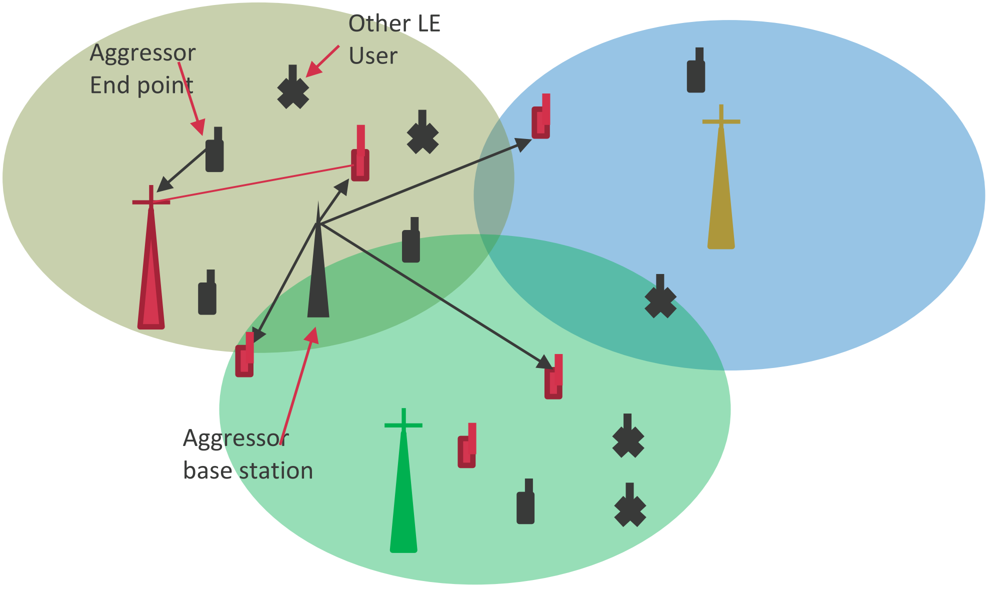
A Comparison of UNB and Spread Spectrum Wireless Technologies as used in LPWA M2M Applications

A Whitepaper by Real Wireless



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Executive summary

Low Power Wide Area (LPWA) network technologies are used to support low rate Machine to Machine (M2M) communication links between remote end-point terminals and central servers. Two main alternative approaches of supporting the physical layer communication link have been adopted – frequency division into very narrowband channels (UNB) typified by Sigfox and Telensa systems and spread spectrum approaches typified by LoRa and Ingenu systems. This White Paper is a study to compare the technical characteristics of these two generic approaches.

Key requirements of LPWA systems are long range, extended battery life and very low end point cost with many use cases only requiring low data rates. Both UNB and spread spectrum system vendors claim to achieve these requirements with spread spectrum vendors claiming to be able to support higher data rates.

Despite high variation in market forecasts, there is expected to be a large increase in the number of M2M devices. This report is primarily focussed on a comparison of the merits of different approaches to supporting LPWA M2M devices. Growth forecasts underline the need for these LPWA systems to be able to co-exist in licence exempt spectrum and that any LPWA solution should support high endpoint capacity – this requirement is likely to become more important over time as the number of devices increases.

For the example network characteristics and idealised assumptions considered in this report, an isolated UNB network would have approximately 5 times the uplink capacity of an isolated spread spectrum network. Shared channel operation, with either a spread spectrum network and a UNB network, or with two spread spectrum networks, will result in mutual interference and uplink blocking of both networks sharing the channel, unless the interfering system has very few simultaneous users - i.e. these networks can only effectively co-exist in very low capacity deployments. Two UNB networks can more effectively share access to the spectrum – essentially sharing the available capacity. In this sense, a spread spectrum LPWA network can be considered a “bad neighbour”.

In addition for this example network, co-existence of spread spectrum LPWA networks will be problematic with either UNB or other spread spectrum LPWA networks. Mitigation of the interference impact will also be difficult to achieve. Uncoordinated UNB deployment is likely to be able to co-exist with other UNB networks as long as dimensioning takes the opportunity for interference into account. In the downlink the opportunity for interference is less than in the uplink. Spread spectrum systems would benefit from synchronisation and UNB-UNB co-existence may require frequency re-assignment where downlink interference occurs.

Furthermore, we have found:

The LPWA Market

- M2M forecasts vary widely but Machina Research estimates that by 2024 14% of 27 billion M2M end points will be LPWA compared to 8% cellular end points – so vendors and end users should expect LPWA systems to be very widely deployed
- LPWA technologies offer a currently unique combination of range, battery life and low cost albeit at relatively low data rates. The number of use cases where LPWA can meet the requirements is increasing and deployments and endpoints quantities are forecast to grow rapidly in specific market segments
- This implies that such systems could be operating in the same location and sharing the same licence exempt spectrum. Successful co-existence capabilities will therefore be required to satisfy this future growth

Spectrum

- These systems are typically deployed in licenced exempt spectrum. The key advantages of licence exempt spectrum are that access to the spectrum can be secured immediately, it is available in a wide range of countries and perhaps most importantly it has zero or minimal cost
- Spectrum below 1GHz is preferred for these long range systems where end-points could be deployed in hard to reach locations. Within Europe, 7 MHz of licence exempt spectrum is currently available for LPWA use in the band 863 MHz to 870 MHz with a further 2x6MHz recommended for use in many countries, although with limited adoption to date. In North America 26 MHz of spectrum can be used by LPWA systems. However, constraints such as transmitter power and duty cycle limits (the proportion of time the transmitter can be active) along with the need for frequency hopping apply to different bands in different countries and can constrain coverage and capacity
- Provided a system can operate with duty cycle limits of (downlink/uplink) 10%/1%, transmitter limits of 500mW /25mW ERP and frequency hop every 0.4s both US and European markets can be addressed with the same equipment. Deployment in Asia would need to be done on a country specific basis due to the lack of regional harmonisation
- Access to licence exempt spectrum that can support higher power transmission is restricted to a 250kHz sub-band in all but 4 European countries. The use of such higher powers facilitates the support of long range downlink communication. Adoption of CEPT's ERC recommendations to permit higher power in a further 6 MHz in more European countries would simplify adoption of these systems in future
- Conditions and regulations for deployment in licence exempt spectrum vary across the three ITU regions and vendors will develop systems that maximise the territories where such system can be deployed. Combining the requirements for Europe and North America is relatively straightforward – Asia Pacific present some problems due to the current lack of region wide harmonisation – although some countries will accept systems that satisfy European or North American regulations

Standards

- Proprietary LPWA solutions have been available for some years and standards activities are currently underway within ETSI. Availability of standards would accelerate market take up

Technology

- Both UNB and spread spectrum approaches can satisfy the high path loss link budget requirements of LPWA systems. However, for the LPWA propagation channel, the limited amount of spectrum available where higher power is allowed (250kHz) is insufficient to provide mitigation to fading. This benefit, normally associated with spread spectrum systems, is not achievable in this case
- The capacity of a spread spectrum system will be limited by its own self noise. Other traditional benefits associated with spread spectrum (such as operating with lower fade margins) do not yield a benefit in an LPWA network. Maintaining tight power control is likely to be difficult with low levels of bi-directional communications. In theory, multi-user detection spread spectrum methods with perfect power control would allow the same capacity to be achieved, but at higher complexity, than the UNB approach
- For isolated LPWA networks, either UNB or spread spectrum approaches would be able to operate effectively. UNB distributes the traffic over many narrow channels and the spread spectrum approach separates users by codes and would require effective power control to limit self-noise
- When a LPWA system needs to operate in the presence of another LPWA system, we note that direct sequence spread spectrum (DSSS) system is likely to be a poor neighbour – it is both difficult to avoid interfering with and suffering interference from a DSSS LPWA network. The impact will be more pronounced on the uplink. The range of the victim uplink will reduce as the aggressor network loading increases. Interference from aggressor end points near the victim base station could effectively jam/block the victim base station
- Co-existence of two UNB LPWA networks is less problematic. Inter-system interference can be easily mitigated by using more channels in each system. This will require base stations to process more channels but there would be no system performance impact

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1. Introduction

The Internet of Things (IoT), powered by machine-to-machine (M2M) connectivity, is already a major industry and is expected to grow to support billions of devices in many diverse user sectors over the coming years.

Long range wireless M2M connectivity has very different characteristics to existing cellular services and to meet these different requirements a number of Low Power Wide Area (LPWA) wireless technologies have emerged to target use cases where long range, extended battery life and very low cost are fundamental necessities and not available in other wireless technologies. LPWA deployments typically require the following capabilities:

- long range - up to 20km
- extended battery life - in excess of 10 years
- low end point modem cost – below US $10
- provide only low data rates – typically below 200bps

This White Paper looks at two competing LPWA approaches – Ultra Narrow Band (UNB) and spread spectrum – comparing the physical layer performance aspects of these wireless technologies. An overview of the LPWA market growth in the next section demonstrates the significant part expected to be played by LPWA in M2M connectivity as the M2M market develops.

2. LPWA in the M2M Market

2.1 LPWA Market Size

The M2M market is forecast to be very large in terms of devices, but with significant variance amongst the various forecasts.

Table 1: LPWA Forecasts below confirms the emerging importance of LPWA technologies with Cisco, for the first time, including LPWA within the 2015 version of their yearly data traffic survey - the Visual Networking Index [1]. It estimates 20 million global LPWA connection in 2015 rising to 933 million by 2019. Analysys Mason predicts, in its M2M report of 2014, [2] around 3bn LPWA connections to be deployed globally by 2023, estimating continued strong growth over a 10-year period. Machina Research estimates 1.8 billion LPWA connections by 2020 [3].

Table 1: LPWA Forecasts

Report	Forecast M2M End Point Quantity	Forecast Year
M2M Connections using LPWA		
Cisco VNI 2015 [4]	20 M LPWA 933 M LPWA	2015 2019
Machina Research 'Combining the four pillars of innovation within the Internet of Things in one platform' White Paper for ThroughTek. Feb 2015 [5]	1.8 bn LPWA	2020
Analysys Mason 'Low Powered Wireless Solutions have the potential to increase the M2M market by over 3 billion connections' Sept 2014 [6]	0.2 bn LPWA 1.2 bn LPWA 3.1 bn LPWA	2017 2020 2023

As can be seen, there are significant variations in the predicted market size for LPWA connections. We see this as a reflection of the market immaturity:

- The IoT and supporting M2M markets are completely new and at a formative stage. New technologies, new use cases, new business models, new start-ups, consortia and groupings all emerge regularly
- Applications are being deployed, often as small scale pilots, in new and varied environments to test take up, benefits and return on investment
- There are a number of competing LPWA offerings which, when combined with the current lack of LPWA standards, makes procurement decisions more difficult and extended with purchasers and end users trying to ensure they avoid a stranded investment

Not all use cases are suitable for LPWA due to bandwidth or quality of service requirements – indeed these LPWA forecasts can be compared to a total M2M forecast by Huawei in their 2015 Global Connectivity Index [7] of 35bn end points by 2020 covering both wired and wireless connectivity.

What is clear however is that LPWA technology is now a serious market player in M2M wireless connectivity alongside cellular, Wi-Fi, Zigbee, Bluetooth and other proprietary solutions. Machina Research's 'M2M Global Forecast & Analysis 2014-24' forecasts LPWA to be 14% of the 27 bn total installed base in 2024 whilst cellular is forecast to be 8% by the same date [8]. LPWA systems are therefore likely to be deployed widely with systems operating in close proximity.

2.2 Market Segmentation

The M2M market readily breaks down into number of market segments with a large and increasing number of use cases as shown in Table 2 below. One purpose of such segmentation is to understand which segments and use cases are appropriate for LPWA technologies. This section and Section 2.3 following give a high level view of how and why LPWA suits some use cases but not others. The varied use cases in each segment will determine whether the characteristics of LPWA systems make it a suitable choice over competing technologies. The four key segments for wireless M2M growth are likely to be: Utilities, Smart Cities, Healthcare and Transportation and Automotive. All have strong government support because of the potential for cost savings, improvements in well-being and reductions in emissions - furthermore these segments have demonstrable tangible benefits for consumers and businesses.

Table 2: LPWA Market Segmentation

Segment	Typical Use Cases
Utilities	Smart meter/Automated Meter Reading systems Smart grid Asset management
Smart Cities	Traffic control Parking management Lighting control Waste management Environmental monitoring
Healthcare	Fitness tracking Patient self-monitoring and remote monitoring Assisted living Remote surgery and telemedicine Smart clothing Automated hospital processes Emergency healthcare
Transportation and Automotive	Connected Car Road management Tolling and speed enforcement systems Vehicle platoons and autonomous vehicles Connected trains, boats and planes Track and highway asset management
Building services	Building automation – automated and remote control of building environment HVAC, lighting, security Building management systems Building security, access control and CCTV Fire and emergency alarms – sprinkler systems
Retail	Building services – as above Goods tracking, shelf life management, inventory management Automated shelf pricing Beacons and location-based services, customer browsing data Shelf compliance Payment processes
Consumers	Wearables Smart home

Segment	Typical Use Cases
Industrial and supply chain	Smart factories Industrial automation – energy tracking Supply chain management Warehouse automation Driverless vehicles Wearables Security
Security and Critical National Infrastructure	Industrial and enterprise security Surveillance First responders – vehicles, persons and devices Monitoring critical infrastructure Asset management
Agriculture and fishing	Crop and livestock management Machinery tracking Irrigation and water quality monitoring Produce tracking through supply chain Weather monitoring
Environment	Air quality monitoring Pollutant level monitoring Water level monitoring and automated flood response

2.3 Wireless M2M Market Requirements

The key technical parameters for consideration in wireless M2M connectivity are:

- Range
- Data rate
- Battery life
- Mobility
- Latency
- Security and resilience
- End point modem cost

The required value of each parameter varies according to the segment and associated use cases. Many use cases require wide area operation – typical of an asset monitoring scenario - possibly with a limited control function and only require low data rates.

By way of example we have analysed the needs of the key four segments previously identified in terms of these parameters, resulting in the parameter value ranges shown in Table 3 below.

Table 3: Key Technical Parameter Range Values

	Utilities	Healthcare	Transportation and Automotive	Smart Cities
Range	Up to 20 km	Most < 20 m Some >5 km	V2X < 50 m Connected Car >5 km Rail and Bus - >5 km	Up to 20 km and some < 100 m
Data Rate	< 1 kbps	100 kps - 1 Mbps	100 kps - 1 Mbps	Most <100 kps Some >1 Mbps
Battery Life	Smart Meter: 10-15 years	1-5 years	Most powered from host vehicle or asset. Some > 5 years	10 years. Some powered from street furniture
Mobility	No	Most limited inside building. Some full mobility	Yes	Most fixed or nomadic. Some full mobility
Latency	Smart Meter: 10-100 ms Smart Grid : 1-10 ms	Some very low latency <10 ms others 10-100 ms	V2X < 15 ms Others 10 – 100 ms	10 – 100 ms
Security and Resilience	Encryption and two-way communication Smart Grid requires high resilience	Encryption and two-way communication	Encryption and two-way communication	Some – no. Some require encryption and two-way communication
Modem Cost (USD)	< US$10	US$10 - $25	US$10 - $50	< US$10

LPWA technologies are therefore highly suited to some of the Utilities and Smart Cities use cases where range, battery life and end point cost are key and the required data rates are low. Other requirements such as video transmission in say remote healthcare require high bandwidths and are therefore not appropriate for LPWA, whilst connected cars require full high speed mobility making LPWA similarly not suitable.

2.4 Market summary

Despite high variation in the forecasts, there is expected to be a large increase in the number of M2M devices. This report is primarily focussed on a comparison of the merits of different approaches to supporting LPWA M2M devices. Growth forecasts underline the need for these LPWA systems to be able to co-exist and that any LPWA solution should support high endpoint capacity – this requirement is likely to become more important over time as the number of devices increases.

3. Regional restrictions on licence exempt spectrum use

Most LPWA systems utilise licence exempt (LE) spectrum – mainly because:

- governments set the spectrum user costs for LE spectrum at zero or at a minimal amount to cover administrative costs and
- the spectrum is immediately available

However, LE spectrum is shared with any other users who deploy a system and there is no requirement for users to co-ordinate to avoid interference – so LPWA systems need to incorporate interference rejection capabilities to operate under such conditions. Most countries require LE spectrum users to meet a number of restrictions relating to power and transmitter frequency occupancy and these restrictions can limit overall system performance. It is of interest therefore to consider the regulatory limits that apply in Europe, the USA and Asia Pacific for such LE spectrum, since these regulatory constraints define the limits to which networks need to conform. In addition, vendors looking to operate globally need to find ways to maximise the regional and country acceptance with the minimum number of equipment variants in order to minimise development and manufacturing costs.

3.1 European regulatory limits

Within CEPT the ERC adopted recommendation ERC/REC 70-03 [9] sets out a common position for the allocation of spectrum for Short Range Devices (SRD) across all CEPT countries which includes the EU and EFTA. This is the recommendation that applies for licence exempt / short range devices including LPWA systems.

ERC/REC 70-03 identifies spectrum at 169 MHz, 433 MHz, 863 MHz, 870 MHz and 915 MHz that are potential candidates for LPWA networks. The spectrum at 169MHz would permit up to 500mW ERP but is limited to 75kHz and would require impractically large endpoint antennas. At 433MHz the power is limited to 10mW. Therefore, we shall focus on alternative spectrum available at 863 - 870 MHz, 870-875.6 MHz and 915-921 MHz.

Though ERC/REC 70-03 is not mandated, Appendix 1 contains a cross-reference matrix identifying which countries have adopted the recommendation. This shows that almost all CEPT countries have adopted this recommendation within the key band 863 – 870 MHz, some with restrictions covering which sub set of frequencies can be used and the transmit power limits. Essentially, however, this band is open for SRD deployment across most of Europe. The constraints identified in this recommendation for sub 1 GHz spectrum, suitable for use in LPWA, are described below.

863-870 MHz band

A key LE band for LPWA systems is the frequency range 863-870 MHz – this band is popular because it presents a good balance of range, building penetration and the ability to use small antennas – this latter point being of practical importance when deploying small end points in outside locations. Different maximum effective radiated power (ERP) and duty cycle limits apply to different sub-bands. The maximum ERP permitted according to [9] varies across the band as shown in Figure 1. The range 869.4 MHz – 869.65 MHz is significant since it is possible to transmit 500mW ERP with a duty cycle as high as 10%. (It is noted that higher duty cycle may be permitted if Listen Before Talk (LBT) and Adaptive

Frequency Agility (AFA) are employed together, but current European Standards [10] for Short Range Devices (SRDs) limits the duty cycle to 2.8%). Within this sub-band no minimum channel spacing or bandwidth is recommended.

A recommended ERP limit of 25mW applies to nearly all of the rest of this band, with duty cycle limits of 1% in 900 kHz of the band and 0.1% in the remainder.

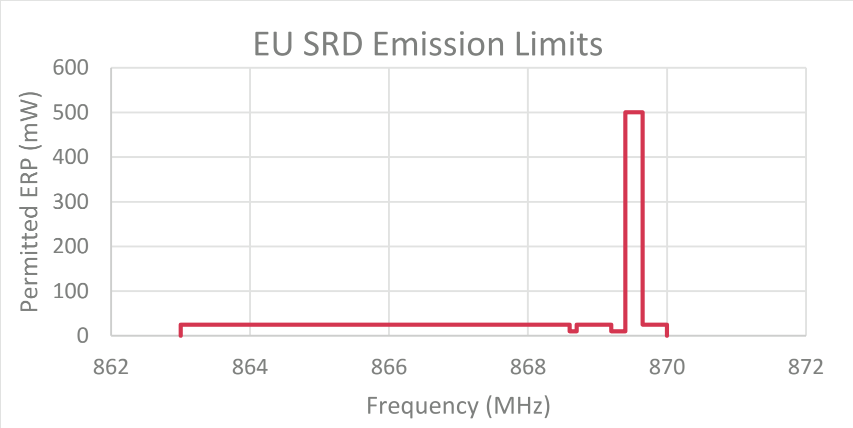

Figure 1: Recommended maximum ERP adopted by most European countries in the frequency band 863-870MHz.

The frequency bands 870 -876 MHz and 915 – 921 MHz are being considered as a possible extension to the 863-870 MHz band by CEPT, although their adoption is not yet mature.

870-875.6 MHz

Within this sub-band CEPT have adopted a different approach, whereby different ERP limits are permitted for different application types. A key relaxation is identified in Note 1 of Annex 2, of [9], which notes:

> *"A duty cycle of up to 10% may be allowed for network relay points forming part of metropolitan/rural area networks such as for utilities or other applications for the purpose of data acquisition. Network relay points should be individually licensed. National regulatory authorities may consider the provision of general authorisations (options as defined in ECC Report 132) for network relay points forming part of metropolitan/rural area networks which have implemented additional Listen-Before-Talk (LBT) and frequency/channel agility/adaptivity mitigation techniques and/or coordination in geographic areas of a high number of network relay points."*

Hence subject to limitations to protect ER-GSM, the sub-band 870-875.6 MHz is recommended to be permitted to use with an ERP of 500mW subject to the above constraints for all SRD applications – which includes LPWA. According to Appendix 1 of [9] on Albania, Denmark, UK, Moldova and Slovenia have currently adopted this recommendation in this sub-band.

915-921 MHz

Annex 11 of [9] recommends that up to 4W ERP can be used – but only for RFID devices. LPWA devices would be constrained by the limits for non-specific devices (Annex 1), which is 25mW ERP and 0.1% duty cycle subject to protection of ER_GSM, except where 100mW ERP can be used in 4 channels, each of 400kHz. This represent another potentially high transmit power option. Again, according to Appendix 1 of [9] only Albania, Denmark, UK, Moldova and Slovenia have currently adopted this recommendation in this sub-band.

3.2 FCC / North American regulatory limits

In the US, licence exempt regulations (Part 15) that apply within the 902 – 928 MHz band are covered by several different regulatory sub parts that each specify different types of technical requirements [11]. For the band 902-928 MHz only the provisions in Part15.247 are of particular relevance to LPWA systems.

For the systems of interest (point to multi-point, digitally modulated networks) the key regulatory constraints as would apply to LPWA systems are:

- A maximum EIRP of 4W
- Frequency hopping dwell times range depending on channel bandwidth:
  - <250 kHz bandwidth: dwell times limited to 0.4 seconds within a 20 second period and at least 50 different hopping channels must be used
  - >250 kHz bandwidth: dwell times limited to 0.4 seconds within a 10 second period and at least 50 different hopping channels must be used
- The power limitations are 1W (Tx power) for systems employing at least 50 hopping channels; and 0.25W for systems employing less than 50 hopping channels, but at least 25 hopping channels

Hence a key difference in the US is the need to hop channels and the peak power can be 7dB more than is permitted in Europe. These limits apply to the whole of the 902-928 MHz band – significantly less restrictive than the European situation.

3.3 Asia Pacific regulatory limits

SRD licence exempt allocations across the Asia Pacific (AP) region are complex because of the large number of geographically dispersed separate countries and overall harmonisation is yet to be fully achieved across all countries. The bands 433 – 435 MHz, 862 - 875 MHz and 875 - 960MHz have gained some support - particularly the 875 – 960 MHz band which is fully or partially implemented in the majority of AP countries [12].

Many different regulations regarding transmit powers by country are to be found – typically these are within the range 10mW – 4W ERP. Beyond that other limits – such as duty cycle or frequency hopping requirements - are yet to be harmonised. Some countries will however accept limits set by CEPT or the FCC [13].

3.4 Summary of regulatory considerations

- Within most European countries there is (only) a narrow 250 kHz sub-band where a peak EIRP of 29.1 dBm (500mW ERP) can be used (with a duty cycle of 10%). A peak EIRP of 16.1dBm (25mW ERP) is available for use with a 1% duty cycle in a further 900 kHz

- Typical base station antenna gains in these bands is approximately 8dBi, and this would provide a benefit in the uplink link budget – but will not increase the permitted EIRP of the base station transmitter. Hence, the narrow 250 kHz is a key sweet spot for base station transmit for any long range low data rate LPWA system – with the base station antenna gain used to compensate for the lower power UL EIRP in other parts of the spectrum where less power is allowed to be transmitted
- In North America 26MHz of spectrum with a peak EIRP of 36dBm is available for use subject to frequency hopping with a dwell time of less than 0.4 seconds
- In the Asia Pacific region licence exempt SRD requirements lack overall harmonisation although spectrum in the 862 - 875 MHz and 875 - 960MHz bands has been allocated for SRDs with various power limits

Therefore, in order to have a system that is able to be deployed globally, conformance with the European emission and duty cycle limits and the US frequency hopping constraints is a key consideration and deployment in Asia would need to be done on a country specific basis. In addition, systems need to be designed to operate in the LE spectrum environment where essentially users have no real protection from systems in the same geographic area and on the same and adjacent channels other than through the LE spectrum regulations pertaining to that country.

4. LPWA Technologies

4.1 Overview

This section gives a high level view of UNB and spread spectrum technologies – providing a backdrop for Section 5 which provides a detailed technical analysis.

LPWA technologies have emerged as a way to meet the need for extended range, long battery life and very low cost for both end points and the required infrastructure. LPWA networks are typically used to provide low data rate transfer between end-points and a central server. Information flow is primarily in the uplink direction (i.e. from end-points to the central server) with acknowledgements, configuration and system updates using downlink connectivity. Acknowledgements can be used to reduce unnecessary uplink re-transmissions, while the configuration allows the network to respond to changing conditions.

The majority of LPWA applications are concerned with reporting information on static, or quasi-static objects (e.g. animals) – many of these end-points have low operating costs and so the opportunity to save money is small unless the cost of the LPWA infrastructure is low. For this reason, low cost end points supported by existing or a minimum amount of new infrastructure is key to successful deployment. Star topologies with one base station supporting a multitude of end point distributed over a potentially wide area have been commonly adopted.

4.2 UNB

UNB technology makes use of narrow RF channels to provide high receiver sensitivity and thus extended range albeit at very low bit rates – typically below a few hundred bits per second. UNB systems use a separate narrowband channel for each transmission – uplink (UL) or downlink (DL) and the spectrum being used is channelised so that multiple UL and DL transmissions can occur simultaneously on a frequency division multiple access basis. As seen in Section 3 transmit power is stipulated on a per device basis hence in UNB all of the power occupies a relatively narrow channel thereby improving the link budget. There are several proprietary systems including Sigfox, Telensa, Nwave as well as the various Weightless proposed standards. Advantages of simplicity and low silicon cost are claimed. Opponents cite the very low and fixed data rates as limiting the applicability of UNB. The range claims by some UNB providers (50-100 km) are at best achieved under highly impractical conditions and only serve to add confusion to procurements. Additionally, the lack of two-way communications in many initial implementations of UNB was seen to further limit the applicability – however most UNB vendors have now developed two-way communications in one form or another.

Sigfox **[**14**]** has created significant visibility and market wins through its UNB technology – it claims deployment in 9 countries with 5 million end points currently and is seeking to standardise its technology via the ETSI LTN (Low Throughput Networks) group. Other LPWA vendors may support this approach in order to gain scale economies and some degree of harmonisation to further reduce costs and increase market acceptance. Sigfox networks operate at 100bps uplink with a 12 byte payload limit and utilise LE ISM bands. In addition, end points are limited in the number of transmissions they can make per day. Sigfox has introduced a basic two-way communication facility to overcome market objections to their one-way offering.

Telensa [**15**] – a spin off from the UK company Plextek - has historically focussed on one part of the market – remote street lighting control - and has had a degree of success with a large global installed base of lighting control devices. It uses the same end-point silicon as Sigfox although has proprietary communications protocols. Telensa talks of millions of lights being controlled by its technology. Telensa also claims that their product is suited to: smart cities and homes; detection and monitoring; tracking and recovery. It operates at a downlink rate of 500bps and an uplink rate of 62.5 bps. Telensa is working with Sigfox in the ETSI LTN (Low Throughput Networks) group.

Weightless [**16**] is a standards Special Interest Group formed to coordinate the standards developing activities of the Weightless standard. It now offers a number of potential standards including Weightless-N which uses UNB technology. However, it is unclear whether Weightless will gain any real traction in the market.

4.3 Spread spectrum

Spread spectrum technology is based on military programmes (see, for example [**18**]) and was used in CDMA cellular standards. Spread spectrum technology vendors claim better resilience to interference, the ability to support higher data rates than UNB and the ability to support different data rates. Opponents cite the additional cost required in silicon and the overall system complexity. Semtech/LoRa and Ingenu/On-Ramp Wireless provide spread spectrum LPWA technology.

Semtech [17] developed, through its acquisition of Cycleo in 2012, a spread spectrum-based proprietary LPWA physical layer with a range of 15-20km, and a battery life of up to 10 years. Though formally frequency agnostic, LoRa equipment is available for operation in the following bands: 868 MHz (Europe), 915 MHz (North America) and 433 MHz (Asia). The technology has also been deployed in licensed-spectrum private networks. LoRa operates at uplink rates from 300 bps to 50 kbps and the spread spectrum capability is said to provide for better co-existence in shared spectrum such as ISM bands albeit at the expense of reducing the data rate according to the spreading factor being used. Semtech is seeking to have a LoRA based standard accepted by 3GPP for use in licensed spectrum, and two workshops have taken place already. They anticipate that this can be developed as part of 3GPP Release 13 or 14 (i.e. at the same time, or behind the LTE-MTC variants).

On-Ramp Wireless recently rebranded as 'Ingenu' offers Random Phase Multiple Access technology operating at 2.4GHz – the company lists Dr Viterbi as a member of the Advisory Board. Their technology is a form of spread spectrum. Few details are available as to Ingenu's deployments although networks are planned for Italy and the US.

5. Technical Comparison of UNB and Spread Spectrum

The analysis in the following sections looks at the technical aspects of UNB and spread spectrum with a view to understanding how these technologies compare in the LPWA application.

This includes developing and evaluating:

- the channel characteristics
- generic link budgets
- the capacity of various multiple access methods
- network topology, interference scenarios and mitigation performance

The analysis that follows allows us to put into perspective the various advantages and disadvantages cited for UNB and spread spectrum technologies. The claimed benefits of these generic approaches are described below.

5.1.1 Generic UNB technology benefits

Ultra narrowband approaches, particularly multicarrier systems using OFDM, are increasingly being used in many applications including mobile (LTE) and wideband applications (variants of 802.11).

Processing a bank of multiple ultra-narrowband carriers can be efficiently computed using FFT-based methods, where each narrowband sub-carrier has benefits of frequency non-selective fading, and delay spreads much less than the symbol rate even in mobile environments. This allows the throughput of multiple orthogonal sub-carriers to be aggregated to increase the overall datarate but to avoid the requirement for equalisation of the sub-carriers. This results in lower complexity receivers than if a wideband channel was processed as a single carrier. Since adjacent sub-carriers can be orthogonal, there is no interference between sub-carriers, and power can be distributed between the sub-carriers to match the fading environment of each carrier.

UNB for LPWA applications essentially uses one sub-carrier for the uplink from each end-point and the base station can process multiple uplink sub-carriers similar to a wideband system using multiple sub-carriers. Use of multiple narrowband sub-carriers reduces the number of end-points sharing access to a given channel to reduce the opportunity for interference from other narrowband users.

5.1.2 Generic spread spectrum technology benefits

Spread spectrum systems have their roots in covert military applications and measurement (see for example [18]) and have been adopted for use in mobile networks.

- Covert communication: Using long spreading sequences (unknown to 3rd party but known to the receiver) results in a low energy density signal that can be difficult to detect or decode by the 3rd party (transmission power density can be below the noise floor). Long spreading sequences and a large bandwidth are typically used
- Resistance to jamming: By spreading the communication signal over a large bandwidth (using a pseudo noise direct sequence spread spectrum code), even though a jammer would contribute noise within the receiver bandwidth this will be spread to the bandwidth of the spread signal within the receiver whilst the desired signal benefits from the processing gain. The jammer will still contribute noise but the desired signal will benefit from processing gain, reducing the jammer to signal power
- Mobile systems: CDMA-based spread spectrum was adopted for use in mobile communications in the IS-95, 3GPP2 CDMA and 3G WCDMA standards. In the 3G system, the channel bandwidth (~5MHz) is more than the channel coherence bandwidth and provides resilience to some frequency selective fading. Base stations are synchronised to a common time basis (i.e. synchronised) and spreading/channelisation codes are used to allow variable data rates to be used yet to maintain orthogonality between different users in the downlink direction. Channel fading reduces orthogonality between users and serves to increase system noise. Link power control is effected 1500 times per second. Compared to the GSM system it was intended to replace, a key benefit of this 3G system is the high data rates and channel bandwidth available, simple methods of supporting diverse data rates between multiple users and the ability of the wideband signal to support link continuity with less average additional margin than previously required

Spread spectrum for LPWA applications uses the spreading codes to allow different end-points to simultaneously share access to a common channel and jamming resistance to reduce the impact of other narrowband users of the channel. The suitability of these generic UNB and spread spectrum benefits in the LPWA environment will be assessed in subsequent sections.

6. Fundamental Physical Layer Considerations

Before assessing the relative merits of UNB versus spread spectrum methods to support LPWA systems it is important to consider the channel and fundamental link budget considerations which reflect the regulatory constraints and target data rates required.

6.1 LPWA channel characteristics

This section considers the propagation channel in which LPWA systems will operate in order to put the claimed benefits of different air interface systems into context. From section 4.1, LPWA systems will predominantly be deployed from fixed locations (urban, suburban and rural) serving mainly fixed or nomadic end-points. In this section we review the characteristics in this environment to determine what physical layer characteristics would be most suited to the channel conditions.

Delay spread is a measure of how much radio propagation smears the signal over time as a result of scattering from objects at various distances – essentially radio echoes. If the delay spread is large compared with the symbol time, there will be interference between symbols, limiting the data rate or leading to a need for complex receivers, see for example [24]. The delay spread in these environments (see, for example [19] and [20]) is likely to span the range of approximately 1µs (corresponding to a round trip additional distance of 300m distance) for urban, or up to approximately 10µs (say 3km from a distant hill). This results in a coherence bandwidth in the range of 100 kHz to 1MHz

The coherence time of the channel is a measure of how long it takes for the channel conditions to change (e.g. from a faded condition to an unfaded condition). The coherence time for these environments with static or slowly moving end points is likely to be relatively long. Telensa have measured this in suburban locations and found that where fading is present the coherence time is approximately 0.5s, i.e. a Doppler frequency of approximately 0.8 Hz, and therefore consistent with little movement and a slowly changing channel.

The practical impact of these channel characteristics on the air interface is:

- Channel bandwidths less than 100 kHz will be frequency non-selective – i.e. they may be faded or unfaded, but the channel bandwidth would need to be significantly more than 100 kHz to allow any fading to be mitigated by unfaded frequency segments of the channel. Symbol durations of more than ~0.1ms will not require any equalization
- Burst durations of less than a few tenths of a second will experience slow fading and burst durations longer than this are likely to be faded over the duration of the burst, and would benefit from interleaving and coding

6.2 Generic LPWA link budget

A key driver for LPWA is a high value for the maximum acceptable path loss. According to [21], a range of different LPWA solutions have a link budget in the range of 156dB up to 172dB, with a typical value of 160dB. For the purposes of this document, we will assume that a target of 160dB is representative of LPWA link budgets.

It is instructive to construct an LPWA link budget based on the regulatory constraints identified in Section 3, public statements from William Webb [22], the Weightless SIG CEO, standards documents on LPWA use cases [23] and the stated claims of the achievable path loss from [17]. Link budgets for downlink and uplink directions are shown in Table 4 and Table 5 respectively below.

Table 4: Downlink link budget derivation for a generic LPWA link.

Attribute	Value	Unit	Comment
Transmit Power	500	mW ERP	Regulatory limit
ERP→EIRP	2.15	dB	Definition
Tx. EIRP	**29.1**	**dBm**	
Thermal noise density	-174	dBm/Hz	290K assumed
Noise Figure	8	dB	End-point NF assumption
Receiver bandwidth/channel	500	Hz	[20] notes asymmetry – this value balances the budget. This would be after de-spreading in a CDMA system.
Required Eb/No	9	dB	Assume non-coherent demod with orthogonal constellation [20].
Sensitivity	**-130**	**dBm**	
Antenna gain	0	dBi	End point omni antenna internal to end-point.
Feeder losses	0	dB	Assumed integrated
Fading and penetration losses	0	dB	Discussed below
Achievable path loss	**159.1**	**dB**	

Table 5: Uplink link budget derivation for a generic LPWA link.

Attribute	Value	Unit	Comment
Transmit Power	25	mW ERP	Regulatory limit
ERP->EIRP	2.15	dB	Definition
Tx. EIRP	**16.1**	**dBm**	
Thermal noise density	-174	dBm/Hz	290K assumed
Noise Figure	5	dB	Base station NF assumption
Receiver bandwidth/channel	250	Hz	[20] This would be after de-spreading for a CDMA system.
Required Eb/No	9	dB	Assume non-coherent demod with orthogonal constellation. [20]
Sensitivity	**-136**	**dBm**	
Antenna gain	8	dBi	base station receive antenna at 870MHz.
Feeder losses	0	dB	Assumed integrated
Fading and penetration losses	0	dB	Discussed below
Achievable path loss	**160.1**	**dB**	

These simple link budgets demonstrate that a maximum path loss of 160dB with the EIRP permitted in LE spectrum can be achieved with data rates limited to approximately 200bps in the uplink and 500bps in the downlink. Clearly any penetration loss and fading losses must be within the 160dB nominal path loss. For the channel characteristics described in Section 6.1, and the channel bandwidths required to satisfy the link budget, the channel will not experience fading across the channel bandwidth or suffer from symbols spreading in time – it will be the most benign channel considered in communications, a so-called Additive White Gaussian Noise channel (AWGN). Spread spectrum techniques will not mitigate fading in the bandwidth needed for the data rate that can be supported.

The increased downlink EIRP (20 times more radiated power, or 13dB) is offset by a gain of 11dB owing to improved noise figure and receive antenna gain at the base station. The assumed increased channel bandwidth to accommodate a higher downlink data rate requires 3dB, resulting in a theoretical 1dB link imbalance deficit in the downlink direction.

In summary, achieving such high path losses with limited transmit power is challenging - but realisable - and the achievable datarate is restricted. The above generic link budgets would apply for either a UNB or a spread spectrum system. In a spread spectrum system that used 125kHz bandwidth (permitting 2 channels to be used in the 250kHz relatively high power European sub-band) would have processing gains corresponding to approximately 24 dB (downlink) or 28dB (uplink). These fundamental link properties will be used in Section 8 when we consider the response of UNB and spread spectrum based systems to co-exist with each other.

7. Capacity of Different Multiple Access Methods

A fundamental issue in any communications network is choosing how to share access to the system capacity between multiple users or devices. Key resources of interest are the power, time and frequency. UNB systems partition users into different narrowband channels – spread spectrum methods allow users to occupy the same wideband channel and separate users by the spreading sequence used. Separating users by frequency as in Frequency Division Multiple Access (FDMA), time using Time Division Multiple Access (TDMA) or by spread spectrum methods such as Code Division Multiple Access (CDMA) have been used for many years. In practice, combinations of these methods are also used.

It is useful to review the capacity of these different generic access methods for the idealised AWGN channel, in terms of the total bit rate for all users per unit of bandwidth available. After [24] we note that the Shannon channel capacity, i.e. the maximum theoretical data rate, C (bps), for a single user in bandwidth W (Hz), and receive power P (W), is:

$$C = W\, log_2\left(1 + \frac{P}{WN_0}\right),$$

Where N_0 is the noise density (W/Hz), and WN_0 is the noise power (W) in the channel bandwidth. It is of interest to consider the impact of sharing the time/frequency space with multiple devices and users.

7.1 Capacity of UNB methods

For a pure FDMA system, the total bandwidth can be split between k users, whose signal is received with a signal power, P, in a bandwidth of W/k, then the total capacity (i.e. the system capacity) available to the k users is k times the capacity available to the kth user, C_k, i.e.,

$$System\ Capacity = kC_k = k\,\frac{W}{k}\,log_2\left(1 + \frac{P}{\frac{W}{k}N_0}\right) = W\,log_2\left(1 + \frac{kP}{WN_0}\right)$$

This is the same as the capacity of a single user of the channel with a received power kP. Therefore, in a fixed bandwidth, W, dividing the channel into smaller frequency segments allows more system capacity as long as the power in each segment can remain the same[1].

Following [24], we can reproduce the spectral efficiency, or normalised capacity, SE_n, for this case, where the total normalised capacity is the total bit rate for all users per unit bandwidth (i.e. bps/Hz), as:

$$SE_n = log_2\left(1 + SE_n\,\frac{\varepsilon_b}{N_0}\right)$$

[1] We note that splitting the user into small time segments has the same result, but requires high instantaneous power which is difficult to achieve, and may not be permitted by EIRP limits.

Where $\frac{\varepsilon_b}{N_0}$ is the energy per bit to noise density ratio for a single user. This relationship is plotted in Figure 2 and shows that the channel capacity increases as individual users' signal to noise ratio (SNR) increases.

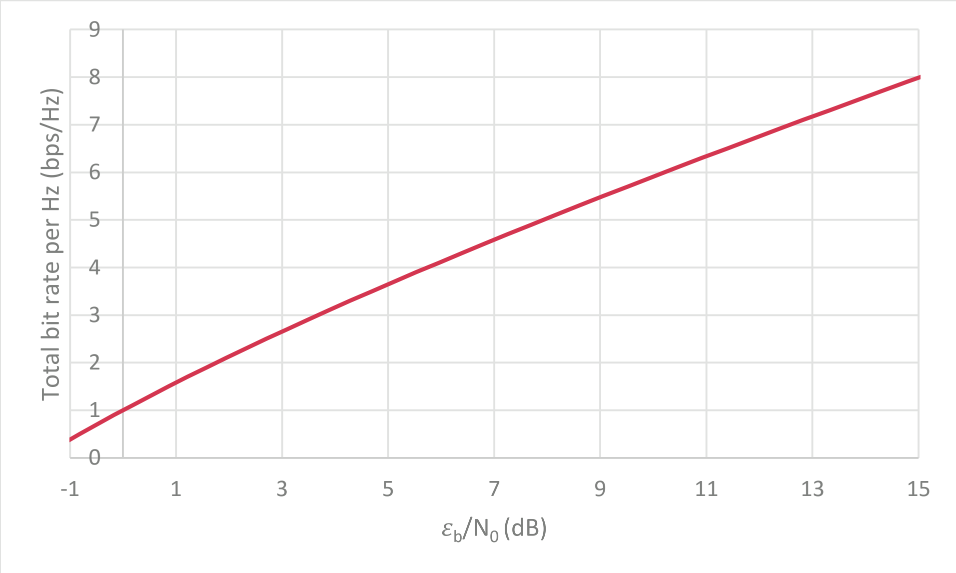

Figure 2: Total capacity per Hertz for a bandlimited spectrum block with FDMA partitioning per user, versus individual user ε_b/N_0.

Hence for an idealised UNB system the system capacity increases if the channel is sub-divided into smaller frequency segments as long as there is no constraint on the power flux density that can be used.

7.2 Capacity of spread spectrum methods

In a spread spectrum system, a user transmits information which is spread across a wide bandwidth at the transmitter which is then despread at the receiver. Multiple users can be simultaneously spread across the same bandwidth and depending upon the level of co-operation among the k users, the impact of other users' channel use (interference) can be mitigated and separated at the receiver. With no co-operation other users' transmissions appear as additional noise-like interference.

7.2.1 Spread spectrum with single user detection

Multiple users are assumed to transmit so that all signals arriving at the receiver have just sufficient power to meet the required SNR (i.e. perfect power control in the uplink). Signals arriving from other spread spectrum users appears as interference to the wanted signal. In this case the capacity per user, assuming all users have the same SNR requirement, is:

$$C_k = W\ log_2\left(1 + \frac{P}{WN_0 + (k-1)P}\right)$$

i.e. the noise contribution is increased by the number of other users whose received signal power assumed to be the same as the wanted signal power.

The spectrum efficiency for each user is:

$$\frac{C_k}{W} = log_2\left(1 + \left(\frac{C_k}{W}\right) \cdot \frac{\left(\frac{\varepsilon_b}{N_0}\right)}{1+(k-1)\left(\frac{C_k}{W}\right)\left(\frac{\varepsilon_b}{N_0}\right)}\right),$$

And the resulting spectrum efficiency for all users is $SE_n = k.\frac{C_k}{W}$.

We can plot this spectrum efficiency as shown in Figure 3.

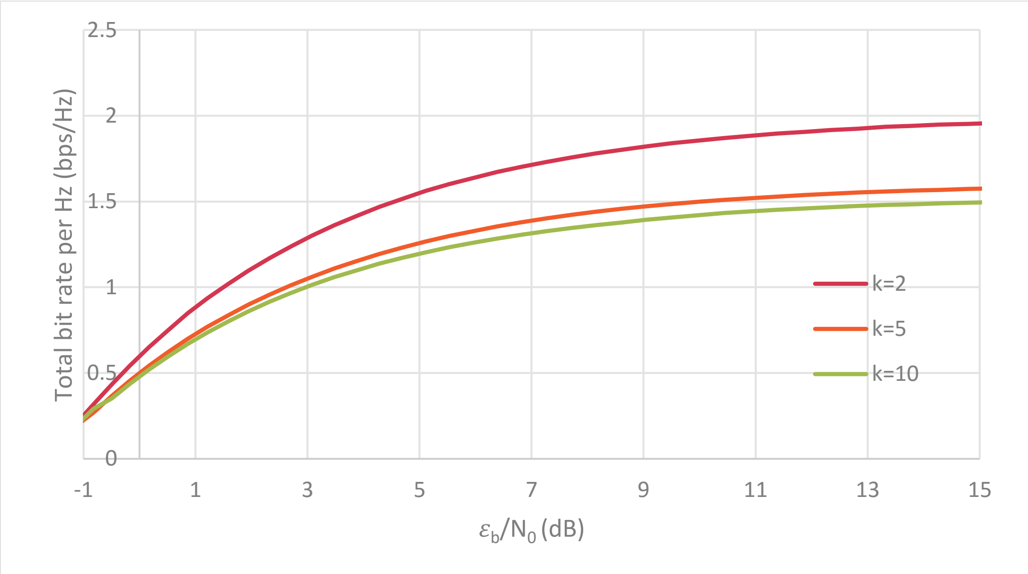

Figure 3: Total capacity per Hertz for a bandlimited spectrum block with CDMA partitioning per user, versus individual user ε_b/N_0.

The key issue with single user detection is that more users sharing the channel contribute additional noise to other users and the network capacity becomes self noise limiting. In contrast to the FDMA case, adding additional users reduces the total network capacity.

7.2.2 Spread spectrum with ideal multiple user detection

If we assume that the code of each potential interferer is known and that the interference from other users can be removed (multiple user detection and decoding) then the capacity of this idealised spread spectrum has a similar form to the UNB case described above when the date rate to each user is the same.

Typically, an efficient method of processing multiple spread spectrum signals so that the impact of other users' interference can be removed relies upon the following conditions:

- Signals from any interfering users are synchronised with the desired signal
- Spreading codes are selected so that the cross correlation with other users is zero

In practice perfect orthogonality between received signals is difficult to achieve in practical environments owing to fading and multipath. Reducing the amount of additional interference from other users is typically accomplished by controlling the transmit power of individual users so that the received signal power that is just sufficient to be decoded effectively. This desire to control the power level is what motivated 3G CDMA networks to update power transmit levels of each individual transmitter 1500 times per second.

Hence a key issue with multiple user detection based spread spectrum access methods is that even with ideal conditions, the spread spectrum capacity is upper bounded by that achievable by an FDMA approach with multiple narrowband channels, each of which are not constrained by power flux density constraints.

7.3 Summary of theoretical capacity considerations

In the preceding sections we have established that the LPWA channel is fundamentally noise limited as opposed to other channel impairments. Operation in licence exempt spectrum requires low power transceivers – but this power can be concentrated into a narrow bandwidth (UNB) or spread over a wider band (spread spectrum).

The capacity of a UNB system increases as the UNB channel bandwidth reduces. Spread spectrum methods that can employ ideal multiple user detection can achieve the same spectrum efficiency as the UNB approach. Spread spectrum systems that use idealised single user detection, even with perfect power control, have a spectrum efficiency that is limited by the network self-noise. This is consistent with the analysis by Viterbi [25] in his paper "When not to spread". In this he notes that "when [SNR] is at a premium … don't contribute further to the noise by having users jam one another, unless bandwidth efficiency is of no concern".

For the LPWA environment, the idealised conditions in which spread spectrum capacity will achieve the same as the UNB system would in practice be difficult to achieve. We can expect that a UNB system can support higher capacity with relatively little system complexity compared to a spread spectrum system.

8. Network Topology, Dimensioning and Interference Considerations

8.1 Network and communication topology

The conventional LPWA network is based on a star configuration, as shown in Figure 4. The communication direction can be in both uplink and downlink directions, with the bulk of the information flow from the end point to the base station.

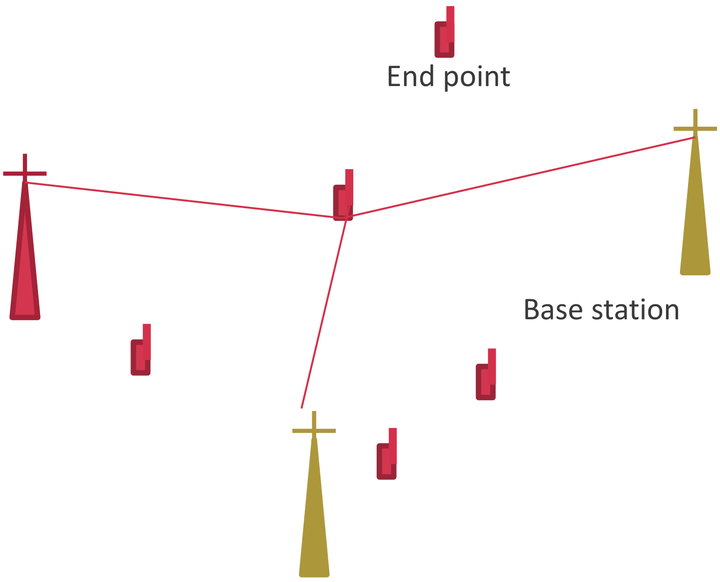

Figure 4: Representation of an LPWA star topology, showing Base Stations used to communicate with a distributed set of end points.

This short paper is not concerned with the methods by which end points are assigned to base stations – but we can assume that this allocation is made by some method and that end points are associated with base stations for the purpose of downlink and/or uplink communication as shown in Figure 5 with some overlap in the coverage areas of base stations to reduce the opportunity of coverage dead spots.

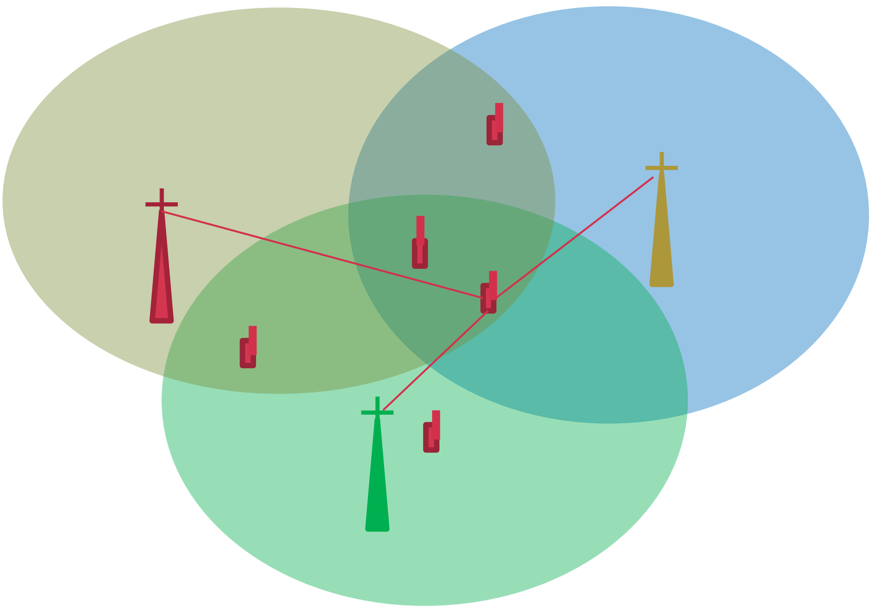

Figure 5: Association of end points with base stations – showing overlapping 'coverage' areas of several base stations.

The generic link margin developed above demonstrates that a maximum path loss of approximately 160dB can be achieved. Not all end points will be at the edge of coverage and the path loss between some end points and base stations will be considerably less.

According to [26], Sigfox claim that the dynamic range of signals received at the base station is up to 120dB. Without power control on the uplink it is highly likely therefore that the received transmissions of some end points will be much stronger than others and be present at a high signal level at multiple base stations in the uplink and receive energy from multiple base stations in the down link.

For an UNB system these downlink transmissions can be separated into narrow frequency channels much like the GSM communication system – but in much narrower channels. From the link budget discussion above, the channels are necessarily ultra-narrowband and there is scope for many of these narrowband channels in both uplink and downlink directions. The relatively high powered 250 kHz sub-band available in most European countries can accommodate several hundred ultra-narrowband downlink channels, with more spectrum available for the uplink. These downlink channels would need to be frequency planned much like a 2G GSM mobile network.

For a spread spectrum system, users can be separated by spreading codes and by different frequency channels. From the link budget discussion above, for the downlink direction in Europe, there is scope for two spread spectrum channels of 125 kHz, and spreading codes able to yield in a processing gain of approximately 25dB.

A key constraint in LPWA networks is the capability of the low cost end point, in terms of processing ability and battery duration. The low data rates in all links motivates keeping all signalling overhead to a minimum since it could typically represent a much higher proportional overhead than in higher data rate systems. This means that power control and synchronisation can be more difficult to achieve, than in higher capacity networks. At the other extreme, assignments of end points to channels or time slots may be done on a random basis, rather than explicit assignment, if any clashes can be resolved.

Different approaches to address this network consideration exist. For example, end points required to transmit an uplink message could be assigned a specific frequency (and code) and timeslot, which would require the end point to maintain time synchronisation and network control channels. An alternative, is that end points access the channels (time and frequency) completely randomly and the base stations resolve the multiple transmissions received – this has the advantage that the end points are not required to be active for much of the time or maintain tight network synchronisation. Intermediate solutions where slotted allocations are used (for either time or frequency) are possible.

8.2 Approximate dimensioning

We can develop an approximate dimensioning of both UNB and spread spectrum LPWA systems based on the generic link budget, capacity considerations and the discussion in Section 8.1 above.

ETSI has published use cases for LPWA networks [23], which suggests that end-points can have data volumes of up to a few 10's of kB per day, requiring overheads of approximately 100% on the physical layer with bursts as short as 12 information bytes. In the uplink, using the generic link budget, each burst would have a duration of 960ms. Telensa [27], state that their base stations can support more than 5,000 end-points. For the purpose of this exercise, we will assume 10,000 end-points per base station and 4kB of data per end-point per day. This results in a data volume of 1.2GB/month per base station and approximately 40 bursts / base station / sec over a 24-hour period, each with 12 bytes of information.

8.2.1 UNB uplink case:

To satisfy the uplink data rate, the 10,000 end points are assumed to randomly select one of many uplink channels for each transmission burst. This has an advantage of reducing the processing and synchronisation burden at end points – but this comes at a price of multiple bursts clashing if transmitted in the same channel at the same time. A good overview of random access methods and their efficiency is described in [28] and a key driver to channel efficiency is maintaining short burst durations to reduce the opportunity of burst clashes from different users of the channel. Maintaining the normalised channel traffic below 0.2 in this random access Aloha protocol would require 185 UNB carriers to be available. Assuming 200 carriers, this would require an uplink bandwidth of 40kHz. Higher uplink data transmission volume would result in more random burst clashes up to the maximum normalised channel traffic of 0.5 – though more carriers could be used to reduce this.

If this example UNB network operates at the peak Aloha traffic rate (i.e. normalised capacity of 0.5) then up to 312 simultaneous uplink bursts could be accommodated in a 125kHz bandwidth uplink channel.

8.2.2 Spread spectrum uplink case:

Using the uplink parameters from the generic link budget, and noting that maintaining uplink orthogonality is not feasible, the noise rise above thermal (RAT) noise contribution of other users at the base station with perfect power control is as shown in Figure 6.

Typically, a network would seek to operate below a noise rise of between 3 and 6dB, resulting in a maximum number of simultaneous uplink transmissions of between 40 and 60 bursts. Based on this, the assumed uplink transmission rate of 40 simultaneous bursts could also be supported with the spread spectrum case in an assumed bandwidth of 125kHz, but 60 simultaneous burst would be the limit in this bandwidth (i.e. DSSS would require approximately 2 times the amount of spectrum required for the UNB case with 60 simultaneous uplink transmissions). Other sources of intra-system or inter-system interference, or a higher uplink data transmission volume, would result in rapidly increasing noise rise at the base station if operated at this level of traffic.

With the assumed generic DSSS parameters, to maintain the uplink RAT below 6dB, with perfect power control and single user detection, only 60 simultaneous uplink bursts could be accommodated in a 125kHz uplink channel. This is approximately 20% of the capacity of the UNB case above.

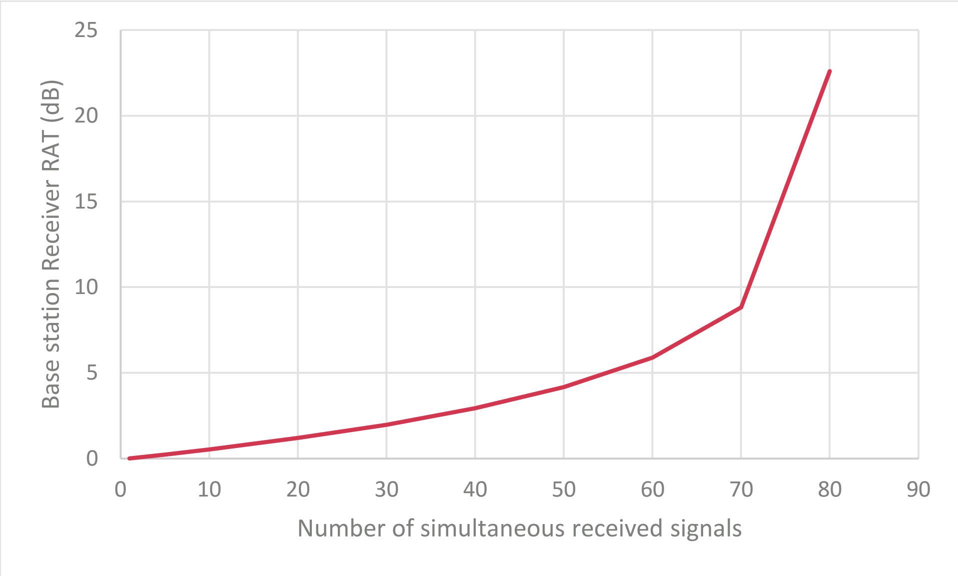

Figure 6: Base station noise rise for multiple uplink transmissions with perfect power control.

8.3 Interference Considerations

We wish to consider the ability of both UNB and spread spectrum approaches to mitigate interference, with different types of assumed network co-ordination in both the uplink and downlink directions. Owing to the regulatory EIRP limits, it is reasonable to assume that uplink and downlink channels use a frequency duplexing method and that, in Europe, the downlink would use the high power 250 kHz sub-band available in European countries.

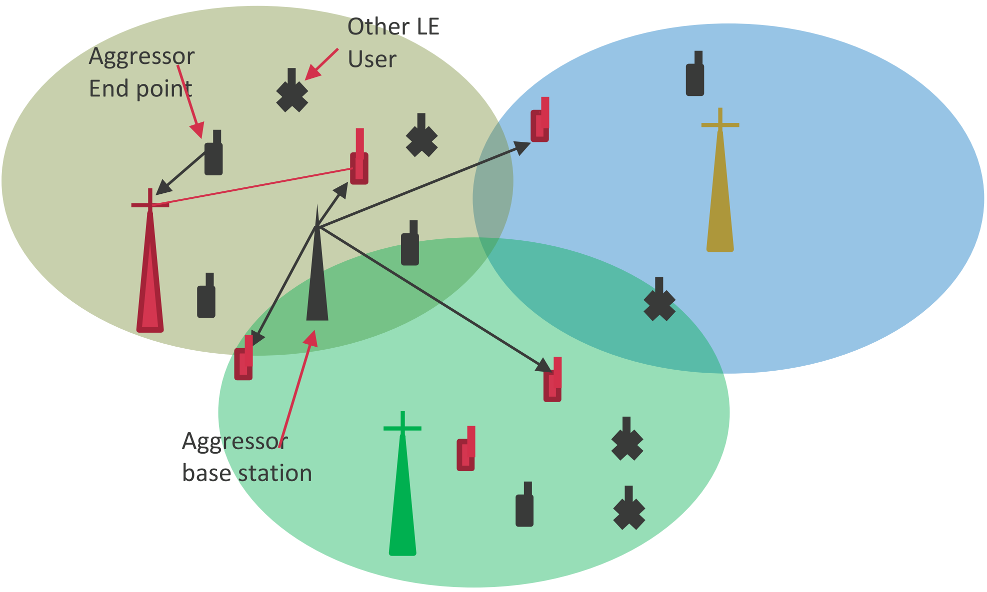

Figure 7: Co-existence of two hypothetical LPWA networks. Indicative coverage areas of the red, blue and green base stations are shown by the grey, blue and green elliptical regions. Interference sources are shown in black and include an uncoordinated base station from another operator, aggressor end-points and other LE users of the band.

Any deployment of an LPWA network in LE spectrum should anticipate the need to co-exist with a similarly loaded and uncoordinated competitor LPWA network and random interference from other LPWA users, as shown in Figure 7. For this reason, all LPWA networks are anticipated to use robust error correcting coding and checking mechanisms to allow recovery of random errors and to detect when these errors cannot be resolved.

8.4 Interference Assessment

In order to understand the interference impact of co-existing LPWA networks using UNB and spread spectrum approaches we will use the following assumptions as representative generic UNB and spread spectrum system values as discussed previously. These are:

- The UNB system will use a channel bandwidth of 500Hz for the downlink and 200Hz for the uplink
- The spread spectrum will use a channel bandwidth of 125 kHz for both uplink and downlink directions, leading to a processing gain of 250 for the downlink (24dB) and 625 for the uplink (28dB) to result in similar de-spread channel rates as the UNB system
- A required Eb/No of 9dB will be assumed for each system
- DL and UL powers will be set at the European regulatory limits set out in Section 3 and as used in the link budget
- Noting that the dynamic range of signals received at the base station can be up to 120dB, we will consider interference from an aggressor with 80dB less path loss than the victim
- Consistent with the approximate dimensioning, we will consider that 40 simultaneous bursts are incident on any LPWA base station at any given time
- We assume that multiple user detection is not possible at the spread spectrum base station, and that intra-system code orthogonality for uplink users is not feasible. We will consider the Direct Sequence Spread Spectrum (DSSS) spread spectrum variant in the rest of this analysis as it is the most widespread spread spectrum technology in use
- Other (non-LPWA) users of the LE band will be an additional source of interference. If these interference bursts are shorter than the LPWA transmissions, then error correction coding can reduce the impact of these non-LPWA transmissions

8.4.1 Interference Assessment of Single Links

Initially it is useful to consider the probability of interference and level of disturbance for the case of a single aggressor and interferer, between UNB and a spread spectrum system. The interference impact of an aggressor transmitting with power Tx, at a path loss L from the victim is shown in Table 6. Gp is the processing gain of the spread spectrum system and is also equal to the number of UNB carriers that can fit in the same bandwidth.

Table 6: Probability of interference and the effective interference impact between different UNB and DSSS spread spectrum systems operating in the same channel bandwidth, supporting the same datarate. A -> B designates that system A is causing interference to system B.

	UNB -> DSSS	UNB -> UNB	DSSS -> DSSS	DSSS -> UNB
Probability of interference	1	1/Gp	1	1
Effective interference impact	Tx/(L.Gp)	Tx/L	Tx/(L.Gp)	Tx/(L.Gp)

Clearly the probability of some interference impact with these co-bandwidth systems is 1 when either the victim or receiver occupies the whole band. Spreading either the aggressor or the victim serves to reduce the interference impact by the processing gain, Gp. The probability of two UNB carriers using the same channel is 1/Gp since a quantity, Gp, of UNB channels can be supported in the bandwidth assumed to be available.

8.4.2 Interference Assessment of Multiple Links

We can consider the impact of multiple links, in both uplink and downlink directions for these same aggressor-victim situations as shown in Table 7. Though there are 4 cases to consider the high level impact is the same for all except the UNB->UNB case.

Table 7: Interference impact assessment for uplink and downlink directions with multiple links for different UNB and DSSS spread spectrum systems operating in the same channel bandwidth, supporting the same datarate. A -> B designates that system A is causing interference to system B. (BS = Base Station)

	UNB -> DSSS	UNB -> UNB	DSSS -> DSSS	DSSS -> UNB
UL impact assessment	Interference impact on any one link reduced by Gp. Highest received interferer will dominate – 40 interferers assumed to be present at any one time	Other UNB using same frequency channels will increase probability of collision in UL. This can be addressed with dimensioning and number of channels	Interference impact on any one link reduced by Gp. Highest received interferer will dominate – 40 interferers assumed to be present at any one time	Interference impact on any one link reduced by Gp. Highest received interferer will dominate – 40 interferers assumed to be present at any one time

	All active UNB (and own uplink DSSS) would interfere with desired DSSS in uplink	available – though processing overhead at BS. Message retransmit strategy required.	All active DSSS (and own uplink DSSS) would interfere with desired DSSS in uplink	All active DSSS will interfere with UL UNB (and some own UNB transmissions will also interfere)
DL impact assessment	Interference impact on any one link reduced by Gp. Likely to only be one dominant DL interferer (10% Duty Cycle) Co-located sites would help reduce sterilisation ‘close’ to aggressor base station. Possibility of 2 DSSS channels of 125kHz – so planning could help.	Other UNB system could use different narrowband DL channel to avoid interference. If co-channel - likely to be one dominant DL interferer (10% Duty Cycle).	Interference impact on any one link reduced by Gp. Likely to only be one dominant DL interferer (10% Duty Cycle) Co-located sites would help reduce sterilisation ‘close’ to aggressor BS. Possibility of 2 DL channels of 125kHz – so planning could help.	Interference impact on any one link reduced by Gp. Likely to only be one dominant DL interferer (10% Duty Cycle) Co-located sites would help reduce sterilisation ‘close’ to aggressor BS. Possibility of 2 DL channels of 125kHz – so planning could help.

The inter-system and intra-system interference issues are discussed for uplink and downlink directions in the following sections.

8.4.3 Interference Assessment of Multiple Links - Uplink direction

Random interference from other low power LE devices will cause interference, which can be mitigated by the robust error detection and coding mechanisms employed. For UNB systems, intra system interference is mitigated by spreading the users between a large number of channels and operating at a load that reduces the probability of burst collision (see Section 8.2.1). For DSSS victim systems, the intra-system interference with effective power control will cause some rise in the interference noise at the base station which will limit capacity (see Section 8.2.2). Users may be allocated into ‘near’ and ‘far’ groups on different frequency channels (each using spread spectrum) to mitigate imperfections in power control that would increase interference at the receiver.

Victim or the aggressor is a DSSS system

When the victim or the aggressor is a DSSS system, though the interference impact of any one link is reduced by the processing gain, there are assumed to be as many as 40 bursts arriving in a channel bandwidth of 125kHz, which cannot be avoided. The strongest interference will dominate the interference impact on the victim receiver and the power of this dominant interference source will not be controllable. Though each victim link has a processing gain advantage and error correcting coding to mitigate burst errors, it is likely that:

- with as many as 40 simultaneous bursts at all times, this interference will appear as a continuous source of noise-like interference and will reduce the ability of the error correcting coding to correct errors in the datastream
- some of the interference will be at high power relative to some of the victim links

For these reasons, the range of the victim uplink will reduce as the aggressor network loading increases. Interference from aggressor end points nearby the victim base station could effectively jam/block the base station. This will limit the capacity of any victim DSSS system or any system subject to interference from a DSSS aggressor.

We can perform a rough assessment of the impact of this blocking assuming that both victim and aggressor networks are equally busy (with 40 simultaneous bursts) and that the aggressor transmits at full power (as would be the case with a UNB device, or a DSSS device distant from its serving cell). Assuming an urban Hata model with 20m base station antenna height and the end-point devices at a height of 1.5m with a penetration loss of 15dB, and circular coverage, the distribution of the users would be as shown in Figure 8. Clearly most of the cell area is close to the edge of coverage – 33% of the cell area is within 3dB of the assumed maximum path loss of 160dB.

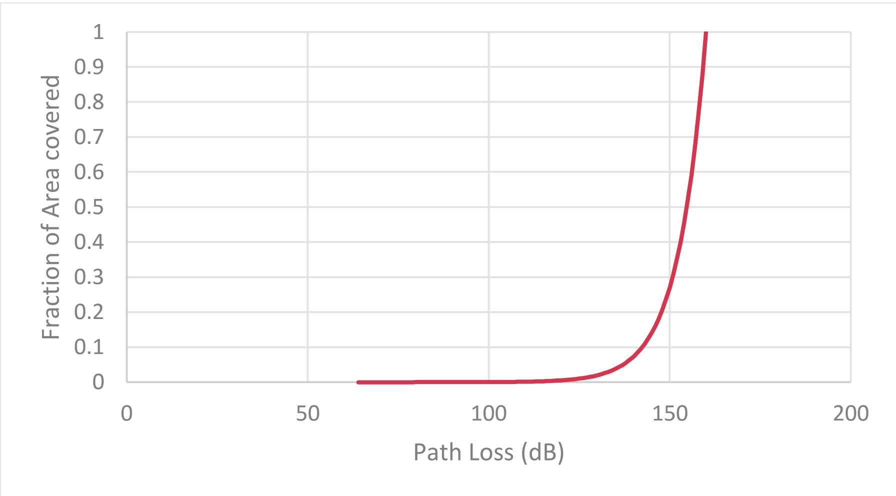

Figure 8: Fraction of the cell covered with increasing path loss

Assuming an uplink processing gain of 28dB and a required Eb/No of 9dB, a full power aggressor would effectively block the uplink transmissions of any end-points more than 19dB path loss from the victim base station. Assuming uniform distribution of users and aggressors throughout the cell, Figure 9 shows the fraction of the number of users blocked as the number of interferers increase for different values of assumed path loss differences required for blocking.

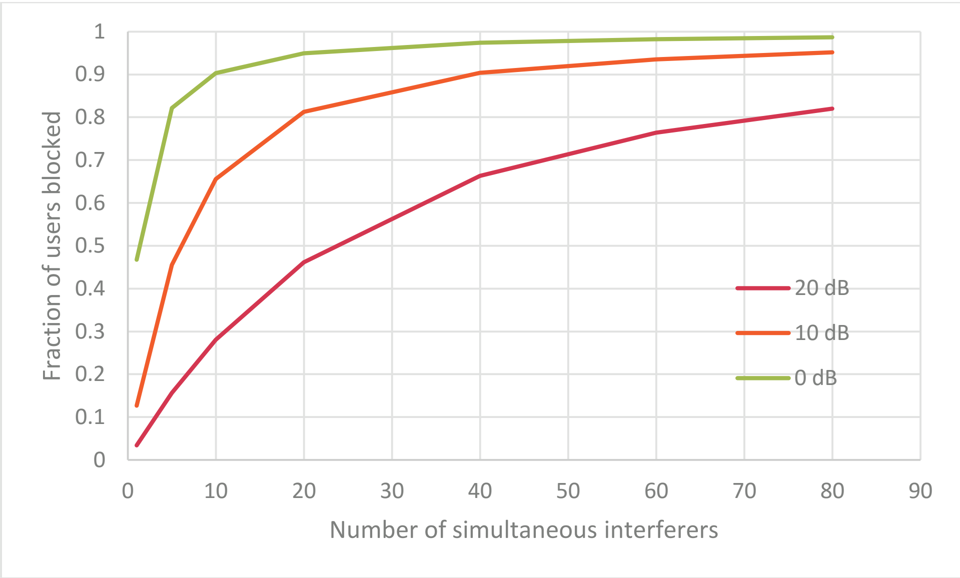

Figure 9: Fraction of users blocked as the number of simultaneous interferers increases.

Even though the processing gain provides a measure of resilience, when the aggressor or victim is a DSSS system in the presence of an uncoordinated network, there is a high probability of user blocking. For the case of 40 simultaneous aggressors active in the cell, 66% of the victim transmissions would be blocked. This level of blocking would essentially preclude co-channel operation unless the aggressor system has very few simultaneous users (i.e. low capacity). This is consistent with the findings of ECC Report 37 [29] where it is noted "if the victim operates within a sub-band, which is completely covered by a DSSS interferer, the victim is effectively jammed". This motivated the ECC to constrain DSSS duty cycle limits for SRDs in the band 863-870 MHz although these duty cycle limits are not applied to 868.0 – 868.6 MHz and 869.4 – 869.65 MHz – these bands are used for the uplink and downlink respectively for LPWA.

Victim and the aggressor are UNB systems

When the victim and the aggressor are UNB systems there is no processing gain advantage and burst clashes will inevitably occur resulting in loss of both bursts in the worst case. This has the impact of increasing the effective normalised channel loading of the Aloha protocol being used – essentially the effective channel loading increases to reflect the increased number of sources occupying the channel but the internal network load is only part of the traffic occupying the channel.

This therefore means that the system loading should be designed to accommodate 'wasted capacity' – so more channels may need to be assigned to maintain the overall channel occupancy within acceptable Aloha operational limits, but only a subset of the capacity is available to the victim system. Previously we had estimated that 40kHz was required to support the 40 burst/base station/sec uplink load – and so increasing this shouldn't require any more spectrum than the DSSS alternative system considered – but would increase the processing burden at the base station.

Therefore, where the victim and aggressor systems are both UNB, the interference can be mitigated by increasing the dimensioning of each system. This will require base stations to process more channels but there would be no other performance impact on range or capacity.

8.4.4 Interference Assessment of Multiple Links - Downlink direction

Again, random interference from other low power LE devices will cause interference, which can be mitigated by the error detection and coding mechanisms employed because the interference bursts are generally much shorter than the LPWA bursts.

For UNB systems, intra system interference is mitigated by frequency planning so that nearby base stations use different frequency channels. For DSSS networks different base stations can be time-synchronised and the downlink directions from different base stations can use orthogonal codes to reduce intra-system interference issues. In the downlink direction the intra-system interference can be well controlled for either UNB or DSSS approaches.

In the downlink direction, we note that base stations do not operate continuously; assuming that un-ordinated systems use different randomly selected access times, inter-system interference will not be simultaneously present at all times. For example, in Europe where each base station would have a duty cycle of less than 10%, two randomly operating un-coordinated systems would expect to be simultaneously active only 1% of the time. Downlink interference should be considered in this context.

Victim or the aggressor is a DSSS system
When the victim or the aggressor is a DSSS system, though the interference impact of any one link is reduced by the processing gain, when present the interference will appear within the victim receive band. At any given end-point, there is likely to be only one dominant source of interference (the nearest aggressor base station) whose impact will depend upon the relative path loss to the aggressor compared to the desired base station.

This would have the effect of reducing downlink message reliability – particularly for users remote from the desired base station and/or close to an aggressor base station (where the processing gain is insufficient to compensate received power level differences).

Co-locating potential aggressor base stations would resolve downlink interference issues for this case, but would impose a challenging co-ordination constraint during deployment with a likely competitor.

Victim and the aggressor are UNB systems
When the victim and the aggressor are UNB systems there is no processing gain advantage but isolation between systems can be achieved if different UNB channels are used.

We note that in a 250kHz bandwidth, 500 UNB channels of the required 500Hz bandwidth are available. Hence without co-ordination there is a small probability that uncoordinated UNB networks will use the same frequency channel. If this does occur, then it would be possible to frequency plan to use an available free channel. Until this new channel is found, there would be reduction in downlink message reliability – particularly to end-points at the end of coverage and/or close to aggressor base stations.

8.5 Interference assessment summary

We can summarise the interference impact and mitigation performance for these interference scenarios as shown in Table 8.

Table 8: Summary of the interference mitigation performance for all interference conditions – this assessment applies to both uplink and downlink directions. Green shading indicates little impact or easily mitigated interference, yellow indicates interference that can be mitigated against with some effort and pink indicates interference that is difficult to mitigate against.

	Victim Systems	
Aggressor Systems	UNB	Spread Spectrum
Own network UNB	Re-transmission strategy part of normal operation. Dimensioned to contain clash probability to acceptable levels	N/A
Other network UNB	Increased uplink clashes can be mitigated by using more channels and additional base station processing. Frequency re-planning may be needed to avoid interference.	Difficult to avoid impact of multiple simultaneous interference across wideband carrier. Impact worse on uplink, reducing range with the potential for some nearby interferers to block base station receiver.
Own network Spread spectrum	N/A	Intra-system interference will constrain (uplink) capacity – particularly with imperfect power control. Splitting users into ‘near’ and ‘far’ groups on different frequency channels can reduce impact but may not be feasible for mobile/nomadic end-points.
Other network Spread spectrum	Difficult to avoid impact of multiple simultaneous interference across all overlapped UNB carriers. Impact worse on uplink, reducing range with the potential for some nearby interferers to block base station receiver. Co-located base stations employing power control would mitigate interference – making deployment co-ordinated.	Difficult to avoid impact of multiple simultaneous interference across all overlapped carriers. Impact worse on uplink, reducing range with the potential for some nearby interferers to block base station receiver. Co-located base stations employing power control would mitigate interference – making deployment co-ordinated.

Based on the above deployment of DSSS LPWA networks will be problematic to co-exist with either UNB or other DSSS LPWA networks. Mitigation of the interference impact will also be difficult to achieve. Uncoordinated UNB deployment is likely to be able to co-exist with other UNB networks as long as dimensioning takes the opportunity for interference into account. In the downlink the opportunity for interference is less than in the uplink. Spread spectrum systems would benefit from synchronisation and UNB-UNB co-existence may require frequency re-assignment where downlink interference occurs.

9. Summary

Key requirements of LPWA systems are long range, extended battery life and very low end point cost with many use cases only requiring low data rates. Both UNB and spread spectrum system vendors claim to achieve these requirements with spread spectrum vendors claiming to be able to support higher data rates.

This report considered aspects of LPWA technologies related to the LPWA market, availability of suitable spectrum and associated regulations, standards development for LPWA and the suitability of UNB and spread spectrum approaches for LPWA use.

The LPWA Market

- M2M forecasts vary widely but Machina Research estimates that by 2024 14% of 27 billion M2M end points will be LPWA compared to 8% cellular end points – so vendors and end users should expect LPWA systems to be very widely deployed
- LPWA technologies offer a currently unique combination of range, battery life and low cost albeit at relatively low data rates. The number of use cases where LPWA can meet the requirements is increasing and deployments and endpoints quantities are forecast to grow rapidly in specific market segments
- This implies that such systems could be operating in the same location and sharing the same licence exempt spectrum. Successful co-existence capabilities will therefore be required to satisfy this future growth

Spectrum

- These systems are typically deployed in licenced exempt spectrum. The key advantages of licence exempt spectrum are that access to the spectrum can be secured immediately, it is available in a wide range of countries and perhaps most importantly it has zero or minimal cost
- Spectrum below 1GHz is preferred for these long range systems where end-points could be deployed in hard to reach locations. Within Europe, 7 MHz of licence exempt spectrum is currently available for LPWA use in the band 863 MHz to 870 MHz with a further 2x6MHz recommended for use in many countries, although with limited adoption to date. In North America 26 MHz of spectrum can be used by LPWA systems. However, constraints such as transmitter power and duty cycle limits (the proportion of time the transmitter can be active) along with the need for frequency hopping apply to different bands in different countries and can constrain coverage and capacity
- Provided a system can operate with duty cycle limits of (downlink/uplink) 10%/1%, transmitter limits of 500mW /25mW ERP and frequency hop every 0.4s both US and European markets can be addressed with the same equipment.

Deployment in Asia would need to be done on a country specific basis due to the lack of regional harmonisation

- Access to licence exempt spectrum that can support higher power transmission is restricted to a 250kHz sub-band in all but 4 European countries. The use of such higher powers facilitates the support of long range downlink communication. Adoption of CEPT's ERC recommendations to permit higher power in a further 6 MHz in more European countries would simplify adoption of these systems in future
- Conditions and regulations for deployment in licence exempt spectrum vary across the three ITU regions and vendors will develop systems that maximise the territories where such system can be deployed. Combining the requirements for Europe and North America is relatively straightforward – Asia Pacific present some problems due to the current lack of region wide harmonisation – although some countries will accept systems that satisfy European or North American regulations

Standards

- Proprietary LPWA solutions have been available for some years and standards activities are currently underway within ETSI. Availability of standards would accelerate market take up

Technology

- Both UNB and spread spectrum approaches can satisfy the high path loss link budget requirements of LPWA systems. However for the LPWA propagation channel, the limited amount of spectrum available where higher power is allowed (250kHz) is insufficient to provide mitigation to fading. This benefit, normally associated with spread spectrum systems, is not achievable in this case
- The capacity of a spread spectrum system will be limited by its own self noise. Other traditional benefits associated with spread spectrum (such as operating with lower fade margins) do not yield a benefit in an LPWA network. Maintaining tight power control is likely to be difficult with low levels of bi-directional communications. In theory, multi-user detection spread spectrum methods with perfect power control would allow the same capacity to be achieved, but at higher complexity, than the UNB approach
- For isolated LPWA networks, either UNB or spread spectrum approaches would be able to operate effectively. UNB distributes the traffic over many narrow channels and the spread spectrum approach separates users by codes and would require effective power control to limit self-noise
- When a LPWA system needs to operate in the presence of another LPWA system, we note that direct sequence spread spectrum (DSSS) system is likely to be a poor neighbour – it is both difficult to avoid interfering with and suffering interference from a DSSS LPWA network. The impact will be more pronounced on the uplink. The range of the victim uplink will reduce as the aggressor network loading increases. Interference from aggressor end points near the victim base station could effectively jam/block the victim base station
- Co-existence of two UNB LPWA networks is less problematic. Inter-system interference can be easily mitigated by using more channels in each system. This will require base stations to process more channels but there would be no system performance impact

- For the example network characteristics and idealised assumptions considered in this report, an isolated UNB network would have approximately 5 times the uplink capacity of an isolated spread spectrum network. Shared channel operation, with either a spread spectrum network and a UNB network, or with two spread spectrum networks, will result in mutual interference and uplink blocking of both networks sharing the channel, unless the interfering system has very few simultaneous users - i.e. these networks can only effectively co-exist in very low capacity deployments. Two UNB networks can more effectively share access to the spectrum – essentially sharing the available capacity. In this sense, a spread spectrum LPWA network can be considered a "bad neighbour"

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