Private Wireless Networks And Multi-Access Edge Compute

A Technical Paper prepared for SCTE by

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1. Introduction

Enterprises are looking for dedicated wireless networks that offer better control, which can be used to solve operational challenges. Private LTE and 5G networks offer reliability, ubiquitous coverage, high user capacity, and built-in security. Private networks combined with multi-access edge computing (MEC) also give the ability for enterprises to keep data on premises and implement use cases that require low latency.

Over the last year, Charter Communications has continued to work with CBRS spectrum in the private networks space. Charter has evaluated various vendor solutions for private LTE/5G networks. In addition, we have also deployed a private LTE network in a large manufacturing plant in Michigan and have plans to work with customers in other verticals. In this paper, we explain the main motivation behind deploying a private LTE/5G network and how it can be implemented. Second, we present different use cases that can be served by this network in the industrial, healthcare, and education verticals. Third, we show the criteria for vendor selection in our lab evaluation. Fourth, we illustrate the deployment of our first private LTE network in a factory.

1.1. Citizens Broadband Radio Services (CBRS) overview

In April 2015, The Federal Communications Commission (FCC) made the decision to establish Citizens Broadband Radio Services spectrum in the United States. This is a section of 150 MHz spectrum between 3.55 GHz and 3.70 GHz, which was originally used by the government for the military or by wireless internet service providers (WISPS). This decision by the FCC opened up CBRS spectrum to be shared on a dynamic basis depending on the user priority [1].

One of the key components of CBRS is the tiered sharing structure. This is achieved by establishing three different tiers of users, each allowed to use the band at any given time. Below is a brief description of some of the key components of this sharing structure in CBRS.

Spectrum Access System (SAS): The spectrum access system was set up to coordinate between the different users using CBRS spectrum. All Citizens Broadband Service Devices (CBSD) must register with the SAS before being allowed to transmit.

Tiers of users

- Incumbents – These are federal government, fixed satellite users and any grandfathered wireless internet service providers. They are granted interference protection from the other tiers below (PAL and GAA)
- Priority Access License (PAL) – These are licensed users who have access to 70 MHz of spectrum and up to a maximum of 40 MHz per licensee. They are protected from interference from the lower tiers but must cease transmitting to protect the incumbents if determined by SAS.
- General authorized access (GAA): These users can use the entire 150 MHz of spectrum as long as there is no one else using the spectrum within the area. They do not receive interference protection from any of the other tiers of users.

CBSD: CBSDs are defined as fixed radiating antennas and could be small cells, remote radio heads, DAS systems or a combination of all. There are two different kinds of CBSDs:

Table 1 - CBSD categories

CBSD category	EIRP limits	Comments
Category A CBSD	30 dBm / 10 MHz	Limited to indoor deployments. Outdoor deployment maximum height is 6 meters height above average terrain (HAAT)
Category B CBSD	47 dBm / 10 MHz	Limited to outdoor deployments and must be installed by CPIs

Certified professional installers (CPI): All CBSDs must be registered with the SAS by a certified professional installer. CPIs are authorized to give detailed information about each CBSD to the SAS before it is allowed to transmit.

End user device (EUD): End user devices are generally user devices like LTE or 5G capable smart phones, tablets, or routers, which communicate via CBSDs to the network. They are limited to a maximum of 23 dBm EIRP.

1.2. Motivation and benefits of private LTE/5G networks

Current connectivity options for enterprises are limited to either public cellular networks or enterprise Wi-Fi. Commercial networks from mobile network operators (MNOs) are designed for public use and do not cater to the specific use cases for enterprises. The advantages described below are a key reason for enterprises to deploy their own private LTE/5G networks.

One of the key benefits of private LTE networks is its ability to cover larger areas as compared to Wi-Fi. Private LTE/5G networks can provide superior coverage in challenging environments like factories with a lot of metallic structures, or in outdoor campus-style environments like universities. They can be used to complement existing Wi-Fi so that end users can benefit from the best of both networks.

Mobility is another use case where private LTE/5G networks can offer a lot of benefit. Seamless handovers and access point neighbor relations are built into LTE/5G networks. This mobility is ideal for use cases like asset tracking, autonomous vehicles, remote guided vehicles, and critical communications.

Private networks also offer a level of customization for the specific use cases for enterprises. Overall bandwidth in a LTE or 5G network can be customized depending on the requirements. The uplink and downlink ratios in the channel can be modified using different TDD frame configurations. For example, a frame configuration of one makes more sense in uplink heavy applications like video streaming while a frame configuration of two can be used for downlink heavy uses. The bandwidth can further be modified by combining channels together using features like carrier aggregation. Frequency re-use can further be used to control interference between different sectors in a venue. Customization can further be achieved by varying Quality of Service (QoS) parameters and assigning them to different groups of end user devices. For example, devices that require high bandwidth can be assigned a QoS that allows for higher throughput and guaranteed bit rates.

Private LTE/5G networks can also be leveraged to bring the benefits of MEC environments. MEC, as defined by ETSI (European Telecommunications Standards Institute,), “offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the network” [4]. Thus, this allows for high bandwidth and low latency applications like video analytics, augmented reality (AR), and other use cases, which benefit from edge processing.

2. Private networks architecture

2.1. Components of a CBRS private wireless network

A private wireless network consists of many components which are either managed by the operator, a third-party system integrator or the end user. A CBRS specific private wireless network consists of the following key components:

A. Wireless spectrum
A private wireless network can be deployed on licensed, unlicensed, or shared spectrum like CBRS. This is granted by a governing body such as the FCC in the United States.

B. Spectrum Access System
The FCC has authorized several spectrum access systems for CBRS. These are deployed in the cloud and CBSDs or the domain proxy must have continuous access to this for regular heartbeats.

C. Radio Access Network (RAN)
Deployed on premises for a private LTE network, the RAN consists of the radios, antennas and baseband functions.

D. 4G or 5G core network
The EPC or 5G core can be located on premises, partially on-premises or entirely on the cloud. This is discussed in more detail in the architecture section of this paper.

E. Multi Access Edge Compute (MEC)
Located on premises to handle data analytics, caching, and other processing functions that would otherwise be deployed in the cloud. This allows for a host of low latency and high bandwidth applications.

F. User devices
The end user devices can be smart phones, tablets, cameras, LTE/5G routers, sensors, etc. and can vary depending on the use case.

G. Management systems
These consist of the portal(s) that help manage the RAN, network core, devices, and orchestration.

2.2. Architecture

The architecture for private networks depends on the deployment venue, use case, and technology (LTE or 5G). Presented below are some common deployments for private LTE, with their respective pros, cons, and usage.

2.2.1. *Cloud-based core network*

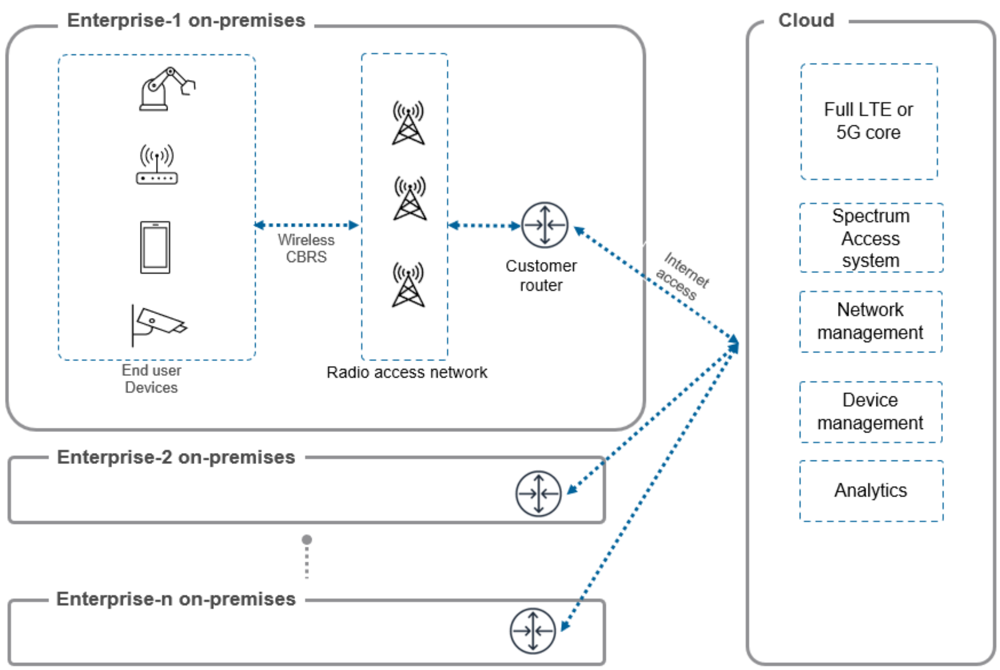

Figure 1 - Network core hosted on cloud

In this deployment, all the network core functions are hosted on the cloud with a dedicated radio access network on premises. This implementation is easy to deploy since there is little infrastructure needed on premises to host the core functions. Further, it can support multiple geographically distant enterprises if they have connectivity to the core.

However, this implementation does not support applications which require low latency since the data has to traverse multiple hops over the internet and back. It is also not efficient for higher bandwidth applications like high-definition video processing or real time streaming. For cameras and video, the backhaul requirements scale very quickly since all processing is done on the cloud. The enterprise still gains the benefit of having dedicated coverage in their venue, which is better than using a public commercial network.

2.2.2. Full network on premises

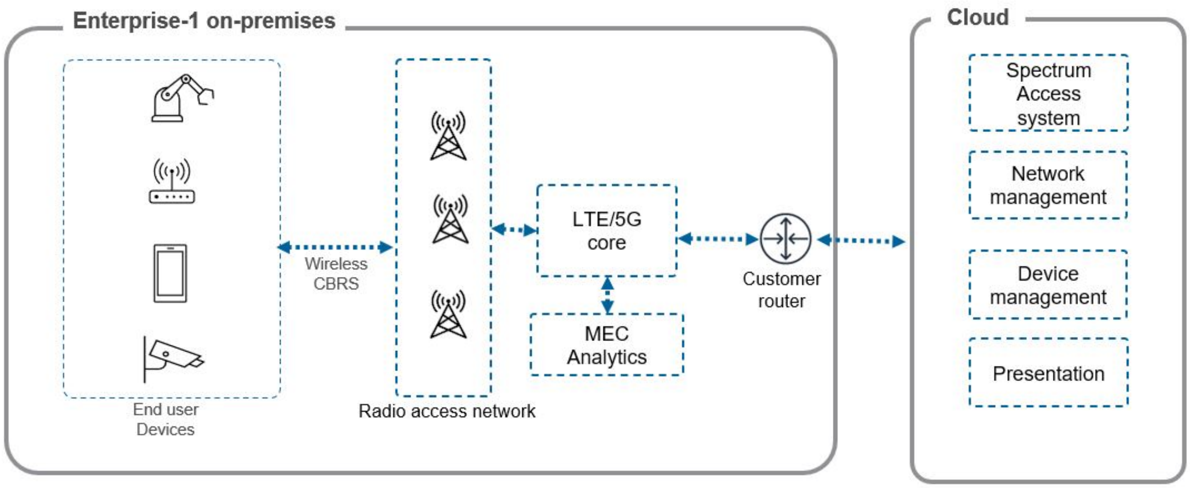

Figure 2 - Full network on premises

In this implementation, all the network core functions are located on premises. This is ideal for low latency applications or applications that require real time processing and high bandwidth like video streaming. For example, this would support a worker safety use case where life feeds from cameras are sent to the edge for further processing and analytics on the edge. While this offers advantages to the enterprise with a dedicated core on premise, it does not scale that well for an operator since separate infrastructure is required on premise for every enterprise.

The management functions can be hosted in the cloud for network operations and orchestration. As in all deployments, the SAS is also hosted separately in the cloud.

2.2.3. Network core at edge data center

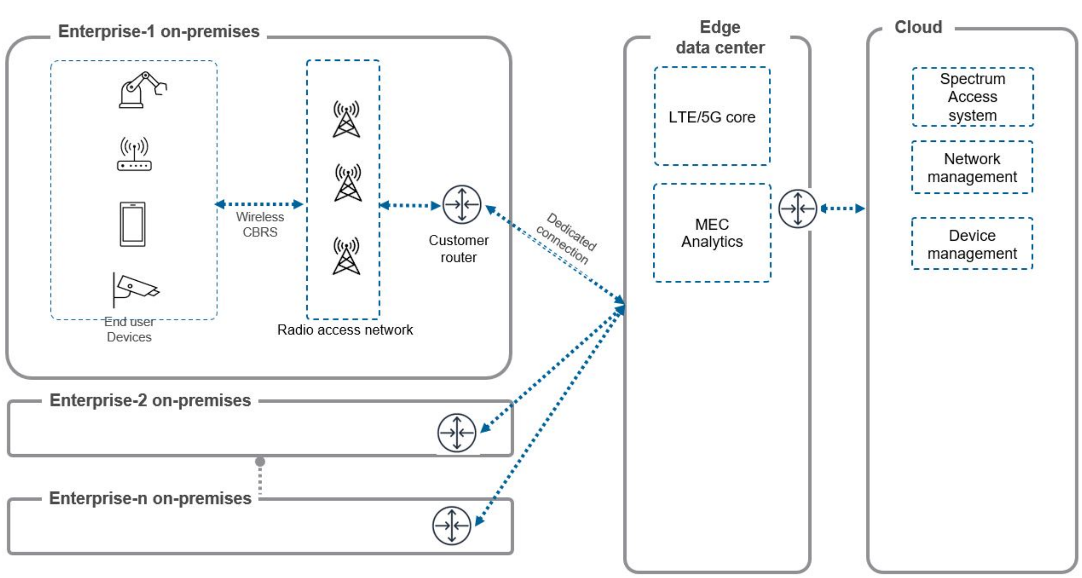

Figure 3 - Network core at edge data center

An edge data center is defined here as a data center with a dedicated connection to the enterprise. This can be owned by either the operator or managed by a cloud service provider as part of their edge offering. This implementation offers a balance between the full cloud and on-premises deployments, while still offering the ability to serve lower latency and high bandwidth applications.

2.2.4. Hybrid architecture

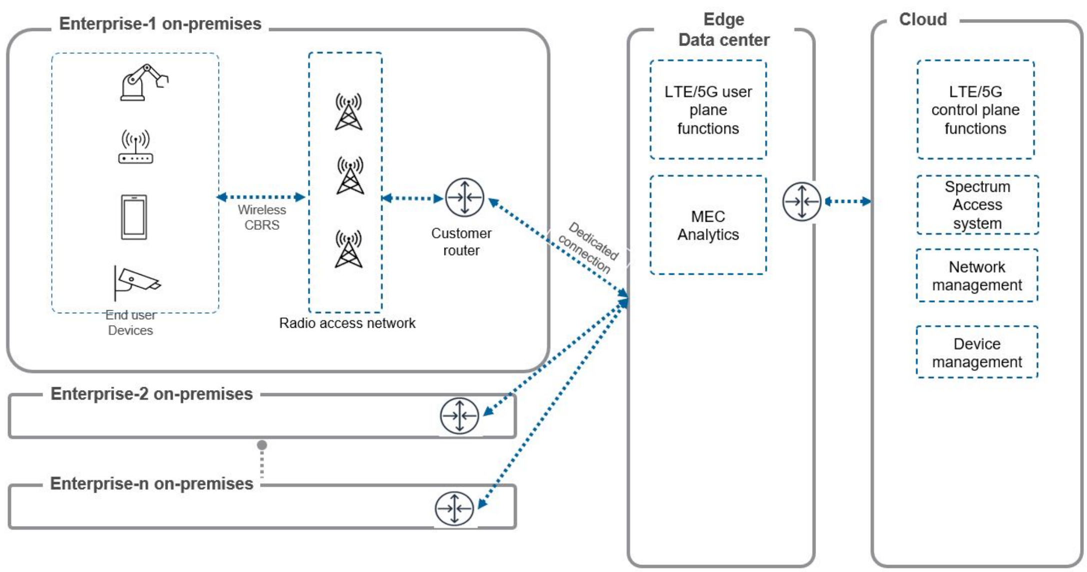

Figure 4 - Hybrid deployment

In this implementation, the use plane functions are located at the edge data center with the rest of the functions hosted in the cloud. For 5G, this means the user plane function (UPF) is hosted at the edge, while the access management functions (AMF), session management function (SMF), policy control function(PCF), network slice selection function(NSSF), authentication server function(AUSF) and unified data management(UDM) functions are hosted in the cloud. This architecture allows multiple enterprises within proximity of the edge data center to be served, while still leveraging the cloud for management.

3. Use cases in different industry verticals

As discussed earlier, private LTE/5G allows for a variety of different applications. Presented below are some of them split by vertical, illustrating how a private LTE network enables them.

3.1. Industrial

a. Worker safety

Safe and accident-free environments are a priority for plant managers in a factory. This can be done is two ways – by enforcing safety standards and then tracking compliance of those standards. Charter, along with its partners, has demonstrated a video analytics worker safety use case. A camera was used to capture video of workers operating a machine in the factory, and sent to the MEC on premises. An algorithm identifies whether the workers are wearing safety gloves, helmets, jackets, and other equipment required for safe operation of the machines. The data is anonymized and recorded for compliance purposes, and automatic notification is sent out if a particular worker is not wearing safety equipment.

b. Autonomous guided vehicles (AGV) and remote-controlled robots

For large warehouses or factories, there is a constant need to move large items from one area to another. Boxes, finished products, and other items must be loaded onto pallets and moved manually by employees dedicated for this task. This uses valuable employee time and resources. Remote controlled robots or AGVs can be used to transport materials within and around the factory to save time. A private LTE network provides this reliable coverage, mobility, and edge processing to realize this use case

c. Push to talk and push to video

In large industrial environments, cellular service is poor because of high penetration loss due to many large metallic structures. In the absence of good public cellular service, private LTE/5G networks can fill the gap. Charter has demonstrated this application to its pilot customer. The push-to-talk server is hosted on premises along with the network core, and factory employees can install a push to talk application on their existing smart phones if it supports CBRS.

d. Predictive maintenance

Factories and warehouses can collect valuable data from their machines with wireless connected sensors. Most mechanical systems have a vibration signature when operating correctly. Sensors can be used to detect any irregular vibrations, which would otherwise go unnoticed. The data is used to train algorithms, which can then predict an upcoming failure. The result is minimizing downtime and gaining insights into machine behavior [3]. Private LTE networks provide the connectivity and reliability to connect hundreds of sensors and process the data at the edge.

3.2. Healthcare

a. Secure communications

Healthcare workers in hospitals and other medical facilities require secure communication with high reliability. Additionally, they may require sensitive patient information to remain on premise. Indoor coverage in hospitals can vary depending on the building material and various medical equipment located indoors. A private LTE network can solve both these problems by providing reliable connectivity with a dedicated RAN, and edge compute to process the data on premises.

b. Augmented reality (AR) applications

Medical personnel equipped with AR headsets can have instructions and information overlaid on medical devices to understand how to properly use them. AR can also be used in a training setting for healthcare professionals to learn to use equipment.

3.3. Education

a. Remote learning

The worldwide pandemic has shown us the importance of having good connectivity at work, universities/schools, and at home. Private networks can be used to extend school connectivity to residential locations around it. Students can access school resources securely and safely from their homes.

b. Campus connectivity

Universities and other campus environments are ideal for private LTE networks since they provide seamless coverage both indoor and outdoor. Students can have access to local applications securely anywhere on the campus. The network can be further used to serve other use cases like providing connectivity for security personnel, faculty communication and interactive learning via VR or AR headsets.

4. Charter Communications lab evaluation

Charter Communications has conducted an evaluation of private network offerings from several vendors to assess the best fit for its customers. The vendor selection depends on customer, type of use case, cost sensitivity and other factors. Our evaluation attempted to take a holistic look at the different criteria that are important for private networks for enterprises.

4.1. Selection criteria

4.1.1. Network

Private LTE and 5G networks can have varying deployment scenarios - indoor industrial, outdoor/indoor campus, hospitals, schools etc.). Selection of the radio access network determines which of these environments can be served efficiently. Some of the different types of RAN options are:

a. Indoor Pico or Femto radios varying in output power from less than 20 dBm to 30 dBm (maximum allowed power for indoor CBRS deployment)
b. Outdoor rated radios with integrated antennas
c. Outdoor rated radios with an option for external antennas
d. Remote radio head which connects to a central baseband

We chose to go with a vendor that has a wide variety of radio options to serve the different deployment scenarios of private LTE/5G. For example, in a factory which has existing Ethernet cabling, we would choose to go with the indoor small cells which backhaul via copper. However, in another scenario for outdoor campus coverage where the antennas are deployed on a tower, we would go with a RRH and external antenna connected via fiber to a central baseband.

To serve the varying bandwidth requirements within a private network, LTE provides the flexibility to modify different TDD frame configurations. For example, a TDD frame configuration of 2 allows for a 3:1 downlink to uplink ratio. Alternatively, a frame configuration of 0 allows for a 1:3 downlink to uplink ratio. The latter could be used in primarily uplink use cases like video security or worker safety based on video analytics. Another factor we looked at was the total aggregated bandwidth. This could range from 10 MHz to the entire 150 MHz with carrier aggregation. This has a big effect on throughput so was an important consideration in selection of RAN.

The total capacity of the system depends on the number of eNodeBs supported by the baseband and the total capacity of the EPC i.e. how many S1 links it supported. Our evaluation looked at how many of each link the network could support, and if there was room for scaling. Lastly, we looked at the network core configuration from the different vendors. For LTE, the evolved packet core (EPC) could either come in different configurations (small, medium, large) each with a different number of supported. Other vendors did not have an upper limit and scaled the core as the network grew.

4.1.2. Management systems

In a traditional network, there are different user interfaces to manage the different functions from RAN and core. There can be a network management system (NMS) for RAN, a separate command line interface (CLI) or graphical user interface (GUI) for the core, another portal for home subscriber server

(HSS) function, etc. For a private network, it is important to have a single pane to manage most functions. Table 2 describes some of these functions and the intended end user.

Table 2 - Functions of management portals and primary user

Function	Primary user
Adding and removing eNodeB	Operator
Modifying cell frequencies	Operator
Modifying / optimizing network parameters	Operator
Creating different QoS groups	Operator
Viewing network status and alarms	Operator / Enterprise
Adding / removing UEs and sims	Operator / Enterprise
Changing aggregate maximum bit rates	Operator / Enterprise
Creating IMSI groups	Operator / Enterprise

4.1.3. Ease of deployment and operations

Private wireless networks need to be easy to deploy and manage for enterprises. The complexity of LTE and 5G networks needs to be abstracted so that the enterprise can easily integrate the private LTE network into their existing infrastructure. In our evaluation we looked at several aspects of the ease of deployment

a. Ease of physical installation: use of existing IT infrastructure in venues is ideal because of obvious cost benefits. In an industrial environment, the wiring must be done either after hours or between shifts. Moreover, exact location of antennas depends on specific venue restrictions.
b. Ease of operations: after deployment, the private network must be managed remotely, with roles split between the operator and the enterprise customer. This is discussed in more detail in section 4.1.2
c. Support: Vendors need to have 24/7 support teams for any troubleshooting or escalations if needed, depending on the specific service level agreements. Our evaluation also considered this level of support from the network vendors.

4.2. Overview of results

Table 3 - Summary of network evaluation

Category	Vendor 1	Vendor 2	Vendor 3	Vendor 3
RAN – available options	a. 17 dBm Indoor radio b. Outdoor CAT-B radio with integrated antenna	a. 24 dBm small cell b. 24 dBm small cell with option for external antenna c. Outdoor radio with option for external antenna d. Outdoor radio with integrated omni antenna e. Baseband with RRH + external antenna	One radio with adjustable power for both indoor and outdoor. Option for external antenna	a. 24 dBm indoor radio b. 30 dBm indoor radio c. 30 dBm outdoor radio

TDD frame configuration options	1 & 2	0,1,2	0-7	1 & 2
Evolve packet core (EPC)	Full on-premises EPC with redundancy	Full on-premises EPC with redundancy	3rd Party EPC on premises with HSS on cloud	Cloud EPC only. Option for on-premises EPC with 3PP
Max allowable bandwidth (depends on SAS grant)	4 carriers 80 MHZ (40+40 MHZ)	3 carriers. 60 MHz (20+20+20)	8 carriers 150 MHz	2 carriers 40 MHz (20 + 20)
Max modulation	256 QAM	256 QAM	256 QAM	256 QAM
MIMO	2x2 or 4x4	2x2	2x2 or 4x4 (extra radio)	2x2
Maximum capacity	Maximum 24 radios	Scalable	Scalable	Depending on 3rd party EPC provider

5. Private LTE deployment in factory

Charter Communications has deployed a private LTE network in a 600,000 sq. km manufacturing plant in Michigan, USA. The following sections describe the planning, design, deployment, and lessons learned from this pilot.

5.1. Planning and design

Like with any network deployment, our deployment started with customer inputs and a discussion of how they would use the network i.e. primary use cases.

a. Size of the factory: The coverage area is important since exclusion zones need to be defined when doing the RF propagation study. In our scenario, the factory was a little over 600,000 sq. km. The main operations of the factory were on the first floor, while the IT and certain other offices were on the second floor.
b. Interior of the factory: We requested a map of all the equipment in the factory (machines, racks, pallets etc.). This is not always available, so site surveys are valuable when mapping out the venue and any design considerations that need to be made
c. Material properties: Industrial environments have a range of different items which affect the overall propagation. In our factory, the walls were concrete, most of the machines were metallic, there were large wooden structures, and 15–20-foot storage racks in many areas. In addition, there were large aluminum ventilation ducts and metal rails along the ceiling. These may be missing on the drawings, but they do affect coverage so should be accounted in the design as best as possible.
d. Acceptable locations to mount antennas: the factory had restrictions on where we could mount the radios and antennas. This was due to either some high equipment, fans on the ceilings, ventilation ducts, or existing antennas and access points from other technologies. We had to make a tradeoff between desired locations for coverage and these customer restrictions.

e. Networking requirements: IT personnel needed to specify what firewalls they have in place, what IP addressing scheme they have, whether they use a public or private domain name server (DNS), switch configuration, and anything else to integrate the private LTE network into their system.

Considering the customer requirements, we performed a RF design of the factory. Figure 5 shows the coverage, while figure six shows the best server plot.

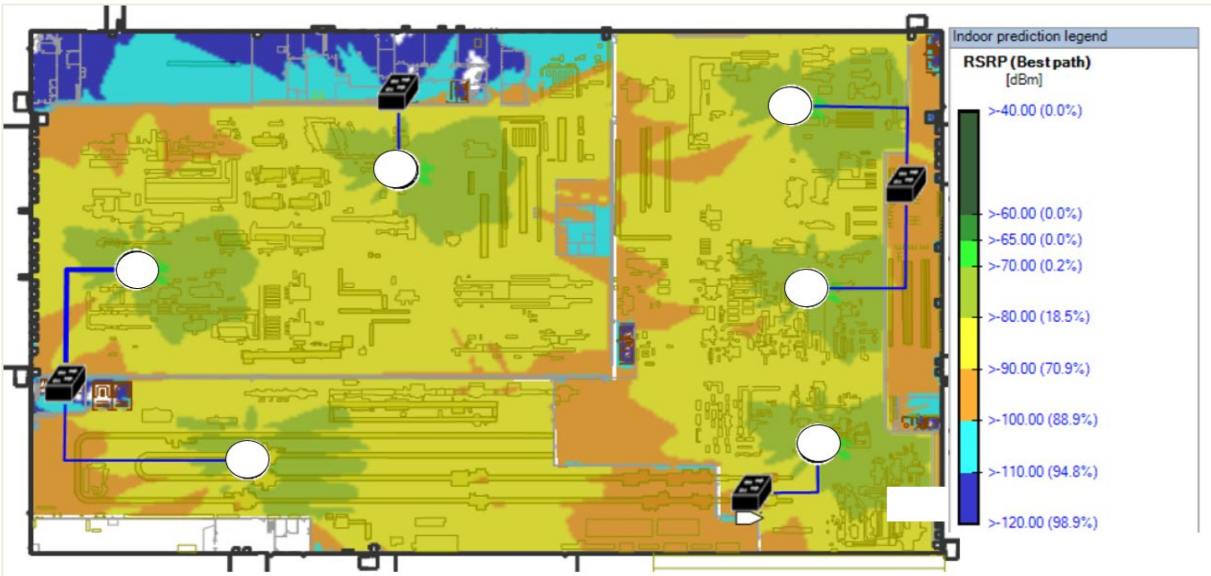

Figure 5 - RSRP plot from RF design

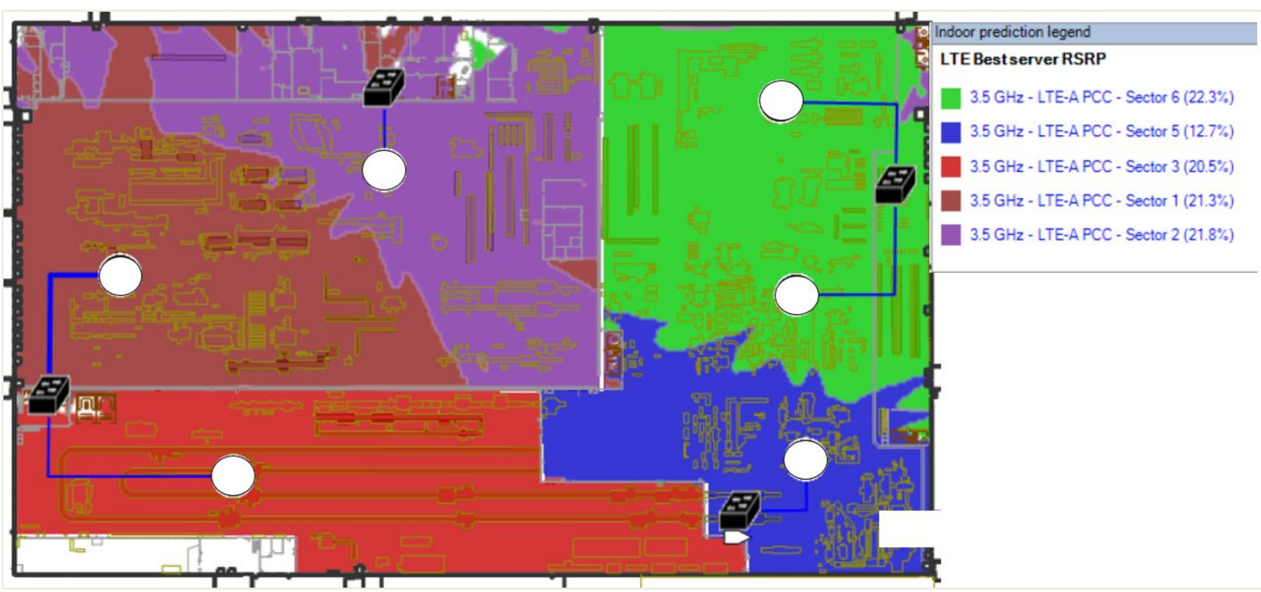

Figure 6 - Best server plot from RF design

The design shows 95% of the plant is covered by a signal level of -110 dBm or better. The intent of the design was to cover the entire factory, and we had to balance between desired coverage and interference between neighboring sectors. While the areas to the north of the factory (cafeteria and copy rooms) had limited coverage, we can add additional radios there if required. We also implemented frequency re-use to limit inter-cell interference.

5.2. Deployment

The installation was done by the factory's approved installers who were familiar with the specific limitations and approvals needed to install. Custom mounts were created to mount the radios and antennas, which were then hung from vertical rails on the factory ceiling. The EPC and MEC servers were in the factory main distribution frame (MDF) room. Figure 7 shows the deployment architecture.

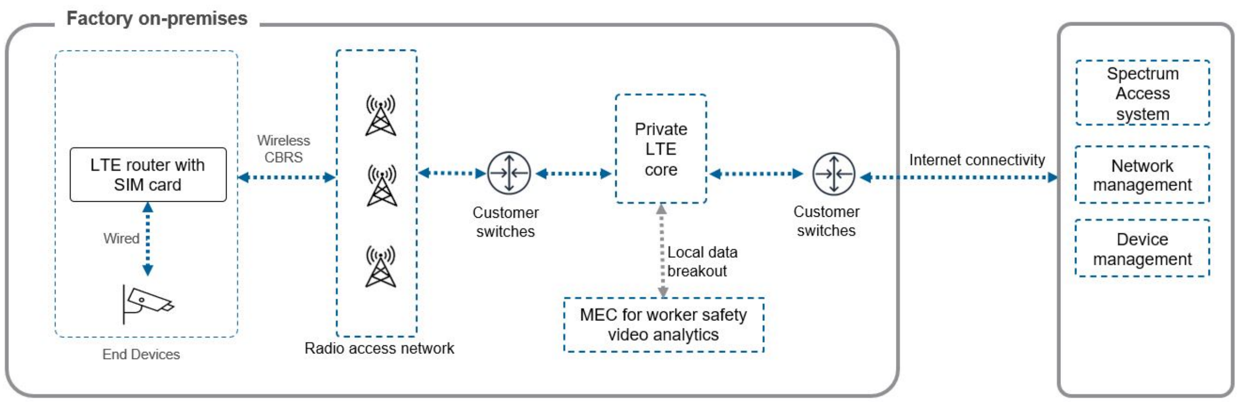

Figure 7 - Deployment architecture

5.3. Post launch testing

After the network was live, Charter conducted performance testing at pre-determined test points to assess coverage, quality, and throughput across the factory. The table below has the results of the testing, and comments where the results deviated from the expected performance.

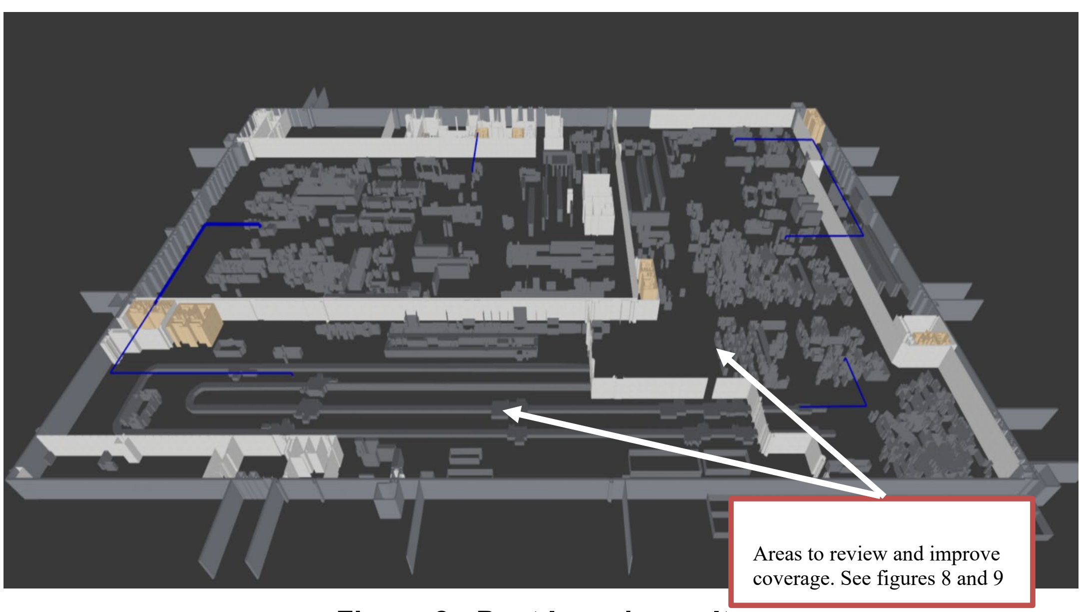

Figure 8 - Post launch results

Table 4 - Performance measurements from live network

	Measured Values				
Test point ID	RSRP	SINR	DL Throughput (Mbps)	UL Throughput (Mbps)	Comments
1	-81.9	29			
2	-78.9	30	170	22	
3	-97.5	24	105	17.6	
4	-104	20.1	90	17	Marked as exclusion in design
5	-105	18	70	5.8	Marked as exclusion in design
6	-75	30	172	17.6	
7	-94	25	100.5	17	
8	-94.5	28	115	17.5	
9	-95		114	17.1	
10	-110	24	95	17	See figure 7
11	-75	30	170	22	
12	-105	15	75	11.2	See figure 7
13	-96	25.9	80	17.5	
14	-108		40	12	
15	-82	27.9	170	17	
16	-95	23	105	17	
17	-72	30/30	170	17	
18	-108	12	90	11	
19	-80	29	125	22	
20	-107	19	105	17	See figure 7
21	-110	10	70	11	See figure 7
22	-102	19	105	17	See figure 8 - Antenna mount needs to be lower or moved
23	-106	23	120	17	See figure 8 - Antenna mount needs to be lower or moved
24	-87	30	123	17	
25	-95	27	112	17	

Based on the results, we assessed where the network performance could be improved and reasons for lower-than-expected performance. Figure 8 shows an example of an area within the factory. Large metallic structures like this can cause fluctuations in signal strength due to diffraction and are difficult to account for in the design. Directional antennas can better accommodate hard to reach areas or can be excluded altogether if the customer does not wish to cover them.

Figure 9 - Metallic and large structures effect coverage

Figure 9 shows the effect of antenna placement on coverage. The antenna in the picture had to be moved because of factory restrictions. However, it is not located between a metal duct and a rail which limits coverage in one direction. Our solution here is to either lower it to avoid the blocking, or to relocate it to a different area.

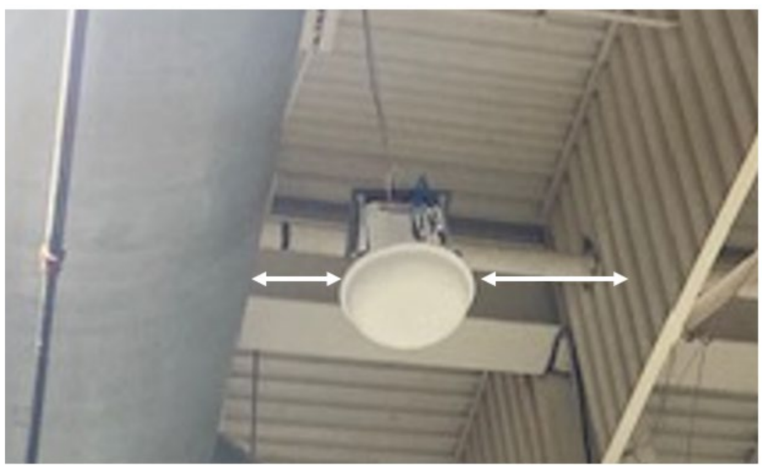

Figure 10 - Antenna blocked by metal duct and rail

5.4. Use case

Charter has demonstrated a worker safety use case based on video analytics. Cameras were set up to stream video over CBRS to the MEC located in the factory MDF. An algorithm was trained to detect if employees were wearing helmets, safety gloves, jackets, and boots. The plant manager then collected metrics for compliance purposes, to see if there were any areas of the factory which needed better safety protocols or signs in place.

5.5. Lessons and best practices from deployment

First, the operator needs to have a detailed discussion of the existing network, firewalls, and any other policies that the IT team has in place. We faced some initial issues with default DNS being blocked, but were able to overcome them by working with IT. This can be resolved by including networking requirements in the initial customer information questionnaire.

Second, the RF designer should factor in movable structures in the design, especially in an industrial environment where this can happen often. This could be accomplished by running several scenarios of propagation with equipment located at different areas. At the same time, defining exclusion zones is important since not every area can be covered. Third, the network installers and designers need to work closely to ensure proper installation. A ten foot change in antenna location may not make a big difference in an office or outdoor environment, but in a factory this could potentially impact coverage if the new location is behind obstructions. Fourth, there should be a discussion on the primary use cases so that coverage and capacity can be targeted to serve those regions as best as possible.

6. Conclusion

In this paper, we presented an overview of CBRS and the motivation for private wireless networks on CBRS. Second, we presented the main use cases in different verticals and how a private LTE/5G network enables those use cases. Third, we presented the evaluation of different network vendors in Charter's lab in Denver, Colorado. Fourth, we presented the planning and results from an actual deployment in a large factory in Michigan.

Private LTE and 5G networks have the potential to streamline operations, provide greater insight into operations and help solve critical challenges for enterprises across many different verticals. Charter communications is committed to investing in private LTE/5G networks and serving the needs of enterprises across the nation.

Abbreviations

AP	access point
bps	bits per second
FEC	forward error correction
HD	high definition
Hz	hertz
SCTE	Society of Cable Telecommunications Engineers
5G	5^{th} generation Cellular technology
LTE	Long Term Evolution
MEC	Multi access Edge compute
CBRS	Citizen Broadband Radio Services
SAS	Spectrum Access System
WISP	Wireless Internet Service provider
PAL	Priority Access License
GAA	General Authorized Access
FCC	Federal Communication Commission
CBSD	CBRS Device
CPI	Certified Professional Installer

HAAT	Height above average Terrain
EUD	End user device
MNO	Mobile network operator
QoS	Quality of Service
TDD	Time division duplex
IT	Information technology
ETSI	European telecommunication standard institute
GSMA	Global system for mobile communications association
RAN	Radio access network
UPF	User plane function
AMF	Access management function
SMF	Session management function
EPC	Evolved packet core
MIMO	Multiple in multiple out
UDM	Unified data management
PCF	Policy control function
NSSF	Network slice selection function
AUSF	Authentication server function
RF	Radio frequency
AGV	Autonomous guided vehicle
VR	Virtual reality
NMS	Network management system
AR	Augmented reality
eNodeB	E-UTRAN NodeB
CLI	Command line interface
GUI	Graphical user interface
QAM	Quadrature amplitude modulation
DNS	Domain name server
RSRP	Reference signal received power
MDF	Main distribution frame
UL	Uplink
DL	Downlink
SINR	Signal - interference noise ratio

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