An examination of CBRS and its applicability to industry private LTE

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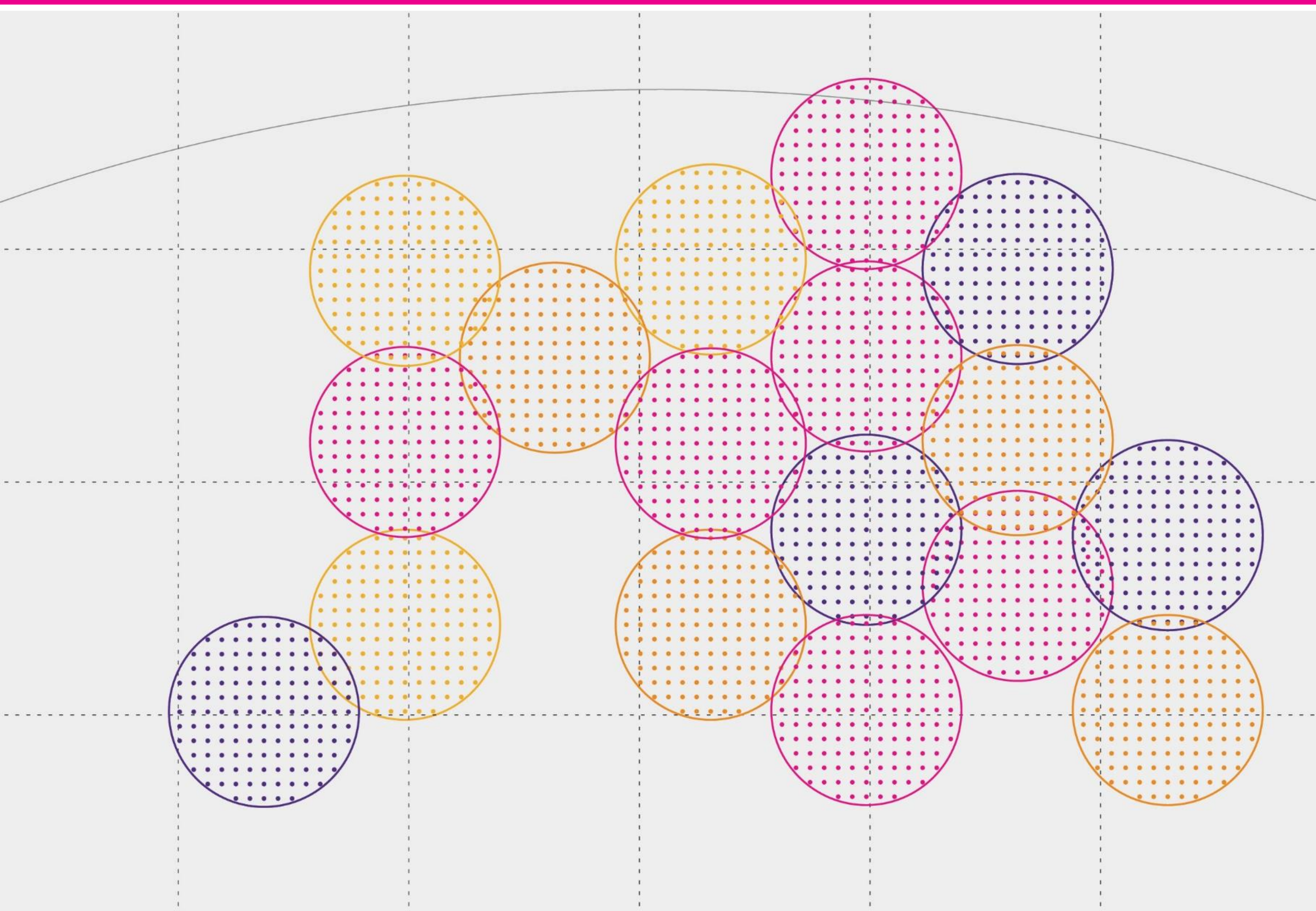

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Plum offers strategy, policy and regulatory advice on telecoms, spectrum, online and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence.

About this study

This study examines the CBRS (Citizens Broadband Radio Service) regulations in the USA and analyses their applicability to private LTE in 4 industry use cases: a port, a mine, a logistics hub and a wind farm. It gives some insights on the business applications of CBRS, particularly in the case of industrial (real-time) automation and shows to what extent CBRS – through the fact it enables flexible, fast and reliable access to spectrum – might be a solution for spectrum access, under some conditions.

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Executive summary

This report considers the CBRS spectrum, its regulation and its applicability to four real industry use cases: a mine, a port, a wind farm and a logistics hub.

CBRS appears as a favorable license scheme to industry for several reasons:

- The flexibility of spectrum use.
- The possibility of licence renewal.
- A quite extended licence period (10 years).

Nevertheless, CBRS displays certain characteristics that appear to be unfavourable to some industry use cases. Using CBRS spectrum potentially incurs incremental costs, while providing a low incremental reliability. In this way, the value of CBRS spectrum is based on the operator' willingness to pay and thus largely based on the value put on the incremental reliability and flexibility compared to use of unlicensed spectrum. Another CBRS constraint is the mandatory heartbeat mechanism that makes its application unreliable (or not feasible) in some use cases.

- In the case of mines, private LTE networks are almost unique in that they are completely separated from any potential public LTE network, not just by geographic distance but also by natural barriers, and as such there is unlikely to be any interference caused by using spectrum which is otherwise used by these networks. This is why mines appear as an ideal place for CBRS spectrum to be used. GAA would be enough to ensure that the private LTE network could operate with enough reliability and consistency. However, the technical working of CBRS is likely to prevent CBRS spectrum being used: The location of private LTE equipment may prevent it from receiving the heartbeat from the controller, and without this heartbeat the network will not be able to operate.

- In ports, networks deployed usually require large bandwidths, and high reliability. As they are also in areas open to the public (e.g. cruise ship terminals and marinas) it is likely that mobile networks will have deployed their own networks to cover at least part of the port area. This mix of requirements from private LTE operators and mobile networks will mean that the only spectrum that could be used for the private LTE network would be that covered by CBRS. Given the need for high reliability, private LTE operators would need access to PAL, but given the county-wide licencing regime of CBRS's new regulations, it would likely be unprofitable for private LTE operators to buy a PAL themselves. Therefore, we would expect a PAL leasing arrangement would be most suitable. However, it may be that not all PAL options across the county of Los Angeles are taken up by other network operators, and the port may then elect to acquire a PAL itself at a low price. The limit is likely to be the bandwidth available – it may be necessary for multiple licences to be used to meet the demands of various networks.

- The majority of large windfarms are situated away from built-up and populated areas. This means that higher frequency spectrum is unlikely to either cause interference or suffer from interference from other sources, given the short propagation distance. The lack of interference will in turn lead to a low opportunity cost associated with the use of CBRS spectrum; PAL holders are unlikely to be inconvenienced if they allow the wind farms to sublease their spectrum. While wind farms appear to be an ideal case for CBRS spectrum sharing, given the lack of interference and likely low opportunity cost, there are several logistical issues to overcome before the benefits can be realised.

- The use of CBRS spectrum in the logistics hub can be considered as two different use cases – indoor and outdoor. Within the fulfilment centres and sorting buildings, CBRS spectrum can be used with little risk of interference to the surrounding region, since the spectrum used for CBRS is generally unable to penetrate walls. However, the outdoor usage has the same issues as described for ports: logistics hubs are likely to be in built-up areas, with many other potential uses for the spectrum, and as a result the opportunity cost of PAL leasing may be high.

1 Introduction

In the United States, the 3.5GHz band is currently used by the Department of Defence (for military radars), fixed satellite systems and some wireless ISP. Nevertheless, at any given time, only a part of this spectrum may be used. In order to make this spectrum available for commercial use while keeping it secure for military use, the FCC has developed the CBRS 3-tier framework that offers a flexible access to shared spectrum via the implementation of a SAS (Spectrum Access System).

The first section of this report examines CBRS rules and specificities, and the latest rules update published in October 2018. It then discusses the balance between costs and benefits when applying CBRS to a business, as well as the impact of this balance on the value of CBRS spectrum.

The following section examines the general applications of private LTE in the industry and shows the key trends of the future factory.

Subsequent sections of the report assess the communications needs for private LTE installations and the potential applicability of CBRS to them. It details the types of applications likely to be used and nature of demand in the four use cases;

- An underground mine: Bailey mine, Pennsylvania.
- A harbour: the port of Los Angeles.
- A windmill farm: the Alta Wind Energy Center, California.
- A logistics hub: The FedEx World Superhub, Memphis.

While there is a focus on the communication requirements of the use cases, which will create specific communication needs, there are also characteristics common across the use cases. Each industry case is studied on a current view and on a future perspective.

2 Examination of CBRS regulation

In the United States, CBRS (Citizens Broadband Radio Service) has been considered as a game changer in the mobile industry, reviewing the traditional concept of spectrum ownership. In 2015, the Federal Communications Commission (FCC) has made available 150 MHz in the 3.5Ghz band for commercial use, applying a spectrum-sharing framework that is described in Section 2.1. This expands the spectrum supply for mobile services using LTE and also makes provision for flexible entry to the band by smaller or specialist spectrum users, including access without a licence requirement. In this way, CBRS creates an improved experience for users (in terms of capacity, speed and flexibility) and applies to business and industry automation, meeting new needs of the future industry as explained in Section 3.

2.1 The CBRS framework

2.1.1 The 3-tier model: "use it or share it"

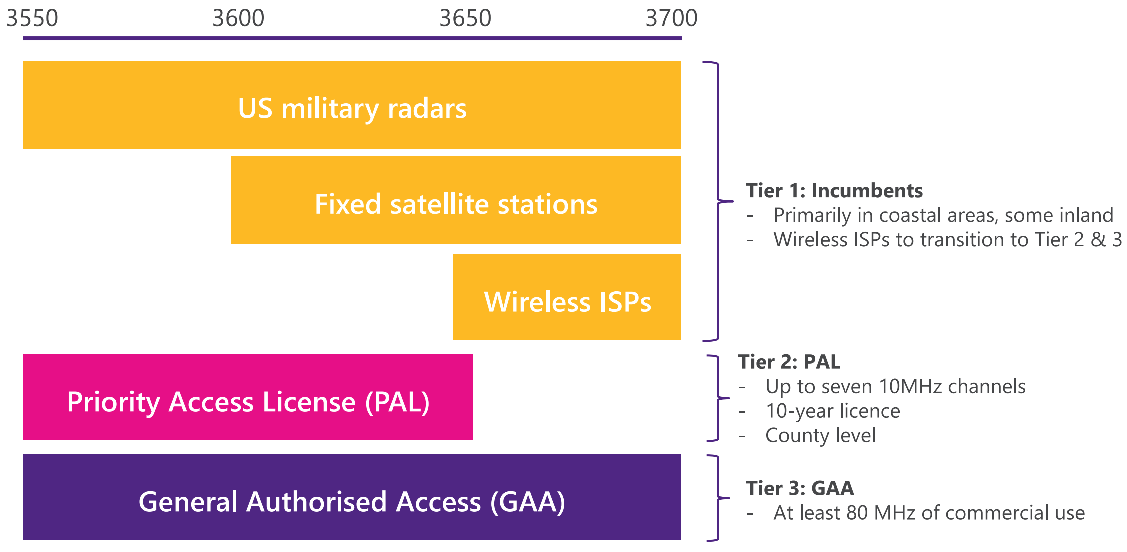
In 2015, the FCC adopted an Order to implement CBRS in the 3.5GHz (3550-3700MHz) band for shared wireless access, opening up a spectrum band previously used by the US Navy. The rules were finalized in a further Order in 2016.

A 3-tier model of licensing structure – 3 levels of CBRS users – has been deployed (Figure 2.1):

- Tier 1: Incumbents (US military radars, fixed satellite stations, wireless ISPs temporarily). They have a permanent priority to spectrum and a specific protection on the registered sites.
- Tier 2: PALs (Priority Access Licensees). They can request up to 4 PA licences over a defined geographic area for 3 years in previous regulation (10 years in latest one).
- Tier 3: GAA (General Authorized Access) users. They use the rest of the spectrum, that is not used by Tier 1 and Tier 2.

Tier 1 is protected from possible interference from lowest tiers (PAL and GAA users). Tier 2 is the following priority access and is protected from GAA users.

Figure 2.1: CBRS 3-tier model



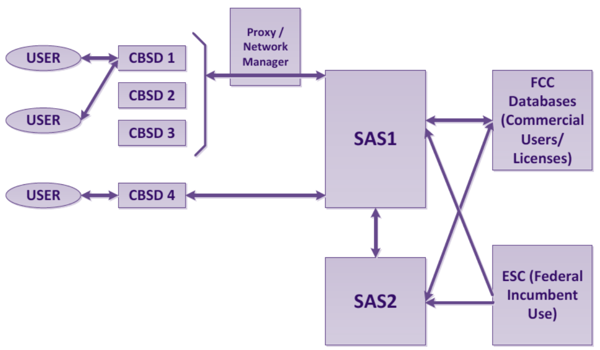
Mobile network operators and other entrants will be able to build LTE networks and use this spectrum to provide coverage and capacity. For mobile network operators this increases their capability and reach.

CBRS offers enterprises and organisations an opportunity to deploy a private LTE network, as a more flexible alternative than Wi-Fi., including higher in-door coverage, higher data capacity, security, opportunity to run industrial IoT applications, opportunity to develop a private network in remote areas.

2.1.2 Spectrum Access Systems and neutral host concept

In order to facilitate shared federal and non-federal incumbents' use of the band and coordinated access between users, SASs (Spectrum Access Systems) – automated frequency coordinators – are used (Figure 2.2).

Figure 2.2: FCC's SAS architecture

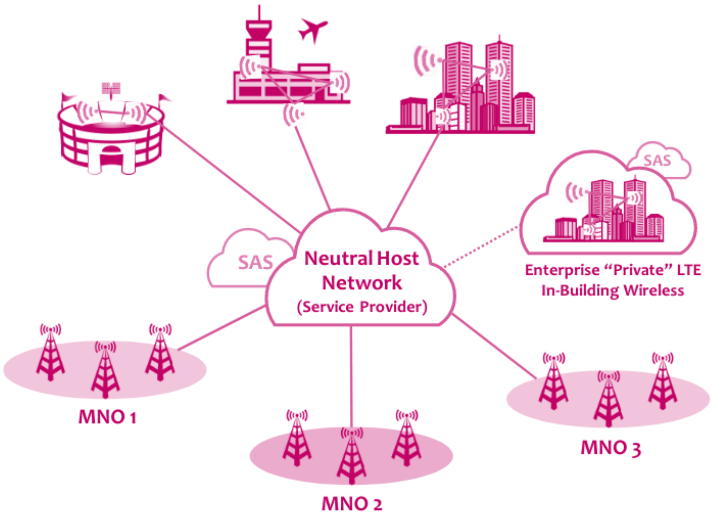


Source: Spectrum sharing: LSA and SAS, M.D. Mueck, S. Srikanteswara, B. Badic, Intel White paper, Oct 2015

SAS provides the means of managing the spectrum, handling the environmental sensing and authorising channels for use: It allocates channels that users (GAAs and PALs) can access.

The neutral host function allows multiple operators to make use of common licensed spectrum and aims at incentivizing small organizations to develop their own network (Figure 2.3) It can be provided by the SAS.

Figure 2.3: Neutral host network provider / Large enterprise LTE network using CBRS



Source: CBRS opens new managed services opportunity, K. Mun, 2017, Mobile Experts / Ruckus Wireless white paper

This SAS concept enables:

- Optimal use of the shared spectrum.
- It does this by calculating likely interference and the mitigation required.
- Dynamic arbitration of tiered usage.

And it responds to a "growing need (...) to bridge the gap between very large projects with direct mobile operator involvements and large numbers of smaller projects that are too small for mobile operators to consider, but too complex for enterprises to handle on their own."[1]

SAS operators' costs incur database monitoring, development costs and operating costs. But for the time being, any insights on SAS fees and business models do not seem to be publicly available.

2.1.3 CBSD (Citizens Broadband Radio Service Devices) characteristics

The FCC has determined two categories of CBSD, that are devices capable to support CBRS band:

- A Category A device is authorized a maximum EIRP of 30 dBm/10MHz. It has to be deployed indoors with antennas below 6 metres. For SAS registration, along with their requested authorization category (PAL or GAA), Category A base stations must provide their FCC ID number, call sign, user contact information, air interface technology, unique manufacturer's[2] serial number and sensing capabilities if supported.
- A Category B device is authorized a maximum EIRP of 40dBm/10MHz. It has to be deployed outdoor with antennas above 6 meters. For SAS registration, along with their requested authorization category

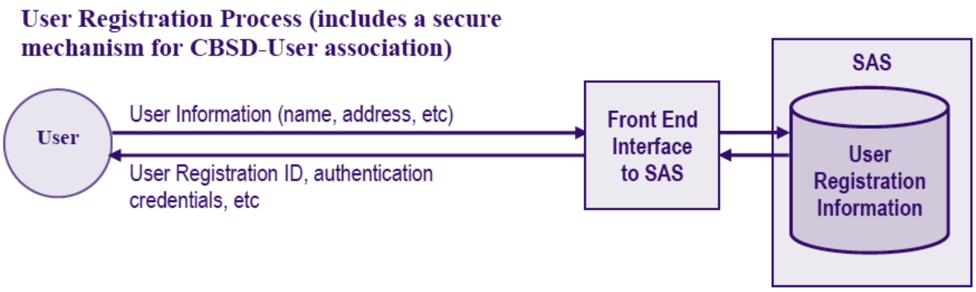
[1] CBRS opens new managed services opportunity, K. Mun, 2017, Mobile Experts / Ruckus Wireless white paper
[2] Equipment Manufacturers are Nokia, Ericsson, Samsung, Ruckus, Cisco, Huawei, etc.

(PAL or GAA), Category B base stations must provide their FCC ID number, call sign, user contact information, air interface technology, unique manufacturer's[3] serial number, sensing capabilities if supported, antenna gain, beam-width, azimuth, down-tilt angle and antenna height.

2.1.4 The CBRS functional process

Before transmission, the radio node has to register with a SAS (Figure 2.4), to request a spectrum grant (desired frequency range and power level, PAL or GAA operation, …) and to receive this spectrum grant before starting operating.

Figure 2.4: User registration process



Source: CBRS protocols technical report, Wireless Innovation Forum, Aug. 2017

During operations, the radio node must maintain connectivity with SAS via heartbeat mechanism[4]. In case of a lost connectivity, the radio node has to cease operations within 300 seconds in order to comply with the incumbent protection principle of CBRS. In case of detection of an incumbent activity, the SAS informs the radio node that it has to modify operation (such as switch frequencies) or cease transmitting.

2.2 Recent updates in CBRS regulation

In October 2017, the FCC published a Notice of Proposed Rulemaking for PAL[5], seeking comments on how new rules – on various subjects including PAL licence term and renewability and secondary markets – would impact the market (e.g. increase PAL licence term to 10 years instead of 3).

In October 2018, final details of CBRS licensing were released[6]:

- Priority Access Licences will be valid for ten years (3 years in previous rules).
- PAL include possibility of renewal (previous rules did not).
- PAL areas have been extended from census to county (Seven PAL available in each county).
- PAL may be partitioned and disaggregated (previous rules did not allow this).

[3] Equipment Manufacturers are Nokia, Ericsson, Samsung, Ruckus, Cisco, Huawei, etc.
[4] For detail on heartbeat procedures and timing, see: CBRS protocols technical report, Wireless Innovation Forum, Aug. 2017 ("Document WINNF-TR-0205)
5 https://transition.fcc.gov/Daily_Releases/Daily_Business/2017/db1024/FCC-17-134A1.pdf
6 For more details, see « Remarks of FCC Commissioner Michael O'Rielly, before the 7th Annual Americas Spectrum Management Conference, Washington DC, October 2 2018 (https://bit.ly/2zai6HR).

- 80 GHz of spectrum is available for unlicensed use.

2.3 Considerations for business applications

As described in the three-tier model, potential users of CBRS spectrum have four options.

- A traditional licence – they can always use the spectrum.
- PAL – can use as long as incumbent traditional licence is not using.
- GAA – can use as long as neither traditional nor PAL is using.
- Alternative unlicensed bands – can use but with no guarantees over interference.

There is a fifth option, however, which sits between PAL and GAA: private LTE network operators can choose to sublease from a PAL holder, giving them additional reliability and security as long as they do not cause interference with the PAL holder's own operations. This form of licensing may be attractive for private networks, particularly as they are unlikely to require spectrum on a county-wide level and so acquiring spectrum covering such a large geographic area is unlikely to represent value for money.

2.3.1 Licence periods

The update of CBRS rules has made licence periods and renewal conditions favourable for its use in private LTE networks. Licence periods are ten years – which will enable investment in networks – and while renewal is not guaranteed, as long as licensees demonstrate that over the course of its license term, the licensee either:

- provided and continues to provide service to the public, or
- operated and continues to operate the license to meet the licensee's private, internal communications needs,

there is an expectation of renewal. For public network use, coverage must be over 50%. Sublicensing is included in this figure – which may encourage PAL holders to offer spectrum for private networks if it helps their coverage statistics.

Further, the fact there are multiple licences available in each county should mean operators have confidence in the long-term nature of their operations.

2.3.2 Characteristics of CBRS

To use licensed CBRS spectrum:

- Monitoring equipment is required and must be maintained to hear the 'heartbeat'.
- Significant capital and ongoing operating expenditure are implied.

CBRS spectrum is not appropriate for areas where required signals cannot be received.

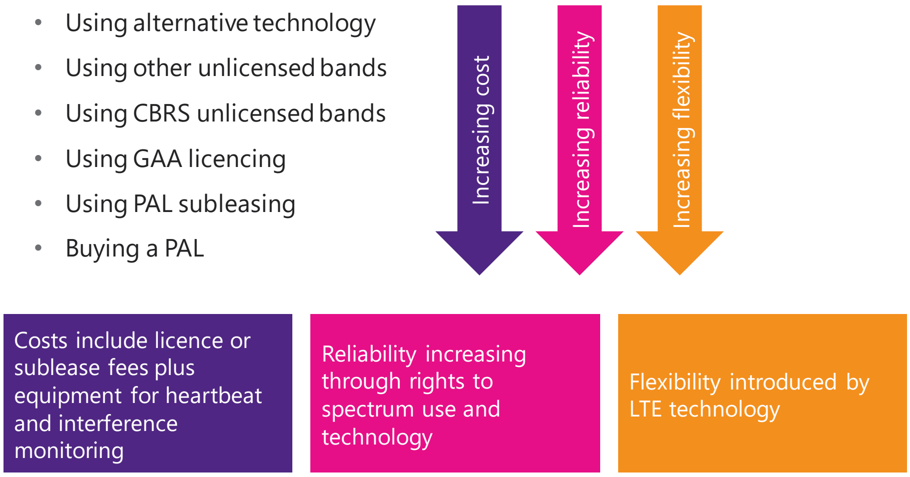
Quality of Service issues must also be considered. Different use cases will require different reliability standards, and the type of licence will therefore confer a different value of spectrum. The geographic nature of the demand will prevent full licencing or PAL from being a realistic mechanism for most private networks, unless micro-regional licences are made available on a reserved band.

Finally, to decide on the appropriate licence, users must compare incremental benefits of reliability and certainty against additional costs that might be incurred. The value of spectrum is driven by this balancing.

2.3.3 Balancing costs and benefits

Potential users have a number of options when considering which spectrum to use in their communications systems. Figure 2.5 sets out a list of potential options and considers how costs and benefits (measured in terms of reliability and flexibility) change with them.

Figure 2.5: Costs and benefits from communications solutions



The cost of using CBRS can be split into two factors:

- The licencing cost of spectrum (for PAL subleasing, PAL holders must consider the opportunity cost of not having access to the spectrum in order to assess this cost, and so this is not driven directly by the private LTE network); and

- The cost of additional monitoring or control equipment. Environmental Sensing Capability (ESC) is mandatory to detect military radar operations before operating CBRS. This may be provided by the SAS operator, or by a third-party ESC operator. In any case, these costs will be passed on to end users through higher service fees.

Other costs, such as running the network and an initial capital outlay are likely to be very similar for all other communications solutions listed above, other than perhaps the first (which would use other consumer-level equipment for communications). These costs therefore represent the incremental cost of using CBRS spectrum. If the private network decides to buy a PAL itself, then obviously the second of these costs rests fully on the network.

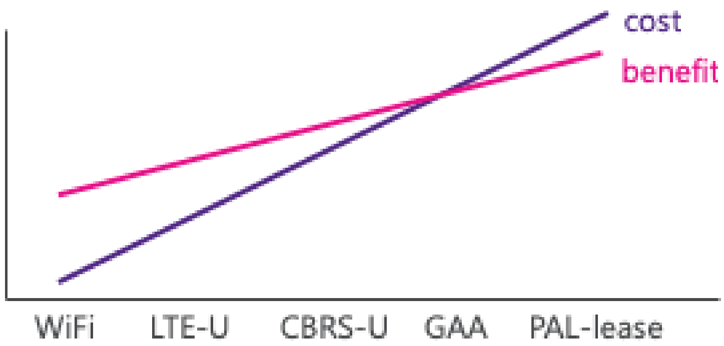
Although these costs may be small, they will still be non-zero, meaning that private network operators must receive a significant benefit from using CBRS spectrum. Users can consider how to quantify the benefits by thinking of willingness to pay – which they already do when considering which systems to use. The main issue faced when looking at the use of CBRS spectrum is the small increment in reliability, meaning there are relatively small benefits.

We can estimate the willingness to pay for reliability by proxies:

- Business continuity insurance – but this is going to consider full loss of service, not just the chance of reduced service;
- Existing investment in failsafe and security; or
- Estimating the cost of loss of productivity if the system fails and multiplying this by the expected failure rate to give comparative benefits.

However, these benefits are going to differ for every specific case, and in almost every example deriving a robust estimate of benefits will be impossible for a third party given the need for confidential operating information and business decisions. Only the potential private network operator will be in a position to compare its own benefits and costs, and it can do so for each potential communications solution as shown in Figure 2.6.

Figure 2.6: Costs vs benefit



The slope of the cost lines is likely to be similar for most use cases, but the slope of the benefit line will depend on the value placed on reliability and flexibility. For many users, the difference in benefits between GAA and PAL subleasing is likely to be very small, and if this is the case then it is unlikely that a PAL sublease will be used.

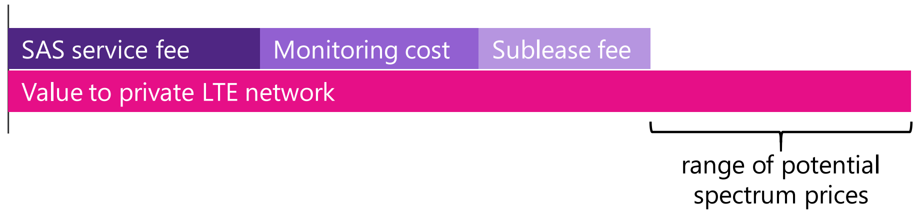
2.3.4 Impacts on the value of CBRS spectrum and application to sub-leasing

This balancing between costs and benefits will be used by private network operators to consider how they value CBRS spectrum; it could also, in theory, be used by PAL holders to work out an appropriate price to charge for a PAL sub-lease, and by SAS operators to work out an appropriate price to charge for their services.

The value of spectrum is determined partially by the net benefit that private network operators can gain from the use of CBRS spectrum but is also partially driven by the potential benefits that could be obtained by using alternative spectrum. The appropriate calculation is not, therefore, just the difference between costs and benefits, but is the difference between the incremental benefit obtained from CBRS over and above those benefits that can be reached from using unlicensed or licence-exempt spectrum, and the difference in costs between these two spectrum options.

In April 2018[7], Plum developed a valuation model to consider how licence holders should work out an appropriate price to charge for subleasing their spectrum to private LTE networks, based on opportunity cost to the licence holder and the incremental benefit to the network operator. Since estimation of the benefits is not possible for the licence holder, the optimum pricing strategy should be to price just above the opportunity cost. An analogy can be drawn to CBRS spectrum use; as it is not possible for a third party to identify the incremental benefits, the price should be kept to a level that just covers costs – while there is a range of potential spectrum prices, it is uncertain where the upper bound of this is.

Figure 2.7: Costs and benefits for PAL subleasing



However, unlike in the case of a single spectrum licence holder deciding on its subleasing strategy, there are multiple stakeholders involved in setting the price for PAL subleases. Conversely, there is no defined willingness to pay for any specific aspect of the CBRS ecosystem (SAS services, PAL subleases, monitoring equipment), but rather the willingness to pay is at the aggregate level, based on the incremental benefits realised from CBRS. Therefore, each stakeholder is advised to set their prices as low as possible to avoid driving away potential spectrum users.

2.3.5 Concluding remarks

Policy decisions may make PAL-leasing unrealistic for the industry.

- Counties are appropriate for small – not tiny – operators (From decisions it is clear that the FCC sees this band as being useful for small wireless providers covering rural communities).
- Monitoring equipment will present a barrier to entry and know-how cost is also high, even if supplied by the SAS: If costs are too high, alternative technologies will be used instead. Even if provided by the SAS operator, the cost of monitoring equipment will need to be covered by the price paid by private network operators for a PAL sublease.

As well as these policy decisions, limitations come from policies baked into CBRS implementation. The need for monitoring equipment increases the cost of implementation, and (as will be seen in the cases of mines and possibly wind farms) may make CBRS spectrum unusable.

Given this, there are some clear policy recommendations.

- Policy-makers should try to keep costs as low as possible.
- Efficient use of spectrum will depend on maximum numbers of networks.
- PAL holders should price just above opportunity cost in order to encourage as much use as possible.

[7] Plum (April 2018), "Access to spectrum and valuation of spectrum for private LTE"

3 Private LTE applications in industry

The applications described below serve the main objectives of industry management, which may be summarised as set out below:

- Operations and productivity (digital automation to increase production efficiency, asset management and tracking to reduce production costs, weather forecasting, etc.).
- Enhancing security and safety (to reduce intrusion or other threats both physical and systems based and create safer working environments).
- Planning and decision making (to create more efficient outcomes).

An ecosystem is required to provide the private LTE applications likely to be required in each of the cases considered in this report. To create the ecosystem requires both suitable devices to provide communications capability and the applications to provide the required industrial functionality.

3.1 The heterogeneity of devices and applications…

There are many devices / sensors likely to be used in industrial automation cases including (See Appendix A for a more detailed view):

- Devices: mobile phones, computer, tablets, modular transceivers potentially used in: vehicles, robots, drones and other machinery…
- Sensors: connected to the devices for monitoring (position, level, movement, temperature, gas…), radars, Lidars[8], photo camera (still image), HD real-time video camera, infrared camera, UV camera….
- Applications (attached to a specific function / objective):
  - Push-to-talk for group communication, emergency call;
  - tagging
  - (real time) video analytics and 3D modelling to detect, count, track, follow… flows of people, assets… (geofencing, mapping, topography)
  - thermography, temperature monitoring and thermal analysis,
  - gas detection,
  - maintenance, predictive maintenance,
  - asset efficiency (monitoring the actual viability of an asset; diagnostic analysis to detect anomalies from comparing previous and current data; determining remaining life of the asset)
  - Push to Video, Push to Data.

[8] Lidars (Laser Imaging Detection and Ranging): remote sensing method using light as a pulsed laser to measure variable distances.

3.2 … will entail a heterogeneity in performance requirements

The current use of private LTE networks and IoT in the industrial sector is characterized by narrowband sensors and driven by simple functional requirements.

The trend is to greater use of broadband sensors – while narrowband sensors keep a role – with enhanced downlink and uplink transmission capabilities. Potential for integration into systems and processes is increasing, while it is currently still limited, as well as network flexibility and ability to adapt to configuration changes.

Figure 3.1 details these trends for each category of application.

Figure 3.1: Future trends for private LTE networks

Voice operational	• Continuity of narrow band operational voice communications • More high definition voice for greater quality / clarity • Greater integration to other processes • Increased facilities for conference and augmenting with image / video
Voice critical / emergency	• Continuity of critical / emergency voice communications • Introduction of enhanced emergency calling features (e.g. group call, fast response PTT, etc) • Integration with video and other features to improve response
Static narrow band sensors	• There will continue to be a role for static narrow band sensors • Expect to see the quantity of them increase over time • Will see a progressive substitution of functions to broadband sensors
Broadband sensors	• Increasing communications capability will facilitate and increase in use of broadband sensors (e.g. video, continuous data transmission, • Partial substitution of narrow band functions

The industrial sector will see growth in applications and network requirements driven by:

- An increasing number of connected sensors and devices for multiple purposes.
- A shift towards greater use of broadband applications: The device environment for today's industrial applications is characterised by the use of many intermittent, low data rate sensors and controllers. In addition to these devices, there is a growing segment of more sophisticated wideband and broadband devices that provide more complex and extensive information and control functions (in both uplink and downlink). For example, provision of more detailed or continuous measurement data, more continuous control function, constant HD video feed. Moreover, the use of more sophisticated devices and enhanced reality could see a shift from many narrowband sensors to platforms (such as drones) that provide a more sophisticated capability.
- Increasing data-driven industry enabling performance improvement in consumer relationship, predictive analyses, demand-driven supply chain management, safety, traceability, sustainability, etc. Predictions for future applications in the industry include:
  - Environment monitoring (solutions to take informative decisions based on data provided by environment monitoring systems).
  - Material and goods management (in warehouse).

  - Customer engagement (personalized marketing and promotions).
  - Supply chain management (tracking and management of delivery fleets).
  - Asset tracking and management.
- The creation of new communication platforms within ecosystems. For example, small cells on vehicles for more flexibility to adapt networks on a site and over time.
- An increasing number of interactive applications: for example, augmented reality will play an increasing role in human or a machine interaction and the use of virtual / augmented reality systems for operation and maintenance purposes could demand very high bandwidth, low-latency communications to be enabled for devices in the use environment.

3.3 The future industry: More an evolution than a revolution

As discussed above, network performance needs for industrial automation are evolving and going towards:

- Higher reliability and lower latency (<1ms): motion control, mobile robotics…
- Higher synchronicity between devices (<1 microsec).
- Higher data rates (up to several Gbps): augmented reality, virtual reality.
- Higher coverage and device density.
- Higher availability of communication service (>99.9999%).
- Enhanced mobility.
- Improved security.
- Accuracy: e.g. localization of equipment (accuracy: 10cm).

In practice, these evolutions are likely to be slow, because of implementation constraints and related costs. The current stage of industry IoT is the stage of experiments and Proofs of Concepts. Businesses identify what works, what is useful and what does not bring sufficient value, before scaling; and implementation is done on a case-by-case basis.

Slow pace of IoT adoption in industry might also come from social reluctance: The strong trade unions of some industries (ports, mines…) might be willing to resist to digitalisation of their sites because of concerns related to loss of jobs.

3.4 Concluding remarks on key trends of the future industry

The increased number and intensity of connected device use raises issues such as performance of devices and of spectrum, flexibility in spectrum award and use, as well as security.

Another key trend on the future industry is the integration of the physical and the digital worlds. Maintenance operators using augmented reality to support their maintenance operations on a machine or piloting a drone that detects maintenance needs on sites that are difficult or dangerous to be reached by a human worker. This trend raises the issue of jobs evolution and new skills development.

In practice, digitalization of the industry has to be more a mean than a goal to reach. A first step for the industry is to define the objective to attain, before choosing to implement any IoT system, by asking ‘why does this factory need to be digitalized?’.

4 Introduction to use cases

The purpose of the following section is not to undertake a detailed network traffic planning on each use case but to give a sense of what would be the requirements and differences in terms of spectrum between the use cases. For this, a set of common assumptions have been made for the deployment of LTE for both indoor and outdoor environments.

4.1 Outdoor sites

The underlying assumptions at the cell level based on use of 3.5 GHz spectrum are shown in Figure 4.1. These are for situations where there is line of sight between the sector antenna and the user device.

Figure 4.1: Line of sight assumptions for LTE sectors

Parameter	Value	
Equivalent radius (km)	1.0	
Coverage (assuming omni antenna) (km^2)	3.1	If a multi-sector site, coverage from each sector will be smaller
Spectrum carrier (MHz)	10	
Spectral efficiency (b/sec/Hz)	1.5	
Maximum capacity loading (%)	80%	
Plan sector throughput (Mbps)	12	

The parameters set out above favour broadband transmission in the downlink. If there is significant data transmission in the uplink, which is expected to be the case as industrial automation applications evolve, the requirement for line of sight between the base sector and device is imperative. If this cannot be achieved, it will be necessary to significantly reduce the cell radius to a point where there is an operating link budget able to support the uplink broadband transmission. Under these conditions the radius could reduce from 1 km as in the above example to a few hundred metres or less.

Figure 4.2: Non-line of sight

Parameter	Value	
Equivalent radius (km)	0.4	
Coverage (assuming omni antenna) (km^2)	0.5	If a multi-sector site, coverage from each sector will be smaller
Spectrum carrier (MHz)	10	
Spectral efficiency (b/sec/Hz)	1.5	
Maximum capacity loading (%)	80%	
Plan sector throughput (Mbps)	12	

As in any wireless network, there is a trade-off between achieving coverage and throughput. So, while the above tables give examples of line of sight and non-line of sight sectors, actual implementations will be driven by the coverage / capacity trade off required.

4.2 Indoor sites

Indoor sites may be covered either by reusing spectrum used in the outdoor environment or licence exempt spectrum. The trade-off between the two will be driven by factors such as the ability to control the interference environment between outdoor and indoor, the QoS required and the communication density required.

- There is a question of how isolated the indoor environment is from outdoors. Modern warehouse and factory buildings may have high building attenuation to frequencies like 3.5 GHz and the lack of windows and other openings may allow sharing of frequencies used in close proximity with outdoors. Care would be required though with buildings with large openings into the outdoor environment. For example, loading bays or rail entrances into depots.

Providing line of sight may be more feasible indoors than outdoors if there is enough height inside the building and devices are mounted reasonably high on fixed installations. This may be more difficult for hand held devices in warehouse or machine rooms.

A typical large industrial building may present a relatively open internal space of 100 x 50 metres (i.e. an internal area of 5,000 m^2. For a line of sight environment, this would be well within the scope of one sector to provide coverage subject to clutter considerations. However, in practice 3-4 sectors may be deployed (e.g. one per corner), which, using the parameters set out in Figure 4.1 above, would provide a throughput of 48 Mbps within the building. Additional carriers or sectors could be added to achieve the required communication density.

Substitutes for use of 3.5 GHz CBRS may be more practical indoors if the interference environment is controlled (e.g. 5 GHz with MuLTEfire) and they potentially offer greater bandwidth with less sectors.

4.3 Devices

Coverage, and more importantly throughput, is a function of the number and type of devices requiring connection. Today, the number may be limited and dominated by narrowband devices, but this is expected to change over time as more broadband sensors are introduced (see Section 3), which is also likely to create a significant uplink bias for broadband traffic.

The precise deployment in industrial situations is likely to vary by location. For the purposes of this study some generic assumptions are made for the device environment in 5 years' time, as listed below:[9]

- Broadband devices per km^2 – 40 with a throughput of 5 Mbps per device.

- Narrowband devices per km2 – 750 with a throughput of 10 Kbps per device.

These parameters would give a traffic density per km^2 of 200 Mbps for broadband devices and 7.5 Mbps for narrowband devices. Using 12 Mbps per sector, this would require 16 sectors to be deployed per km^2, assuming a relatively uniform geographic distribution of devices.

In the following four chapters, examples are developed for the outdoor scenarios in each of the use cases.

[9] Based on Plum estimates.

5 The case of mines

5.1 Introduction

The mining industry is a supplier of coal, metals, industrial minerals, sand, gravel to businesses, manufacturers, utilities and other economic agents. In 2009, an estimated 1,400 mines were operating in the United States.

Open pit mining is used to extract the ore that is near the surface, by creating terraces to progressively go deeper into the earth. To extract the ore that is not at the surface of the earth, underground mining is used: a vertical shaft or a horizontal tunnel is dug. Then trucks or trains are used to transport the ore to a plant, where it is processed and refined. Mine production is currently undergoing a significant shift from underground mining to open pit mining.

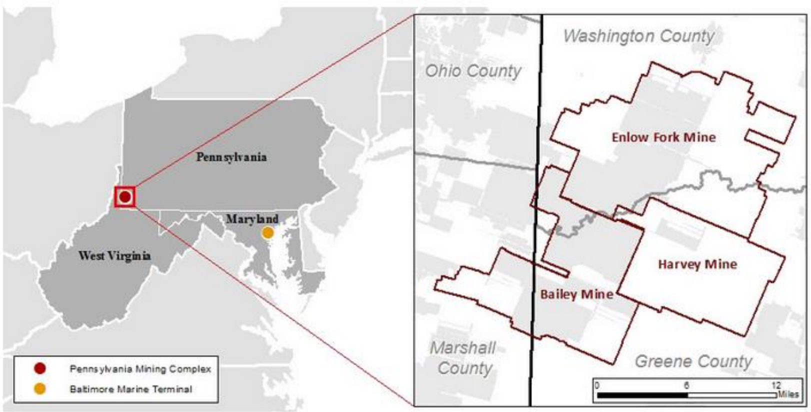
The mining industry increasingly makes the most of private LTE, IoT and automatization.

5.2 A mine use case: The Bailey mine, Pennsylvania

5.2.1 Presentation and environment

The Pennsylvania Mining Complex (Figure 5.1), run by Consol Energy, is the largest underground coal mining complex in North America. 28,5 million tons coal per year are produced by its 3 mines (Bailey, Enlow Fork and Harvey).

Figure 5.1: Pennsylvania mining complex



The Bailey mine (Figure 5.2) is the largest underground coal mine in the US, with 12 million tons production of coal in 2016 (and 11,5 as an average annual production capacity). It is made of 2 longwalls and 7 continuous mining sections and spread over an estimated surface of 83 miles^2 (215km^2).

Figure 5.2: Aerial view of the Bailey Mine

The Pennsylvania complex owns a centralized coal processing facility (that washes and processes up to 8,200 tons of coal per hour) as well as an onsite logistics infrastructure operating 24/7 – a dual-batch train loadout facility – that loads up to 9,000 tons of coal per hour with 10 unit trains per day. The coal processing facility is made of 9 raw coal silos (total capacity: 153,000 tons) and 6 clean coal silos (total storage capacity: 132,500 tons). The logistics infrastructure accommodates multiple unit trains for increased efficiency and is made of 19.3 miles of track (three side tracks).

5.2.2 Calculation of example spectrum requirements

In the case of the Bailey mine, applications used require wide area operation across outdoor (e.g. rail-served site) and some indoor areas (e.g. underground tunnels and working offices/areas).

In the outdoor environment, activity will mostly be focused on discrete working areas. This potentially means that for a significant proportion of the surface site, the data communication requirements will be minimal with higher densities occurring at work areas. Also, the nature of the site means that line of sight communication will be possible for most devices.

It was assumed that most of the communications requirement would be across 20% of the site for this example. Using the device densities set out in Section 4, this generates a throughput requirement of 1,245 Mbps across an area of 6 km^2.

If 3 sector sites are used in areas with high data density, 35 sites would be required to serve the throughput demand, if each sector is limited to one 10 MHz carrier. Alternatively, if:

- Each site had two 10 MHz carriers per sector, then 18 sites would be required.
- Each site had three 10 MHz carriers per sector, then 12 sites would be required.

5.3 Private LTE applications in mines

5.3.1 Current applications in mines

In order to get safe and efficient underground mining, the main technologies used include:

- Sensors to monitor the condition of equipment, to track rock movements, underground blasting, autonomous vehicles movements, cooling systems, etc. (e.g. As rail car is loaded, online quality monitoring systems analyze coal quality and ensure it is below 0.03% sulfur.) Sensors used in mining environments must be able to withstand high temperature conditions.
- Data analytics systems: The data collected by these sensors are then sent via a wireless network to a central database where they are stored and where experts can monitor them.
- Autonomous vehicles and machines (e.g. automated loader to transfer ore). Some projects are investigating the creation of battery-powered vehicles (that would not require an electric cable).

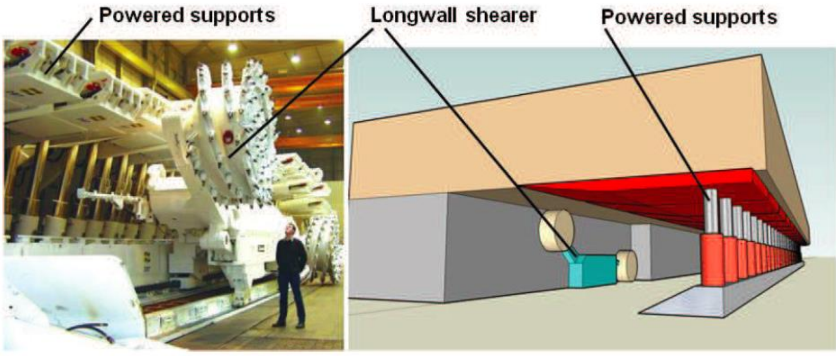
The following list details these technologies and what they apply for:

- Voice applications for group communication, emergency call system (by worker).
- Industrial wearables (sensors) in helmets and wristbands to track employee safety and spot hazardous scenarios:
  - track health metrics (body temperature, pulse and activity levels).
  - monitor extremes in environmental temperatures and presence of radiation and toxic gases.
  - detection of soil shifts.
- Indoor monitoring systems (sensors):
  - temperature monitoring.
  - Indoor-Air-Quality monitoring (IAQ).
  - Smart HVAC (Heating, Ventilating, Air Conditioning).
- Machine condition monitoring, for asset efficiency management and predictive maintenance
- Static geofencing (sensors).
- Mobile geofencing (sensors on drones).
- Connected longwall shearers (Figure 5.3) for coal mining [10]
- Autonomous drill technology (e.g. Rio Tinto[11] (UK/Australian mine in Pilbara, Western Australia).

[10] Developed by Joy Global (US mining equipment maker). These longwall shearers can send wirelessly 7000 data points per second to the data centre (https://www.komatsuamerica.com/our-company/press-releases/2017-04-05-komatsu-acquires-joy-global)
[11] https://www.iotworldtoday.com/2016/08/17/autonomous-vehicles-what-fleets-want/

- Autonomous loading: driverless trucks and trains to extract ore (e.g. Rio Tinto[12] (UK/Australian mine in Pilbara, Western Australia).
- Remote control centre complex (A remote worker oversees multiple drills from a single console).
- Asset visibility for workers safety: Detection of persons near the working machine (sensor) for security system stopping the machine.

Figure 5.3: Longwall mining[13]



5.3.2 Focus on topographical surveys by drones in the mine industry[14]

Topographical surveys are usually used to calculate the mine production capacity. Most of the time, it is done by surveyors: It requires the operations to cease, presents a danger to the surveyors and measurements done are not the most accurate. This is a time-consuming, dangerous and expensive activity to conduct.

Drones respond to various visualization needs. Data collected are then used to perform measurements (volume calculations, contour lines, imagery of land disturbance, 2D and 3D models…).

Drones can be launched from a distance away and without interrupting the operations. Technology based on large imaging sensors can capture sharp, colour-rich images, even in dark or cloudy conditions. Drones can have battery-swapping capabilities.

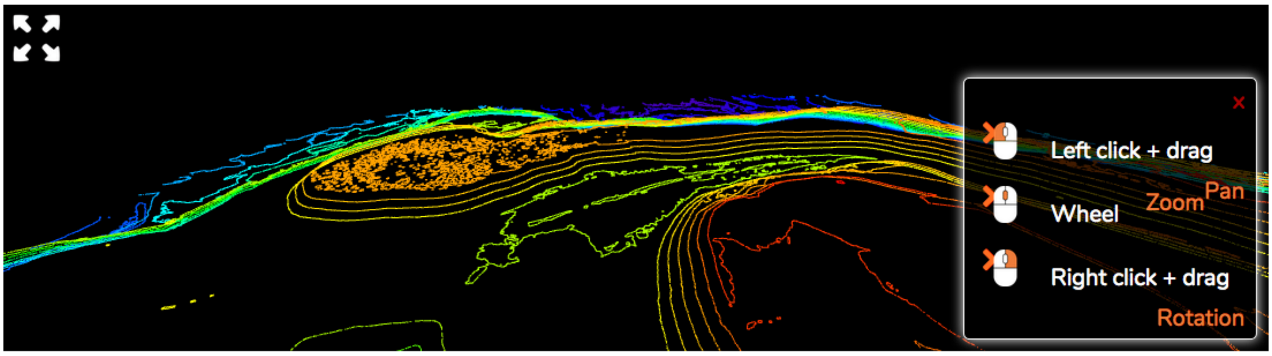
Drones can help improving:

- Safety by:
  - Minimizing human intervention for topography survey in the field
  - Detecting and identifying potential hazards (and anticipate accidents).
- Productivity and planning:
  - Enabling to not stop operations in the surveyed zone
  - Minimizing topography costs and times

[12] Ditto
[13] Source: Mining machines in technical practices, H. Gondek, K. Frydrysek, 2011
[14] See video on examples of drone applications in a mine: https://bit.ly/2P31oDK

- Providing accurate PIT[15] models (contour and elevation maps) to improve planning (Figure 5.4)
- Estimating stock pile volumes (calculating inventory and preventing waste): indicates how much raw material was extracted in order to allow planning of subsequent steps.

Figure 5.4: Example of drone contour map of a mine[16]



Depending on use and related costs, mines can use Drone as a Service (outsourced) or own their own drones.

5.3.3 Future potential applications in mines

Indoor and outdoor monitoring sensors are multiplying and expanding in the mining industry.

It is possible to imagine the use and development of drones on mine sites in the following cases.

- Identification of new deposits of underground ore: Today, ore detection on surfaces can be made by drones on mine sites. One can imagine the use of drones in the civil world in a near future to detect underground ore.
- First aid drone: on-site image captured by drones, heart defibrillator sent by a drone[17]
- On-site machine (e.g. crushers) maintenance made by a robot that is sent by a drone in order to avoid human presence on dangerous fields and reduce time of intervention.

5.4 Applicability of CBRS to mines

Private LTE networks in mines are almost unique in that they are completely separated from any potential public LTE network, not just by geographic distance but also by natural barriers, and as such there is unlikely to be any interference caused by using spectrum which is otherwise used by these networks. Other than narrow access shafts, the underground parts of mines are completely sealed to the outside and the significant depth of rock will prevent radio signals from penetrating – particularly signals above 2GHz.

Given this, mines would be an ideal place for CBRS spectrum to be used. There would be very limited scope for any interference or alternative use of the spectrum, meaning that GAA licencing would be sufficient to ensure

[15] PIT: Point In Time
[16] Source: Delair professional drones
[17] Ambulance drone bringing defibrillator operating in civil society in Netherlands, 2015

that the private LTE network could operate with sufficient reliability and consistency. Even if there was a concern that outside equipment could be introduced by visitors which would operate on a GAA basis (and therefore interfere at the same priority level as the mine's own equipment), a PAL sublicense could be obtained cheaply since it would present a very low opportunity cost for the PAL holder, given the lack of potential for interference outside the mine.

However, the technical working of CBRS is likely to prevent CBRS spectrum being used. The location of private LTE equipment may prevent it from receiving the heartbeat from the controller, and without this heartbeat the network will not be able to operate. This is more the case in underground mines, but even open mines may suffer from difficulties in receiving the heartbeat due to a lack of line-of-sight to the transmitter.

Indeed, this appears to be a limitation of the CBRS framework. Areas where the heartbeat cannot be accessed – which would be ideal areas for the spectrum to be used – will be prohibited.

Instead, private LTE networks in mines under these conditions will require a sublease of alternative LTE spectrum from mobile network operators, such as in the 2600 MHz band or even the 1800 MHz band. Again, given the location this is unlikely to cause interference with the mobile network and so the sublease could be negotiated at a relatively low price. Alternatively, the private LTE network could operate using licence exempt or unlicensed spectrum, again because the location will restrict the potential interference.

6 The case of ports

6.1 Introduction

Ports are maritime industrial and commercial facilities for ships to load and discharge cargo and passengers. Port activities are diverse: the primary function is to host ships, particularly during loading and discharging, provision, fuelling and maintenance of ships are also done in ports.

Ports are important economic stakeholders, shipping imports and exports, supporting employment (23 million people work in the US seaport cargo industry) and supporting local and national economic growth.

The US port industry currently undergoes significant changes in service operations, where technology progress and robotics have become real differentiators.

6.2 A port use case: the port of Los Angeles

6.2.1 Presentation and environment

The Port of Los Angeles is located in San Pedro (20 miles south to downtown L.A). It has been ranked the 1st container port in North America since year 2000, has moved 9.3 million TEU[18]'s in 2017 with 100,000 people working on the docks and 2000 ships transiting per year.

The Port includes ships docks for goods:

- furniture, auto parts, apparel, electronics, footwear (as imports),
- paper/wastepaper, animal feed, scrap metal, fabrics, soybeans (as exports),
- There are 5000 to 10,000 containers on a ship,
- It takes 5 days to unload a ship.

The Port also includes ship docks for passengers, with 500,000 passengers in 2017 and 15 marinas.

It covers an area of 30km^2 (7,500 acres) in San Pedro's bay - 13km^2 (1,295ha or 3,200 acres) in water and 17 km^2 (1,740ha or 4,300 acres) land – with 43 miles of waterfront. It is mainly an outdoor environment with some indoor areas:

- Port warehouses (5,2 ha, along 525m of berth length)
- Cold storage facilities (10ha).

In terms of facilities and equipment, the Port of Los Angeles (Figure 5.1) includes:

- 8 container terminals over 675 ha

[18] TEU: twenty-foot equivalent unit

  - with container-lift equipment incl. rubber-tire gantry cranes, rail-mounted gantry cranes, reach stackers and top picks (86 ship-to-shore container cranes as a whole)
  - Terminal support facility (e.g. gate entry).
- Rail (113 miles): 5 on-dock and 1 near-dock rail (100 trains/day, in/out San Pedro Bay).
- Warehousing and distribution:
  - Port warehouses over 5,2ha (13 acres) along 1,720 feet of berth length, that are accessible by rail and compatible with Foreign Trade Zone.
  - Cold storage facilities with a storage capacity of 10ha, handling perishable products that require refrigerated storage (fruits, meat, fish and shell fish) and providing repacking services, blast freezing, USDA inspections, reefer logistics, etc.
  - 4 fire stations in each direction of the port complex. Emergency communications are done via Wireless Emergency Alerts (to WEA-capable mobile devices); Emergency Alert System (broadcast to various media outlets), cable TV, AM radio, satellite radio and amateur radio.
  - Port Optimizer Data Solutions Portal is a cloud-based software solution (supply chain performance & predictability) developed with GE Transportation. It provides real-time and data-driven insights in order to give visibility at every step of the supply chain and enable predictive analysis.

Figure 6.1: Aerial view of the port of Los Angeles

6.2.2 Calculation of example spectrum requirements

The port is a large and complex environment and the cell density required will rapidly drive up costs if the density of uplink BB traffic per km^2 is high.

In the outdoor environment, there are land and water covered areas.

- Over the water, the number of devices will be lower than that found on docksides and in container and handling areas.
- In order to address this, it was assumed that 40% of the site is water and 60% land. Of the land area, it is further assumed that 30% is covered by buildings, which will have their own internal data network capability.

Coverage over water is assumed to be line of sight for the purpose of assessing spectrum requirements, while coverage over land is assumed to be non-line of sight given the highly cluttered nature of a port environment (cranes, container piles, etc.,).

Land coverage

For the outdoor land area of the port, the data throughput requirement is calculated as 3,500 Mbps.

If 3 sector sites are used to serve this throughput in a non-line of site environment, around 90 sites would be required to serve the throughput demand, if each sector is limited to one 10 MHz carrier. Alternatively, if:

- Each site had two 10 MHz carriers per sector, then 45 sites would be required.
- Each site had three 10 MHz carriers per sector, then 32 sites would be required.
- Each site had four 10 MHz carriers per sector, then 24 sites would be required.

Water coverage

For the outdoor water area of the port, the data throughput requirement is calculated as 540 Mbps.

If 3 sector sites are used to serve this throughput in a non-line of site environment, around 15 sites would be required to serve the throughput demand, if each sector is limited to one 10 MHz carrier. Alternatively, if:

- Each site had two 10 MHz carriers per sector, then 8 sites would be required.
- Each site had three 10 MHz carriers per sector, then 5 sites would be required.

6.3 Private LTE applications in ports

6.3.1 Current applications in ports

Connected devices on private LTE are more and more widespread in the harbour industry for operations and security optimization:

- Real-time location systems for access to sites and geofencing:
  - Employees' and technicians' access to sites.

   - Detect deviations in crew or operations (productivity and safety purposes) through industrial wearables (sensors).
   - Security and detection of unusual movements: alarm sensors, security camera (CCTV), HD real-time video and HD video analytics used for person or vehicle detection (fixed video or embarked on vessel or drone). This increases the use of data and video uplink.
   - Static geofencing (sensors) vs. mobile geofencing (sensors on drones).
- Emergency systems (safety of workers): voice applications for group communication, Push-to-Talk, Push-to-Video.
- Container tagging.
- Container tracking (shipment arriving and departure).
- Cold chain monitoring of containers and real-time assessment of safety of products (shipping temperature, humidity sensors).
- Autonomous cranes and vehicles.
- Machine condition monitoring, for asset efficiency management and predictive maintenance.
- For container shipping, sensors and data analytics are used to
   - Track assets and optimize fuel consumption.
   - Control temperature of refrigerated containers.
   - Inform how containers are stored and where they are located (e.g. Maersk, Danish shipping company).
- Monitoring condition of routes and vessels gives extra value to the service provided to customers of the port (shipping companies).[19]

6.3.2 Potential future applications in ports

Some fully automated container terminals[20] have been implemented, with autonomous cranes and trucks (Shanghai, Rotterdam[21]), based on:

- AI (performance of visual perception, decision-making, speech recognition).
- Computer vision (by gaining information from video cameras about the environment).
- Machine learning.

[19] https://www.portofhelsinki.fi/en/emagazine/piloting-tools-fit-ipad
[20] Video on Asia's first automated container terminal (2017): https://bit.ly/2OIJhU0
[21] Article: https://bit.ly/2RaUrh5

Projects of autonomous vessels (tugs, ferries) for fairway areas are tested, based on monitoring systems that enable to have accurate situational awareness during the way to harbour. Status information will be generated either from vessels or from the port.

- Smart fairways and autonomous traffic in test (Vuosaari, Rauma - Finland).
- Sensor test project conducted in Vuosaari, Finland, using lidar[22] to create real-time 3D mapping.

Aerial imaging solutions through drones can be used for:

- Infrastructure inspection and maintenance.
- Site surveillance and security (e.g. vehicle detection).

Nautical drones are used for environmental analyses and topography of seabed. They could be used to test ballast water and meet environmental regulations, for instance.

6.4 Applicability of CBRS to ports

The networks to be deployed in the port will require large bandwidths, particularly given the streaming video applications, and high reliability. As they are also in areas open to the public – particularly surrounding the cruise ship terminals and marinas – it is likely that mobile networks will have deployed their own networks to cover at least part of the port area.

This mix of requirements from private LTE operators and mobile networks will mean that the only spectrum that could be used for the private LTE network would be that covered by CBRS: mobile network operators will not be willing to sublease their spectrum since they will either be using it or have a reasonable belief they will use it in the near future; while unlicensed or licence-exempt spectrum would not have sufficient reliability and security, or the ecosystem to support the applications needed.

Given the need for greater reliability, private LTE operators would need access to PAL, but given the county-wide licencing regime of CBRS's new regulations, it would likely be unprofitable for them to buy a PAL themselves. Therefore, we would expect a PAL leasing arrangement would be most suitable. However, it may be that not all PAL options across the county of Los Angeles (Figure 6.2) are taken up by other network operators, and the port may then elect to acquire a PAL itself at a low price. The limit is likely to be the bandwidth available – it may be necessary for multiple licences to be used to meet the demands of various networks.

[22] Laser teledetection

Figure 6.2: County of Los Angeles in California

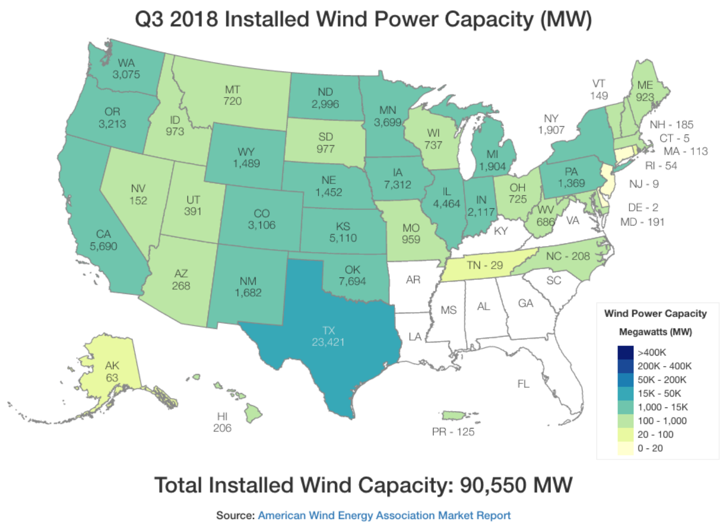
Therefore, the exact licencing plan that can be used in the port of Los Angeles will depend on the demand for other services in other areas across Los Angeles county. This is a fairly significant drawback to the use of CBRS for this licensing – the impact of unrelated decisions on the possibilities for spectrum use. However, given the lack of options it may be the best way forward.

7 The case of wind farms

7.1 Introduction

Wind power is a renewable energy and a viable substitute to traditional energy sources. Wind farms are groups of turbines placed in the same location, sometimes over very extended areas, and used for electricity production. The largest wind capacity and investment in the USA are located in Texas; Oklahoma, Iowa and California also have large production capacities (Figure 7.1).

Figure 7.1: US installed wind power capacity, 2018



Source: https://windexchange.energy.gov

Automation benefits the industry by increasing profitability and reducing risk. Turbine automation enables to maximise the availability of assets and optimize their efficiency, while digital solutions for power transmission (grid access) and financial solutions make power generation more flexible.

7.2 A windmill farm use case: the Alta Wind Energy Center, California

7.2.1 Presentation and environment

The Alta Wind Energy Center (AWEC) is an onshore windfarm of 600 operational units located in California, operating since 2010.

Mostly owned by NRG Energy, the site area covers 3,200 acres (13 km^2). With an electric capacity of 1320 MW, it is the largest wind facility in the US and the second in the world).

Figure 7.2: Aerial view of AWEC

In terms of equipment, the wind farm (Figure 7.2) is equipped with:

- Turbines.
- Collector system.
- A substation collecting the energy.
- Access roads to each turbine site.

Individual turbines are interconnected with a medium voltage (usually 34.5 kV) power collection system and a communication network. At the substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage transmission system.

7.2.2 Calculation of example spectrum requirements

The wind farm is a relatively uniformly laid out environment with good potential for line of sight communication for most devices. It is therefore assumed that most of the communications requirement would evenly spread across this site. Using the device densities set out in Section 4, this generates a throughput requirement of 1,350 Mbps across an area of 13 km^2.

If 3 sector sites are used, 37 sites would be required to serve the throughput demand, if each sector is limited to one 10 MHz carrier per sector. Alternatively, if:

- Each site had two 10 MHz carriers per sector, then 19 sites would be required.
- Each site had three 10 MHz carriers per sector, then 13 sites would be required.

7.3 Private LTE applications in windmill farm

7.3.1 Current applications in windmill farm

A primary objective is to set up communication between turbines and the central office, which is not always the case and requires manual on-site interventions.

As the windmill farm business is largely based on weather conditions and on energy market prices, real-time data are particularly valuable for these wide areas.

Private LTE apply in windmill farms to optimize operations with the purpose of increasing productivity and decreasing costs, as well as lower risk and predict failures:

- Monitoring wind turbines in real time to ensure maximisation of air flow and mechanical power (temperature, vibration sensors and data).
- Optimizing planned maintenance of turbines by tracking characteristics of each turbine (asset management). A lot of windmill farms have a mix of legacy turbines, old and more recent equipment.
- Gathering real-time data on power production.
- Improving planning and decision making based on weather predictions.
- Optimizing production in real-time: Tracking real-time data from the energy market as well as current operations of the windmill farm in order to enable to monitor real-time productivity (keep operating vs. stop if making no money).
- Inspecting wind turbines and having a view on erratic behaviour of turbines (through sensors and real-time video systems on drones) in order to analyse equipment and event, monitor maintenance in real-time an detect early signs of problems.
- Site security and worker safety: geofencing via drones and video camera to reduce intrusions, Push-to-talk and emergency calls.

7.3.2 Potential future applications in windmill farm

For the time being, it seems that drones are used as complements for human intervention on maintenance of the windmill farm. If expanded, their usage can contribute to lower duration and costs of intervention or inspection, improve worker safety (as human intervention is traditionally required) and improve quality of data reporting.

As in previous use cases, it is possible to imagine the use and development of drones on windmill farm sites for the following examples:

- First aid drone: on-site image captured by drones, heart defibrillator sent by a drone[23]
- Maintenance equipment dropped by a drone for human intervention.

[23] Ambulance drone bringing defibrillator operating in civil society in Netherlands, 2015

- On-site maintenance made by a robot that is sent by a drone in order to avoid human presence on dangerous sites and reduce time of intervention.

7.4 Applicability of CBRS to windmill farm

Unlike ports, the majority of large windfarms are situated away from built-up and populated areas. This means that higher frequency spectrum is unlikely to either cause interference or suffer from interference from other sources, given the short propagation distance. The lack of interference will in turn lead to a low opportunity cost associated with the use of CBRS spectrum; PAL holders may be unlikely to be inconvenienced if they allow the wind farms to sublease their spectrum. This may not be true for other potential LTE bands; the wider propagation of these could lead to surrounding villages suffering interference.

Indeed, the location of wind farms is itself problematic. In order to be at their most efficient, wind turbines tend to be tall buildings located high on hills, which means that any signals sent by transmitters placed on the turbines themselves are ideally located to achieve maximum range. This will reduce the willingness of mobile operators to allow for subleasing of their spectrum and may also reduce the possibilities for PAL leasing as well, depending on how PAL holders plan to use the spectrum in surrounding areas.

The remoteness of the location also provides a problem when considering the heartbeat mechanism; the networks will need to be able to receive the heartbeat which will require additional investment in transmitting equipment to cover the site. While the heartbeat signal will not be blocked by rock as in the case of a mine, it may still prove a barrier to a reliable network.

One further issue that must be considered is the size of the site. Wind farms can be very large and spread over a large geographic area, particularly where the geography requires straight lines of turbines. The second largest wind farm in the US, the Shepherds Flat Wind, covers more than 30 square miles in the Morrow and Gilliam counties in Eastern Oregon. Where this lies in two different counties, it will require multiple agreements to sublease PAL for CBRS spectrum – and it may not be possible to obtain compatible licences in the two different counties.

Given this, while wind farms appear to be an ideal case for CBRS spectrum sharing, given the lack of interference and likely low opportunity cost, there are a number of logistical issues to overcome before the benefits can be realised.

8 The case of logistic hubs

A logistics hub is a specific place where transport, logistics and distribution are carried out, both for national and international transit. Operators of the hub may be owners or tenants of the facilities and infrastructures.

FedEx successfully applied the spoke-hub distribution model to logistics in the 1970s. This distribution model enables to optimize transport topology by organizing routes based on "spokes" that connect places to central hubs. The spoke-hub model applies to many kinds of transportation: sea transport, rail transport, cargo airlines, etc. The FedEx Express hub in Memphis, examined below, is an example of airline spoke hub.

8.1 A logistics hub use case

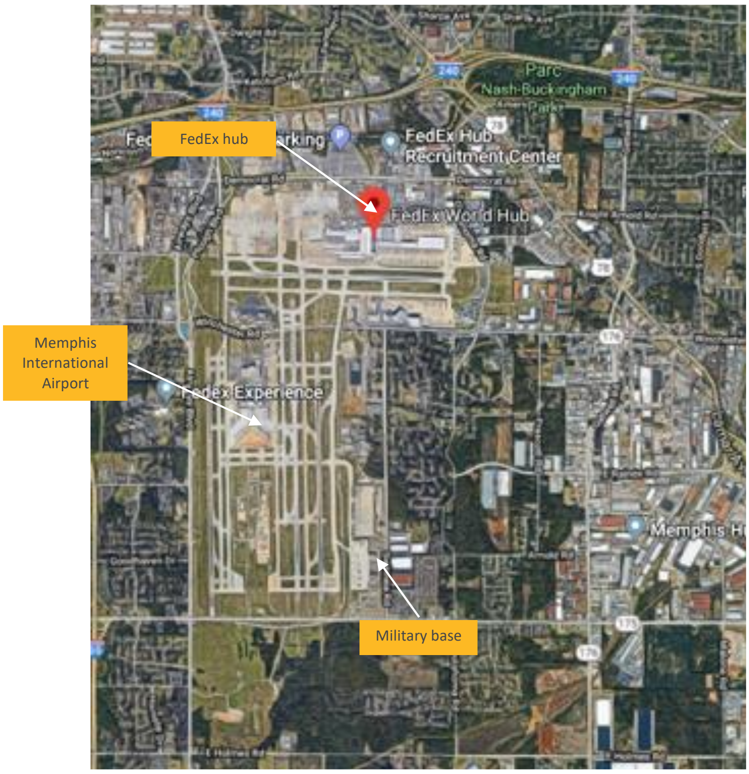
8.1.1 Presentation and environment

The Memphis International Airport is home to the FedEx Express world "SuperHub" (Figure 8.1), which has access to 220 countries & territories. 150 flights transit through the Hub every night and 90 in the day. The Hub extends over an area of 3,6km^2 (15 million square feet or 880 acres), both indoor and outdoor:

- The indoor environment includes offices, sort areas with 80 miles of conveyer belts and a Cold Chain Center (large areas: 50.000 square feet) for frozen, cold, and temperature-controlled packages.
- The outdoor environment includes airport facilities.

The Hub employs around 11.000 team members: 8000 associates for day and night shifts, plus 3000 support employees (including its own police & fire departments). It sorts and loads 2 million packages a day (1.9 million a night, 0.6 million a day).

Figure 8.1: Aerial view of the FedEx super hub, Memphis



A package goes through the Hub in 15 minutes according to the following process:

- Arrival by inbound airplane.
- Inbound container.
- Sorting space: package scanned (sender, package dimensions, weight, destination).
- Outbound container.
- Outbound plane for departure.

8.1.2 Calculation of example spectrum requirements

Whatever the network used on the Hub, it should not create interferences with the close by military base.

In the outdoor environment, activity will mostly be focused on working areas, which are assumed to cover a significant proportion of the site. The nature of the site means that line of sight communication will be possible for most devices with suitably mounted antennas.

It was assumed that most of the communications requirement will be relatively uniform across the site and generate a throughput requirement of 750 Mbps. However, there are likely to be large numbers of vehicles moving around the site with potentially demanding data requirements, which could cause localized peaks of traffic and require some planning flexibility.

If 3 sector sites are used, 21 sites would be required to serve the throughput demand, if each sector is limited to one 10 MHz carrier. Alternatively, if each site had two 10 MHz carriers, then 11 sites would be required.

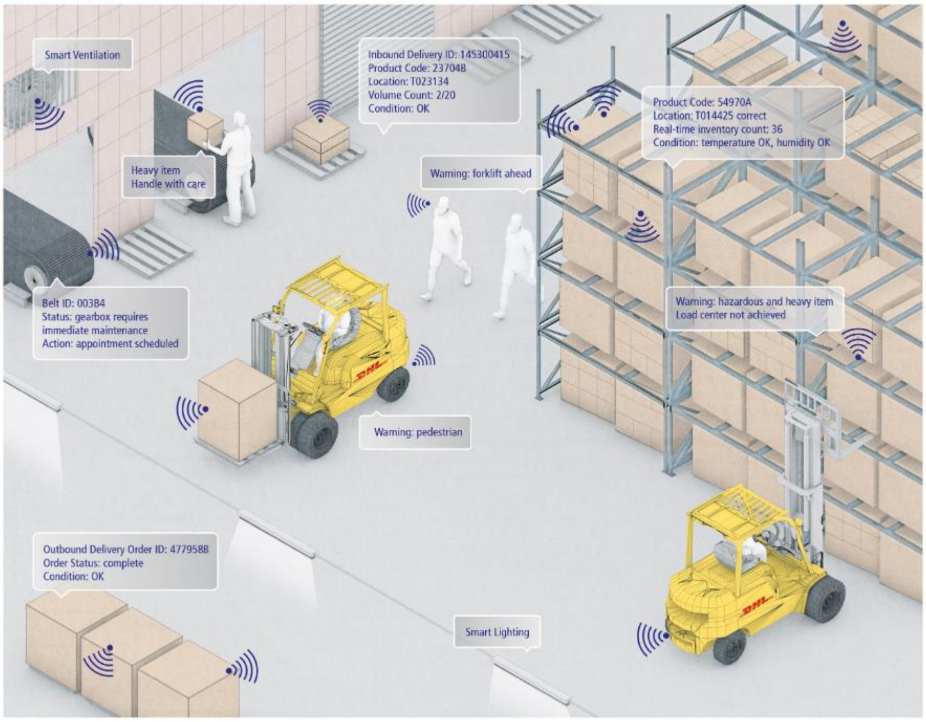
If broadband device demand at the site increases to say two times the assumption set out in Section 4, then around 40 three sector sites would be required to handle the throughput. If each site had three 10 MHz carriers, 14 sites would be required.

8.2 Private LTE applications in logistics hub

8.2.1 Current applications in logistics hub

Like for most of industry use cases, private LTE networks are used in logistics hubs in order to optimize operations (improved productivity, lower costs and risks) based on a large panel of applications Figure 8.2).

Figure 8.2: Examples of IoT uses in warehouse



Source: Internet of things in logistics, DHL/Cisco, 2015

- Real-time location systems for access, geofencing and security:
  - Employee/technicians access.
  - Security and detection of unusual movements: alarm sensors, security camera (CCTV), automatic locking of doors.
  - Asset visibility for workers safety: Detection of persons near the working machine (sensor) for security system stopping the machine.
- Emergency systems (safety of workers): voice applications for group communication, Push-to-Talk, Push-to-Video.

- Parcel tagging.
- Parcel tracking (shipment arriving and departure).
- Cold chain monitoring and real-time assessment of safety of food and pharma products (shipping temperature, humidity sensors):
  - For products requiring extreme cold, the "Deep Frozen Shipping Solution", a FedEx priority alert service monitors the temperature at every step.
  - For packages requiring consistently cold ("Cold Shipping Package"), an embedded near-real-time active monitoring solution ("SenseAware" by FedEx) alerts stakeholders if shipment goes outside of the temperature ranks specified.
- Optimization of efficiency and maintenance of vehicles (e.g. ground vehicles in airport runway) and machinery (e.g. forklifts, Automated Guided Vehicles): weight and counting sensors, sensors to monitor maintenance needs on assets. optimize fuel consumption of ground vehicles.

8.2.2 Potential future applications in logistics hub

Indoor and outdoor sensors are multiplying and expanding in the logistics industry.

8.3 Applicability of CBRS to logistics hub

The use of CBRS spectrum in the logistics hub can be considered as two different use cases – indoor and outdoor. Within the fulfilment centres and sorting buildings, CBRS spectrum can be used with little danger of interference to the surrounding region, since the spectrum used for CBRS is likely to be experience high building losses. As long as issues over receiving the heartbeat can be overcome, then this would be a good example of how CBRS spectrum can be used on private networks.

However, the outdoor usage has the same issues as described for ports in Section 6 above; logistics hubs are likely to be in built-up areas, with many other potential uses for the spectrum, and as a result the opportunity cost of PAL leasing may be very high. Unlike the case of ports, however, the use of spectrum outdoors at the logistics hub is likely to be restricted to fixed point-to-point links, and this further reduced the likelihood of CBRS spectrum being used, since higher frequencies (such as 26 GHz) can be used instead with little loss in quality.

The spectrum needs of a logistics hub are therefore most likely to be met with a mix of CBRS and other bands. The relevant mix will depend on the usage of CBRS in surrounding regions, derived from the demand for FWA or other services. Indeed, this demand will affect CBRS in two ways: will interference clash with high demand (preventing PAL leasing or GAA at all) or will low demand mean there is no PAL sublicensing at all?

9 Summary of use cases

The key characteristics of the use cases are shown in Figure 9.1. While there are many common characteristics across the cases there are differences that may accentuate over time as the requirement for increased broadband capability develops. As previously noted, this is likely to place a significant data requirement in the uplink, which in turn creates more demanding transmission conditions and will decrease the size of cells.

In all cases high QoS is a prerequisite but there are likely to be differences in the static vs dynamic aspects of each case. For example, for surface applications at the mining site, once a work area and its communications capability are established, they are likely to remain static until the work area moves elsewhere on the site (which may be a matter of weeks or more). Similarly, in the case of the wind farm, the deployment of facilities is likely to remain static once the site is constructed. However, in this case, there may be maintenance teams that move around the site creating a moving area of data demand. In the case of the port and logistics hub there are likely to be many vehicular movements, which may require large data transmissions on a periodic basis. The same could also be true for aircraft at the hub, which may dump data on landing and take on data before departure.

So, while there are common characteristics, the actual usage likely to be experienced at each site will vary and require careful consideration if the QoS and other aspects of the site requirements are to be successfully met (Figure 9.2). Over time, more applications will become users of data communications. These could include safety of life, which may impose very high quality and resilience requirements. This is likely to be a factor at any heavy or dangerous industrial location and possibly all the cases identified here. More generally, the traffic density is likely to increase, particularly in areas of intense activity such as the port or logistics hub with increased business volume.

Figure 9.1: Use case characteristics

	Bailey mine	Port of LA	AWEC	Fedex hub
Activity	Coal extraction from below ground On-site processing facilities Loadout facilities (train)	Ships docks for goods and passengers	Turbines and substation generating and collecting wind power	Logistics facilities including collection, storage and sorting of packages.
Activity specificities	High QoS requirements for mission critical operations and safety of life	High QoS requirements for safety of life	High QoS requirements for safety of life	Fast pace (15 minute-process)
Dimension	215km^2 Wide area	30km^2 Wide area	13km^2 Wide area	3,5km^2 Not wide (lower requirement for reach)
Area specificities	Underground activities	13km^2 water 17 km^2 land		Airport Military base
Type of environment	Outdoor (LOS) (+Indoor)	Outdoor (NLOS) (+ Indoor)	Outdoor (LOS) (+Indoor)	Indoor (+Outdoor)
Environment specificities	High temperatures	Marine environment		Specific sensors for low temperatures (Cold Chain Center)
Time periods for operations	24/7	24/7	24/7	24/7 Night activity (1,3 million packages): twice the day activity (0,6 million packages)

In most cases there is a dense communications requirement needing multiple sites and carriers. While LTE may be a means of supporting these needs, especially if access to larger amounts of CBRS spectrum is possible, some cases where traffic density is very high, may also be cases for early deployment of mm-wave services.

Figure 9.2: CBRS suitability to use cases

	Bailey mine	Port of LA	AWEC	Fedex Hub
Interference risks	Low	High	Low	Indoor: low Outdoor: high
CBRS suitability to use case	+	-	++	Indoor: +++ Outdoor: --
Use of CBRS spectrum	GAA sufficient PAL licence in some cases	PAL necessary Final choice depends on demands for other services in the county	GAA PAL sub-licence	GAA
Sub-leasing	Quite cheap (very low opportunity cost for PAL holder)	High opportunity cost	Cheap (low opportunity cost for PAL holder)	High opportunity cost
Technical & regulatory limitations	Limited/impossible reception of heartbeat in some cases	County-level award makes PAL unprofitable for private LTE networks	Unreliable reception of heartbeat in some cases	Numerous other spectrum use on site

10 Concluding remarks

The heterogeneity of industrial use cases, applications and requirements leads to a flexibility requirement in spectrum award and use. This makes CBRS relevant and suitable for small-cell deployments and private LTE applications in industry.

In its latest regulatory updates, CBRS appears as a favorable license scheme to industry:

- Flexibility of spectrum use.
  - Necessary protection to incumbents.
  - Prioritization of shared access to the band (availability basis).
  - Additional shared use when and where incumbents do not use spectrum.
- Licence renewal possibility.
- Licence periods of 10 years are an incentive to investment.

Nevertheless, CBRS displays certain characteristics that appear to be unfavourable to some industry use cases. Using CBRS spectrum incurs incremental costs, while providing a low incremental reliability. In this way, the value of CBRS spectrum is based on the operator' willingness to pay and thus largely based on the value put in the incremental reliability and flexibility compared to unlicensed spectrum. Another CBRS constraint is the mandatory heartbeat mechanism that makes its application unreliable or not feasible in some use cases.

This report has studied four industry use cases: a mine, a port, a wind farm and a logistics hub. The use case that appear to make the most of CBRS spectrum use is the logistics hub in indoor environment. There may be a good availability of spectrum in mines and wind farm areas with low interference risks, but these use cases may face a technical issue by not being able to access the heartbeat signal. Both the port use case and the outdoor environment of the logistics hub appear as being less likely to make the most of CBRS spectrum.

Appendix A Detail on devices and applications

- Sensors include simple narrow band devices and modules to detect changes in systems or the environment, through to broadband devices that could be providing large volumes of continuous real time data. Sensors can be embarked on robots, drones or vehicles. Services associated can cover 3D modelling, thermography (infrared camera), mapping and topography, as well as monitoring and analysis of flow of people.

- Voice: feature built into some devices (voice recognition, voice-controlled speakers, vocal communications).

- Tagging refers to the use of RF devices for monitoring location of assets, goods and personnel.

- Geofencing: *"creating a virtual boundary in which a device, individual or asset can be tracked and monitored or detected if the boundary is violated"*[24]. Geofencing technology works through a software or a mobile app and can be used to track entry and exit of people, equipment and vehicles to the premises (tracking transport fleets, pieces of equipment, protect from equipment theft, trespassers, etc.). Sensors detect unauthorized movement of equipment, can shut down equipment if operated outside the authorized areas, monitor vehicles and employees' movements.

- Control and activation using radio to turn on, off or adjust equipment. It could be simple commands (narrow band) or more complex information (broadband) to provide large volumes of data to equipment for it to do a specific function.

- Autonomous vehicle control includes the issue of commands and receipt of data from vehicles being used in the environment. It could also include real time control of vehicles. In the use cases considered, vehicles could range from fork lift trucks through to vehicles for the movement of people and goods. Note that there may be other communications capability on these vehicles such as transmission of video images to/from the vehicle and other sensors. It is assumed that autonomous vehicles require a continuous resilient connection to the network.

- Drone (UAS, Unmanned Aircraft Systems) control is similar to vehicle control but operating in three dimensions rather than two. It is assumed that drones require continuous resilient connection to the network. There may be other communications capability on the drone such as transmission of video images and other sensors. It is assumed that drones require continuous connection to the network. Drones provide services covering security, inspection, mapping and surveying and emergency response. Sensors included in drones are visual sensors (high-fidelity camera to take visual and other imagery) and LIDAR sensors for collision avoidance and obstacle detection. Other features may include audio detection / transmission, and signal relay. Drones will require a continuous secure and resilient connection to the network.

- Robot control could apply to both static or moving robots. It may include the issue of commands and receipt of data from the robot. there may be other communications capability on the robot such as transmission of video images and other sensors. It is assumed that robots require continuous secure and resilient connection to the network.

- Safety systems. These could include many systems for physical and personal safety and may be a mixture of location, sensor and other devices. Functions could include hazardous situation monitoring

[24] https://www.gartner.com/it-glossary/geofencing/

(e.g. radiation, fumes) and vital sign monitoring. It is assumed that these systems will require continuous or near continuous connection.

- Security systems. These could include systems for physical or personal security and may include sensors and control elements. It is assumed that these systems will require continuous or near continuous connection.