox in the US.[22]

Table 7 shows interferers that exist within the ISM band and they duty cycle required to jam a MHz of spectrum. The relative fragility of the Sigfox system becomes apparent. The fundamental problem is that wideband signals (extremely common in FCC domains) do not play nicely with the narrowband system of Sigfox.

In Europe, the interference situation is also of concern. The amount of spectrum available in the 868 MHz band is very small. There is only 200 kHz available that allows 27 dBm transmit power, which is what's required for a reasonable Link Budget in Europe. Over time, it is certainly possible that multiple systems will occupy this very narrow amount of spectrum. Lora systems are already being contemplated where Sigfox exists today. The result of this could be especially disastrous for Sigfox given the relatively wider bandwidth of the Lora system. In Europe, a relatively brief 10 ms pulse every 20 seconds is enough to cause the marginally acceptable 10% Packet Error Rate (PER) that Sigfox requires for robust operation. That is only a 0.05% duty cycle and Lora (and many other systems) would likely be considerably higher duty cycle.

For ***RPMA***, by contrast, even a very strong wideband jammer only diminishes link budget by 20log(1-D). Even at 50% duty cycle, that only corresponds to a 6 dB Link Budget which represents a very useable site. By contrast, due to the lack of coding on the Sigfox waveform, very low duty cycle interferers cause a very leveraged amount of jamming. A small pulse every 3.5 seconds causes a 10% PER which is the full PER budget which represents the Sigfox system being marginally useful at this point.

One real-world example depicted in Figure 6 is the interference found on the first RPMA Access Point deployment in 2010. The ~25% duty cycle local jammer has minimal impact on the RPMA reception. However, even if that duty cycle was reduced down to 0.01%, that jammer would basically cripple the Sigfox system.

Table 8. US Real-World Link Budget Comparison

	Link Budget Inteference Degradation (dB)		Remaining Link Budget (dB)		Coverage Area (square miles)	
	Sigfox	RPMA	Sigfox	RPMA	Sigfox	RPMA
Mt. Woodson (suburban)	28	10	136	170	0.6	300
Black Mountain (urban)	38	16	126	164	0.1	100

[22] The Noise Floor row in Table 6 is somewhat less than the values for both ***RPMA*** and Sigfox due to Mt. Woodson and Black Mountain being a bit nosier than the average tower location.

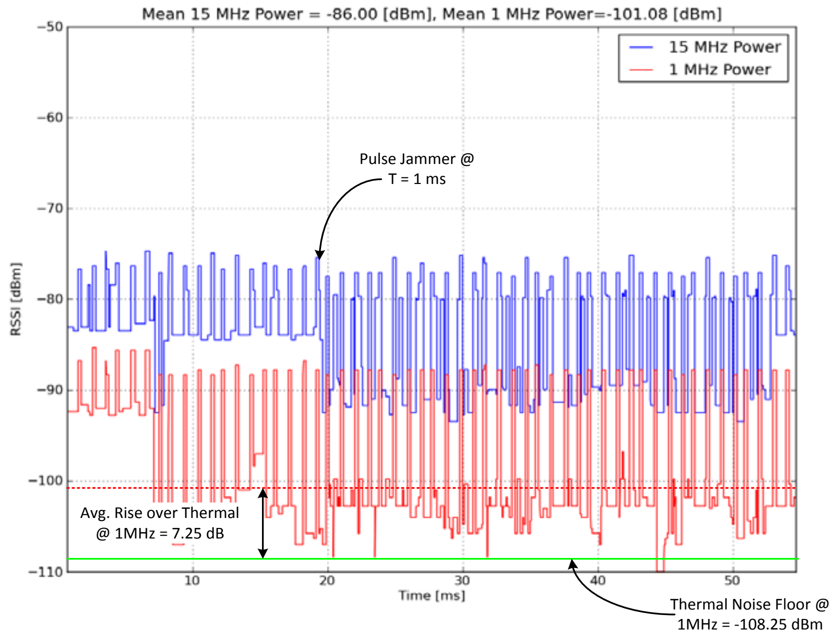


Figure 6.Mt. Woodson: First RPMA Deployment Interference Profile

4.1.3 Example: Link Budget Comparison with Sigfox

Sigfox represents a good comparison point since it is an industry-leading alternative with good initial traction. ***RPMA*** has an 8 dB link budget advantage over Sigfox in Europe and a 16 dB advantage in the US.[23] That Link Budget advantage can be spent in a few different ways.

1. As shown in the Coverage Area column in Tables 3 and 4 below, consider a Sigfox network with a fixed budget for penetration (e.g Outdoors, Indoors, or Underground) and providing a certain depth of coverage (e.g., the probability that a randomly placed endpoint has reliable coverage). With an 8 dB Link Budget advantage that RPMA enjoys in Europe, you could deploy the similarly performing network with 1/4 the infrastructure which means close to 1/4th the network cost. With the 16 dB advantage that RPMA enjoys in the US, you could deploy the same performing network with 1/19th the amount of network infrastructure.

2. Another way to "spend" the Link Budget advantage is to use the same amount of infrastructure, guarantee the same probability of coverage, but extend where that guarantee is valid. As shown in the Penetration column in Tables 3 and 4 below, that would mean that replacing the Sigfox network infrastructure designed for outdoor coverage with RPMA at the same set of locations would provide significantly better penetration. In Europe, for example, that outdoor Sigfox network would then provide the same guaranteed probability of coverage to indoor endpoints. In the US, that outdoor Sigfox network would then provide the same guaranteed probability of coverage even to underground assets.

[23] RX antenna diversity compensates for Sigfox being at lower frequency – so Link Budget as defined here is the apples-to-apples comparison.

3. The third way to "spend" the Link Budget benefit that RPMA provides is in a much more reliable network. As shown in the Coverage Depth Examples in Tables 3, and 4 below, for a given Sigfox network infrastructure providing a certain probability of coverage, the RPMA network would provide additional fade margin to provide a much higher probability of coverage. As an example, a network that covered 94% of the endpoints with Sigfox, would cover 99.5% in Europe based on the additional 8 dB advantage. And in the US, a network that covered 86% of the endpoints with Sigfox, would cover 99.5% in the US based on the additional 16 dB advantage.[24]

In a typical RPMA vs. Sigfox network comparison, the spending of the ***RPMA*** Link Budget advantage would be consumed by some combination of the 3 ways. But that should give you a feel for the fact that Link Budget isn't just a disconnected number, but is a parameter that describes ***RPMA*** as a radically better performing networking technology.

Table 9. Significance of RPMA vs. Sigfox Link Budget Advantage (Europe)

	Link Budget Advantage	Coverage Area	Penetration Example	Coverage Depth Example
Sigfox	-	1 x	Outdoor	94% Probability of Coverage
RPMA	6 dB	3 x	Indoor	99.5% Probability of Coverage

Table 10. Significance of RPMA vs. Sigfox Link Budget Advantage (US)

	Link Budget Advantage	Coverage Area	Penetration Example	Coverage Depth Example
Sigfox	-	1 x	Outdoor	86% Probability of Coverage
RPMA	16 dB	19 x	Underground	99.9% Probability of Coverage

4.2 Capacity

How many devices can a piece of infrastructure support? This is a separate constraint and determines the economics of a fully built out and utilized network. Once the capacity of a network is exceeded, additional infrastructure must be placed to support the additional endpoints (if the technology is even Capacity Scalable as described in Section 4.2.4.)

Table 8 summarizes the calculation of capacity for ***RPMA***, Sigfox, and Lora. The term ***Total Application Throughput*** describes the rate of useful data that a single piece of infrastructure (Access Point, base station, etc.) can receive from the network.

The amount of ***Total Application Throughput*** directly translates into the economics the network can support. As you can imagine, a system that can only serve a limited number of endpoints based on capacity will struggle to be economically viable (see Section 5.1.1 for some economic comparisons).

Table 11. LPWA Capacity Derivation (Per MHz)

[24] Coverage probability based on empirical measurements is Gaussian distributed with an 8 dB standard deviation (e.g., 8 dB of Link Budget increases probability of coverage by 1 sigma).

		Line	Technology Approach			
			RPMA	Sigfox	Lora (Ideal MAC)	Lora (Realistic MAC)
PHY Calculation	Link Data Rate (bps)	1	60 to 960	100	600 to 18k	600 to 18k
	Number of Simultaneous Links	2	1200	167	-	-
	Sectorization Multiplier	3	4	1	1	1
	PHY Throughput *(1 x 2 x 3)*	4	312,000	16,700	1000[25]	76[26]
MAC Calculation	Repetition Derate	5	1	3	1	1
	Other Cell Interference De-rate	6	1.4	4	1[27]	1[28]
	Half-Duplex De-rate	7	2	1	2	2
	MAC Protocol De-rate	8	3[29]	2[30]	2	2
	Headroom De-rate	9	2	2	2	2
Total Application Throughput (bps)/MHz *(4 ÷ (5 x 6 x 7 x 8 x 9))*		10	**19,000**	**348**	**125**	**10**

4.2.1 RPMA Capacity

The ***RPMA*** capacity model is very clean and deterministic. A single MHz frequency on a single sector is capable of demodulation of more than 1000 PDU (data units) independent of the spreading factor. Figure 3 shows how any combination of PDUs is able to be received by the Access Point.

25 Output of Monte-Carlo PHY/MAC Simulation

26 Output of Monte-Carlo PHY/MAC Simulation

27 Accounted already in Monte-Carlo Simulation

28 Output of Monte-Carlo PHY/MAC Simulation

29 Out of a 16 byte frame, 8 bytes are overhead (CRC/MAC Header/Tail BIts) and 2 bytes are for the MAC Forward Error Correction support. That leaves 16-8-2 = 6 bytes of application data per frame.

30 Sigfox has 12 bytes of application payload in a 26 byte packet.

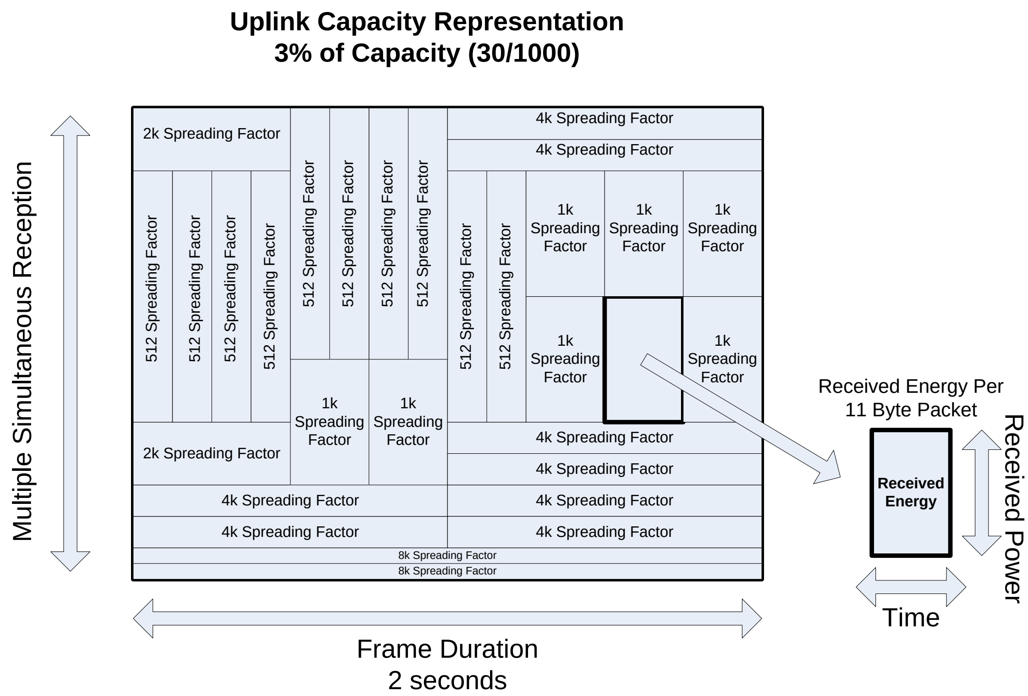


Figure 7. Depiction of RPMA Capacity Model

4.2.2 Sigfox Capacity

Sigfox decided years ago to make the fairly elegant tradeoff of enabling a very low complexity endpoint which allows for low endpoint communication module cost. The tradeoff for this decision was a much lower capacity relative to RPMA. Sigfox uses a very narrowband 100 Hz signal in their European network[31] that is randomized in both time and frequency across the 500 kHz spectrum in Europe[32]. As long as multiple transmissions do not overlap in time or frequency, the 12 byte payload will likely be successfully received.

Sigfox is fundamentally an unslotted Aloha scheme as confirmed in their paper.[33] We can compare their simulation result in Table III against the known formula for unslotted Aloha[34]:

$P_{collision} = e^{-2G}$

[31] In their FCC system, Sigfox plans on using 600 Hz bandwidth to comply with FCC regulations. It can be shown that this has little to no effect on the spectral efficiency of the system.

[32] The US channelization is not publically known at this time.

[33] "*Interference Modelling and Analysis of Random FDMA schemes in Ultra Narrowband Networks*" by Minh-Tien Do (Sigfox Wireless Company) and Claire Goursaud and Jean-Marie Gorce (INSA-Lyon, CITI-Lab). https://www.dropbox.com/s/uevep4afmmqfthv/Interference_Modelling_and_Analysis_of_Random_FDMA_schemes_in_Ultra_Narrowband_Networks.pdf?dl=0

[34] http://en.wikipedia.org/wiki/ALOHAnet

where G is the Poisson refers to the mean used in the Poisson distribution over transmission-attempt amounts: that is, on average, there are *G* transmission-attempts per frame-time. In 1 MHz, the paper indicates 434 simultaneous users to achieve a 10% $P_{collision}$ (G = 434/10,000 channels = 0.0434). Plugging into the formula above we get a more favorable 477 simultaneous users to achieve 10% $P_{collision}$ (G = 0.0477). In the subsequent analysis, we round up to 500 simultaneous users to calculate capacity.

Thus, the calculation follows a linear chain that is outlined in the Sigfox column in Table 8. Walking through this analysis line-by-line for Sigfox

4. A single Sigfox link is a 100 bps physical layer data rate.
5. From the above Aloha model, a Sigfox base station is able to demodulate ~500 multiple links simultaneously within a 1 MHz bandwidth[35]. One factor the Sigfox paper fails to take into account is the lack of power control - typical strong signals leak significant power into at least the 2 adjacent channels (and often more)[36]. This reduces the 500 by a factor of 3 to 167.
6. Sigfox basestation doesn't support multiple sectors.
7. Thus, the PHY Throughput is 100 bps x 167 links = 16,700 bps.
8. To get the applications ***Total Application Throughput*** number, we must also take the MAC layer into account. Since Sigfox relies upon open loop transmissions without a network acknowledgment, the Sigfox protocol transmits each message 3 times. That results in a 3x degradation in capacity.
9. There is an additional factor of 4 that is easy to forget about. This is what happens when no Transmit Power Control is used. In this situation, an average transmission will actually be heard by 4 Sigfox base stations[37]. This has the benefit of increased reliability for the non-worst-case endpoints, but comes as quite the cost in terms of capacity. On average, a single endpoint is thus, consuming 4 channels over 4 base stations.
10. There is little downlink activity, so Sigfox wouldn't suffer from sharing much of the uplink time with the downlink time.
11. Half of the Sigfox packet is MAC overhead that contains no application data.
12. 50% margin is good engineering design.

So the net result is 348 bps of steady-state ***Total Application Throughput*** out of 1 MHz of channel bandwidth.

[35] In Europe, Sigfox uses a 200 kHz channel, Section 5 normalizes the per MHz result based on this when calculating the economics of the Sigfox system.

[36] Although Sigfox references "highly selective FIR filters", these filters are are not able to filter out adjacent channel leakage that occurs on the TX. If you look at a typical TX mask, there is energy a few channels out that is significantly above the noise floor for multiple adjacent channels. From Monte Carlo simulation using an actual adjacent channel specification for a narrowband radio (Texas Instrument's CC-1020) it was determined that on average 3 x 100 Hz (or 600 Hz) channels are jammed based on real-world distributions of channel loss to endpoints based on actual values from the SDG&E RPMA network (3000 endpoints over 4100 square miles).

[37] This value of 4 comes from empirically measured channel data from a statistically significant 3000 endpoint network covering 4100 square miles.

4.2.3 Lora Capacity

Understanding the capacity of the Lora system is somewhat complicated by the fractured ownership of the system. Semtech developed the Lora chip, but other companies develop the MAC layer protocol. Also, these systems have very limited traction in the real-world so there is not much data available regarding the performance of the MAC layer. Note that the MAC is a critical aspect in understanding the capacity of the system.

Since Lora MACs are not commercially deployed, there is a fairly wide range of assumptions on how they will behave in the real world. The philosophy is to present bounds:

- The "ideal" MAC that certainly doesn't exist and will likely never reach that performance bound.
- The "realistic" MAC that is based on the claims of the current MAC providers.

The capacity will likely start off at the "realistic" and perhaps as the system owners (e.g., the MAC developers) learn over the next few years the reality of real-world deployments, they will be able to evolve the system over time. So given this approach, we can develop lower-bounds and upper-bounds on the performance of the Lora system.

To study these bounds, a Monte Carlo simulation was developed that has the following features:

- The input is a real-world propagation-loss distribution based on an actual RPMA network.[38]
- For the Lora waveform, the driving consideration is that signals at same "spreading factor" are not simultaneously demodulated. Based on the Eb/No, the stronger signal needs to be +5 dB stronger for demodulation to occur.
- The capacity limit is determined by the most robust modulation mode being demodulated at a reasonable packet error rate (PER) of 20%.
- Assumed the very standard Rayleigh distribution that de-correlated over, at most, a few hours – certainly at a once per day rate.

Then the two bound were modeled. The "Ideal MAC":

- Ideal Data Rate selection
- Ideal Handover
- Ideal Power Control

And then the "Realistic MAC":

- Date Rate Selection of once per day, which is the rate that Link Labs (MAC provider) claims.
- No Transmit Power Control (since it is not mentioned by a MAC provider). Also, the Lora chip only seems to support a very limited range of Transmit Power Control.
- Handover is at same rate as claimed Data Rate selection (once per day).

[38] The network modeled is the San Diego Gas and Electric RPMA network which covers 4100 square miles and 3000 devices. The path-loss data is actual measurements as gathered from the Network Operations Center (NOC).

Table 12. LPWA Capacity Derivation (Per MHz) [REPEAT]

		Line	Technology Approach			
			RPMA	Sigfox	Lora (Ideal MAC)	Lora (Realistic MAC)
PHY Calculation	Link Data Rate (bps)	1	60 to 960	100	600 to 18k	600 to 18k
	Number of Simultaneous Links	2	1200	167	-	-
	Sectorization Multiplier	3	4	1	1	1
	PHY Throughput *(1 x 2 x 3)*	4	312,000	16,700	1000[39]	76[40]
MAC Calculation	Repetition De-rate	5	1	3	1	1
	Other Cell Interference De-rate	6	1.4	4	1[41]	1[42]
	Half-Duplex De-rate	7	2	1	2	2
	MAC Protocol De-rate	8	3[43]	2[44]	2	2
	Headroom De-rate	9	2	2	2	2
Total Application Throughput (bps)/MHz *(4 ÷ (5 x 6 x 7 x 8 x 9))*		10	**19,000**	**348**	**125**	**10**

So walking through Table 13 row by row:

13. In a 1 MHz bandwidth, the data rate for Lora adjusts between 600 bps and 18 kbps based on channel conditions.
14. This is all addressed by the Monte Carlo simulation on Line 4.
15. A Lora basestation will not support multiple sectors.
16. The Monte Carlo simulation indicates a range of 76 bps to 1 kbps based on the MAC performance. At these throughputs, the lowest data rate modes (highest Link Budget modes) reach 20% Packet-Error-Rate (PER) which is deemed marginal for performance.
17. Repetition is not a significant factor in Lora.
18. The Other Cell Interference Derate is already built into the Monte Carlo model so it is not book-kept in this line..
19. Typically, a single downlink would serve multiple uplinks, so Lora wouldn't suffer from sharing much of the uplink time with the downlink time for a given channel.

[39] Output of Monte-Carlo PHY/MAC Simulation

[40] Output of Monte-Carlo PHY/MAC Simulation

[41] Accounted already in Monte-Carlo Simulation

[42] Output of Monte-Carlo PHY/MAC Simulation

[43] Out of a 16 byte frame, 8 bytes are overhead (CRC/MAC Header/Tail BIts) and 2 bytes are for the MAC Forward Error Correction support. That leaves 16-8-2 = 6 bytes of application data per frame.

[44] Sigfox has 12 bytes of application payload in a 26 byte packet.

20. Half of the Lora packet is MAC overhead that contains no application data.
21. 50% margin is good engineering design.

So the net result is 10 bps (“Realistic MAC”) to 125 bps (“Ideal MAC”) of steady-state application ***Total Application Throughput*** per 1 MHz of channel bandwidth per piece of network infrastructure.

4.2.4 Capacity Scaling

Whereas, if an ***RPMA*** cell ever gets capacity overloaded, it is almost trivial to place additional infrastructure to “absorb” capacity, that is, not the case for a technology that does not use Transmit Power Control.

To illustrate, let’s trace a network deployment scenario over time. When a network if first deployed, there are naturally very few users, and the objective is to optimize the network for coverage (e.g., capacity is not an issue). The best way to do this is by leveraging highly elevated sites like communication towers. Though these may be expensive locations to deploy, they tend to cover 100x the area of lower sites such as utility poles.

Then, the density of endpoints increases in the success case. At some point, the capacity limit is reached, and the optimal economics described in Table 6 are achieved. At this point, ***RPMA*** would simply deploy additional infrastructure and the optimal economics would be maintained at all increasing densities of endpoints. Transmit Power Control would allow for endpoints better covered by the additional infrastructure to connect to the new piece of infrastructure and not continue to contribute to the capacity load of the original elevated site.

Without power control, however, that is not the case. At some endpoint density, a given tower base station will have an aggregate data rate that exceeds the capacity. And at this point, nothing can be done to reduce the load on this base station. So they elevated sites become inoperable. The only alternative would be to replace these sites with lower sites. But since lower sites cover 1/100th the area as high sites, this would be an incredibly expensive way to cover large areas. So perversely, the per-endpoint economics get worse with more endpoints sharing the network infrastructure.

That is probably the reason that no wide-area star topology system has ever been successfully deployed not using power control.

The previous analysis indicating the disadvantaged economics due to Sigfox’s capacity limitation is not the full story. There is the very real scenario in play where Sigfox becomes the victim of its own success.

As an example, Sigfox claims to cover Spain with 1500 elevated sites. Performing the capacity calculation on the middle Silver capacity plan means that these 1500 sites would support 2 Million devices. Given that the population of Spain is 50 Million people, this means that the ration of IOT devices to people would be 1/25. This is certainly not the Internet of Things vision where there are many *more* “things” than people not *less*.

5 RPMA - Total Cost of Ownership (TCO)

Building a wide area network involves considerable expense prior to any revenue being generated. An amount of network infrastructure to achieve a viable level of coverage must be deployed before even the first service is sold. In the successful case, the network infrastructure will be capacity limited – that is servicing the maximum number of devices that it can. One important fact that is apparent when contemplating building such a network: the total cost of infrastructure vastly dominates the cost. So other than relatively small fixed costs, the total cost of a network is directly proportional to the amount of network infrastructure deployed. The total cost of a given piece of network infrastructure consists of costs such as site development, cost of base station, recurring tower rental costs, backhaul costs, power costs, maintenance, and management.

Thus, ***Capacity*** and ***Coverage*** figure directly into these economics:

- ***Coverage*** dictates the amount of infrastructure for that initial, viable level of coverage and thus most of the expense of launching a service.
- ***Capacity*** considerations determine the viability of the successful business. The subscriptions of the number of endpoints on a fully loaded base station must certainly clear the cost of that base station for any profit to be generated.

In this section we explore the Total Cost of Ownership (TCO) of RPMA connectivity.

In Section 5.1, we'll begin by exploring the fundamental tradeoff of Network Cost vs. Endpoint Cost. We'll show that similar to cellular, the Network Cost can easily dominate the economics. The conclusion is that due to the very low cost of processing on endpoints based on Moore's Law, higher technology solutions that only infinitesimally increase the cost of the endpoints (e.g., digital gates are practically free) can massively reduce the TCO based on reducing Network Costs by 1-2 orders of magnitude.

Section 5.2 describes RPMA's support of long battery life. Battery Life can often contribute significantly to TCO as frequent battery replacements can be costly for these numerous, low-value endpoints with long expected lives of 20+ years often in hard-to-access locations.

5.1 Network Cost vs. Endpoint Cost

Two potentially dominant costs of network connectivity are the Network Cost and the Endpoint Cost. To compare these costs, it is useful to normalize the total Network Cost by the number of endpoints sharing the common infrastructure. As we'll show, a result that may be surprising is that this normalized Network Cost can be potentially very large.

The cost of the network infrastructure, the cost of installation on towers, and the cost of maintenance of the network infrastructure can be very large. Minimizing the Network Cost means minimizing the amount of network infrastructure. ***RPMA*** was developed from the ground up specifically to do this. As will be shown, ***RPMA***'s order(s) of magnitude of Coverage and Capacity allow for order(s) of magnitude less network infrastructure.

Optimizing Endpoint Cost at the expense of Network Cost (e.g., by using low-technology "simple" endpoint modems) can cause the TCO to balloon based on dramatic increase in Network Cost in exchange for incremental reduction in Endpoint Cost.[45]

Note that there is nothing inherent in RPMA technology that drives significant endpoint cost:

- Moore's law has rendered the significant node-side digital complexity to be very inexpensive and low-power consuming.
- RPMA waveform does not need highly linear Power Amplifiers allows for >50% efficiency.
- Leverages off-the-shelf reference crystals for timing and frequency. Same crystals as GPS and Sigfox.[46]
- Low peak-current draw means commodity regulators and power-supplies.

Additionally, as long as the endpoint complexity is reasonable relative to the current stage of technology, the Endpoint Cost follows a fairly standard curve:

- New technology starts high in cost, but as volume and silicon integration activities proceed, a steep reduction occurs until the cost reaches a very low floor. RPMA endpoints have been in development for the last 7 years and are approaching the low floor quite rapidly.
- RPMA has a tremendous amount of capacity, so the network can be shared across large number of endpoints. The result is that as more and more endpoints come on-line, the less the Network Cost per endpoint since no additional infrastructure needs to be added.
- The result is the success case of billions of endpoints enjoying ubiquitous connectivity; the cost of using RPMA becomes extremely small, thus allowing connectivity for even the lowest value endpoints.

Contrast this to the Other LPWA players (e.g., Sigfox and Lora). Though these commodity radios may initially be less expensive, it is negligibly small compared to the initial normalized cost of the network. Over time, since the capacity of these systems is low, additional infrastructure must be deployed as number of endpoints increases[47]. The result is that the Network Cost approaches a floor that is actually very substantial – especially for the low-value endpoints that require inexpensive connectivity.

A well-known example of this Network Cost vs. Endpoint Cost tradeoff occurs in the cellular industry. In the cellular industry, each technology evolution provides better Network Cost (e.g., LTE Coverage/Capacity is far less expensive than 3G Coverage/Capacity is far less expensive than GSM Coverage/Capacity which in turn is far less expensive than analog Coverage/Capacity). The interesting thing is that for each technology evolution, the endpoint cost is significantly more expensive, at least temporarily. The savings in Network Cost far more than compensates for the Endpoint Cost and is the reason why wireless technology does not stagnate.

Table 1313 performs the relatively straightforward calculation of determining the cost of connectivity for a fully loaded piece of Network Infrastructure. This cost calculated from the Application Throughput numbers per Network Infrastructure per MHz of bandwidth as described in Table 6. Dividing this throughput by the various classes of service that the Sigfox network offers and assuming a 10-year TCO

[45] The assumption is that Network Cost must be paid by the "owner" of the endpoint, likely, with some additional markup in order for the carrier to be willing to provide this "public" service.]

[46] https://www.dropbox.com/s/2cdn1ouwhpjgklu/Sigfox Pros and Cons | IoT jumble.pdf?dl=0

[47] If its even possible to effectively scale the network see Section 4.2.4.

value per Network Infrastructure yields the numbers below. Note that ***RPMA*** can achieve close to these economics since the technology lends itself very easily to Coverage Scalability (in contrast to Sigfox or Lora).

Table 13. LPWA Capacity Economics Example (RPMA vs. Sigfox) – Europe (Sigfox Using Full 200[48] kHz of Spectrum)

Data Plan Name *(Sigfox Naming Convention If Exists)*	Data Plan Description		Network Cost to Provide Data	
	UL Data per Day (Bytes)	DL Data per Day (Bytes)	Sigfox	RPMA
One	24	0	$0.64	$0.002
Silver	600	8	$16.00	$0.06
Gold	1200	16	$32.00	$0.12
Platinum	1680	32	$45.00	$0.17
RPMA Medium[49] (Light DL)	16800	200	$450.00	$1.68
RPMA Medium (Full DL)	16800	4000	NA	$1.68

*Assumes $20k Total Cost for Each piece of Network Infrastructure

** Cost is TCO over 10 years

5.2 Battery Life

Things like solar panels, oversized batteries, and/or frequent battery replacement are very costly and ideally avoided. The cost of delivering power to “things” will be a non-starter. Oversized batteries can easily begin to dominate the economics of connectivity and must be avoided. RPMA allows for a dramatic increase in battery life using adaptive spreading factors which minimizes the on-time of the radio.[50] This is in contrast to Sigfox, for example, which operates at the lowest data rate at all times. As opposed to transmitting at worst-case minimum data rate (which drains the battery due to longest on-time), RPMA will transmit at only what’s needed to close the radio link.

RPMA connects both continuously powered devices, such as electric meters and remote monitoring units, and battery powered devices, such as gas meters, water meters, and FCIs. The protocol is purpose-built to be extremely efficient for battery-powered devices, ***RPMA*** is powered by an extremely efficient ASIC hardware for these applications. The key power-saving features include:

- The endpoint can be in a low power “deep sleep” mode most of the time. Depending on the data transmission requirements, it is awake for only a short period of time to receive and transmit data.

[48] Sigfox uses 868.4 MHz-868.65 MHz which is 250 kHz of spectrum (200 kHz of occupied bandwidth) based on Slide 4 in order to operate at the higher 27 dBm transmit power. https://www.dropbox.com/s/nhx0wk3vfkfyv03/ARROW_IOE___Wireless_Day_2.0_Presentation.pdf?dl=0

[49] Not possible in Europe for Sigfox due to regulatory restrictions, possible in US.

[50] The typical spreading factor is typically a factor of 50 less than the worst case. Thus, adaptive spreading factors represents a factor of 50x reduction in transmit power. Transmit power tends to dominate the impact on battery life.

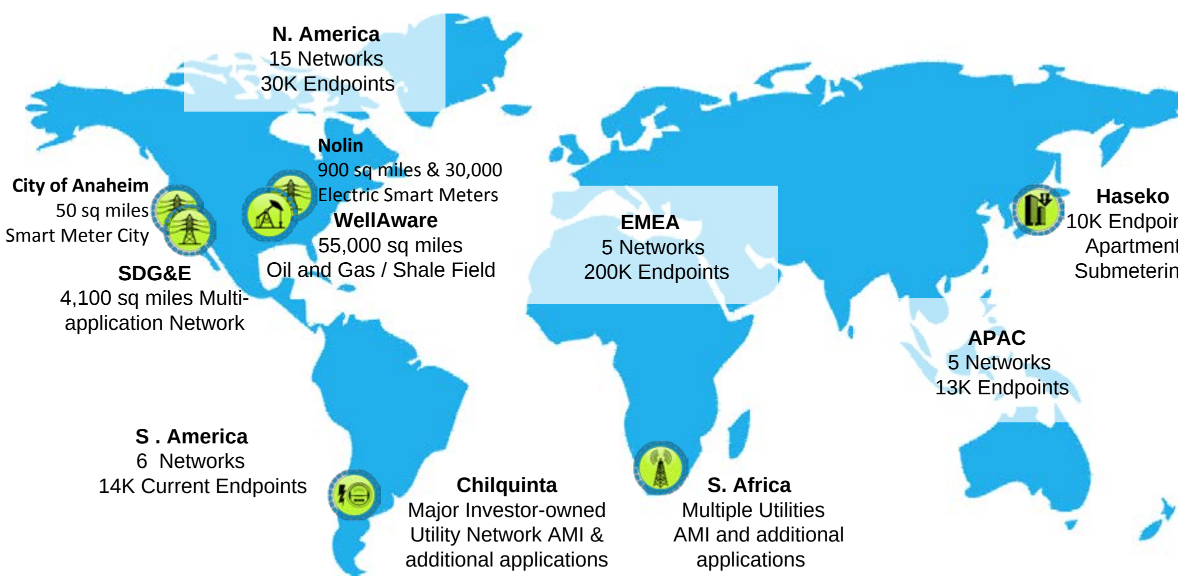
- The endpoint transmits at the minimum processing gain required to close the link, based on a locally calculated RSSI inferred from parameters received in the downlink portion of the frame cycle.
- The endpoint has a patented, low power network acquisition algorithm that saves power through maintaining synchronization to the ***RPMA*** Network.
- ***RPMA*** employs has a simple star topology, as opposed to wireless mesh, so there is no requirement for endpoints to be awake to repeat traffic.

6 RPMA Traction

6.1 RPMA Today

Over the last 7 years, ***RPMA*** has been evolved from a radio link into a fully optimized carrier-grade network with dozens of deployed networks and continual cost-optimization of the technology. To support this ecosystem and application developers, On-Ramp Wireless offers a range of radio modules, reference designs and integration support (through the ***RPMA*** Developer Program) that allow partners to quickly create devices and applications that can connect to any deployed ***RPMA*** Network, with the data from their application accessible via a simple web services connection to the operator's back office enabling transfer of data and control to the applications that truly deliver on the promise of the Internet of Things.

As ***RPMA*** networks have been commercially proven and deployed, the set of applications available that are certified and ready to be "Connected by ***RPMA***" is growing rapidly. Today there are several dozen devices and applications that can be deployed today - providing connectivity and value for smart grid, advanced metering, industrial pressure and flow monitoring, smart street lighting and much more.



Global Totals

- 31 networks
- 250,000+ committed endpoints
- 8-10 million endpoint opportunity with current customers

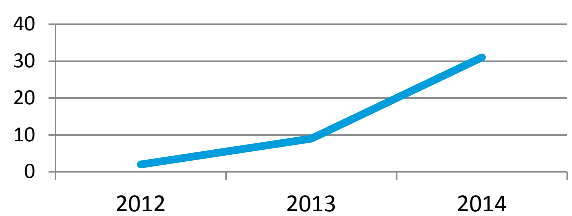


Figure 8. RPMA Deployments Worldwide

Table 14. Actual RPMA Deployments

Production RPMA Deployments Examples	Why RPMA?	Why Not Cellular?	Why Not Other LPWA?
Distribution Automation (San Diego Gas & Electric, California) *4,100 Square Miles*	At an endpoint density of just 1 per square mile, the network cost of $180 per endpoint justified the high value information the Faulted Circuit Indicator endpoint was providing. The network has since been loaded with 5 more applications and is at 0.01% capacity.	Couldn't come close to meeting the 15 year battery life requirement. Additionally, much of the territory was lacking Cellular coverage.	At a density of 1 per square mile: Sigfox → $14,600 per endpoint of network cost. Lora→ $7,000 per endpoint of network cost. Based on cost alone, this cost would be a non-starter.
Oil and Gas (Eagleford Shale, Texas) – *20,000 Square Miles*	At an endpoint density of just 1 per square mile, the network cost of $180 per endpoint justified the high value information the Pressure Gauge and Cathodic Protection endpoints were providing.	Couldn't come close to meeting the 15 year battery life requirement. Very little Cellular coverage in these remote regions.	At a density of 1 per square mile: Sigfox → $14,600 per endpoint of network cost. Lora→ $7,000 per endpoint of network cost. Based on cost alone, this cost would be a non-starter.
Rural Smart Meter (Nolin, Kentucky) *900 Square Miles*	Uniquely able to provide 100% connectivity to all meters at an extremely low price point.	Extremely expensive and has significant coverage holes in the rural territory.	At a density of 30 per square miles: Sigfox → $500 per endpoint of network cost. Lora → $250 per endpoint of network cost. This is very expensive for an electric meter. Additionally, electric meters need way more throughput, robustness, and security than these systems can provide.
Investor Owned Utility (Pretoria, South Africa) *1000 Square Miles*	Internationally RPMA is making incredible traction in South America and South Africa at large utilities because it uniquely satisfies the requirements.	Too expensive and has poor coverage internationally.	Not nearly robust, secure, and lacks the capacity to support many devices on the system.
Smart City (Anaheim, CA) *50 Square Miles*	Because only a 3 Access Points are required to cover municipalities, RPMA is easily justified in single applications such as Street Lights.	Far too expensive and doesn't allow for battery powered endpoints.	Not nearly sufficiently robust, and secure. Also lacks the capacity to support many devices on the system.

6.2 RPMA for the Internet of Things

These **9 billion** devices do not have a good solution for connectivity today. Today only ***RPMA*** is actively providing optimal connectivity for LPWA endpoints that other technology approaches simply cannot. ***RPMA*** will be the technology to uniquely and optimally fulfill the requirements of at least these **9 billion** endpoints and perhaps many more.

RPMA has been providing incredible value that only ***RPMA*** can provide via privately owned networks in the Utility, Smart City, and Oil and Gas segments. In the process, ***RPMA*** has matured into an extremely high performance, robust, and secure Wide Area Network over the last 7 years. ***RPMA*** is creating a very respectable footprint deploying private networks for relatively high value endpoints that cannot be connected by any other technology (see Table 1414).

However, the vast majority of the 9 Billion endpoints will require a public network. Most of the applications represented by this endpoint count will simply not justify the economics of deploying single purpose networks. Thus, the future of ***RPMA*** will continue to be Private Networks for those high value applications/endpoints that justify such a network, but also begin the deployment of world-wide public network.[51]

[51] Note that due to the extreme amount of world-wide spectrum in the 2.4 GHz band, there are no technical challenges having separate, uncoordinated private and public networks in a given region that do not interfere with each other.