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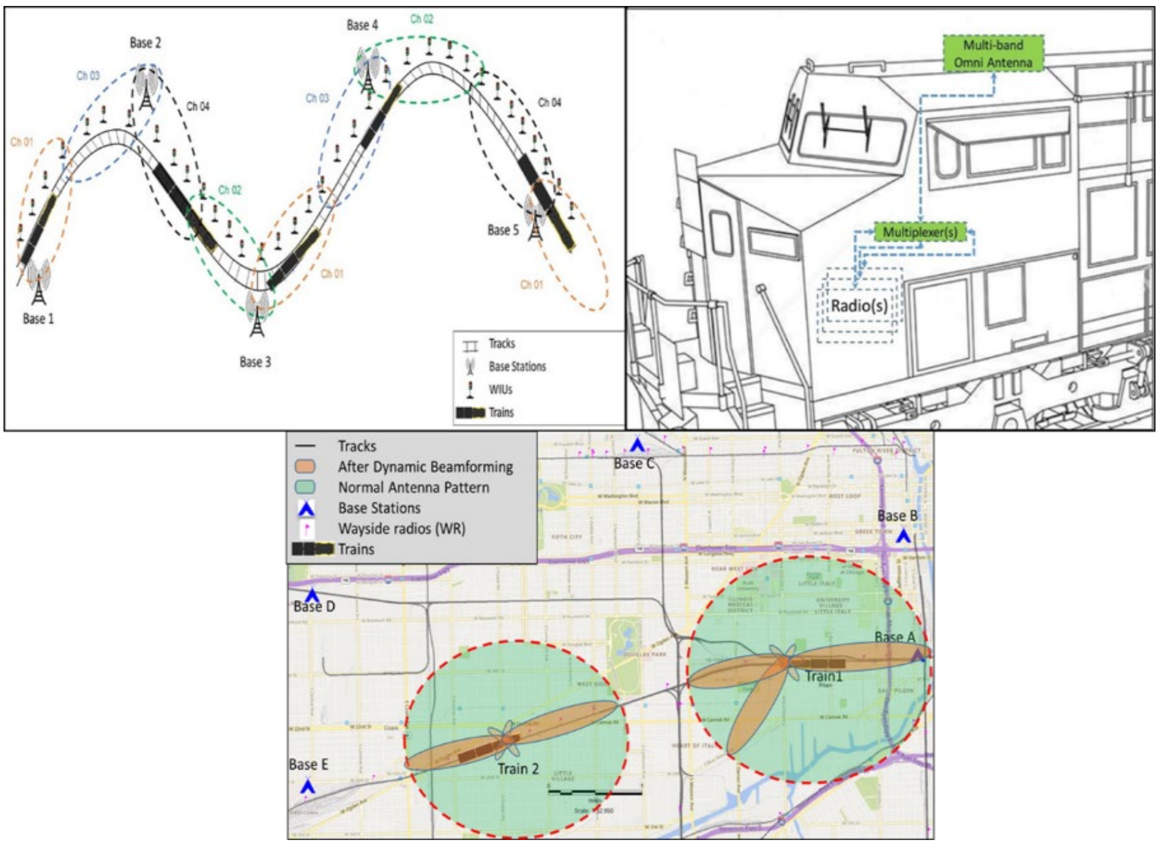
Multi-band and Directional Antennas: Research and Development



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14. ABSTRACT

The Federal Railroad Administration (FRA) contracted a research team from TTCI (now MxV Rail) to assess the potential use of multi-band and directional antennas to meet the current and future wireless communication needs of the U.S. railroad industry. FRA supported this project due to the high level of complexity involved in developing requirements for and quantifying the benefits of multi-band and directional antennas. The research team found that significant communications capacity gains could be achieved in dense urban areas using more directional antennas, particularly on base stations, with additional gains possible through increased use of directional antennas at wayside locations and/or use of smart antenna systems on locomotives.

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Executive Summary

The Federal Railroad Administration (FRA) contracted a research team from Transportation Technology Center, Inc. (TTCI, now MxV Rail) to research the potential use of multi-band and directional antenna technologies to address challenges the industry faces relating to available spectrum and growing demand for wireless mobile applications. The team found that significant communications capacity gains could be achieved in dense urban areas (DUA) using more directional antennas, particularly on base stations, with additional gains possible through increased use of directional antennas at wayside locations and/or use of smart antenna systems on locomotives. The locomotive platform could benefit most significantly from multi-band antennas, due to the number of applications and frequency bands that must be supported. More than one supplier indicated that a quad-band antenna was feasible for the locomotive platform. For fixed sites (base stations and waysides), researchers found that multi-band antennas were most feasible when combining just the two lowest of the four railroad bands with a dual-band omni antenna.

Potential benefits from a multi-band and/or directional antennas include:

- Increased capacity − Directional antennas could provide the benefit of increased capacity. The use of directional antennas (which must also be steerable for mobile links) would reduce the co-channel interference, which in turn could allow more frequency reuse and more capacity within a geographical area.
- Reduced space and size in a mobile environment – Use of a multi-band antenna on a mobile platform (locomotive or hi-rail vehicle) may reduce the space required for antennas.
- Fewer cables and penetrations through roofs of mobile platforms – Use of a multi-band antenna could reduce the number of antenna cables required.
- Reduce weight and wind loading on wayside poles and towers – A single multi-band antenna could replace multiple single-band antennas with possible reduction in total weight and wind loading.
- Increased reliability – A single multi-band antenna could provide redundancy for multiple single-band antennas, potentially making antenna redundancy more feasible.

Major tasks and results of this project were:

Concept of operations (ConOps) – The team conducted a needs analysis with input from the project AG to identify base operational cases across different railroad platforms and scenarios in a ConOps document. The platforms addressed were mobile (locomotive and hi-rail), wayside applications, and base stations. The scenarios addressed were urban, suburban, rural and mountain.

Multi-band and directional antenna requirements – The team developed system requirements for multi-band and directional antennas that could be deployed on the various railroad platforms. Options, tradeoffs, and applicability to the railroad industry were addressed. Considerations included functionality, performance, cost, size, weight, reliability, as well as compatibility with existing railroad radios.

Spectrum reuse analysis – The team conducted analysis and tradeoff studies for the spatial reuse of spectrum. Methods were investigated to reuse channels in the same area via spatial discrimination to obtain more capacity from the limited available spectrum. The analysis was performed for all three types of platforms. The research team found that significant communications capacity gains could be achieved in a DUA using more directional antennas, particularly on base stations. Additional capacity benefits can be obtained by either using more directional antennas on waysides and/or using smart antenna systems on locomotives.

Technology survey – The team conducted research on available existing technologies that might be applicable or could be modified to be applicable. This included literature searches as well as requesting information from leading antenna suppliers regarding their solutions for meeting the system requirements developed by TTCI. The information obtained was used in tradeoff studies as well as to assess the feasibility and maturity of the desired technologies.

Tradeoff analysis – The team conducted tradeoff studies to develop the most effective strategies to allow the railroads to deploy multi-band and directional antennas within their wireless communication networks. Multi-band antennas are particularly significant for the locomotive platform, which must support several different applications on different frequency bands. However, some size and weight reductions are also attainable with multi-band antennas at base stations, in order to reduce loading on poles and towers. Researchers found that a multi-band (quad-band or tri-band) single-element antenna solution (only omnidirectional) was only feasible for the mobile (locomotive and hi-rail) platform. A dual-band, single-element antenna solution (both omnidirectional and directional) was possible, however, for base station and wayside platforms. Various forms of directional antennas were considered, and capacity gains could even be attained with the simplest fixed directional antennas in certain base station and wayside scenarios.

1. Introduction

The Federal Railroad Administration (FRA) funded a research team from the Transportation Technology Center (TTCI, now MxV Rail) to analyze and develop railroad multi-band and directional antenna requirements, research available technologies, perform tradeoff studies, investigate the potential for spatial reuse of spectrum, and develop recommendations to support railroad wireless mobile applications, especially those pertaining to operations and safety.

1.1 Background

Railroads have numerous and ever-growing needs for wireless mobile applications to support safe and efficient operations. Currently, several different types of radios and frequency bands, requiring several different antennas, are used to support the various applications. The need to purchase, install, and maintain multiple, discrete antennas to support voice and data communications at multiple frequency bands on multiple platforms (some of which have limited space) and limitations on the availability of wireless radio frequency (RF) spectrum are significant challenges.

To address these challenges, several recent and ongoing efforts have been undertaken. Additionally, the industry has been exploring synergistic radio technologies, such as a software-defined radio (SDR) for railroad applications, with potential benefits that include reduced hardware, supporting migration of applications, dynamic adaptability to changing environment and/or availability of spectrum, and upgradeability and flexibility for future expansion, among others.

Development of directional antennas that could be used on a variety of platforms increase the potential for spectrum reuse, which can provide more communications capacity from available RF spectrum. The potential to combine multiple antennas into one multi-band antenna would help address the challenges discussed above, especially on platforms where space is limited, such as the roof of a locomotive cab, or where weight and wind loading are critical, such as on wayside antenna poles.

Potential benefits from a multi-band and/or directional antennas include:

- Increased capacity – The use of directional antennas (which must also be steerable for mobile links) can reduce the co-channel interference that, in turn, allows more frequency reuse and more capacity within a geographical area. With the ever-increasing demand for greater wireless throughput and decreasing supply of RF spectrum (resulting in very high cost to purchase), such alternative methods of increasing capacity must be sought.
- Reduced space and size in a mobile environment – Implementation of multi-band antennas on a locomotive or hi-rail vehicle may reduce the space required to install the antennas in a mobile platform.
- Reduced weight and wind loading – Poles and towers used to support railroad antennas for base stations and other wayside applications have limited total antenna weight and wind loading capacity. Often, there is need to add another radio and antenna at a wayside site, but the existing pole cannot support the weight or wind loading of the additional antenna. If several of the antennas already installed on the pole could be replaced with a single, multi-band antenna that has less weight and wind loading than the combination of

antennas being replaced, then the addition of the new radio antenna could be accommodated (either separately or as part of the multi-band antenna).

- Increased reliability – Significant space saved by replacing several discrete, single-band antennas with a single multi-band antenna (e.g., on a locomotive) could provide room to install a second multi-band antenna along with a switching mechanism to support fail-over. This would result in dual-redundancy of antennas for all radios supported by the multi-band antenna with only having to add one backup antenna. The revised setup could provide significant improvement in reliability as compared with the current situation of no redundancy for most railroad radio antennas.
- Fewer antenna cables and penetrations through roofs of locomotives and other mobile platforms for antenna cables

1.2 Objectives

The objective of this project was to identify the most relevant antenna technologies and recommend solutions for railroads that can:

- Increase RF communications capacity by using directional antennas to achieve spatial reuse of spectrum.
- Reduce the size/number of penetrations and number of cables through roofs of mobile platforms by using multi-band antennas.
- Reduce space and size in a mobile environment by using multi-band antennas.
- Reduce weight and wind loading from wayside antennas by using multi-band antennas.
- Increase the reliability of railroad antennas by using one multi-band antenna as a backup for several single-band antennas (or for a primary multi-band antenna).

1.3 Overall Approach

TTCI took the following approach for each task:

- For Tasks 1 and 2, the team created a stakeholder AG made up of FRA and railroads and established communication channels as appropriate. Periodic calls, email exchanges, and other communication methods promoted the exchange of information, resolved issues, and made required decisions. Researchers controlled the project budget and recorded/stored all project documentation. Resources were allocated to handle all the work required for this project.
- For Task 3, the team conducted a needs analyses with input from project stakeholders and identified operational use cases across platforms and scenarios. Researchers also used the results from this task to develop antenna requirements in Task 4.
- For Task 4, the team gathered specifications for the existing omnidirectional and bi-directional antennas used by the railroads. Project stakeholders' input was also used in developing requirements for multi-band omnidirectional and bi-directional antennas. Researchers developed requirements for directional antennas based on those currently used by the railroads and from Task 5 simulation results.

- For Task 5, the team performed modeling and simulations to evaluate spectrum savings and capacity improvements for base stations, waysides, and locomotives. Researchers used the following modeling and simulation tools: MATLAB, Infovista's Planet®, Meteorcomm's ITCnet Planning Module (IPM) and a frequency and slot plan optimization tool (FreSPOT), beam width calculator (BWC), and locomotive WSM reception simulator (LWRS). The team also planned to develop additional in-house tools as needed.
- For Task 6, the team researched available existing technologies that might be applicable or could be modified to be applicable. This included literature searches as well as requesting information from leading antenna suppliers regarding their solutions to meeting the requirements developed by the research team. In addition, the team used the information obtained in tradeoff studies to assess the feasibility and maturity of the desired technologies.
- For Task 7, the team developed this final report with all the results and findings obtained from the work conducted for the tasks described above.

1.4 Scope

This scope of work was divided into seven tasks to achieve the objectives of the project as defined in Section 1.2.

Task 1 – Project Management – Ongoing task throughout the entire project. The team applied the required resources and tools to maintain progress.

Task 2 – Stakeholder Engagement – Ongoing task throughout the entire project, this involved working with the industry AG to maintain alignment with industry objectives.

Task 3 – Develop ConOps – The team conducted a needs analysis with input from the project stakeholders to identify base operational cases across different platforms and scenarios and determined desired functions.

Task 4 – Develop Multi-band and Directional Antenna Requirements – The team developed a system requirements document that included key performance requirements.

Task 5 – Spectrum Reuse Analysis – Researchers developed simulations and tradeoff studies for spatial reuse of spectrum.

Task 6 – Technology Survey – The team conducted research on the currently available technologies and products and performed trade studies.

Task 7 – Final Report – The team developed this final summary report describing the work performed, analysis, recommendations, and other results.

1.5 Organization of the Report

This report is organized into seven major sections:

- Introduction: Provides an overall description of the project objectives and the work conducted.
- Concept of Operations: Provides an overview of the concept of operations (ConOps) for various potential antenna solutions.

- Multi-band and Directional Antenna Requirements: Provides all the antenna requirements developed for each of the platform types.
- Spatial Reuse Analysis: Provides an overview of how different RF optimization techniques were implemented to evaluate spectrum savings and/or capacity improvements.
- Technology Survey: Provides an overview of the how technology survey was conducted.
- Tradeoff Analysis: Provide an overview of various tradeoff analyses performed.
- Conclusion: Provides an overview of results, findings, and recommendations.

2. Concept of Operations

This section presents the operational concepts that the research team developed based on use cases for new antenna solutions for railroad applications. Use cases were derived from a combination of various operational scenarios and platforms that currently exist. Operational scenarios were developed by identifying different track scenarios based on geodata. Various platforms were defined that are applicable in the railroad environment.

2.1 Approach for Determining Operational Cases

To derive use cases for implementing antenna solutions in the railroad environment, various operational scenarios and platforms were identified first. The operational scenarios and platforms were mapped to different use cases that are applicable. These use cases were then considered when developing requirements for the implementation of various antenna solutions.

The operational scenarios were identified based on topography and physical structures around the railroad tracks, which have significant effects on the propagation of the radio signals. Propagation characteristics of a radio wave vary depending on the surrounding environment. A radio wave can propagate a long distance if there is a clear line of sight (LOS) between transmitter and receiver. However, the radio waves are subject to issues like multi-path fading, scattering, and diffraction when there are tall buildings, canyons, or mountains, thus deteriorating the performance of the communication link. Based on these considerations TTCI identified the following operational scenarios: urban, rural, and mountain.

Scenarios and examples are presented in Section 2.2. Additional considerations were given to the railroad track configurations. Railroad track configurations also affect the type of antenna solution that is applicable, specifically:

- The tracks might be relatively straight for many miles.
- The tracks might have curves and diamond crossings within a short distance of one another.
- The tracks might pass through canyons and mountains.

The team identified the following platforms based on current railroad operations and current radio networks: base station, mobile, and wayside. An in-depth assessment of each platform was performed and is presented in Section 2.3.

Each platform was then mapped to various operational scenarios to develop operational use cases as illustrated in Figure 1. Operational use cases were derived and are explained in Section 2.4.

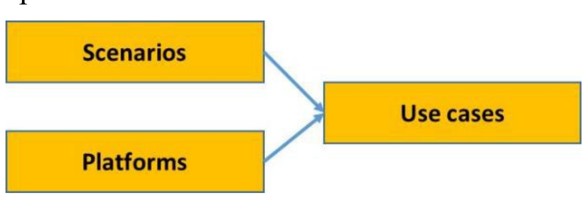


Figure 1. Derivation of use cases from operational scenarios and platforms

Researchers identified different types of antenna solutions that are applicable to the railroad industry as explained in Section 2.5 and further analyzed potential antenna solutions per platform as explained in Section 2.6.

2.2 Identification of Scenarios

2.2.1 Urban Scenario

In an urban scenario, the volume of the train traffic is very high as a multitude of railroads lines – freight, commuter, and passenger – converge and their infrastructure can be densely distributed.

For the urban scenario, multiple track configurations were identified and are explained in the following sub-sections.

Straight Railroad Tracks with Minimum Curves

In this scenario, railroad tracks are relatively straight and do not require coverage anywhere except along the tracks. A directional antenna with a back-to-back configuration can help focus the signal along the tracks only.

Figure 2 illustrates an urban scenario with relatively straight track in which one track may be served by a single base station.

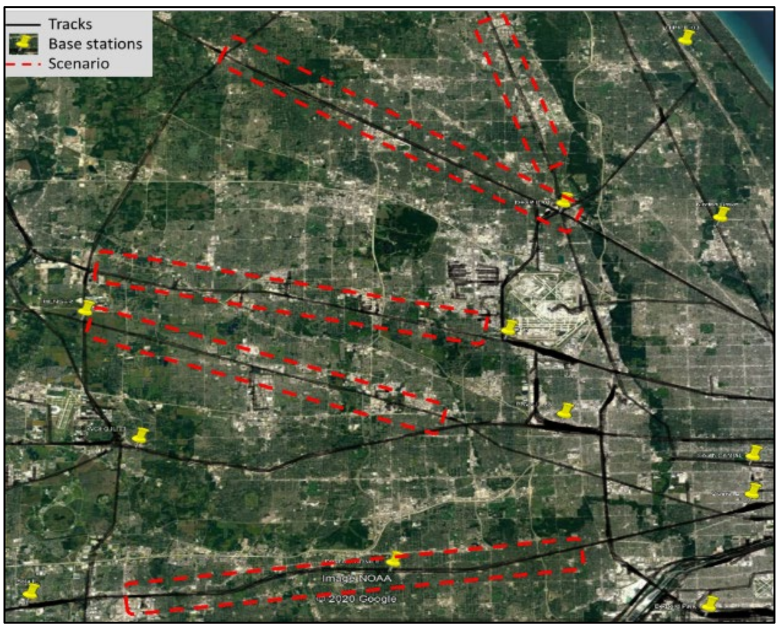


Figure 2. Example of straight railroad tracks in an urban scenario

Railroad Tracks with Curves and Diamond Crossings

It is typical for tracks to cross each other in urban areas, as numerous railroads converge in the same area. Usually, base stations in this scenario use omnidirectional antennas; however, sectorizing the base stations to cover tracks going in different directions could help improve capacity and mitigate any interference issues.

Figure 3 illustrates an urban scenario where the railroad tracks have curves and numerous diamond crossings (Source: Google Earth).

Figure 3. Example of railroad tracks with curves and diamond crossings in an urban scenario

2.2.2 Rural Scenario

In rural scenarios, train traffic volume is very low and base stations are sparsely distributed. Typically, base stations in this scenario are very tall since they need to cover a lot of track area. However, having tall base stations at lower frequencies means the signals from these base stations potentially can be heard by other base stations hundreds of miles away when there is clear LOS, which could cause B-B interference issues. Using directional antennas, along with appropriate height and power reductions, could help alleviate potential B-B interference issues. Figure 4 shows a rural scenario with predominately straight track, and Figure 5 shows a rural scenario with curves and diamond crossings (Source: Google Earth).

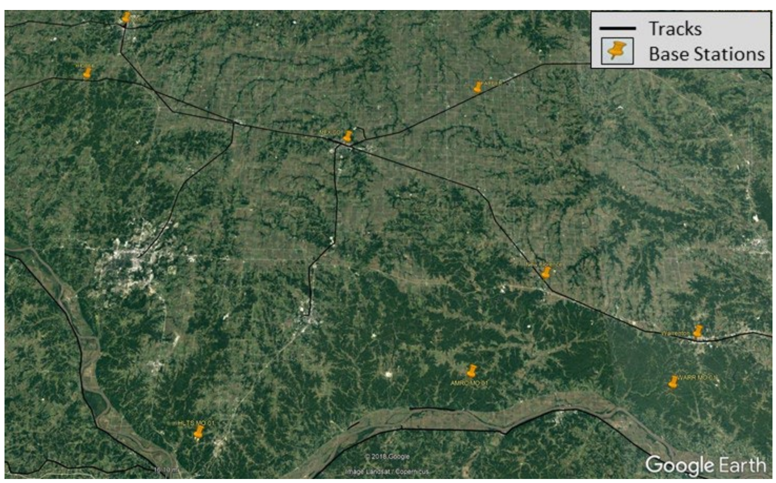


Figure 4. Example of straight railroad tracks in a rural scenario

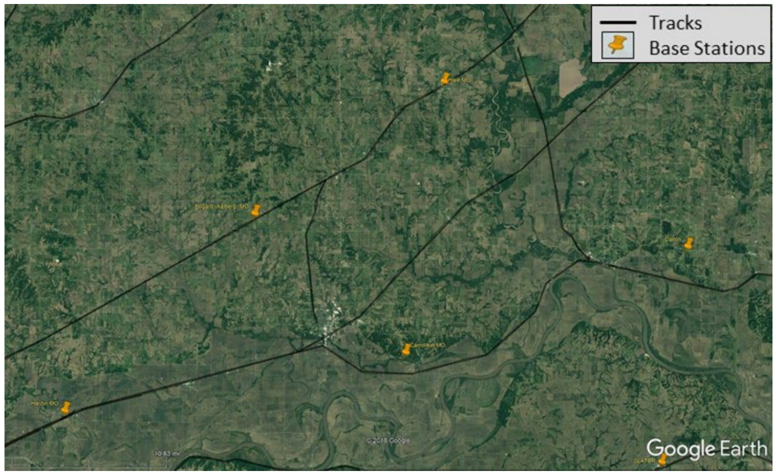


Figure 5. Example of railroad tracks with curves and diamond crossings in a rural scenario

2.2.3 Mountainous Region

In mountainous regions, there are two possible scenarios for railroad communications: 1) railroad tracks with a clear LOS, and 2) tracks passing through canyons or around curved mountain sides with no clear LOS. In most cases, railroads, like other industries that depend on wireless communication, install base stations at higher elevations to overcome LOS issues. Unfortunately, directional antennas may not be very useful in this case due to the relative angular separation between base stations and the track. However, if the base stations are also located at the wayside, then directional antennas are highly applicable, particularly for the scenario with no clear LOS.

Straight Railroad Tracks

Figure 6 illustrates a mountainous scenario where the tracks are relatively straight and there are two base stations, one closer to the track and another farther away, and both are located on hilltops (Source: Google Earth). In this example, the base that is farther away from the track should probably use an omnidirectional or a slightly bi-directional antenna. However, the base station closer to the track could use a more directional antenna, e.g., one with a back-to-back configuration.

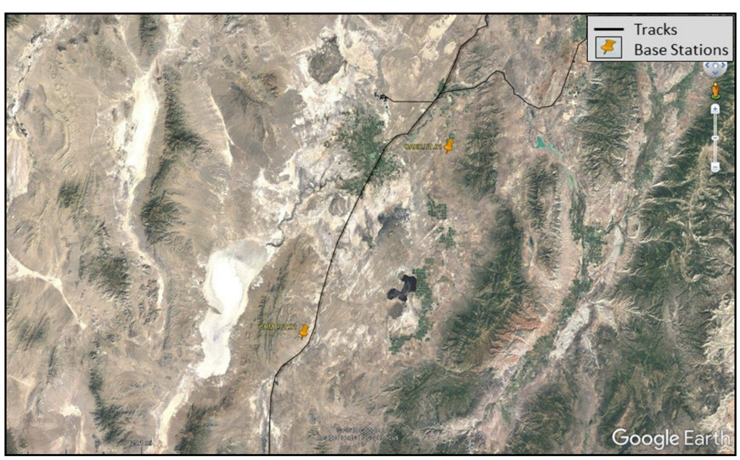


Figure 6. Example of straight railroad tracks in a mountainous region

Curved Railroad Tracks with Limited or No LOS

In an extreme operational use case, curved railroad tracks pass through canyons with poor LOS. Radio signals are subject to multi-path fading and diffraction in this type of scenario. Directional antennas can help alleviate the poor LOS issues and increase link reliability. Figure 7 and Figure 8 illustrate railroad tracks through canyons in a mountainous region (Source: Google Earth).

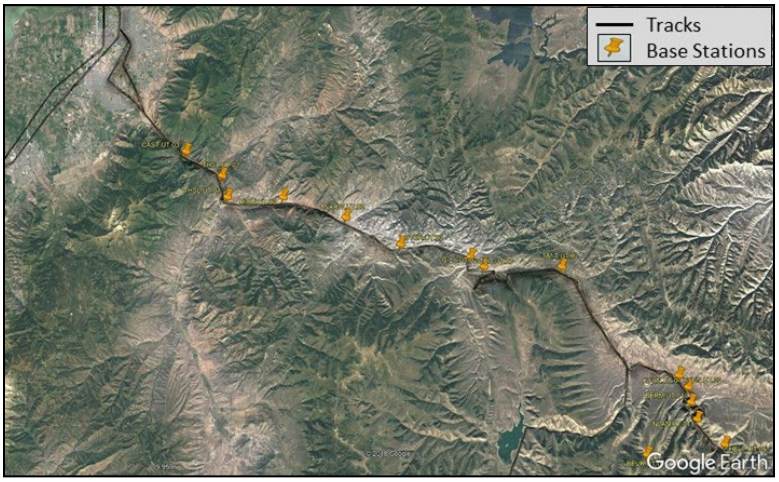


Figure 7. Example of railroad tracks with curves in a mountainous region, top view

Figure 8. Example of railroad tracks with curves in a mountainous region, lateral view

2.3 Identification of Platforms

The next step toward developing operational use cases was to identify the relevant platforms. The antenna needs for each platform were evaluated based on the availability of the space, capacity improvement, and interference mitigation requirements.

For railroad application, the identified platforms were base station, mobile, and wayside.

2.3.1 Base Station

The base station platform is a key element of the overall radio network for the railroad industry. Base stations connect the back office/dispatching systems to the remote units. This platform handles multiple applications using different railroad frequency bands. Data gathered from multiple railroads indicate that most base stations have radio systems that operate in three or more frequency bands. Table 1 illustrates the number of frequency bands deployed at base stations across multiple Class I railroads in the U.S.

Table 1. Number of frequency bands used by railroad base stations

Railroads	Minimum number of bands used at base stations	Percent of sites having three or more bands	Widely used frequency bands (MHz)
Railroad A	3	100	160, 220, 900
Railroad B	3	50	160, 220, 900
Railroad C	3	~ 49	160, 220, 900
Railroad D	3 (most have 4)	Typically, at all bases	44, 160, 220 (most 900)

Some of the challenges associated with the current antenna installations at base station platforms are as follows:

- Typically, each frequency band uses a separate antenna for RF communications, which requires an individual coaxial cable running from each radio to its associated antenna. Antenna size and weight varies with frequency and design. Available space (at the necessary height), wind loading, and weight bearing capacity of towers vary. Many towers currently bear the maximum number of antennas that they can support. To support additional new applications needed by the railroads without having to replace an entire tower structure, existing single-band antennas could be replaced with dual-band or multi-band antennas to make capacity available for the new applications' antenna needs.
- Capacity improvement is another issue that must be addressed through this platform. Spectrum utilization analysis shows that the demand for wireless RF spectrum will increase significantly over the next 10 years and beyond to support increased automation because of quasi-moving block (QMB), full-moving block (FMB), and other next-generation train control applications. The spectrum will need to be utilized to its fullest capacity to support current and future applications that depend on wireless RF spectrum.
- Most of the base stations currently have omnidirectional antennas, making them more vulnerable to interference issues – particularly B-B interference issues. Results from analysis of spectrum utilization and potential capacity gains from spatial reuse are provided in Section 4 of this report.

2.3.2 Mobile

Railroad operations utilize two main types of mobile vehicles: locomotives and hi-rails. Typically, railroads use the same antenna solutions designed for locomotives on hi-rail vehicles. As a result, TTCI focused on the locomotive platform. Researchers identified the following challenges with the current antenna installations on the locomotive platform:

- The growing number of applications in the locomotive platform operating in different frequency bands requires more antennas to be installed on top of locomotives. This increases the need for more space on the roof of a locomotive for antennas, the potential for mutual interference, and the effort for their installation.

- The number of feeder cables going from the radio to the antenna increases with the increase in number of antennas, requiring more or larger holes in roofs for installation.

However, there are issues that are common to any type of locomotive antenna solution:

- Plate L requirements define the maximum height of a locomotive with appurtenances. These requirements restrict the types of antennas that can be used at the locomotive platform.
- The equipment installed in the mobile platform needs to withstand extreme temperatures and absorb vibrations caused by locomotive movement.

2.3.3 Wayside

Wayside units are located along the railroad tracks and are typically used to communicate the following types of information:

- Switch and signal status to back office and mobile units
- Reports from defect detectors (e.g., hot bearings, dragging equipment) pertaining to a recent train that passed
- Block status using track circuit status (e.g., occupied, broken rail)

Currently, the wayside platform supports applications operating in one or two frequency bands. However, per the feedback, railroads are interested in leveraging existing wayside infrastructure to support more applications and possibly more frequency bands.

Challenges associated with the current antenna installations at wayside platforms are as follows:

- Based on the input from the AG and one major tower supplier, the current tilt-down towers installed at waysides by most of the railroads can only support a maximum of two railroad omni/bi-directional antennas per tower.
- Omni/bi-directional antennas currently used at waysides are contributing to a large number of unnecessary messages received at the locomotive radio (LR) receiver. This requires more processing power at the locomotive receiver, thus requiring upgraded radios/processors as the railroads add more message traffic to the wayside applications.

Currently, efforts are underway in the railroad supplier marketplace for dual-band near-omnidirectional antennas, which are smaller in size compared to having two individual near-omnidirectional antennas. Dual-band directional antennas could provide significant benefits including reduced wind loading, reduced wright, and increased capacity.

2.4 Operational Use Cases

After identifying various operational scenarios and platforms, operational use cases were developed and are discussed in this section of the report. Use cases were developed by combining operational scenarios with the platforms and their associated communications needs resulting in 18 use cases to be analyzed. The next step after developing the use cases was to develop antenna requirements for the use cases. Table 2 illustrates the use case matrix generated from the combinations of different platforms and operational scenarios.

Table 2. Operational use case matrix

	Scenarios					
	Urban		Rural		Mountain region	
	Straight railraod tracks with minimum curves	Railroad tracks have curves and diamond crossings	Straight railraod tracks with minimum curves	Railroad tracks have curves and diamond crossings	Straight railraod tracks with minimum curves [1 2]	Curved Railroad tracks with no RF LOS [2]
Platforms						
Base Station	1-B	2-B	3-B	4-B	5-B	6-B
Wayside	1-W	2-W	3-W	4-W	5-W	6-W
Locomotive	1-M	2-M	3-M	4-M	5-M	6-M

LOS: line of sight
1. Possible tunnel effect
2. Possible multipath

The use cases identified in Table 2 were further characterized and analyzed individually, as shown in Table 3. Each of the consideration factors below was assigned a rating to assess its impact on the use case. The ratings assigned were on a scale of 1 to 5; with 1 being low impact and 5 being high impact. The analysis of each use case was based on the overall rating for the consideration factors below.

1. **Size and weight constraints:** Antenna size is most consequential for a platform on which space is very limited. For example, at mobile platforms the space for antenna installation is very limited and bulky multiple antennas are not preferable. The antenna solution for mobile platforms must have a small form factor while maintaining the required antenna efficiency.

   Compact and small antennas that require less space for the installation and can operate in multiple bands are preferred. For this reason, at mobile platforms, a multi-band antenna solution might be a preferred solution. Additionally, a multi-band solution might also be a preferred solution for base stations and especially waysides, due to reduced weight and wind loading on the towers.

2. **Capacity needs:** Meeting the capacity need has always been a challenge in an environment where frequency spectrum is limited. As the demand for wireless services grows higher, current assignments of the frequency spectrum to base stations will not be enough to accommodate all the applications.

   As detailed in Section 4, the demand for wireless RF spectrum is expected to increase significantly over the next 10 years and beyond.

   By using multiple directional antennas and transceivers at base stations, for example, capacity improvement could potentially be achieved in urban areas where train traffic is very high. Also, with the implementation of directional antennas on the base stations, frequency reuse distance can potentially be decreased, allowing for more reuse of that frequency channel, and in turn, increasing the capacity of the network.

3. **Interference:** Current implementation of the antenna system in the urban area mostly uses omnidirectional antennas at base stations. Since an omnidirectional antenna radiates energy in all directions, there must be considerable separation in all directions between the base stations that use the same frequency to avoid interference.

For example, directional antennas use at base stations can improve the signal-to-interference (S/I) ratio. This will reduce the co-channel interference between base stations and the same frequency can be reused at relatively shorter distances – particularly at base stations that are located perpendicular to the direction of required communications coverage (up and down the track). This is achieved at the cost of increased number of antennas and/or radios at a base station.

4. **Relative platform velocity:** The railroad environment involves both static and dynamic communication links. The dynamic link for a mobile user moving along the railroad track will be different from the static link between base stations and waysides.

   For example, if a steerable directional antenna is used, the beam steering rate will need to be high in a dynamic environment where the mobiles are moving fast. The antenna system must be able to accommodate these changing environmental conditions.

5. **Complexity of scenario configurations:** The scenario configurations affect not only the angular beam steering rate (if a steerable antenna is used), but also the narrowness of beam width needed to discriminate between the desired communications pairs versus an interferer.

Table 3. Characterizing use cases across various considerations

Use case number	Use case	Size and weight constraints	Capacity needs	Interference	Relative platform velocity	Complexity of scenario geometry
1-B	Base station near straight railroad tracks with minimum curves (Urban)	1-2	5	5	1	5
1-W	Wayside near straight railroad tracks with minimum curves (Urban)	3	3	4	1	4
1-M	Mobile on straight railroad tracks with minimum curves (Urban)	5	4	3	1	5
2-B	Base station near railroad tracks with curves and diamond crossings (Urban)	1-2	5	5	1	5
2-W	Wayside near railroad tracks with curves and diamond crossings (Urban)	3	3	4	1	4
2-M	Mobile on railroad tracks with curves and diamond crossings (Urban)	5	4	3	1	5
3-B	Base station near straight railroad tracks with minimum curves (Rural)	1	3	3	5	3
3-W	Wayside near straight railroad tracks with minimum curves (Rural)	3	1	2	5	2
3-M	Mobile on straight railroad tracks with minimum curves (Rural)	5	2	1	5	3
4-B	Base station near railroad tracks with curves and diamond crossings (Rural)	1	3	3	5	3
4-W	Wayside near railroad tracks with curves and diamond crossings (Rural)	3	1	2	5	2
4-M	Mobile on railroad tracks with curves and diamond crossings (Rural)	5	2	1	5	3
5-B	Base station near straight railroad tracks with minimum curves (Mountain)	1	3	4	3	3
5-W	Wayside near straight railroad tracks with minimum curves (Mountain)	3	1	3	3	2
5-M	Mobile on straight railroad tracks with minimum curves (Mountain)	5	2	2	3	3
6-B	Base station near curved railroad tracks with limited or no LOS (Mountain)	1	3	3	3	3
6-W	Wayside near curved railroad tracks with limited or no LOS (Mountain)	3	1	2	3	2
6-M	Mobile on curved railroad tracks with limited or no LOS (Mountain)	5	2	1	3	3

2.5 Classification of Antennas Applicable in the Railroad Environment

Classifications of various antenna types considered for potential applicability in the railroad environment are listed below and described in greater detail in the proceeding subsections. Fixed, omnidirectional, *single-band* antennas are not listed because they comprise the existing baseline that are candidates to be replaced by the more advanced antenna types listed here.

- Fixed omnidirectional antenna:
  - Multi-band omnidirectional
- Fixed directional antennas:
  - Single-band directional
  - Multi-band directional
- Smart antenna systems:
  - Mechanically steerable system
  - Switched-beam system
  - Phased array system

2.5.1 Fixed Omnidirectional Antenna

Among antenna types, omnidirectional antennas are the most widely used antenna types in the railroad environment. As illustrated for a monopole in Figure 9, these types of antennas have a circular radiation pattern in the azimuth plane and directional pattern in the elevation plane. This type of antenna radiates and receives radio waves in all directions of the azimuth plane and has some attenuation in the elevation plane, except toward the horizon.

Multi-band, omnidirectional antennas can operate in multiple frequency bands while maintaining the circular radiation pattern in the azimuth plane. However, the gain values could vary across different frequency bands.

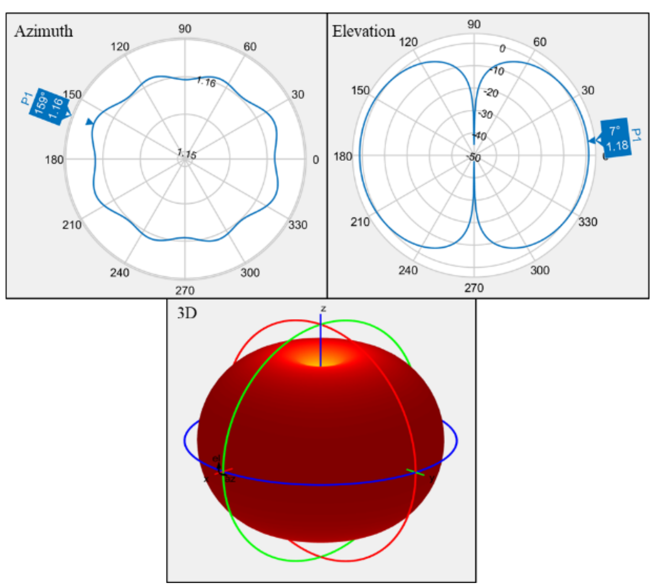


Figure 9. Radiation pattern of a typical monopole antenna

2.5.2 Fixed Directional Antenna

Unlike omnidirectional antennas, directional antennas direct radio waves in a certain direction – typically toward a single point along the horizon for land-mobile wireless applications – instead of propagating equally in all azimuth directions (see Figure 10). This directivity increases the gain of the antenna significantly in the main lobe. Particularly relevant for increasing communications capacity is that a directional antenna will reject interfering signals arriving from directions other than where the main lobe is pointed. A fixed directional antenna is pointed in the desired direction, typically during the installation.

A multi-band directional antenna radiates and receives in multiple bands, maintaining the directionality in the desired direction. However, the gain values could vary with frequency.

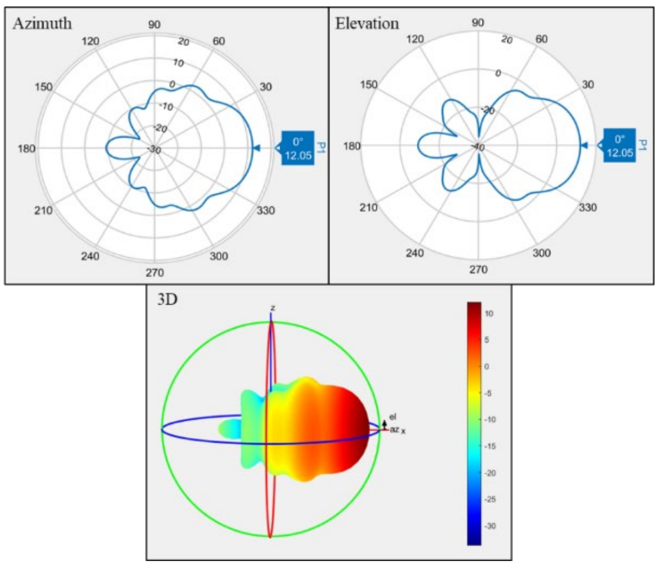


Figure 10. Radiation pattern of a typical Yagi antenna

2.5.3 Smart Antenna Systems

Spatial processing is the core idea of phased antennas, or smart antenna systems. Smart antenna systems date back to World War II and were mainly used in military applications. However, advancement in powerful, low-cost, digital signal processors and software-based signal-processing techniques (algorithms) helped bring smart antenna systems to commercial markets.

Smart antenna systems provide substantial capacity improvements through an improved signal-to-interference ratio (SIR). This type of antenna can steer beam(s) and null(s) dynamically, in any direction needed. The team identified the following three types of smart antenna systems potentially applicable to the railroad industry:

1. Mechanically steerable antennas
2. Switched-beam antennas
3. Phased array antennas

The superior SIR performance, achievable with a smart antenna for mobile links, comes at a cost. There must be a means (“smart” technology) of determining the direction in which to point the beam (and the nulls if null steering capability is included as well). Two potential methods for steering an antenna beam are:

1. Tracking: This method moves the antenna beam as needed to maximize the received strength of the desired signal. This is usually achieved either by: a) having a special multi-channel receiver that detects and compares the levels of the desired signal from separate antenna beams that are steered slightly off boresight, or b) dithering the pointing of a single beam to detect which pointing angle provides the maximum received signal strength. Tracking antennas have limitations in that they require a means to initially find and identify the desired signal versus undesired signals. Further, the lower the duty cycle of the desired signal, the poorer is their ability to track that signal.
2. Open Loop Pointing: This method overcomes the limitations cited above for the tracking antenna and does not require a special multi-channel receiver. However, it requires additional information – namely, the real-time location of both the transmit and the receive platforms as well as the real-time orientation of the platform(s) hosting the smart antenna(s). From that information, a controller processor can steer the antenna.

As explained above, smart antennas generally require some accommodations from other subsystems; they are not simple drop-in replacements for non-steerable antennas.

Mechanically Steerable Systems

A mechanically steerable antenna is dynamically pointed in a specific direction by physical movement of the entire antenna, typically using actuators or motors. This type of antenna system can be implemented using fixed directional antennas, as explained in Section 2.5.2, or using an antenna array without the complexity of electronic beamforming. For a land-mobile application such as a railroad, it would typically consist of a conventional fixed directional antenna with a fixed pattern that can be mechanically rotated 360 degrees in the azimuth plane.

The mechanically steerable antenna technology is mature, but use of this approach has decreased due to poor reliability of the mechanical components compared to electronic components and advancements in field phased array antennas.

Switched Beam Systems

A switched beam system can choose from one of many predefined beam patterns to communicate with a user, as illustrated in Figure 11. The switched beam system tracks a mobile user (e.g., by detecting its signal strength or by knowing its relative location) and chooses the appropriate beam pattern for that user. This system switches the beam pattern as often as necessary [1].

Compared with a phased array system, a switched beam antenna system is less complex from a design perspective (not necessarily from an implementation perspective), but offers less flexibility in terms of beam and null patterns when compared with what is possible with a phased array (see Figure 12).

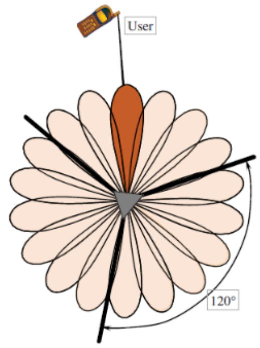


Figure 11. Radiation pattern of a switched-beam system [1]

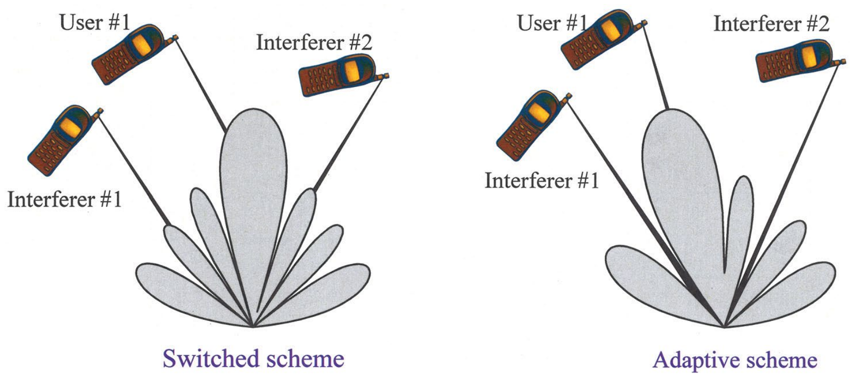


Figure 12. Comparison of switched-beam system and phased array system [1]

Electronically Steerable or Phased Array Systems

An electronically steerable phased array antenna system has more flexibility and agility than other types of antennas to accommodate mobile platforms and changing RF environments in real time. It consists of multiple antenna elements along with signal processing (analog or digital) and a controller that adjusts the relative phase and amplitude of each element individually and a combiner/divider network to form one or more beams and/or nulls. A phased array system can track users and interferers and adjust the radiation pattern to enhance communication while minimizing interference, as illustrated in Figure 13 [1].

A phased array system can improve the performance of a communication system by forming beams in the desired direction and nulls in the direction of the interference. In an environment with a high level of interference, the null steering feature can provide significant rejection to the interfering signals. Phased array systems will also be able to produce multiple beams simultaneously in a multi-user environment but requires multiple parallel beamformers operating independently [1].

Although phased array systems can perform very well in an environment where interference is very high, physical implementation involves a high level of complexity in the feeder network design, and algorithms are therefore costlier than switched-beam systems.

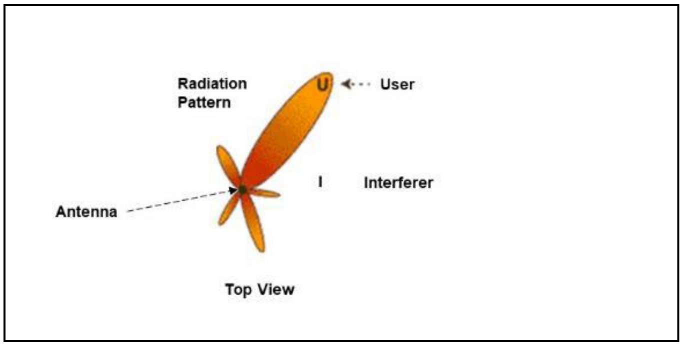


Figure 13. Radiation pattern of a phased array antenna

2.6 Potential Solutions

This section presents TTCI's analysis of how various antenna solutions could be useful in different operational scenarios and platforms to reduce interference and increase capacity.

2.6.1 Fixed Directional Antennas at Base Station Platforms

Based on the use cases identified in Table 3, base stations are mostly impacted by factors such as interference and capacity needs, particularly in urban areas. Although, experiences working with the railroads RF network designs indicate that base stations in the rural or suburban areas can sometimes significantly contribute to interference at base stations in urban areas.

Most railroad base stations have single-band omnidirectional antennas installed. Figure 15 is an example of a current scenario of a railroad RF network with omnidirectional and slightly bi-directional antennas installed at base stations. The issues with this type of antenna installation at base stations are B-B interference issues and/or capacity needs.

The team identified two ways of mitigating these issues:

- Using directional antennas: By simply replacing existing omni/bi-directional antennas with directional antennas, unidirectional or composite back-to-back configurations can significantly improve B-B interference. Figure 14 illustrates a composite back-to-back configured Yagi antenna.

  However, there is one key consideration when using composite antennas on a single radio antenna port: the spacing between the driven elements of the individual antennas. Typically, the horizontal distance between the driven elements needs to be in multiples of a wavelength (λ) to avoid any phase mismatching issue. But it can be impractical to have composite back-to-back Yagi antennas with such spacing between driven elements, particularly at lower frequencies such as many of the typical railroad bands, including 160 MHz, 220 MHz, and possibly 450 MHz.

  As a result, several manufacturers or system integrators use a coaxial delay line inserted in one of the legs before connecting the feed line of the driven element to the splitter, as illustrated in Figure 14, to compensate for the missing physical spacing between the driven elements.

  The length of the coaxial delay line can be calculated using the following formula:

$$L_{\text{delay line}} = (\lambda - D) \times \text{V.F.}$$

where

D = horizontal distance between driven elements

λ = wavelength and V.F. = velocity factor of the coaxial cable used for the delay line

- Using directional antennas and multiple sectors: Figure 16 illustrates how potential B-B interference could be mitigated for base stations on Channel 1 using highly directional antennas and pointing beams away from the co-channel sites. Additionally, the example illustrated in Figure 16 also indicates that the frequency reuse distance can be reduced, and the same frequency can be reused at a shorter distance to increase the capacity by adding multiple sectors at existing locations.

  Note that Figure 15 and Figure 16 are included for the purpose of explaining the concept of fixed directional antennas at base stations and are not the results of any simulations based on actual scenarios.

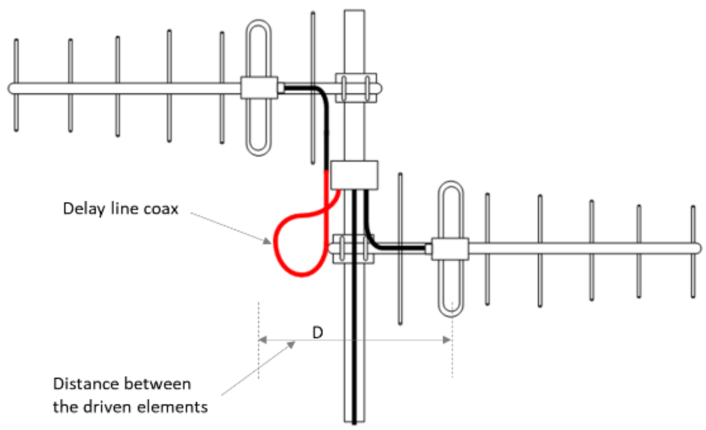


Figure 14. Yagi antennas in back-to-back configuration

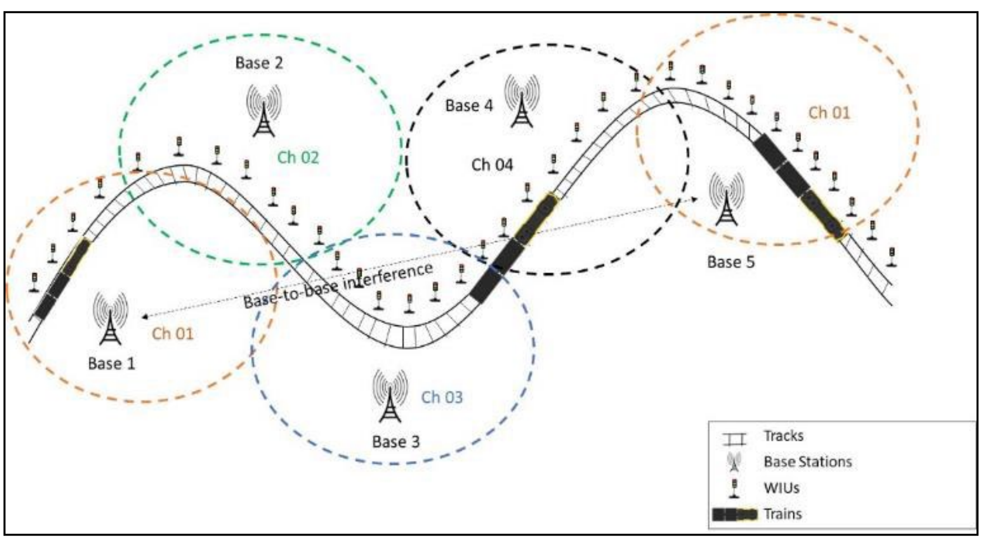


Figure 15. Example of traditional installation of omnidirectional antennas at base stations

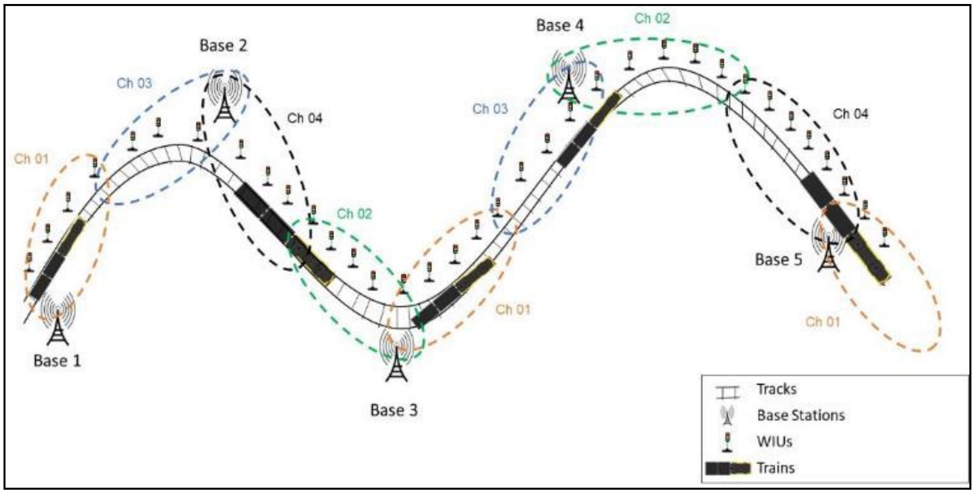


Figure 16. Implementation of fixed directional antennas and adding multiple sectors at base station platforms

2.6.2 Smart Antenna Systems at Base Station Platforms

Although fixed directional antennas provide benefits of increasing the capacity and mitigating interference, the available spectrum could be used even more efficiently by directing the beams dynamically in real time. Figure 17 illustrates the concept of implementing a phased array system at base stations in a dense urban area (DUA). In this example, Base station 1 is continuously tracking and directing beams towards Trains 1 and 2. Similarly, Base station 2 is directing beams dynamically toward Trains 3, 4, and 5.

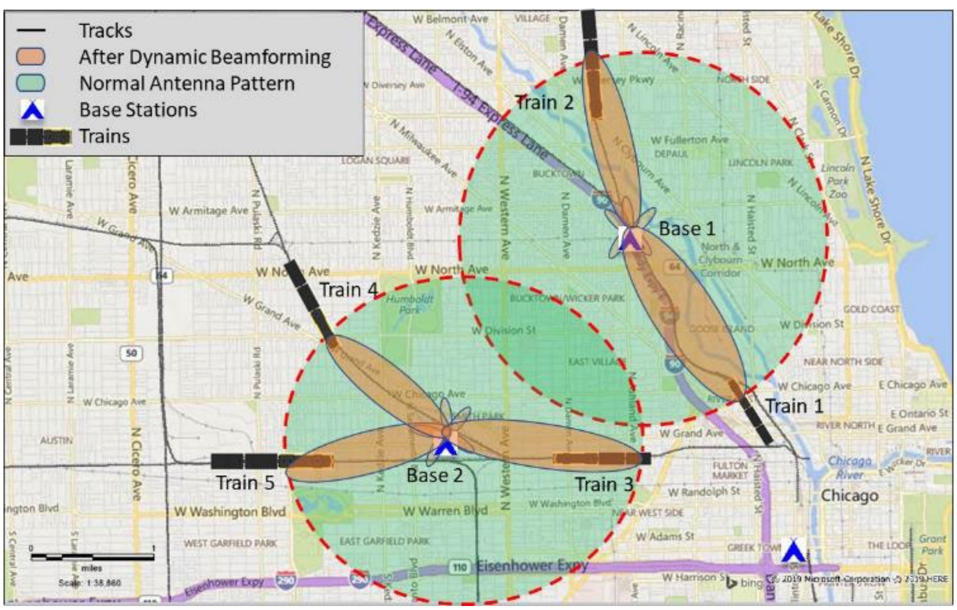


Figure 17. Implementation of smart antenna system at base station platform

A smart antenna system is continuously changing/adapting the radiation pattern toward the desired incoming traffic source(s) and outgoing traffic destination(s) while suppressing the pattern in the direction of interferers. Implementing this antenna system could allow the network to use the limited available spectrum more efficiently by increasing the frequency reuse. The same channel can be used simultaneously for other nearby links in directions that are suppressed by the smart antenna pattern, reducing overall interference in the RF network. Further, the higher gain of the directional beam can support higher order modulations that achieve higher data rates.

2.6.3 Fixed Directional Antennas at Wayside Platforms

Fixed directional antennas could mitigate some of the issues discussed in Section 2.3.3. Fixed directional antennas like Yagi antennas are highly suitable at wayside platforms due to their proximity to the track, particularly when there are no crossings and/or no sharp curves. Additionally, Yagi antennas better withstand wind loading than the omni/bi-directional antennas.

Unlike base stations, sectoring is generally not useful for wayside platforms. As a result, the only fixed directional antenna solution suitable for most wayside sites is the composite antenna (such as a Yagi) with back-to-back configuration. Note that having a dual-band directional antenna can further reduce the wind loading effects on wayside towers – *if* a dual-band antenna is available with less surface area than the combined total of two single-band antennas.

2.6.4 Smart Antenna System at Wayside Platforms

Smart antenna systems can provide additional benefits to wayside platforms in terms of increasing the wayside-to-base (W-B) link reliability (by increasing link margin), a crucial communications link for some applications. Figure 18 illustrates an example of a smart antenna system implementation at a wayside platform. In this example, the smart antenna system at the wayside radio (WR) can form individual beams to cover the tracks and also to create multiple redundant W-B links, e.g., WR to Base B and Base C so WR can immediately switch to Base B or Base C if W-B to Base A fails.

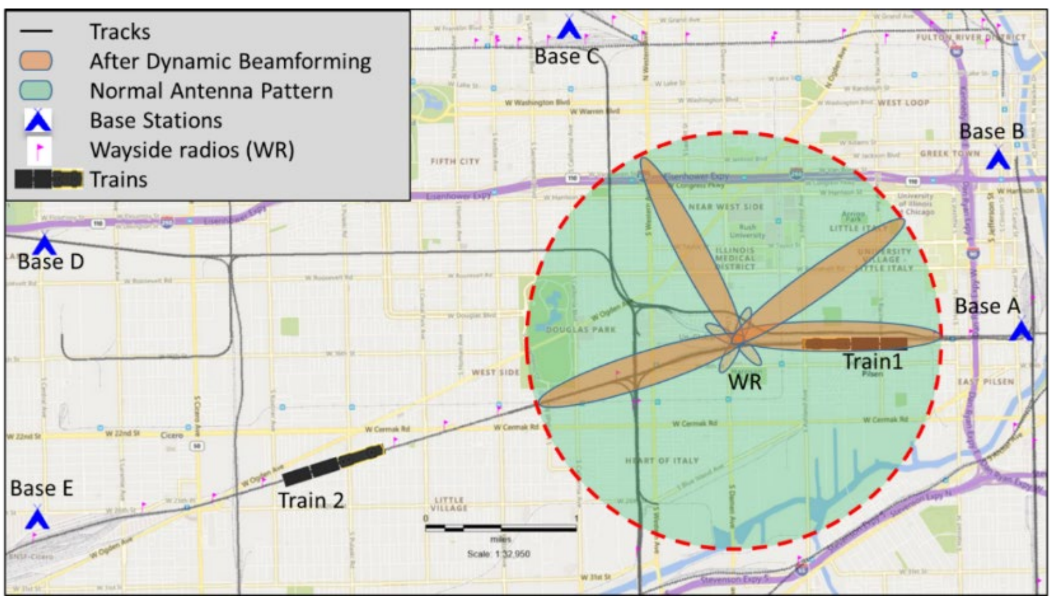


Figure 18. Implementation of a smart antenna system at a wayside platform

Fixed directional antennas can point up and down the track to provide equivalent benefit as a smart antenna in those directions. However, a smart antenna system (e.g., a steerable beamforming antenna) can dynamically create multiple beams to cover changing targets, which in this case would be the fail-over (backup) base station. It is doubtful that this benefit would justify deployment of a phased array antenna at wayside sites since it could also be achieved with fixed beams pointed at the primary and backup base stations.

Another potential benefit of phased array antennas for wayside sites is that they could alleviate the need for careful sighting (pointing) of fixed narrow-beam antennas during installation. This might become practical if the additional cost of a phased array antenna becomes less expensive than the labor required to sight and maintain a fixed directional antenna.

2.6.5 Multi-band Omni Antenna at Locomotive Platforms

From Table 3, two of the main considerations in selecting a locomotive antenna are the size and weight constraints. Figure 19 illustrates common configuration of antennas on a locomotive. Every communication path/radio has its own filter and feeder cable going to a dedicated antenna. As the number of radios/communication paths increase, more space is required at the locomotive for installation, which is currently near saturation on many locomotives.

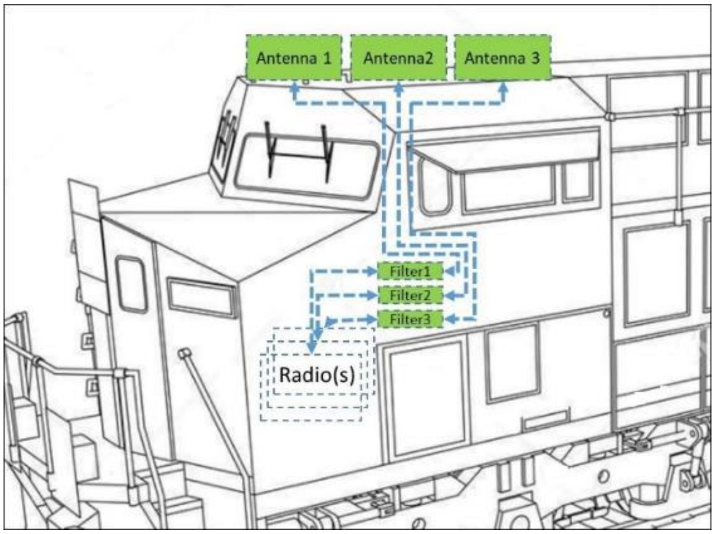


Figure 19. Typical installation of antennas on a locomotive

TTCI envisioned a multi-band antenna solution involving a multi-band antenna with a single port and a multiplexer, as shown in the left illustration of Figure 20 . Instead of using multiple filters, one multiplexer (with RF filtering capability) can be used to get the same performance while only needing a single coaxial cable from the cabin to the roof of the locomotive. This antenna implementation is a potential solution roof space and roof hole proliferation issues on mobile platforms.

Alternatively, railroads could use a multi-band radio that has filtering capabilities within the radio (if practical), as shown in the right illustration of Figure 20. This would eliminate the need for a multiplexer to connect multiple radios to a multi-band antenna. With the advancement in SDR technologies, this alternative might be an ideal solution for the locomotive platform in the future.

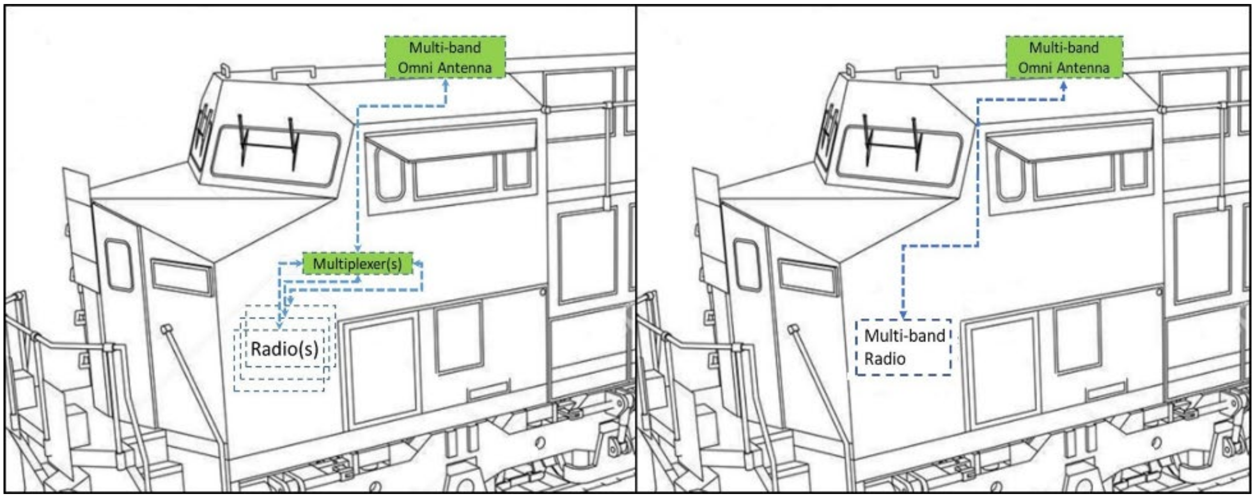


Figure 20. Comparison of multi-band antenna architecture with multiple radios (left) versus a single multi-band radio (right)

2.6.6 Smart Antenna Systems at Locomotive Platforms

A fixed directional antenna would be physically attached to the locomotive; thus, the direction of the beam would depend on the direction of the locomotive orientation. This would be unacceptable since it would result in many missed messages from the desired targets. A smart antenna system is the only suitable directional antenna option for the locomotive platform due to the mobility aspect.

Figure 21 illustrates an example of a smart antenna system implementation at the locomotive platform. The smart antenna system at Train 1 creates three separate beams: two to cover the desired targets (WRs) 5.5 miles ahead of it, and one to cover the connected base station, Base A.

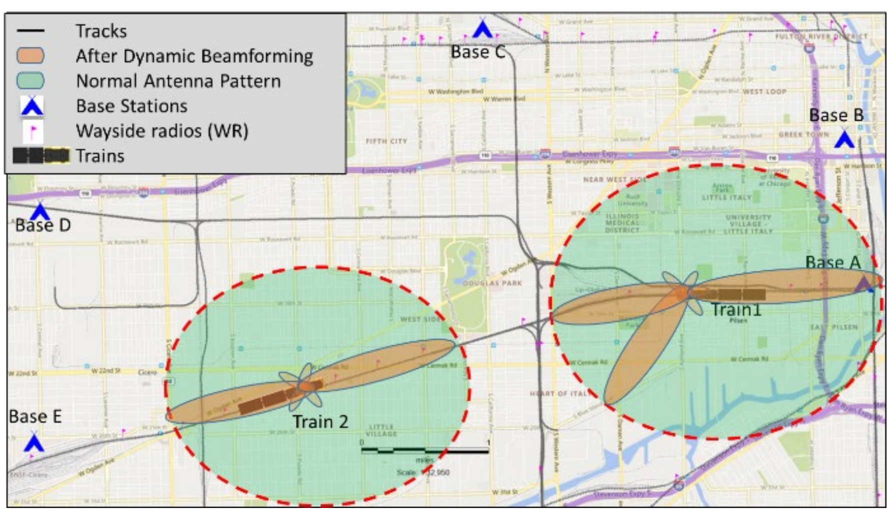


Figure 21. Implementation of a smart antenna system at locomotive platform

The significant benefit of implementing smart antennas at locomotive platforms is the reduction in the number of undesired WSMs that the LR receives due to the restricted field of signal reception. As a result, there is less interference at the locomotive and a smaller number of WSMs that a LR receiver needs to process compared with a system using an omni antenna.

Additionally, the implementation offers potential security benefits, such as resilience to electronic jamming, which can significantly reduce the SIR at the LR receiver – thus preventing the LR from receiving any information. Smart antenna systems can create nulls in the direction of the jamming signal, improving the SIR and the ability to receive information at the LR receiver.

2.6.7 Summary of Potential Antenna Solutions

TTCI gathered all the potential antenna solutions discussed in Section 2.6.1 through Section 2.6.6 and prepared a summary for all 21 use cases identified in Table 2.

Table 4 presents a preliminary summary of potential antenna solutions for the operational use cases.

Table 4. Potential antenna solutions for all the operational use cases

Use case number	Use case	Potential antenna solutions
1-B	Base station near straight railroad tracks with minimum curves (Urban)	-Fixed directional antennas connected to separate radios in multiple sectors -Smart-antenna systems
1-W	Wayside near straight railroad tracks with minimum curves (Urban)	-Fixed directional antennas in back-to-back configuration connected to same radio -Smart-antenna system
1-M	Mobile on straight railroad tracks with minimum curves (Urban)	-Multi-band omnidirectional -Smart-antenna system
2-B	Base station near railroad tracks with curves and diamond crossings (Urban)	-Multi-band omni/bi-directional -Fixed directional antennas with multiple sectors connected to separate radios -Smart-antenna systems
2-W	Wayside near railroad tracks with curves and diamond crossings (Urban)	-Multi-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio -Smart-antenna system
2-M	Mobile on railroad tracks with curves and diamond crossings (Urban)	-Multi-band omnidirectional -Smart-antenna system
3-B	Base station near straight railroad tracks with minimum curves (Rural)	-Multi-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio
3-W	Wayside near straight railroad tracks with minimum curves (Rural)	-Multi-band omni/bi-directional
3-M	Mobile on straight railroad tracks with minimum curves (Rural)	-Multi-band omnidirectional -Smart-antenna system
4-B	Base station near railroad tracks with curves and diamond crossings (Rural)	-Multi-band omni/bi-directional
4-W	Wayside near railroad tracks with curves and diamond crossings (Rural)	-Multi-band omni/bi-directional
4-M	Mobile on railroad tracks with curves and diamond crossings (Rural)	-Multi-band omnidirectional -Smart-antenna system
5-B	Base station near straight railroad tracks with minimum curves (Mountain)	-Multi-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio
5-W	Wayside near straight railroad tracks with minimum curves (Mountain)	-Multi-band omni/bi-directional
5-M	Mobile on straight railroad tracks with minimum curves (Mountain)	-Multi-band omnidirectional -Smart-antenna system
6-B	Base station near curved railroad tracks with limited or no LOS (Mountain)	-Fixed directional antennas in back-to-back configuration connected to same radio
6-W	Wayside near curved railroad tracks with limited or no LOS (Mountain)	-Fixed directional antennas in back-to-back configuration connected to same radio
6-M	Mobile on curved railroad tracks with limited or no LOS (Mountain)	-Multi-band omnidirectional -Smart-antenna system

3. Multi-band and Directional Antenna Requirements

As outlined, one of the main objectives of the project was to reduce the size of the required antennas, if feasible, by replacing multiple single-band antennas (e.g., at 160 MHz, 220 MHz, 450 MHz, and 900 MHz) with a single multi-band antenna solution. To achieve this objective, the team developed requirements for multi-band antennas for each platform type. The primary focus of the multi-band endeavor was to develop requirements for a single-element, multi-band antenna solution as opposed to a package with multiple individual single-band elements.

To reduce the space required by individual filters in each band and to reduce the number of cables going from individual radios to the antenna, researchers found it necessary to develop the requirements for a multiplexer that can be used to combine signals from different radios and feed them to the multi-band antenna (and vice-versa for signals being received). These requirements were sent to suppliers in the form of a request for information (RFI) to evaluate the potential benefits regarding cost and size that these multiplexers can bring to the railroad environment.

One of the potential architectural solutions for implementing multi-band antennas on the top of the locomotives is presented in Section 2.6.5. Figure 20 illustrates that connecting the multi-band antenna to the existing radios requires a multiplexer with RF filtering capabilities. Multiplexers are also needed to implement multi-band antennas at base stations and wayside platforms. However, the need for multiplexers can be eliminated with the use of a multi-band radio.

3.1 Multiplexer Requirements

The team developed multiplexer requirements for all three platform types – base station, wayside, and locomotive (mobile).

3.1.1 Multiplexer Requirements for Base Station Platforms

As shown in MHz in Table 5, researchers developed multiplexer requirements for base stations to support a multi-band antenna that can operate in all four railroad bands (160, 220, 450 and 900). Multiplexer requirements were developed in a way that, when deployed, this single device can replace any filtering and duplexer needs at the base station.

Key requirements for a base station multiplexer:

- Stopband attenuation/isolation: All the radios connected to the multiplexer are not necessarily in sync with their transmissions, which means there is potential for desensitization of a radio front end. The team determined that the stopband attenuation must be at least 75 dB to avoid the radios desensing each other.
- 900 MHz filter requirements: Current 900 MHz railroad base station radios are frequency division duplex (FDD) radios and use duplexers to transmit and receive at the same time on different frequencies. To reduce additional system losses due to increased components, the team developed requirements to ensure the base station multiplexer can also perform duplexing at 900 MHz.

Figure 22 illustrates the potential architecture for a base station quad-band multiplexer.

Table 5. Quad-band multiplexer requirements for base station platform

	160 MHz Filter	220 MHz Filter	450 MHz Filter	900 MHz Tx. Filter	900 MHz Rx. Filter
Specifications	Value	Value	Value	Value	Value
Frequency Range (MHz)	Passband : 160 - 162	Passband : 219.5-222	Passband : 450-460	Passband : 935-937	Passband : 896-898
Power Handling (watts)	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Stopbands - 75 Watts PEP at 50 % duty Cycle Passband - 1 mW
Connector Type	N-type, unless supplier recommends other				
VSWR	1.5:1 or better				1.5:1 or better
Insertion Loss (dB)	< 1				< 1.5
Stopbands (MHz)	1 : 44-45 2 : 217-222 3 : 450-460 4 : 896-898 5: 935-937	1 : 44-45 2 : 160-162 3 : 450-460 4 : 896-898 5: 935-937	1 : 44-45 2 : 160-162 3 : 217-222 4 : 896-898 5: 935-937	1 : 44-45 2 : 160-162 3 : 217-222 4 : 450-460 5 : 896-898	1 : 44-45 2 : 160-162 3 : 217-222 4 : 450-460 5 : 935-937 6 : 869-894
Stopband attenuation (dB)	75			15	Stopbands 1-5 : 75 dB Stopband 6 : 15 dB
Impedance (Ω)	50				
Temperature range (°C)	-40 to +70 (up to 5 min at +100 when in a tunnel)				
Humidity (non-condensing)	Max = 95% ; Min = 40%				
Vibration	5 to 10 Hz = 7.6mm				
	10 to 200 Hz =1.5 G				
	Mech. Shock = 10G				
Dimensions (WxDxH)	Specific requirements for the filter size will be defined by the individual railroads purchasing equipment. For the purpose of this specification, it is recommended that the filters be implemented to be as compact as possible.				

Notes:
1. Attenuation between the stopbands may, but doesn't necessarily have to, achieve the specified attenuation requirements (except, of course, for the passband).
2. Each port on the radio-side of the device needs to handle 75 watts PEP in its designated band, simultaneously, the antenna port must be able to accept 75 watts PEP being received at each of the designated bands, i.e., combined total power incident upon the device can be 600 watts Peak.

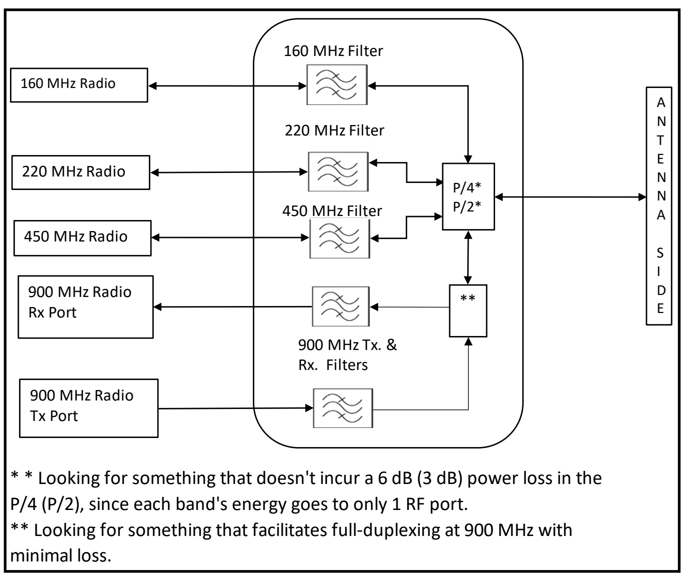


Figure 22. Potential architecture for a base station quad-band multiplexer

3.1.2 Multiplexer Requirements for Locomotive Platforms

The research team developed two multiplexer requirement specifications for locomotives.

1. Triplexer requirements to support a multi-band antenna that can operate in three railroad bands (160, 220, and 450 MHz), as shown in Table 6. The multiplexer requirements were developed in a way that, when deployed, this single device can replace any filtering needs at the locomotive.

Figure 23 illustrates the potential architecture for a locomotive triplexer.

2. Future-proof multiplexer requirements to support 900 MHz and other new frequency bands that railroads might acquire in the future, in addition to the three frequency bands currently used at the locomotives. Table 7 presents the future-proof multiplexer requirements for the locomotive platform.

   Figure 24 illustrates the potential architecture for a locomotive future-proof quad-band multiplexer.

Key requirements for a locomotive multiplexer:

- Stopband attenuation: The requirement is same as that of the base station radios. The stopband attenuation requirement is set to 75 dB for the reason mentioned in Section 3.1.1.
- Wideband filter requirement of the future-proof multiplexer: Stopband 6 falls within the passband (500–960 MHz). TTCI requested that the supplier/designer recommend the minimum feasible guard bands on either side of the Stopband 6 while meeting all the requirements specified herein, particularly the insertion loss and the stopband attenuation.

Table 6. Triplexer requirements for locomotive platform

	160 MHz Filter	**220 MHz Filter**	**450 MHz Filter**
Specifications	Value	Value	Value
Frequency Range (MHz)	Passband : 160 - 162	Passband : 219.5-222	Passband : 450-460
Power Handling (watts)	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle
Connector Type	N-type, unless supplier recommends other		
VSWR	1.5:1 or better		
Insertion Loss (dB)	< 1		
Stopbands (MHz)	1 : 44-45 2 : 217-222 3 : 450-460	1 : 44-45 2 : 160-162 3 : 450-460	1 : 44-45 2 : 160-162 3 : 217-222
Stopband attenuation (dB)	75		
Impedance (Ω)	50		
Temperature range (°C)	-40 to +70 (up to 5 min at +100 when in a tunnel)		
Humidity (non-condensing)	Max = 95% ; Min = 40%		
Vibration	5 to 10 Hz = 7.6mm 10 to 200 Hz =1.5 G Mech. Shock = 10G		
Dimensions (WxDxH)	Specific requirements for the filter size will be defined by the individual railroads purchasing equipment. For the purpose of this specification, it is recommended that the filters be implemented to be as compact as possible.		

Notes:
1. Attenuation between the stopbands may, but doesn't necessarily have to, achieve the specified attenuation requirements (except, of course, for the passband).
2. Each port on the radio-side of the device needs to handle 75 watts PEP in its designated band, simultaneously, the antenna port must be able to accept 75 watts PEP being received at each of the designated bands, i.e., combined total power incident upon the device can be 450 watts Peak.

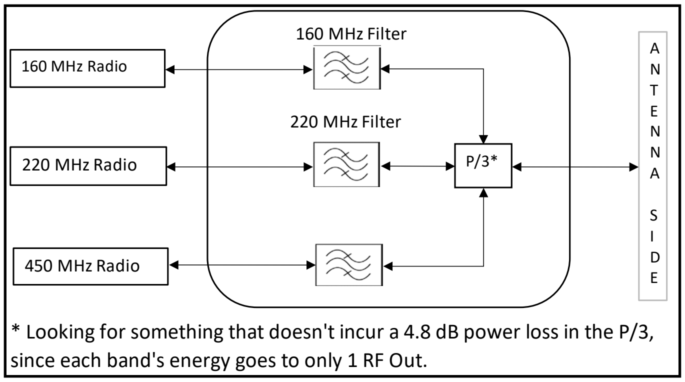


Figure 23. Potential architecture for a locomotive triplexer

Table 7. Future-proof multiplexer requirements for locomotive platform

	160 MHz Filter	**220 MHz Filter**	**450 MHz Filter**	**Wideband filter**
Specifications	Value	Value	Value	Value
Frequency Range (MHz)	Passband : 160 - 162	Passband : 219.5-222	Passband : 450-460	Passbands : 410-430, 500-960
Power Handling (watts)	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle	Passband - 75 Watts PEP at 50 % duty Cycle
Connector Type	N-type, unless supplier recommends other			
VSWR	1.5:1 or better			
Insertion Loss (dB)	< 1			
Stopbands (MHz)	1 : 44-45 2 : 217-222 3 : 450-460 4: 410-430 5: 500-960	1 : 44-45 2 : 160-162 3 : 450-460 4: 410-430 5: 500-960	1 : 44-45 2 : 160-162 3 : 217-222 4: 410-430 5: 500-960	1 : 44-45 2 : 160-162 3 : 217-222 4: 450-460 5: N/A 6: 869-894
Stopband attenuation (dB)	75			Stopbands 1-4 : 75 dB Stopband 6 : 15 dB
Impedance (Ω)	50			
Temperature range (°C)	-40 to +70 (up to 5 min at +100 when in a tunnel)			
Humidity (non-condensing)	Max = 95% ; Min = 40%			
Vibration	5 to 10 Hz = 7.6mm 10 to 200 Hz =1.5 G Mech. Shock = 10G			
Dimensions (WxDxH)	Specific requirements for the filter size will be defined by the individual railroads purchasing equipment. For the purpose of this specification, it is recommended that the filters be implemented to be as compact as possible.			

Notes:
1. Attenuation between the stopbands may, but doesn't necessarily have to, achieve the specified attenuation requirements (except, of course, for the passband).
2. Each port on the radio-side of the device needs to handle 75 watts PEP in its designated band, simultaneously, the antenna port must be able to accept 75 watts PEP being received at each of the designated bands, i.e., combined total power incident upon the device can be 600 watts Peak.
3. For the wideband filter, Stopband 6 falls within the passband (500-960 MHz); the expectation is that the supplier/designer will recommend the minimum feasible guard bands on either side of the Stopband 6 while meeting all the requirements specified herein, particularly the Insertion Loss and the Stopband attenuation.

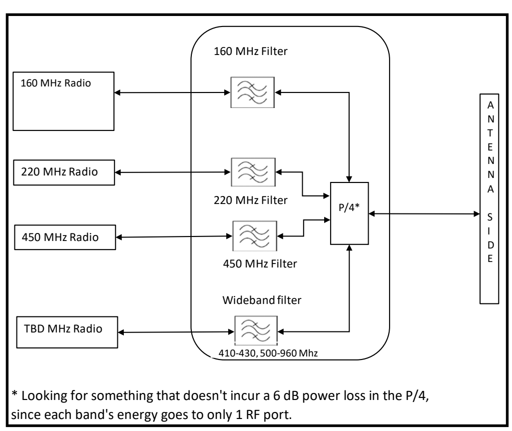


Figure 24. Potential architecture for a locomotive triplexer future-proof multiplexer

3.1.3 Multiplexer Requirements for Wayside Platform

The team developed diplexer requirements for waysides to support a dual-band antenna that can operate at 160 MHz and 220 MHz, as shown in Table 8. The diplexer requirements are developed in a way that, when deployed, this single device can replace any filtering need at the wayside site.

The key requirement for the wayside diplexer is the stopband attenuation. The requirement is same as that of the base stations. The stopband attenuation is set to 75 dB for the reason mentioned in Section 3.1.1.

Figure 25 illustrates the potential architecture for a wayside diplexer.

Table 8. Diplexer requirements for wayside platform

	160 MHz Filter	220 MHz Filter
Specifications	Value	Value
Frequency Range (MHz)	Passband : 160 - 162	Passband : 219.5-222
Power Handling (watts)	Passband - 75 Watts PEP at 50 % duty Cycle	
Connector Type	N-type, unless supplier recommends other	
VSWR	1.5:1 or better	
Insertion Loss (dB)	< 1	
Stopbands (MHz)	1 : 44-45 2 : 217-222	1 : 44-45 2 : 160-162
Stopband attenuation (dB)	75	
Impedance (Ω)	50	
Temperature range (°C)	-40 to +70 (up to 5 min at +100 when in a tunnel)	
Humidity (non-condensing)	Max = 95% ; Min = 40%	
Vibration	5 to 10 Hz = 7.6mm 10 to 200 Hz =1.5 G Mech. Shock = 10G	
Dimensions (WxDxH)	Specific requirements for the filter size will be defined by the individual railroads purchasing equipment. For the purpose of this specification, it is recommended that the filters be implemented to be as compact as possible.	

Notes:
1. Attenuation between the stopbands may, but doesn't necessarily have to, achieve the specified attenuation requirements (except, of course, for the passband).
2. Each port on the radio-side of the device needs to handle 75 watts PEP in its designated band, simultaneously, the antenna port must be able to accept 75 watts PEP being received at each of the designated bands, i.e., combined total power incident upon the device can be 150 watts Peak.

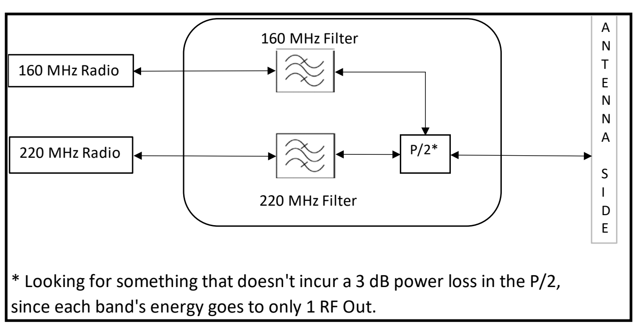


Figure 25. Potential architecture for a wayside diplexer

3.2 Multi-band Antenna Requirements

The team developed multi-band antenna requirements for omnidirectional and bi-directional antenna patterns for platforms, including base station, locomotive, and wayside. The bi-directional antennas envisioned as part these requirements are the near-omnidirectional antennas currently used by the railroads. For developing the antenna requirements, researchers gathered inputs from the AG, particularly the gain values of the existing antennas across all frequency bands.

Data gathered from the railroads suggest that all the railroads use individual antennas for each frequency band. One of the objectives of developing requirements for multi-band antennas was to come up with a single-antenna solution that can support multi-band operation in all railroad bands. The requirements for each platform were set to meet the equivalent capabilities, functionalities, and coverage provided by the existing antennas deployed by the railroads.

The team developed four variations of the multi-band omnidirectional and bi-directional antenna requirements based on gain requirements and number of ports. While the primary focus was on single-element, single-port, multi-band antenna requirements, commercial-off-the-shelf (COTS), separate-port antenna solutions were also investigated for comparative purposes. The variations are as follows:

1. Antenna requirements with low gain and single port for all four frequency bands across different platforms, as shown in Table 9
2. Antenna requirements with high gain and single port for all four frequency bands across different platforms, as shown in Table 10
3. Antenna requirements with low gain and separate ports for all four frequency bands across different platforms, as shown in Table 11
4. Antenna requirements with high gain and separate ports for all four frequency bands across different platforms, as shown in Table 12

Table 9. Multi-band antenna requirements with low gain and single port

<table>
<tr><th>Requirement Category</th><th>Antenna Parameters</th><th>Quadband Antenna Base Station</th><th>Quadband Antenna Base Station</th><th>Dualband Antenna Wayside</th><th>Triband Antenna Wayside</th><th>Triband Antenna Locomotive</th><th>Multiband Antenna Locomotive Future-proof</th></tr>
<tr><td></td><td>Horizontal pattern</td><td>Omni directional</td><td>Bi-directional</td><td>Bi-directional</td><td>Bi-directional</td><td>Omni directional</td><td>Omni directional</td></tr>
<tr><td rowspan="9">Electrical requirements</td><td>Frequency range (MHz)</td><td>157-174, 219.5-222, 450-460, and 896-937</td><td>157-174, 219.5-222, 450-460, and 896-937</td><td>157-174, 219.5-222</td><td>157-174, 219.5-222, and 896-937</td><td>157-174, 219.5-222, and 450-460</td><td>157-174, 219.5-222, 410-960</td></tr>
<tr><td>Polarization type</td><td>Vertical</td><td>Vertical</td><td>Vertical</td><td>Vertical</td><td>Vertical</td><td>Vertical</td></tr>
<tr><td>Gain (dBi) (Min)</td><td>3.1 @ 157 - 174 MHz
6.5 @ 219.5 - 222 MHz
3.1 @ 450-470 MHz
9.6 @ 896-937 MHz</td><td>5.6 @ 157 - 174 MHz
8.2 @ 219.5 - 222 MHz
5.1 @ 450-470 MHz
8.6 @ 896-937 MHz</td><td>5.6 @ 157 - 174 MHz
8.2 @ 219.5 - 222 MHz</td><td>5.6 @ 157 - 174 MHz
8.2 @ 219.5 - 222 MHz
8.6 @ 896-937 MHz</td><td>2.15</td><td>2.15</td></tr>
<tr><td>Max input power (W)</td><td>300 Watts PEP (total); 75 watts per band</td><td>300 Watts PEP (total); 75 watts per band</td><td>70 Watts PEP (total); 35 Watts per band</td><td>105 Watts PEP (total); 35 Watts per band</td><td>225 Watts PEP (total); 75 watts per band</td><td>300 Watts PEP (total); 75 watts per band</td></tr>
<tr><td>Front-to-Back ratio (dB)</td><td colspan="6">N/A</td></tr>
<tr><td>Electrical Down Tilt (degrees)</td><td colspan="6">N/A</td></tr>
<tr><td>VSWR</td><td colspan="6">< 1.5</td></tr>
<tr><td>Impedance</td><td colspan="6">50Ω</td></tr>
<tr><td>PIM (dBc)</td><td colspan="6">-150</td></tr>
<tr><td rowspan="12">Environmental Requirements</td><td>Temperature range (°C)</td><td colspan="4">-40 to +70</td><td colspan="2">-40 to +50 (up to 5 min at +140 when in a</td></tr>
<tr><td>Humidity (condensing)</td><td colspan="4">Max = 95% ; Min = 0%</td><td colspan="2"></td></tr>
<tr><td>Humidity (non-condensing)</td><td colspan="4"></td><td colspan="2">Max = 95% ; Min = 0%</td></tr>
<tr><td rowspan="5">Vibration</td><td colspan="4">5 to 10 Hz = 2mm</td><td colspan="2">5 to 10 Hz = 5mm</td></tr>
<tr><td colspan="4">10 to 50 Hz = 2.8 G</td><td colspan="2">10 to 50 Hz = 2.5 G</td></tr>
<tr><td colspan="4">50 to 100 Hz = 2.8 G</td><td colspan="2">50 to 100 Hz = 2.5 G</td></tr>
<tr><td colspan="4">100 to 200 Hz =2.8 G</td><td colspan="2">100 to 200 Hz =2.5 G</td></tr>
<tr><td colspan="4"></td><td colspan="2">200 to 1000 Hz =2.5 G</td></tr>
<tr><td rowspan="2">Mechanical Shock</td><td colspan="4">Shipping (11 msec pulse) = 10 G</td><td colspan="2">Shipping = 36-in. drop</td></tr>
<tr><td colspan="4">Mounted (11 msec pulse) = 10G</td><td colspan="2">Mounted (11 msec pulse) = 10G</td></tr>
<tr><td>Max. Survival Wind Velocity (no ice) (mph)</td><td colspan="4">150</td><td colspan="2" rowspan="2">To be specified by the suppliers (TBSS)</td></tr>
<tr><td>Max. Survival Wind Velocity (1/2" ice) (mph)</td><td colspan="4">100</td></tr>
<tr><td rowspan="4">Mechanical requirements</td><td>Connector type</td><td colspan="6">N-type</td></tr>
<tr><td>Weight</td><td colspan="6">To be specified by the suppliers (Suppliers are encouraged to minimize weight and wind loading, especially for the wayside antenna.)</td></tr>
<tr><td>Dimension</td><td colspan="4">To be specified by the suppliers</td><td colspan="2">TBSS but should not exceed 70"x 40"x4"</td></tr>
<tr><td>Number of port(s)</td><td colspan="6">1</td></tr>
<tr><td colspan="8">Note: Suppliers are requested to provide
1. Mounting specifications,
2. Wind loading area (no ice), and
3. Wind loading area (1/2" ice)</td></tr>
</table>

Table 10. Multi-band antenna requirements with high gain and single port

Requirement Category	Antenna Parameters	Quadband Antenna Base Station	Quadband Antenna Base Station	Dualband Antenna Wayside	Triband Antenna Wayside	Triband Antenna Locomotive	Multiband Antenna Locomotive Future-proof
	Horizontal pattern	Omni directional	Bi-directional	Bi-directional	Bi-directional	Omni directional	Omni directional
Electrical requirements	Frequency range (MHz)	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222	157-174, 219.5-222, and 896-937	157-174, 219.5-222, and 450-460	157-174, 219.5-222, 410-960
	Polarization type	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
	Gain (dBi) (Min)	9.1 @ 157 - 174 MHz 8.6 @ 219.5 - 222 MHz 13.1 @ 450-470 MHz 13.6 @ 896-937 MHz	11.1 @ 157 - 174 MHz 11.1 @ 219.5 - 222 MHz 11.6 @ 450-470 MHz 11.6 @ 896-937 MHz	11.1 @ 157 - 174 MHz 8.2 @ 219.5 - 222 MHz	11.6 @ 157 - 174 MHz 8.2 @ 219.5 - 222 MHz 11.6 @ 896-937 MHz	2.15	2.15
	Max input power (W)	300 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band	70 Watts PEP (total); 35 Watts per band	105 Watts PEP (total); 35 Watts per band	225 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band
	Front-to-Back ratio (dB)	N/A					
	Electrical Down Tilt (degrees)	N/A					
	VSWR	< 1.5					
	Impedance	50Ω					
	PIM (dBc)	-150					
Environmental Requirements	Temperature range (°C)	-40 to +70				-40 to +50 (up to 5 min at +140 when in a	
	Humidity (condensing)	Max = 95% ; Min = 0%					
	Humidity (non-condensing)					Max = 95% ; Min = 0%	
	Vibration	5 to 10 Hz = 2mm				5 to 10 Hz = 5mm	
		10 to 50 Hz = 2.8 G				10 to 50 Hz = 2.5 G	
		50 to 100 Hz = 2.8 G				50 to 100 Hz = 2.5 G	
		100 to 200 Hz =2.8 G				100 to 200 Hz =2.5 G	
						200 to 1000 Hz =2.5 G	
	Mechanical Shock	Shipping (11 msec pulse) = 10 G				Shipping = 36-in. drop	
		Mounted (11 msec pulse) = 10G				Mounted (11 msec pulse) = 10G	
	Max. Survival Wind Velocity (no ice) (mph)	150				To be specified by the suppliers (TBSS)	
	Max. Survival Wind Velocity (1/2" ice) (mph)	100					
Mechanical requirements	Connector type	N-type	N-type	N-type	N-type	N-type	N-type
	Weight	To be specified by the suppliers (Suppliers are encouraged to minimize weight and wind loading, especially for the wayside antenna.)					
	Dimension	To be specified by the suppliers				TBSS but should not exceed 70"x 40"x4"	
	Number of port(s)	1	1	1	1	1	1

Note: Suppliers are requested to provide
1. Mounting specifications,
2. Wind loading area (no ice), and
3. Wind loading area (1/2" ice)

Table 11. Multi-band antenna requirements with low gain and separate ports

Requirement Category	Antenna Parameters	Quadband Antenna Base Station	Quadband Antenna Base Station	Dualband Antenna Wayside	Triband Antenna Wayside	Triband Antenna Locomotive	Multiband Antenna Locomotive Future-proof
	Horizontal pattern	Omni directional	Bi-directional	Bi-directional	Bi-directional	Omni directional	Omni directional
Electrical requirements	Frequency range (MHz)	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222	157-174, 219.5-222, and 896-937	157-174, 219.5-222, and 450-460	157-174, 219.5-222, 410-960
	Polarization type	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
	Gain (dBi) (Min)	2.1 @ 157 - 174 MHz 5.5 @ 219.5 - 222 MHz 2.1 @ 450-470 MHz 8.1 @ 896-937 MHz	4.6 @ 157 - 174 MHz 7.2 @ 219.5 - 222 MHz 4.1 @ 450-470 MHz 7.1 @ 896-937 MHz	4.6 @ 157 - 174 MHz 7.2 @ 219.5 - 222 MHz	4.6 @ 157 - 174 MHz 7.2 @ 219.5 - 222 MHz 7.1 @ 896-937 MHz	2.15	2.15
	Max input power (W)	300 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band	70 Watts PEP (total); 35 Watts per band	105 Watts PEP (total); 35 Watts per band	225 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band
	Front-to-Back ratio (dB)	N/A					
	Electrical Down Tilt (degrees)	N/A					
	VSWR	< 1.5					
	Impedance	50Ω					
	PIM (dBc)	-150					
Environmental Requirements	Temperature range (°C)	-40 to +70				-40 to +50 (up to 5 min at +140 when in a tunnel)	
	Humidity (condensing)	Max = 95% ; Min = 0%					
	Humidity (non-condensing)					Max = 95% ; Min = 0%	
	Vibration	5 to 10 Hz = 2mm				5 to 10 Hz = 5mm	
		10 to 50 Hz = 2.8 G				10 to 50 Hz = 2.5 G	
		50 to 100 Hz = 2.8 G				50 to 100 Hz = 2.5 G	
		100 to 200 Hz =2.8 G				100 to 200 Hz =2.5 G	
						200 to 1000 Hz =2.5 G	
	Mechanical Shock	Shipping (11 msec pulse) = 10 G				Shipping = 36-in. drop	
		Mounted (11 msec pulse) = 10G				Mounted (11 msec pulse) = 10G	
	Max. Survival Wind Velocity (no ice) (mph)	150				To be specified by the suppliers (TBSS)	
	Max. Survival Wind Velocity (1/2" ice) (mph)	100					
Mechanical requirements	Connector type	N-type					
	Weight	To be specified by the suppliers (Suppliers are encouraged to minimize weight and wind loading, especially for the wayside antenna.)					
	Dimension	To be specified by the suppliers				TBSS but should not exceed 70"x 40"x4"	
	Number of port(s)	4	4	2	3	1	1

Note: Suppliers are requested to provide
1. Mounting specifications,
2. Wind loading area (no ice), and
3. Wind loading area (1/2" ice)

Table 12. Multi-band antenna requirements with high gain and separate ports

Requirement Category	Antenna Parameters	Quadband Antenna Base Station	Quadband Antenna Base Station	Dualband Antenna Wayside	Triband Antenna Wayside	Triband Antenna Locomotive	Multiband Antenna Locomotive Future-proof
	Horizontal pattern	Omni directional	Bi-directional	Bi-directional	Bi-directional	Omni directional	Omni directional
Electrical requirements	Frequency range (MHz)	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222, 450-460, and 896-937	157-174, 219.5-222	157-174, 219.5-222, and 896-937	157-174, 219.5-222, and 450-460	157-174, 219.5-222, 410-960
	Polarization type	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
	Gain (dBi) (Min)	8.1 @ 157 - 174 MHz 7.6 @ 219.5 - 222 MHz 12.1 @ 450-470 MHz 12.1 @ 896-937 MHz	10.1 @ 157 - 174 MHz 10.1 @ 219.5 - 222 MHz 10.6 @ 450-470 MHz 10.1 @ 896-937 MHz	10.1 @ 157 - 174 MHz 7.2 @ 219.5 - 222 MHz	10.6 @ 157 - 174 MHz 7.2 @ 219.5 - 222 MHz 10.1 @ 896-937 MHz	2.15	2.15
	Max input power (W)	300 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band	70 Watts PEP (total); 35 Watts per band	105 Watts PEP (total); 35 Watts per band	225 Watts PEP (total); 75 watts per band	300 Watts PEP (total); 75 watts per band
	Front-to-Back ratio (dB)	N/A					
	Electrical Down Tilt (degrees)	N/A					
	VSWR	< 1.5					
	Impedance	50Ω					
	PIM (dBc)	-150					
Environmental Requirements	Temperature range (°C)	-40 to +70				-40 to +50 (up to 5 min at +140 when in a tunnel)	
	Humidity (condensing)	Max = 95% ; Min = 0%					
	Humidity (non-condensing)					Max = 95% ; Min = 0%	
	Vibration	5 to 10 Hz = 2mm				5 to 10 Hz = 5mm	
		10 to 50 Hz = 2.8 G				10 to 50 Hz = 2.5 G	
		50 to 100 Hz = 2.8 G				50 to 100 Hz = 2.5 G	
		100 to 200 Hz =2.8 G				100 to 200 Hz =2.5 G	
						200 to 1000 Hz =2.5 G	
	Mechanical Shock	Shipping (11 msec pulse) = 10 G				Shipping = 36-in. drop	
		Mounted (11 msec pulse) = 10G				Mounted (11 msec pulse) = 10G	
	Max. Survival Wind Velocity (no ice) (mph)	150				To be specified by the suppliers (TBSS)	
	Max. Survival Wind Velocity (1/2" ice) (mph)	100					
Mechanical requirements	Connector type	N-type					
	Weight	To be specified by the suppliers (Suppliers are encouraged to minimize weight and wind loading, especially for the wayside antenna.)					
	Dimension	To be specified by the suppliers				TBSS but should not exceed 70"x 40"x4"	
	Number of port(s)	4	4	2	3	1	1

Note: Suppliers are requested to provide
1. Mounting specifications,
2. Wind loading area (no ice), and
3. Wind loading area (1/2" ice)

3.3 Directional Antenna Requirements

The team developed antenna requirements for fixed directional antennas for base station and wayside platforms, but not for locomotive platforms due to the reason explained in Section 2.6.6. Per Section 5.2.1, supplier response for multi-band antennas indicated that tri-band and quad-band solutions are not feasible for base station and wayside platforms. As a result, researchers focused on developing dual-band directional antenna requirements. Table 13 present the dual-band antenna requirements for base station and wayside platforms.

Most of the key requirements, such as horizontal beam width, sidelobe attenuation, gain, and front-to-back ratio, were developed based on inputs derived from various scenarios in which directional antennas were used to perform simulations in Planet®, a RF planning and simulation tool. The minimum gain observed across all the various directional antennas was 8 dBi; however, suppliers were encouraged to propose antenna solutions with higher gain which can be used to provide coverage over long distances.

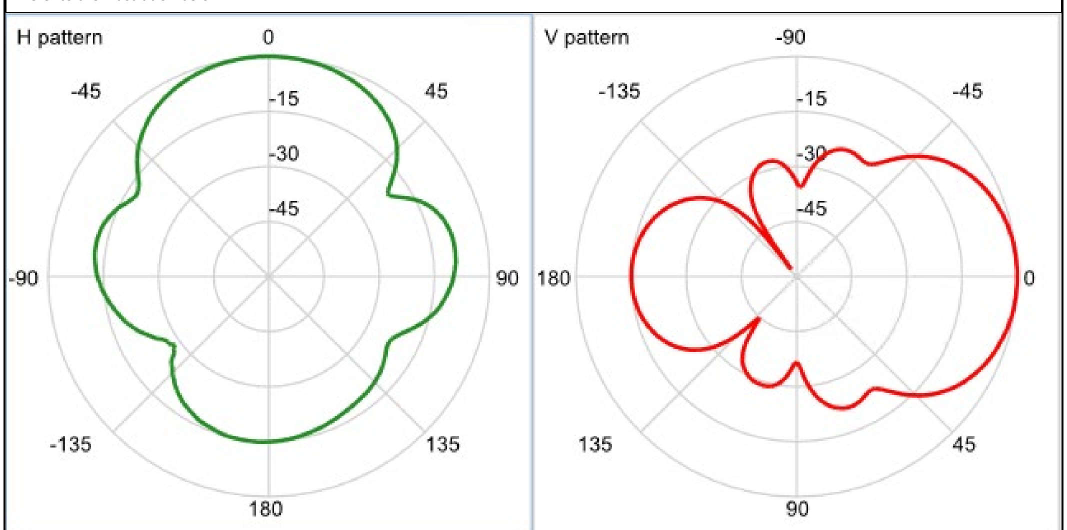
A minimum sidelobe attenuation of 12 dB is specified for the horizontal pattern based on the typical Yagi antennas currently available in the market for 220 MHz. For the vertical pattern, a minimum sidelobe attention of 35 dB is required to provide isolation between co-located radios. A minimum of 20 dB front-to-back ratio is required to minimize interference issues due to signal propagation through the back lobe.

The horizontal beam width requirement depends on the coverage requirements and the topology of the coverage area. However, based on Planet® simulations, the team established a range from 30 degrees to 60 degrees for the required horizontal beam width and requested suppliers to specify technically achievable horizontal beam widths within the specified range.

Table 13. Dual band directional antenna requirements for fixed sites with single port

Requirement Category	Antenna Parameters	Directional Antenna Base Station	Directional Antenna Base station or Wayside	Directional Antennas for Base station Collocation
	Horizontal pattern	Directional	Bi-directional (back-to-back)	Directional
Electrical requirements	Frequency range (MHz)	157-174, 217-222		
	Polarization type	Vertical		
	Horizontal Beamwidth Range (3dB)[1]	30º to 60º		
	Minimum Attenuation (dB) Horizontal pattern Other than main lobe (-45 to -135 degrees & +45 to +135 degrees[2])	12		
	Gain (dBi) (min.)	8		
	Max input power (W)	150 Watts PEP (total);		
	Front-to-Back ratio (dB) Horizontal Pattern	>20	N/A	>20
	Minimum Attenuation (dB) Vertical patterns Other than main lobe (-91 to -100 degrees[2])	N/A		35
	Electrical Down Tilt (degrees)	N/A		
	VSWR	<1.5		
	Impedance	50Ω		
	PIM (dBc)	-150		
Environmental Requirements	Temperature range (°C)	-40 to +70		
	Humidity (condensing)	Max =95%; Min = 0%		
	Vibration	5 to 10 Hz = 5mm		
		10 to 50 Hz = 2.8 G		
		50 to 100 Hz = 2.8 G		
		100 to 200 Hz =2.8 G		
	Mechanical Shock	Mounted (11 msec pulse) = 10G		
		Mounted (11 msec pulse) = 10G		
	Max. Survival Wind Velocity (no ice) (mph)	150		
	Max. Survival Wind Velocity (1/2" ice) (mph)	100		
Mechanical requirements	Connector type	N-type		
	Weight	To be specified by the suppliers (Suppliers are encouraged to minimize weight and wind loading, especially for the wayside antenna.)		
	Dimension	To be specified by the suppliers		
	Number of port(s)	1		

Notes:
1. Suppliers to specify the technically achievable beamwidth given all other requirements
2. refer to the illustration below



4. Spatial Reuse Analysis

The objectives of spatial reuse analysis were to identify potential spectrum savings by analyzing improvements in spectrum reuse and to identify potential capacity improvements by analyzing the possibility of adding multiple sectors without adding more spectrum.

The team gathered information on current spectrum utilization and future spectrum needs based on the preliminary analysis performed as part of its Railroad Wireless Communications Roadmap Phase 2 project. The analysis indicated that the demand for wireless spectrum will significantly increase in the next 10–20 years, as illustrated in Figure 26. There are many applications across multiple platforms identified by the Railroad Wireless Communication Roadmap project that contribute to the future spectrum needs. This increasing demand from applications, along with the limited and decreasingly available frequency spectrum, requires solutions that use these spectra more efficiently.

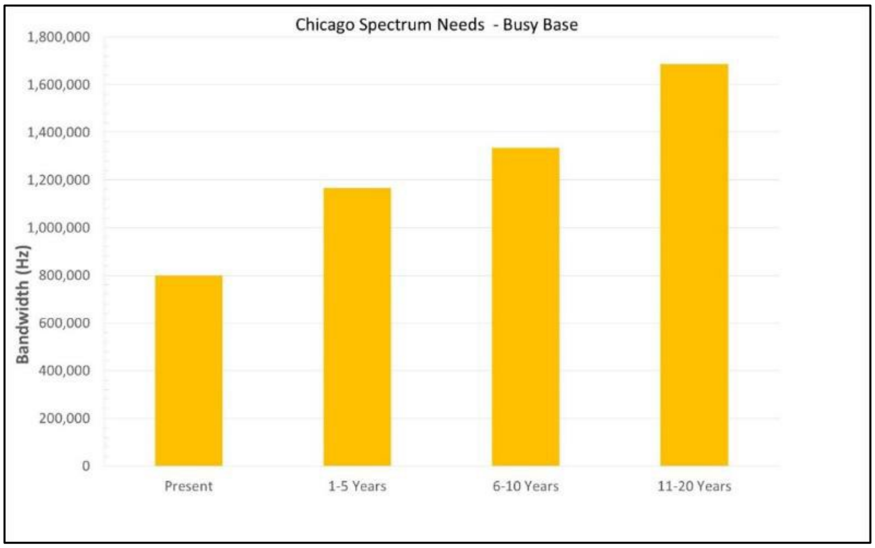


Figure 26. Current and projected spectrum usage in railroad frequency bands

There are many potential solutions to increase the efficient use of the available spectrum in the railroad environment. One is the use of directional antennas (including smart antenna systems) at applicable platforms. The use of directional antennas reduces co-channel interference, which in turn allows for better frequency reuse and more capacity within a geographical area. This also has the potential to reduce B-B interference – one of the major issues experienced in current railroad RF networks.

It is challenging to model or simulate spatial reuse in the railroad bands. Researchers identified some industry-proven tools to model the spatial reuse analysis for the 220 MHz band. In general, the results for some of the platforms can be scaled to the 160, 450, and 900 MHz bands.

The team performed spatial reuse analysis simulations for the 220 MHz spectrum on all three platforms (base station, wayside, and locomotive) using a Planet® model of the Chicago PTC RF network design, Meterocomm's IPM tool, and TTCI's in-house RF planning tools (FreSPOT, BWC, LWRS).

4.1 Spectrum Savings

The current Chicago PTC RF network design uses all the available 220 MHz spectrum – 22 channels, including the common channel.[1] The objective of the spectrum savings task is to modify the current RF design employing a variety of optimization techniques, such as using more directional antennas, reducing powers, and reducing heights – across all the platforms to determine if any of the 22 channels can be freed up. Researchers identified base stations to be a key driver for potential spectrum savings and performed simulations in Planet® according to the methodology flowchart illustrated in Figure 27. Refer to Section 5.1.1 for further details of the threshold criteria used in the methodology flow chart.

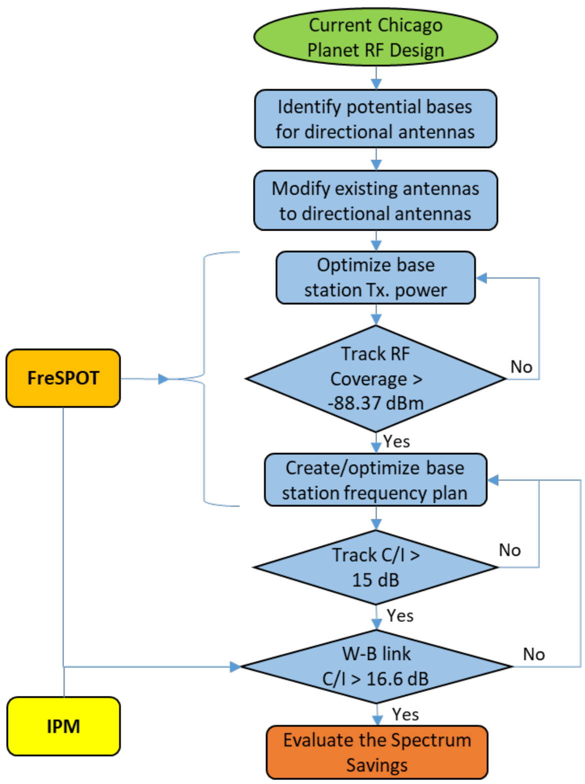


Figure 27. Methodology flow chart for base station spectrum savings analysis

4.1.1 Simulations and Results

The team identified potential base station locations at which to simulate directional antennas based on the use cases defined in Table 4. Most if not all the base stations identified in the Chicago DUA are located at wayside, which means they are located close to the tracks so that they can provide coverage to the tracks in both directions (up and down the track). However, typical directional antennas – such as Yagi and corner reflector – are unidirectional and are not able to provide significant coverage in directions other than that of the main lobe. A solution for

[1] A common channel is the single frequency channel shared by all radios everywhere in the radio network.

this scenario is a composite back-to-back antenna made up of two individual Yagi or corner reflector antennas. Fortunately, the current Planet® antenna library does have composite back-to-back Yagi antennas whose radiation pattern already accounts for all the losses due to additional hardware that will be used to split the power equally between both the antenna elements.

Figure 28 and Figure 29 illustrate the radiation patterns of the most highly used directional antennas and composite back-to-back Yagi antennas in the 220 MHz RF design simulations.

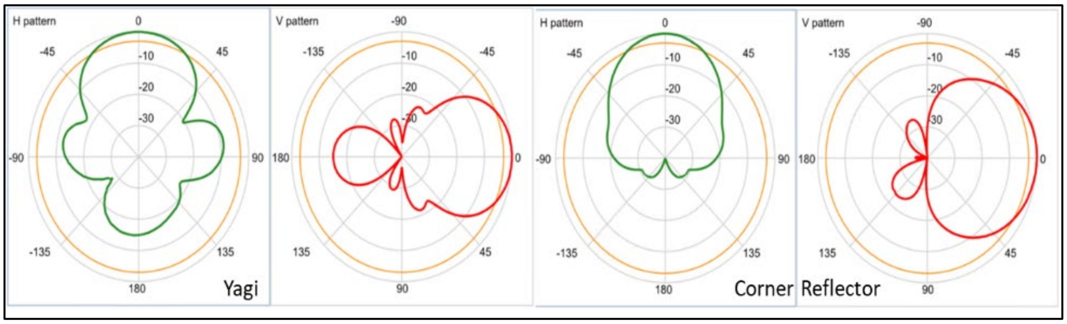


Figure 28. Radiation patterns of commonly used directional antennas in 220 MHz RF design simulations

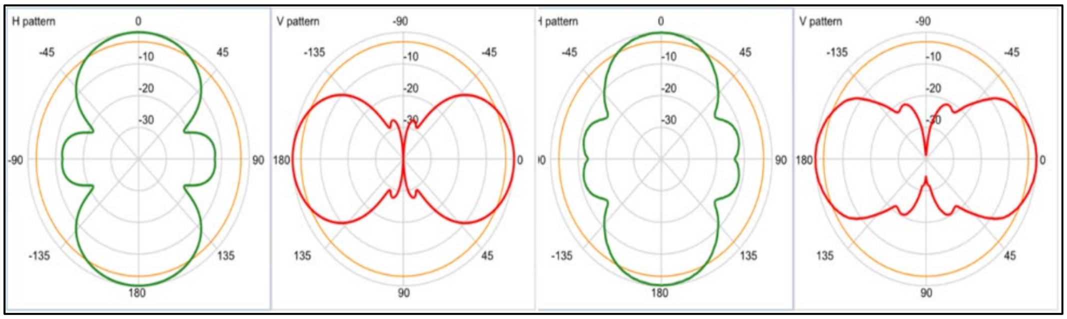


Figure 29. Radiation patterns of commonly used back-to-back Yagi antennas in Planet® simulations

The team simulated coverage on both sides of the track with the composite antennas shown. TTCI used the same design criteria established for the PTC RF network designs to perform simulations in Planet®. The key design requirement is for the received signal strength indicator (RSSI) to be greater than -94.37 dBm and the co-channel carrier-to-interference (C/I) to be greater than or equal to 15 dB for the coverage provided by base stations and waysides on the tracks. Additionally, the design requires a C/I of 16.6 dB for the W-B link. Note that the RSSI threshold used for base station transmit power optimizations is -88.37 dBm – 6 dB higher than the current RF design RSSI requirement. The reason for using a 6 dB higher RSSI threshold is to account for the 6 dB standard deviation inherent to signal strength predictions generated by the Planet® tool.

The research team established the baseline RF design to be the current Chicago PTC Planet® RF design as illustrated in Figure 30 and Figure 31. Researchers started working on the simulations focusing on the Chicago DUA, which is an area that could have particularly significant benefits from spectrum savings. TTCI identified potential base stations and modified antennas and carried out the simulations as per the methodology illustrated in Figure 27.

However, the simulations soon became an iterative loop when trying to optimize the base station frequency plan to reduce the number of B-B interference issues compared to the baseline RF design. Upon further analyses of the interferers responsible for outstanding B-B interface issues, the team discovered that most of the interference offenders were the base stations outside the DUA. As a result, TTCI expanded the scope of the simulations to the entire Chicago Major Trading Area (MTA).

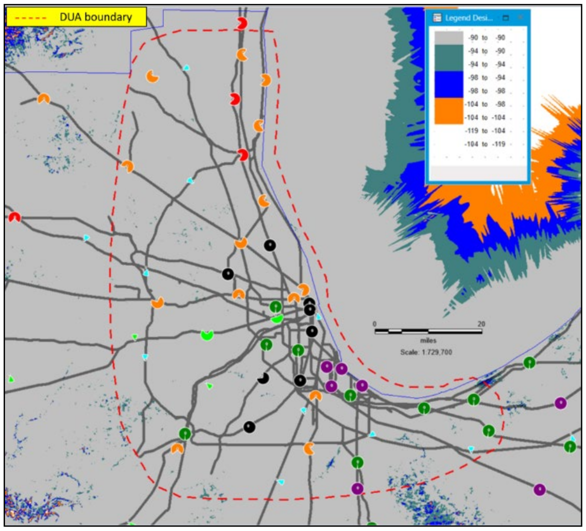


Figure 30. Chicago DUA base station RF coverage plot of the baseline RF design

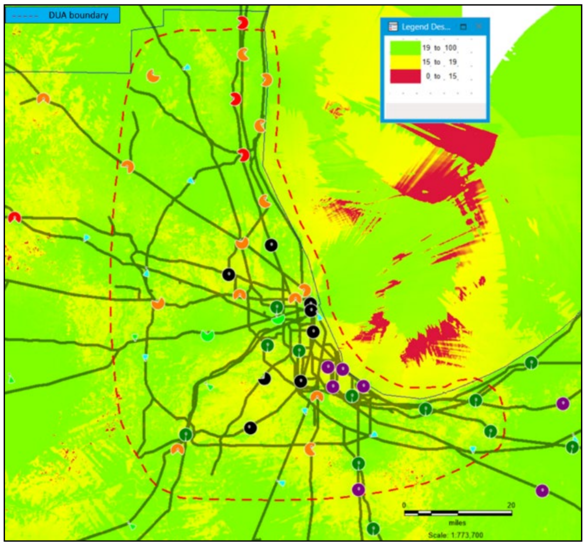


Figure 31. Chicago DUA base station RF C/I plot of the baseline RF design

The team made the following changes to the baseline RF design:

- Replaced existing omnidirectional antennas with directional antennas on over 160 base station
- Applied power reductions on 76 base stations
- Reassigned frequencies on 294 base stations

After making these optimizations, the coverage and co-channel C/I ratio on the track were within the acceptable thresholds as illustrated in Figure 32 and Figure 33, respectively. However, the simulations did not result in the elimination of all B-B interference issues. At this stage in the simulations, the design was already using all the available spectrum and trying to resolve the remaining B-B interference issues would only use more spectrum. As a result, researchers minimized the number of B-B interference issues but did not pursue the simulations further to eliminate the B-B interference issues.

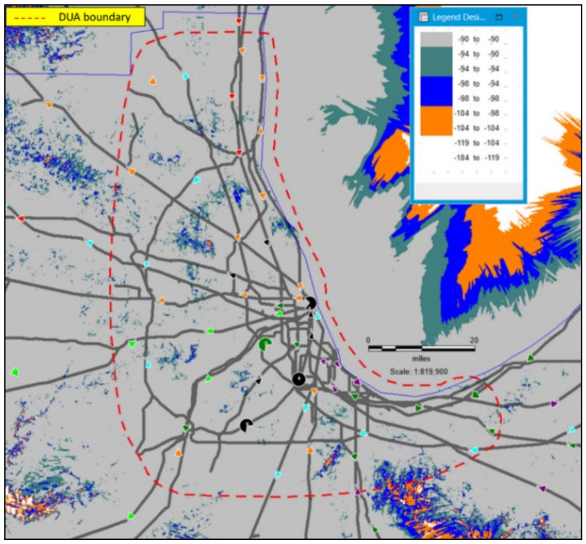


Figure 32. Chicago DUA base station RF coverage plot after spectrum saving optimizations

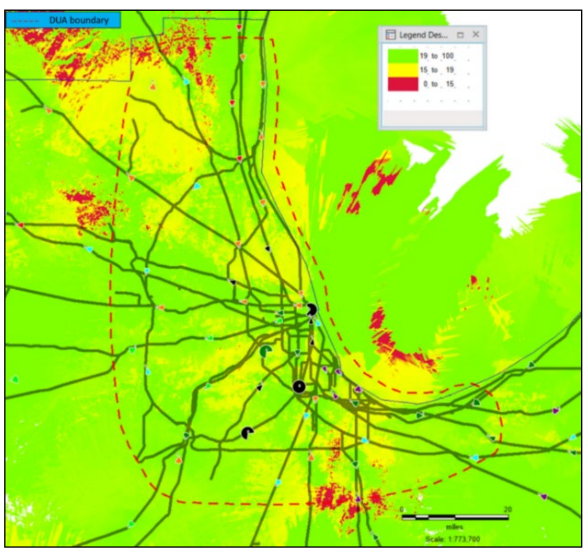


Figure 33. Chicago DUA base station RF C/I plot after spectrum saving optimizations

Despite employing all the optimization techniques in the RF design, spectrum savings do not appear to be possible in Chicago due to the following:

- Fifteen out of 22 available channels have some level of restriction, minimizing the reuse of those channels within the RF design.

- Eight out of the 15 channels are regional channels that cannot be used outside a specific geographical area, as evident in Figure 34.
- Eleven out of the 15 channels have waiver restrictions. These are the restrictions put in place by FCC to protect the incumbent licensees in the 221 to 222 MHz spectrum band.
- Four out of the 15 channels are common to both geographical and waiver restrictions.

- B-B interference: This is the interference between base station radios disrupting the base station's ability to successfully hear a remote radio. B-B interference should be minimized, if not eliminated, to protect the W-B links that play a crucial role in the success of the dynamic short broadcast (DSB) type RF network design as well as other remote-to-base communications.

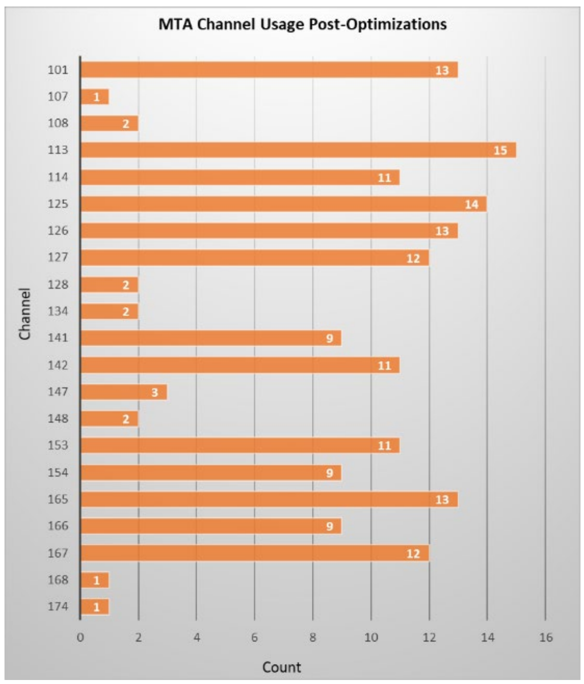


Figure 34. Chicago MTA channel usage after spectrum saving optimizations

Although spectrum savings do not appear to be possible in the Chicago DUA, it is possible to save spectrum by performing RF optimizations in DUAs that have fewer channel restrictions than Chicago.

4.2 Capacity Improvements

The objective of this task was to modify the current RF design employing a variety of optimization techniques, such as using more directional antennas, reducing powers, and reducing heights, to evaluate any potential capacity improvements within the same available spectrum.

While cellular network capacity is often increased in dense areas by reducing cell size, this cannot be done as simply for PTC as for cell phone networks. Shrinking cells can increase the number of base stations required for wayside status relay service (WSRS),[2] which can counteract the potential capacity increase. Thus, for railroads, the reduced cell size often needs to be a long, narrow cell around a track so that trains on that track can still travel several miles without having to connect to a different base station. The cell size is reduced by making it narrower (rejecting interference from the sides).

The team identified that all three platforms (base station, wayside and locomotive) could contribute to potential capacity improvements; however, the methodology used in determining capacity improvements was different for each platform.

4.2.1 Base Station Platform

For the base station platform, the capacity improvements can be evaluated using two methods:

- Potential for adding more base stations to the baseline RF design within the available spectrum
- Potential for increasing the time available for additional D-frame[3] traffic within the 4-second superframe[3]

Potential for Adding More Base Stations

Although the RF design simulations with spectrum savings optimizations did not free up any channels, the team used those simulations as the starting point for evaluating the potential for adding more base station radios according to the methodology illustrated in Figure 35.

When adding multiple sectors at the same location (co-located radios), isolation between the sectors is the biggest challenge. The D-frame portion of the superframe in the current protocol used by the 220 MHz PTC radio is asynchronous, meaning that one base station radio may be transmitting to the wayside or locomotive radios that it is serving, while another base station radio is trying to receive from the wayside or locomotive radios it is serving. As a result of this asynchronous behavior and the fact that the current 220 MHz PTC radio front end can be desensitized (blocked) by a signal stronger than -21 dBm, there is a high chance that the radios can desensitize each other when co-located without proper isolation.

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[2] The basic purpose for WSRS is to fill gaps that otherwise can occur in wayside radio coverage areas by using base stations to relay wayside status messages. In some cases, fixing wayside radio coverage problems by simply increasing ERP can be cost prohibitive, in which case WSRS provides a better solution. Also, WSRS can help in increasing the overall reliability in wayside status messaging.

[3] Each local channel is divided in time into periodically repeated superframes of 4-second duration. The superframes are synchronized across all local channels. Each superframe is partitioned into fixed time domain multiple access (FTDMA) and dynamic time division multiple access (DTDMA) partitions. FTDMA and DTDMA partitions are commonly referred to as F-frame and D-frame.

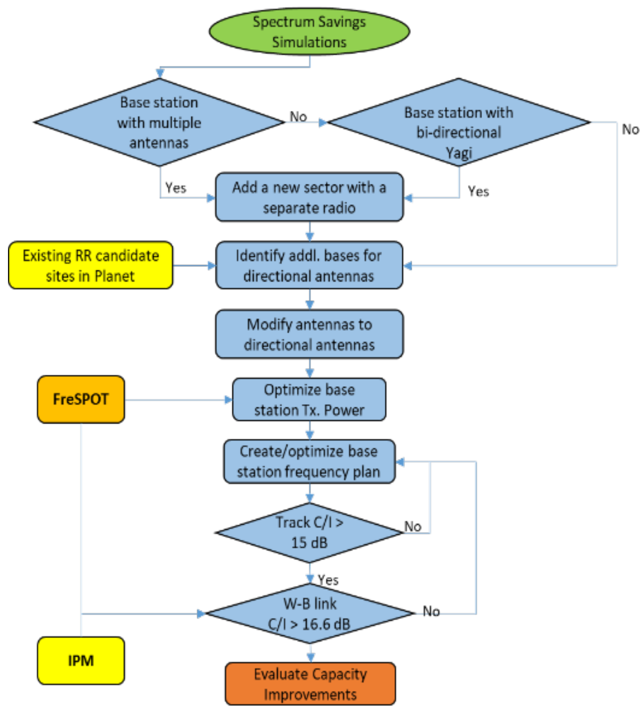

Figure 35. Methodology for improving capacity at base station platform

The isolation required is explained by the following equation:

Radio transmit (Tx.) power (dBm)	= -48.75
Radio blocking threshold (dBm)	= -21
Required isolation (dB)	= Tx. power - desensitization threshold
	= 48.75 - (-21)
	= 69.75
Required isolation (dB)	= ~70

To overcome the blocking issue, there needs to be at least 70 dB of isolation between the two co-located radios. Having 70 dB of isolation between co-located radios also helps with the radio's dynamic range limitation. The current 220 MHz PTC radios have a dynamic range of 80 dB, which defines the radio's ability to process both stronger and weaker signals at the same time. The base station radios in the current RF designs were planned to receive signals -98.37 dBm or stronger.

The weakest signal that can be processed by co-located radios with an isolation of 70 dB is explained by the following equation:

Isolation (dB)	= 70
Signal strength of the strong signals processed by the radio (dBm)	= -21
Radio dynamic range (dB)	= 80

Signal strength of the weakest signal that can processed by the same radio (dBm)	= Strong Signal - Dynamic Range
	= (-21) - 80
	= -101

The co-located radios with 70 dB isolation can process signals as weak as -101 dBm.

The 70 dB of isolation required for co-located radios can be achieved through multiple steps:

1. Directional antennas with deep nulls: Use directional antennas with at least 35 dB of attenuation along the y-axis of the vertical pattern and align the nulls by placing the antennas one below the other.
2. Vertical separation of the directional antennas: Although the 35 dB of attenuation along the y-axis in each antenna can provide 70 dB, it is best to maintain 9 to 12 feet of vertical separation, depending on the length of the antenna to avoid any potential near-field issues. The location of nulls in the antenna's elevation pattern should be considered as well in determining the optimum vertical spacing.

   The vertical separation required is explained in the following equation:

Frequency (MHz)	= 220
Wavelength (λ) (m)	= 1.36
Near-field (m)	= $<< \lambda$ for $D < ½ (\lambda)$
	= $< 2D^2/ \lambda$ for $D > ½ (\lambda)$
Required vertical separation (m)	= 2λ for $D < ½ (\lambda)$
	= $2D^2/ \lambda$ for $D > ½ (\lambda)$

   where D is the largest dimension of the antenna in meters.

   For example, if both the co-located radios are connected to 5-foot long Yagi antennas, then the antennas need to be separated by a vertical distance of approximately 11 feet, as illustrated in Figure 36.

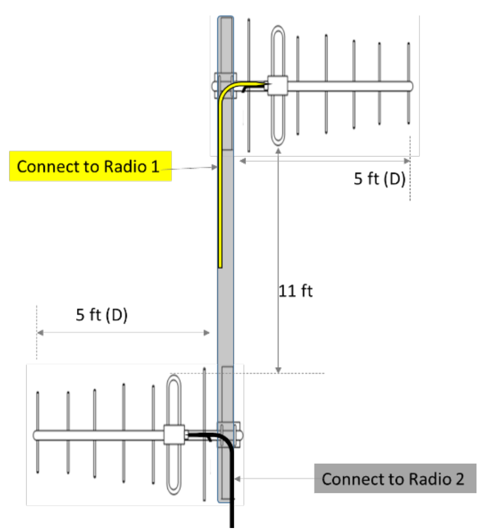

Figure 36. Example of Yagi antenna configuration for collocating base station radios

Having vertical separation also provides an additional 20–30 dB of isolation via signal propagation losses.

3. Using different transmit frequencies: The current 220 MHz PTC radios have an adjacent channel rejection of 70 dB. The farther the transmit frequencies are from each other, the better the isolation.

Simulations and Results

The main difference between the simulations performed to analyze potential capacity improvements (described in this section) compared with the simulations performed to analyze potential spectrum savings (described in Section 4.1.1) was the addition of new base station radios. In addition to adding new sectors at the existing base station locations, the team enlisted some of the existing railroad candidate sites in Planet® to address coverage gaps that appeared during the height reduction of one of the sectors of the dual-sector base stations. Existing candidate sites are locations where railroads have existing infrastructure possibly used for other wireless applications that can accommodate a new 220 MHz base station radio system.

Researchers made the following changes to the baseline RF design:

- Added 13 new radios in the DUA without additional spectrum – 25 percent increase in the number of radios currently deployed in the Chicago DUA RF network
- Modified existing omnidirectional antennas into directional antennas on over 160 base stations
- Applied power reductions on 83 base stations
- Reassigned frequencies on 294 base stations

After making the optimizations described above, the coverage and C/I ratio on the track were within the acceptable thresholds, as shown in Figure 39 and Figure 40, respectively. In addition, the optimizations also resulted in the elimination of any potential B-B interference issues. Figure 37 illustrates the comparison of base station local channel usage within the Chicago DUA before and after capacity improvement optimizations.

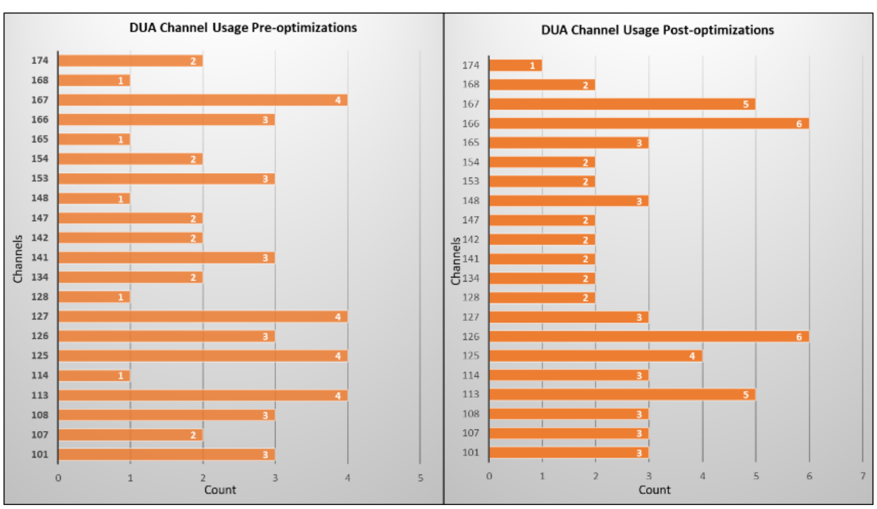

Figure 37. Chicago DUA base station local channel usage before and after capacity improvement optimizations

Note that the channel usage was more evenly distributed across all the channels compared to the design without any optimizations. The channel usage distribution could be further improved in DUAs where there are fewer channel restrictions, such as those explained in Section 4.1.1; however, it is not practical in Chicago.

The RF optimizations performed for capacity improvements also resulted in a considerable improvement in the spectrum reuse distance (see Table 14).

Table 14. Comparison average frequency reuse distance before and after optimizations

Scenario	Number of base stations	Average channel reuse distance (mi)
Chicago DUA baseline RF design	51	26.9
Chicago DUA after RF optimizations	64	23.5

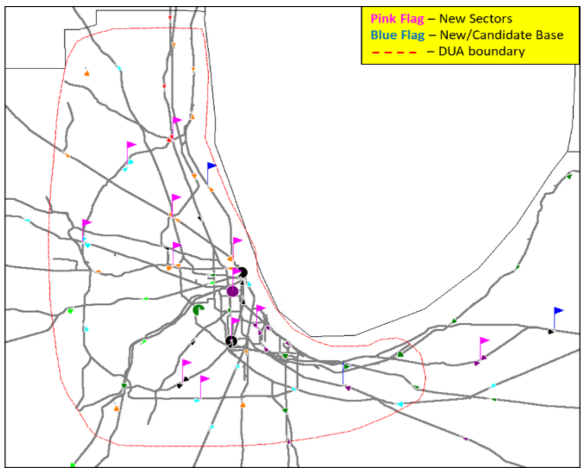

Figure 38. Chicago DUA – base stations radios at new locations and new sectors with additional radios at existing locations

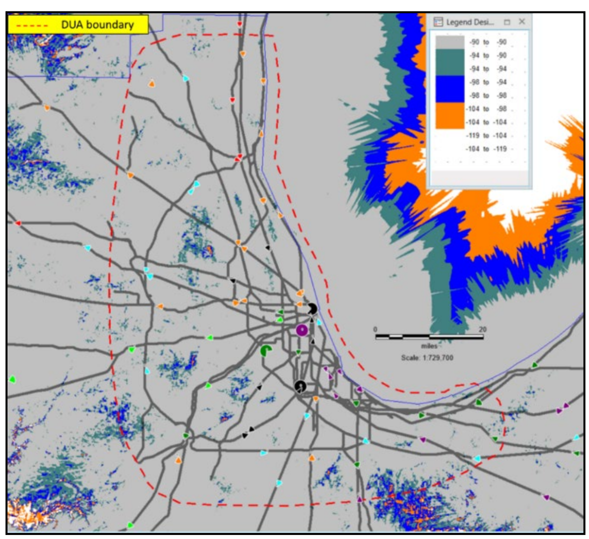

Figure 39. Chicago DUA base station RF coverage plot after optimizations and adding new base station radios

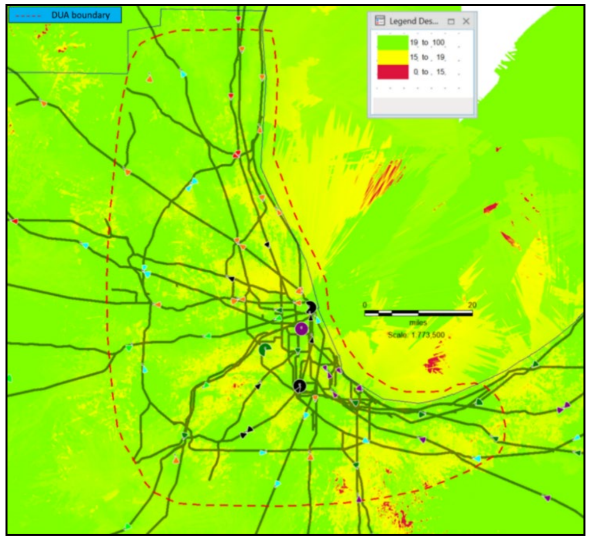

Figure 40. Chicago DUA base station C/I plot after optimizations and adding new base station radios

The research team, with input from the AG, identified that base station RF coverage redundancy could be impacted by the capacity improvement optimizations. Researchers analyzed the impacts of these optimizations on the base station RF coverage redundancy and compared it against the baseline RF design as illustrated in Table 15.

Table 15. Comparison of redundancy percentages before and after optimizations

Scenario	Total Number of Track points	Best Server Signal Strength > -94.37 dBm	Second Best Server Signal Strength > -94.37 dBm	Percent Redundancy
Baseline	124,642	124,613	123,142	98.8
Capacity Improvement Optimizations	124,642	124,639	122,252	98.1

Although the overall percentage reduction in the redundancy was not significant, there were areas with significant reduction in the redundant base station RF coverage compared to the baseline RF design as illustrated in Figure 41 and Figure 42. However, the areas of reduced redundancy were of no significance since there is no track there.

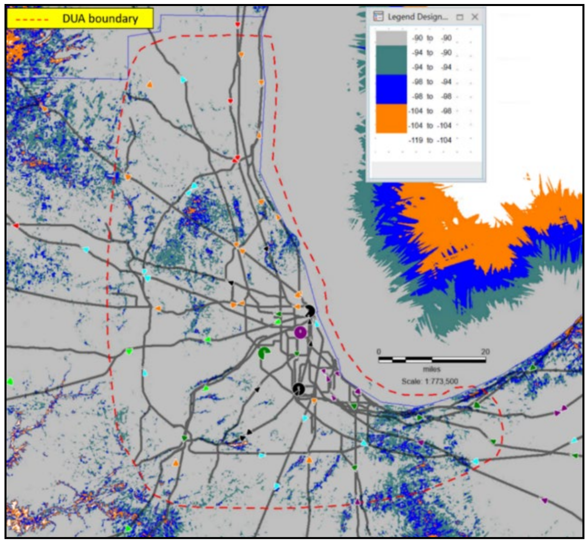

Figure 41. Chicago DUA base station RF coverage redundancy plot for baseline RF design

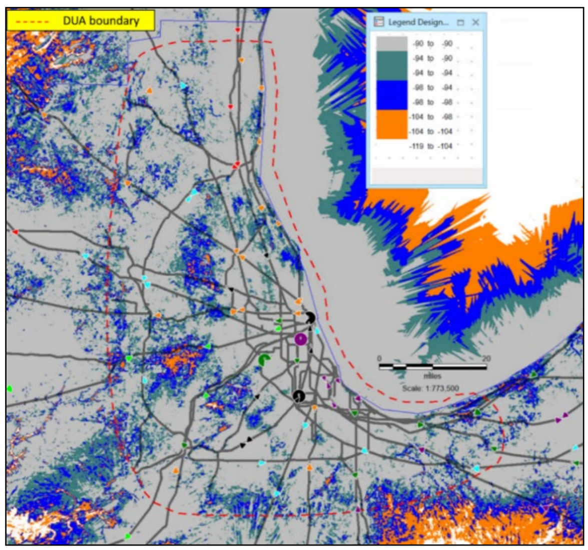

Figure 42. Chicago DUA base station RF coverage redundancy plot after capacity improvement optimizations

Potential Increase in the Time Available for Additional D-Frame Traffic within the 4-second Superframe

Once additional base station radios were added to the RF design, the team performed simulations using the IPM tool with the same design criteria established for the PTC RF network designs. Based on the results from the IPM tool, researchers identified the potential for a 45 percent (on average) reduction in the safe short broadcast zone (SSBZ), as illustrated in Table 16. SSBZ is the F-frame equivalent of the DSB RF network that indicates the time needed for all the wayside status message (WSM) transmissions. The reduction in SSBZ can be translated to an increase in the time available for additional D-frame traffic within the 4-second superframe. In summary, the modifications to use directional antennas and reduce power at base stations results in significant additional D-frame capacity.

Table 16. Comparison of SSBZ for baseline versus capacity improvement optimizations at base station platform in the Chicago DUA

Site ID	Baseline Estimated Max. SSBZ (ms)	Post-optimize Estimated Max. SSBZ (ms)	Improved by (ms)	SSBZ reduction (%)	Site ID	Baseline Estimated Max. SSBZ (ms)	Post-optimize Estimated Max. SSBZ (ms)	Improved by (ms)	SSBZ reduction (%)
3550046618	2899	1485	1414	49	3103010715	1633	1471	162	10
3076022078	2752	1441	1311	48	2510000014	1626	638	988	61
2510000003	2647	1495	1152	44	2802000130	1621	866	755	47
3103010300	2565	320	2245	88	2802000034	1608	1311	297	18
2802001247	2550	1582	968	38	3125203034	1495	1234	261	17
3076022079	2545	1626	919	36	3125203049	1468	1056	412	28
2802000109	2511	988	1523	61	2510000004	1386	1523	-137	-10
3076022080	2452	1373	1079	44	3103010590	1367	543	824	60
2105980232	2438	1219	1219	50	3125203192	1366	703	663	49
2802001244	2395	986	1409	59	3103010583	1301	749	552	42
2802000122	2372	1187	1185	50	2802000126	1280	817	463	36
2802000123	2355	1314	1041	44	3550116621	1227	740	487	40
2802001246	2234	827	1407	63	3125203013	1134	1229	-95	-8
3103010395	2199	298	1901	86	3125203082	1128	673	455	40
2802000004	2173	1123	1050	48	3076024442	1090	606	484	44
2802000128	2113	1658	455	22	3125203162	1036	471	565	55
3103010170	2040	1234	806	40	3550036618	952	554	398	42
2105980245	1853	892	961	52	3103010400	917	301	616	67
2510000009	1832	596	1236	67	3125203123	908	573	335	37
2510000002	1783	1307	476	27	3103010175	861	370	491	57
2510000006	1774	1434	340	19	3125203156	795	301	494	62
3125203109	1773	1096	677	38	2510000007	780	443	337	43
2802000115	1772	759	1013	57	2510000010	744	280	464	62
2802000117	1747	792	955	55	3550036621	676	143	533	79
2802000114	1651	1612	39	2	3550036624	671	181	490	73
								Average SSBZ Reduction (%)	**45**

4.2.2 Wayside Platform

For the wayside platform, the capacity improvements can be evaluated using two methods:

- Potential for reducing the number of WSMs heard by the locomotive radios (LRs)
- Potential for increasing the time available for additional D-frame traffic within the 4-second superframe

Potential for Reducing WSM Count Heard by Locomotives

The team performed similar RF optimizations as described in Section 4.1 on WIU radios (WRs) to analyze the potential for reducing the number of WSMs heard by LRs per the methodology illustrated in Figure 43.

Researchers began to identify WR locations that could potentially benefit from directional antennas manually by looking at the locations of WRs and track points that needed to be covered (see Figure 44). Unlike base stations, identifying potential WR for directional antennas visually was a challenge due to the density of the wayside radios and track points within the Chicago DUA. As a result, the team developed the beam width calculator (BWC) to calculate the required antenna beam widths for each WR, which assisted in identifying the WR locations suitable for directional antennas.

For example, the required beam widths for all the wayside radios within the red box illustrated in Figure 44 were in the range of 180–300 degrees, which indicates that those wayside radios were not good candidates for directional antennas, and therefore were left with omnidirectional antennas.

Note that BWC did not replace the need to visually identify the potential locations, but rather, helped narrow down the potential areas.

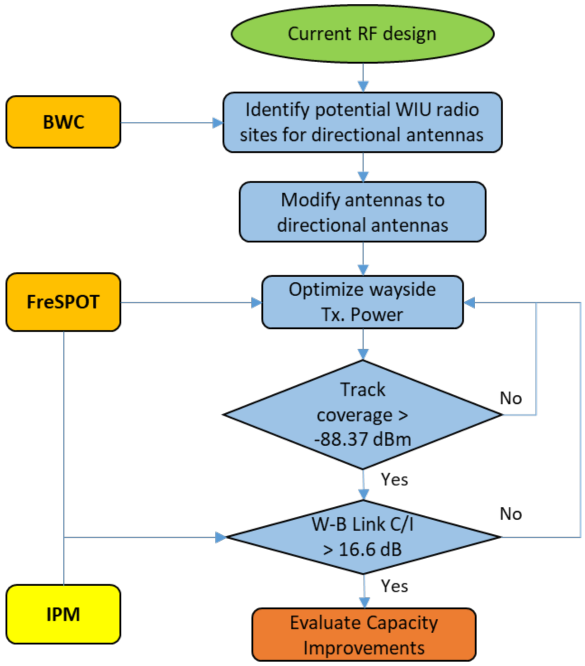

Figure 43. Methodology for capacity improvements at wayside platform

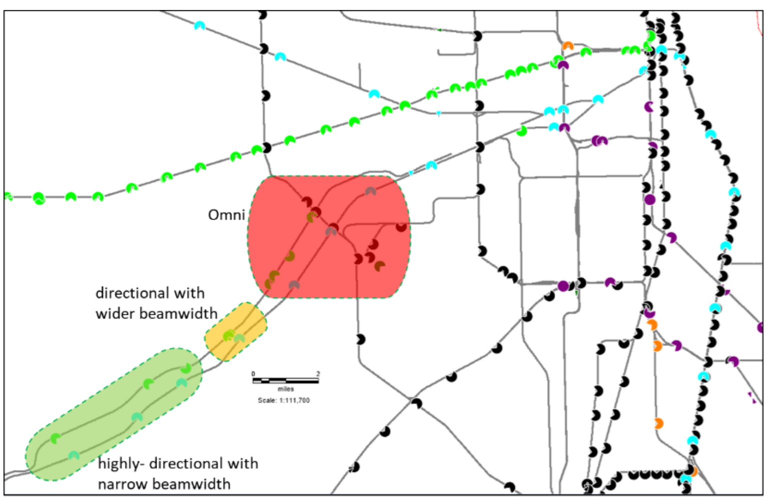

Figure 44. Visual identification of waysides for potential use of directional antennas

The team established the baseline to be the current RF design in which all WRs have omnidirectional antennas. For comparative purposes, researchers developed the scenario matrix illustrated in Table 17 to evaluate the reduction in WSM count across different optimization techniques for comparative purposes.

For each scenario, the team used the WR signal strength values on the tracks, generated by IPM using signal strength predictions in Planet®, to evaluate the number of WRs with signal strength of -94.37 dBm or stronger at each track location. In most cases, a single WR transmits multiple WSMs; thus, the count of WSMs at any track point is higher than the count of WRs that can be heard at that track point. Finally, the team calculated an average of all the WSM counts across all the track points for each scenario. Table 17 illustrates the average WSM counts for each scenario and the reduction in average WSM count across different scenarios.

Table 17. Number of WSMs heard by locomotives for different optimization techniques at wayside platforms

SN	Scenario	Wayside Optimizations	Avg. WSM count/SF	Avg. red. in WSM count/SF (% red.) #1 to #2	Avg. red. in WSM count/SF (% red.) #1 to #3	Avg. red. in WSM count/SF (% red.) #1 to #4
1	Baseline Waysides	No changes	275			
2	Baseline Waysides + Power red.	Powers reduction only	250	25 (9%)		
3	Wayside Azimuth and Antenna changes	Antenna and Azimuth Changes	176		99 (36%)	
4	#3 & Power red.	Changes in #3 & Power reductions	172			103 (37%)
Notes: SN - scenario number; SF - super frame; Red. – reduction; Avg.- average						

The signal strength values generated at the track points indirectly represents the signal strengths received by the LR receiver because Planet® models signal strength predictions considering the locomotive height. As a result, the number WSMs that can be heard at each track point can be inferred as the number of WSMs received by the LR receiver at that track point.

Based on the analysis, the reduction in the average number of WSMs was significant when the antennas at WRs were changed to directional antennas and azimuths were adjusted to direct the RF propagation more along the tracks. Applying power reductions in addition to antenna changes only improved the percent reduction by 1 percent; however, it could help reduce the interference in the overall RF network.

Note that the actual number of WSMs heard by LRs could be lower because of interference issues at the LR receiver, and the fact that a LR tunes its receivers to only six channels at any time.

The team identified that W-B links could be impacted by the capacity improvement optimizations for the WRs. Researchers analyzed the impacts of these optimizations on the W-B links and compared them against the W-B links in the baseline RF design, as illustrated in Table 18. On average, there was a 32 percent reduction in the number of base stations available for a wayside to potentially connect with, but that still left more than enough possibilities. Note that the actual usable base station connections for waysides could be lower due to factors like potential B-B interference issues, base station duty cycle, and other base station selection criteria.

Table 18. Comparison of average number of base stations available for W-B connections

Scenario	Number of WRs	Avg. Number of base stations
Baseline	712	22
Capacity improvement optimizations	712	15
Reduction (%)		31.8

Potential for Increase in the Time Available for Additional D-Frame Traffic within the 4-second Superframe

The team performed simulations using the IPM tool to evaluate the potential benefits of RF optimizations at WR locations. Researchers used the same design criteria established for PTC RF network designs. Based on the results from the IPM tool, the team identified that there was a potential for a 46 percent (on average) reduction in the SSBZ, as presented in Table 19. The reduction in SSBZ can be translated to increase in the time available for additional D-frame traffic within the 4-second superframe.

Note that the capacity improvement optimizations performed for the base station platform were not present in the baseline results shown in Table 18 but were included in the results for the capacity improvement optimizations at the wayside platform. As shown in Figure 15, there was a 45 percent reduction in SSBZ due to the base station optimization and, as a result, the actual SSBZ reduction due to optimizations for wayside radios was only 1 percent.

Table 19. Comparison of SSBZ for baseline RF design against capacity improvement optimizations at wayside and base station platforms in the Chicago DUA

Site ID	Baseline Estimated Max. SSBZ (ms)	Post-optimize Estimated Max. SSBZ (ms)	Improved by (ms)	SSBZ reduction (%)	Site ID	Baseline Estimated Max. SSBZ (ms)	Post-optimize Estimated Max. SSBZ (ms)	Improved by (ms)	SSBZ reduction (%)
3550046618	2899	2080	819	28	3103010715	1633	438	1195	73
3076022078	2752	1731	1021	37	2510000014	1626	699	927	57
2510000003	2647	1227	1420	54	2802000130	1621	324	1297	80
3103010300	2565	369	2196	86	2802000034	1608	276	1332	83
2802001247	2550	1777	773	30	3125203034	1495	847	648	43
3076022079	2545	2114	431	17	3125203049	1468	1220	248	17
2802000109	2511	1110	1401	56	2510000004	1386	1233	153	11
3076022080	2452	904	1548	63	3103010590	1367	239	1128	83
2105980232	2438	1274	1164	48	3125203192	1366	687	679	50
2802001244	2395	1395	1000	42	3103010583	1301	890	411	32
2802000122	2372	951	1421	60	2802000126	1280	827	453	35
2802000123	2355	1547	808	34	3550116621	1227	1511	-284	-23
2802001246	2234	857	1377	62	3125203013	1134	1228	-94	-8
3103010395	2199	326	1873	85	3125203082	1128	564	564	50
2802000004	2173	1717	456	21	3076024442	1090	655	435	40
2802000128	2113	486	1627	77	3125203162	1036	209	827	80
3103010170	2040	1866	174	9	3550036618	952	973	-21	-2
2105980245	1853	423	1430	77	3103010400	917	409	508	55
2510000009	1832	492	1340	73	3125203123	908	904	4	0
2510000002	1783	1475	308	17	3103010175	861	759	102	12
2510000006	1774	2162	-388	-22	3125203156	795	249	546	69
3125203109	1773	1317	456	26	2510000007	780	475	305	39
2802000115	1772	446	1326	75	2510000010	744	319	425	57
2802000117	1747	693	1054	60	3550036621	676	142	534	79
2802000114	1651	412	1239	75	3550036624	671	98	573	85
								Average SSBZ Reduction (%)	**46**

4.2.3 Locomotive Platform

For the locomotive platform, the team followed a similar method to evaluate the capacity benefits, i.e., evaluate the potential for reduction in the number of WSMs heard by LRs.

The team determined the key optimization would be to modify the omnidirectional antenna used by LRs to a directional antenna. However, due to the mobility aspect of the locomotive, it is not practical to use fixed directional antennas, as the required antenna steering and beam width constantly changes as the locomotive moves from location to location.

Figure 45 illustrates an example scenario where a LR has a directional antenna with a fixed beam width of 45 degrees, whereas the required beam width at that location for the locomotive is approximately 170 degrees based on the WRs circled in blue. The issue in this scenario was that the signals from WRs coming from a direction other than that of the main lobe would incur high attenuation, which could lead to unacceptably low RSSI at the LR receiver.

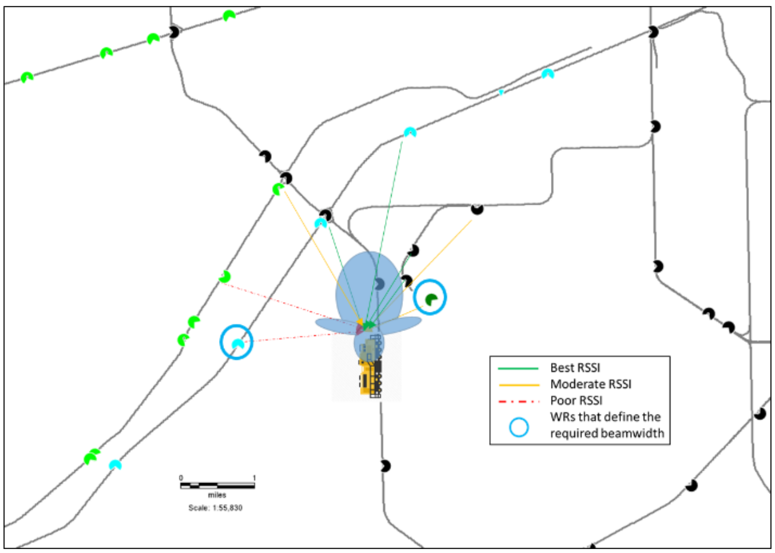

Figure 45: Example of potential issue with fixed directional antenna on locomotives

The only directional antenna solution that can address these issues is a smart antenna system that can dynamically change the required beam width and direction of the beam toward the targets as the locomotive changes direction. However, the challenge is to simulate the smart antenna system on locomotives to evaluate the capacity improvements. Unlike base station and wayside radios, there are no existing methods or tools to simulate smart antenna system optimizations on locomotives.

As shown in Figure 46, researchers developed a methodology of evaluating capacity improvement without the need to simulate a smart antenna system. The key tool that made it possible is the BWC, which calculates the required antenna beam width at every track point considering all the necessary targets – that is, WRs within 5.5 miles and the base stations providing WSRS. Note that the beam width requirement could be different for the same track point depending on which direction the train is heading; hence, there is a need to calculate the required beam width for trains operating in both directions.

The team encountered a few edge cases when calculating required beam width using BWC where the angle between the locomotive and the necessary targets was 0 degree. It is impractical and not feasible to achieve a 0-degree beam width with any antenna system. As a result, researchers used 30 degrees as the minimum beam width – which is more practical, based on the MATLAB® modeling performed as part of the technology survey discussed in Section 5.4.

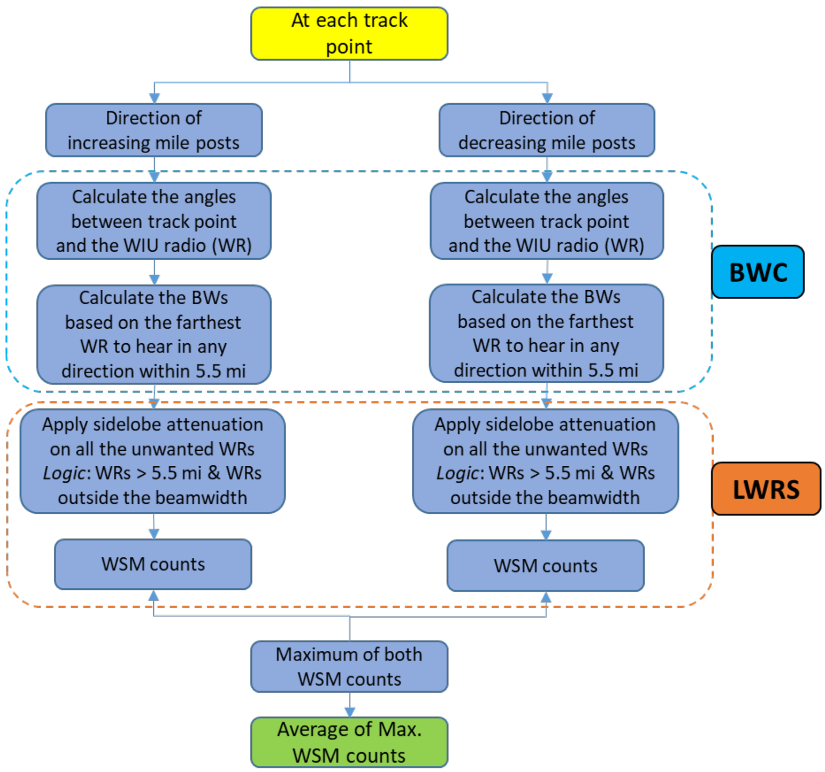

Figure 46. Methodology for capacity improvements at locomotive platform

In addition, the team also developed the LWRS tool specifically to calculate the potential reduction in the number of WSMs at a LR receiver for different sidelobe attenuation values. The tool works in conjunction with BWC to distinguish the wanted versus unwanted targets, applies necessary sidelobe attenuations, and only counts the WSMs whose signals are -94.37 dBm or stronger at the LR receiver. Figure 47 illustrates an example of the required beam width calculations and applying sidelobe attenuation based on the required beam width. From the example, the required beam width is 80 degrees in the northbound direction and 45 degrees in the opposite direction (locomotive moving southbound).

The team made the following key assumptions for the evaluation of the capacity improvements for the locomotive platform:

- A smart antenna system can be implemented that can support the required beam width values calculated by the BWC.
- The smart antenna system will have a 10 to 20 dB attenuation range in the sidelobes.

Researchers established the baseline to be the omnidirectional antenna currently used on locomotives that can receive signals with equal antenna gain in all azimuth directions. The team evaluated the capacity improvements on the locomotive platform modeling a smart antenna system at the locomotive platform with and without antenna optimizations at the wayside for comparison. Table 20 shows the average WSM counts for each scenario and the reduction in average WSM count across different scenarios.

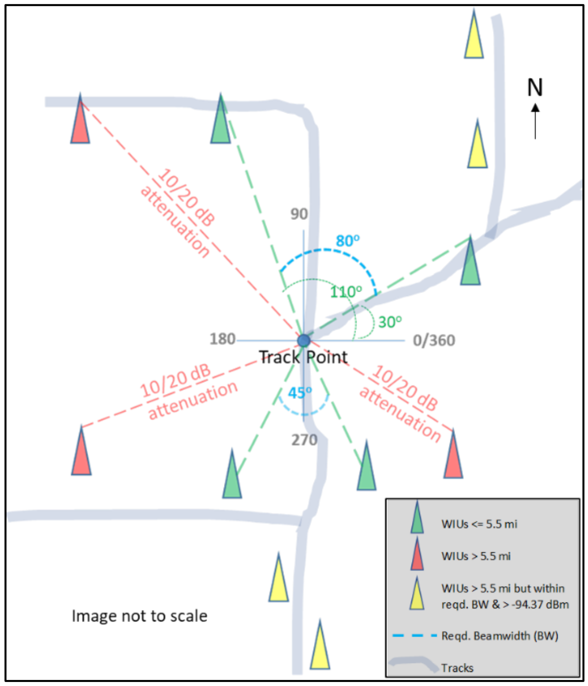

Figure 47. Example of required beam width calculations and applying sidelobe attenuation to signals coming from unwanted WRs

Table 20. No. of WSMs heard by locomotives for different optimization techniques at wayside and locomotive platforms

S/N	Loco optimizations	Wayside optimizations	Sidelobe Attenuation (dB)	Avg. WSM count/SF	Avg. Red. in WSM count/SF (% red) #1 to #2	Avg. Red. in WSM count/SF (% red) #1 to #3
1	Baseline – Omni	none	N/A	275		
2	Smart antenna	none	10	174	101 (37%)	
			20	159	116 (42%)	
			40	151	124 (45%)	
3	Smart antenna	Wayside Azimuth & Antenna Changes	10	121		154 (56%)
			20	113		162 (59%)
			40	110		165 (60%)

Based on the analysis, there was a 42 percent reduction in the average number of WSMs heard at the LR receiver with a smart antenna system on board that can apply 20 dB average sidelobe attenuation. For a smart antenna system at the LR receiver combined with antenna optimizations at WR, the reduction was 59 percent for a locomotive antenna average sidelobe attenuation of 20 dB. Even if the smart antenna system can only provide 10 dB average sidelobe attenuation, there was a 37 percent reduction in the average number of WSMs and 56 percent reduction in the average number of WSMs when combined with antenna optimizations at a WR. The further reduction in the average number of WSMs was not very significant with a smart antenna system that can support 40 dB average sidelobe attenuation.

4.3 Recommendations

Researchers observed that antenna changes at each platform can contribute individually to improvements in spectrum reuse and capacity. However, significant capacity benefits can be achieved by a railroad without greatly increasing system complexity by implementing the following fundamental changes at base station and wayside platforms:

1. Base stations: Perform RF optimizations such as directional antennas, power reductions, and height reductions – particularly in urban areas. However, RF optimizations should be performed in all areas for good RF network health.
2. Wayside: Perform RF optimizations such as directional antennas and power reductions – particularly in urban areas. If omnidirectional or bi-directional (elliptical pattern) antennas need to be used, consider power reductions without introducing additional coverage gaps.

The results also showed that capacity benefits can be achieved on locomotives by using dynamically steerable directional antennas. Due to the added complexity of dynamically steerable antennas, the feasibility of their implementation is addressed subsequently.

5. Technology Survey

The research team conducted research on available existing multiplexer and antenna technologies that might be applicable or could be modified to be applicable to the railroad platforms. This included literature searches as well as requests for information from leading antenna suppliers regarding their solutions to meeting the different sets of requirements explained in Section 3. The information obtained was used in tradeoff studies as well as to assess the feasibility and maturity of the desired technologies.

5.1 Commercial-off-the-Shelf Multiplexers

Researchers conducted research for any COTS multiplexer solutions that met the multiplexer requirements for use with a multi-band antenna on the various platforms presented in Section 3.1. The basic requirements that a COTS solution needed to satisfy, or closely match, were the frequency bands and stopband attenuation or isolation. The team did not find any COTS products that satisfied these basic requirements. However, some products had operating frequency bands close to the frequency bands in the requirements, as listed in Table 21.

Table 21. Technology survey results for COTS multiplexer

Supplier Name	Frequency bands (MHz)	Power rating (W)	Isolation (dB)
Supplier 1	30-180/330-520/740-960	50 per port	45
Supplier 1	763-776/851-869	600	45
Supplier 2	150/450/800	50	N/A
Supplier 2	138-174/380-512	200	N/A
Supplier 2	138-174/746-960	200	N/A
Supplier 2	150-174/450-512/740-868	100	N/A
Supplier 4	380-960/1695-2700	15,000/8,000	50
Supplier 5	138-174/380-512	200	40
Supplier 5	138-174/746-960	200	40
Supplier 5	138-512/746-960	200	40
Supplier Q	1.3-170/350-540	500	60
Supplier Q	1.3-30/49-470	600	45
Supplier Q	1.3-150/200-320/390-500	600	40
Supplier Q	1.6-150/220-225/400-550	500	40

5.1.1 Multiplexer RFI Responses

As COTS multiplexer solutions were not found to be available, the team issued an RFI to multiple suppliers, including some of the suppliers from Table 21. The inquiry sought information as to whether the supplier could design practical solutions that could meet the multiplexer requirements presented in Section 3.1.

The team created a compliance matrix with the suppliers' responses against key requirements such as insertion loss, stopband attenuations, and dimensions (Table 22). Based on the responses, it appeared that Suppliers 3 and 4 could design a solution that would comply with all requirements for all platforms, with Supplier 3's solution having the smallest size of all the different supplier solutions.

Table 22. Comparison and compliance matrix of supplier response to multiplexer RFI

Base Station Quadplexer RFI Response Comparison						
Item	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Comments
Dimensions - WxDxH (inches)	12.6x9x3.5	10.0x6.14x1.81	6.69x4.72x3.03	10.87x8.93x3.8	19x11.81x3.48	
Volume (Cu. inches)	397	111	96	369	780	
Insertion loss	Comply	Not Comply	Comply	Comply	Not Comply	S2: 2.2 dB at 900 MHz Rx port S5: All ports 2.0 dB are higher
Stopbands & Attenuation	Comply	Comply	Comply	Comply	Comply	
Loco Triplexer RFI Repsonse Comparison						
Dimensions - WxDxH (inches)	7.5x7.5x3.5	6.30x5.75x1.81	3.93x4.13x1.29	5.81x8.93x3.80	19x11.8x3.48	
Volume (Cu. inches)	197	66	21	197	780	
Insertion loss	Comply	Comply	Comply	Comply	Not Comply	S5: 1.8 to 2.2 dB across all ports
Stop Band	Comply	Comply	Comply	Comply	Comply	
Locomotive Quadplexer RFI Responses Comparison						
Dimensions - WxDxH (inches)	12x10x3.5	13.94x18.99x5.24	7.8x5.9x5.1	9.63x9.93x3.8	17 x12x3.5	
Volume (Cu. inches)	420	1387	235	363	714	
Insertion loss	Not Comply	Not Comply	Comply	Comply	Not Comply	S1:1.5dB at 450 and above S2: 2.5db at 450 S5: All ports 2.0 dB are higher
Stop Band	Comply	Not Comply	Comply	Comply	Comply	Incomplete Passband for wideband port – notch at 600-746 MHz
Wayside Diplexer RFI Responses Comparison						
Dimensions - WxDxH (inches)	9.7x6.5x4.8	3.07x5.75x1.81	3.93x4.13x1.29	8.93x4.58x3.8	5.75x4.33x1.5	
Volume (Cu. inches)	302	50	21	155	37	
Insertion loss	Comply	Comply	Comply	Comply	Not Comply	S5: 2.2 dB across all ports
Stop Band	Comply	Comply	Comply	Comply	Comply	

5.2 Commercial-off-the-Shelf Multi-band Antennas

Researchers conducted research for any COTS multi-band antenna solutions that met the multi-band antenna requirements across all the platforms, per Section 3.2. The basic requirements that a COTS solution needed to satisfy, or closely match, was the set of frequency bands. The survey indicated that very few antenna suppliers/manufacturers had a multi-band antenna solution that partially satisfied the requirements. Most of the multi-band solutions had higher operating frequencies that were more applicable to the commercial cellular industry. There were a few multi-band antenna solutions in the desired frequency range, but they were all low antenna gain, omnidirectional, and multi-port solutions.

Table 23 provides the results of the technology survey for COTS multi-band antenna solutions.

Table 23. Technology survey results for multi-band antenna

Supplier	Band of Operation (MHz)	Directionality	Applicable Platform
A	225-400 / 960-1220	Omnidirectional	Mobile
A	30-400 / 960-1220	Omnidirectional	Mobile
B	1695-2690	Directional-sector antenna	Base station/Wayside
C	136-174 / 380-520 / 762-960	Omnidirectional	Base station/Wayside
D	698-960 / 1710-2700	Omnidirectional	Base station/Wayside
D	698-960 / 1710-1990 / 2100-2700	Omnidirectional	Mobile

Supplier	Band of Operation (MHz)	Directionality	Applicable Platform
D	806-960 / 1575.42 / 1710-2170 / 2400-2500	Omnidirectional	Mobile
D	806-870 / 821-896 / 890-960 / 902-928 / 1850-1990 / 2400-2500 / 4900-6000	Omnidirectional	Mobile
E	740-2700	Omnidirectional	Base station/Wayside
F	220-222 / 2400-2485 / 1575.42	Omnidirectional	Mobile
G	146 / 220 / 440	Omnidirectional	Base station/Wayside
G	146 / 220 / 440	Omnidirectional	Mobile
H	155-165 / 440-470	Omnidirectional	Mobile
H	160-166 / 453-488 / 806-854	Omnidirectional	Other (wall mount)
I	138-174 / 350-2700	Omnidirectional	Mobile
J	689-924 / 1710-2700	Omnidirectional	Base station/Wayside
K	698-896 / 1700-2700	Omnidirectional	Base station/Wayside

5.2.1 Multi-band Antenna RFI Responses

As COTS multi-band antenna solutions were not available, the team issued an RFI to multiple suppliers – including those outside the normal railroad marketplace. Researchers asked suppliers to indicate whether they currently had any products that met the antenna requirements. Further, if they did not have said products, they were asked if they could design practical solutions that met the antenna requirements presented in Section 3.2.

Most of the companies outside the railroad supplier marketplace either did not indicate any intention to participate in the RFI process or did not follow through with a response after they received the RFI. In addition, all respondents indicated that quad-band and tri-band antennas with a single port were not feasible. Some of the suppliers indicated the same for the locomotive platform. Table 24 is a feasibility matrix of requirements developed for certain antenna configurations that were deemed to be not feasible.

Table 24. Feasibility matrix for various multi-band antenna requirements

<table>
<tr><th></th><th colspan="3">Single port</th><th colspan="3">Separate ports</th></tr>
<tr><th></th><th>Quadband/
Future-proof (loco only)</th><th>Triband</th><th>Dualband</th><th>Quadband</th><th>Triband</th><th>Dualband</th></tr>
<tr><td>Base station</td><td>NF - All suppliers</td><td rowspan="2">NF - All suppliers</td><td rowspan="2">F</td><td colspan="3" rowspan="2">F</td></tr>
<tr><td>Wayside</td><td>N/A</td></tr>
<tr><td>Locomotive</td><td colspan="2">NF - Most suppliers
F - 2 suppliers</td><td>N/A</td><td colspan="3">N/A</td></tr>
<tr><td colspan="7">Notes:
F - feasible; NF - Not feasible; N/A - Not applicable</td></tr>
</table>

Table 25, Table 26, and Table 27 are compliance matrices with the suppliers' responses against key requirements such as frequency range, gain, voltage standing wave ratio (VSWR), weight and dimensions. Based on supplier responses in Table 25, it appears that Supplier 3 and Supplier 12 could design solutions for a multi-band, single port antenna for the locomotive platform, with Supplier 3's solution complying with most of the key requirements. Supplier 12 indicated that its solution is COTS, and that they have performed testing with some railroads in North America.

Table 25. Comparison and compliance matrix of supplier responses to locomotive multi-band omni directional antenna RFI

Platform	Parameters	Supplier 1	Supplier 3	Supplier 8	Supplier 10	Supplier 11	Supplier 12
Triband Loco 1-port	Frequency range (MHz)	Opted out	Comply	Response not in compliance with the requirements	Response not in compliance with the requirements	Response not in compliance with the requirements	Comply
	Gain (dBi) (Min)		2.6 @ 157 - 174 MHz 3.1 @ 219.5 - 222 MHz 2.7 @ 450-460 MHz				0 dB(λ/4 monopole) across all RR bands
	VSWR		Not comply (< 2.0) required <1.5				Not comply (< 2.0) required <1.5
	weight (lb)		3				14.3
	dimensions (L x W X D) (in)		9 x 9 x 1.5				25.6 x 10.2 x 6.5
Future-proof Loco 1-port	Frequency range (MHz)		Comply				Comply
	Gain (dBi) (Min)		2.6 @ 157 - 174 MHz 3.1 @ 219.5 - 222 MHz 2.7 @ 450-460 MHz				0 dB(λ/4 monopole) across all RR bands
	VSWR		Not comply (< 2.0) required <1.5				Not comply (< 2.0) required <1.5
	weight (lb)		3				14.3
	dimensions (L x W X D) (in)		9 x 9 x 1.5				25.6 x 10.2 x 6.5

Based on the supplier responses in Table 26, it appears that Suppliers 1, 3, and 8 can design solutions for dual-band single port antennas for the wayside platform, with Supplier 8's solution complying with most of the key requirements. The same solutions can be applied to the base station platform as well.

Based on the supplier responses in Table 27, only Supplier 1 provided detailed design solutions for a base station quad-band antenna with four separate ports. Note that most of the suppliers indicated that quad-band solutions were not practical due to size and weight.

Table 26. Comparison and compliance matrix of supplier responses to wayside multi-band bi-directional antenna RFI

Platform	Parameters	Supplier 1	Supplier 3	Supplier 8	Supplier 10	Supplier 11	Supplier 12
Dual-band Wayside low gain 1-port	Frequency range (MHz)	Comply			Response not in compliance with the requested format. Supplier couldn't provide modified response in time to be included in this report.	Opted out	
	Gain (dBi) (Min)	8.2 @ 157-174 MHz 10.8 @ 219.5-222 MHz	5 @157-174 MHz 6 @ 219.5 - 222 MHz	9.15 @157-174 MHz 9.15 @ 219.5 - 222 MHz			
	VSWR	Comply	Not comply required <1.5	Comply			
	weight (lbs.)	Info not provided	18	36			
	dimensions (L x W X D) (in)	150 x 45 x 6	110 x 32	140 x 40			
Dual-band Wayside high gain 1-port	Frequency range (MHz)	Comply					
	Gain (dBi) (Min)	11.1 @ 157-174 MHz 13.5 @ 219.5-222 MHz	8 @157-174 MHz 9 @ 219.5-222 MHz	11.15 @157-174 MHz 11.15 @ 219.5-222 MHz			
	VSWR	Comply	Not comply required <1.5	Comply			
	weight (lbs.)	Info not provided	32 lbs.	78 lbs.			
	dimensions (L x W X D) (in)	256 x 45 x 6	228 x 32	250x40			
Dual-band Wayside low gain 2-port	Frequency range (MHz)	Comply					
	Gain (dBi) (Min)	4.8 @157-174 MHz 7.6 @ 219.5-222 MHz	6.6 @157-174 MHz 7.2 @ 219.5-222 MHz	Comply			
	VSWR	Comply					
	weight (lbs.)	35	25	78			
	dimensions (L x W X D) (in)	125 x 45 x 3	89 x 61	250 x 40			
Dual-band Wayside high gain 2-port	Frequency range (MHz)	Comply					
	Gain (dBi) (Min)	9.3 @157-174 MHz 7.8 @ 219.5-222 MHz	10.1 @157-174 MHz 7.2 @ 219.5-222 MHz	Comply			
	VSWR	Comply					
	weight (lbs.)	68 lbs.	40 lbs.	114			
	dimensions (L x W X D) (in)	246 x 45 x 3	195 x 61	370 x 40			
Triband Wayside low gain 1-port	Frequency range (MHz)	Response not in compliance with the requirements	Not feasible	Not feasible			
	Gain (dBi) (Min)						
	VSWR						
	weight (lbs.)						
	dimensions (L x W X D) (in)						
Triband Wayside high gain 1-port	Frequency range (MHz)						
	Gain (dBi) (Min)						
	VSWR						
	weight (lbs.)						
	dimensions (L x W X D) (in)						
Triband Wayside low gain 3-port	Frequency range (MHz)	Comply	Opted out	Opted out			
	Gain (dBi) (Min)	4.8 @157-174 MHz 7.4 @ 219.5-222 MHz 8 @ 896-937 MHz					
	VSWR	Comply					
	weight (lbs.)	35					
	dimensions (L x W X D) (in)	125 x 45 x 3					
Triband Wayside high gain 3-port	Frequency range (MHz)						
	Gain (dBi) (Min)	9.2 @157-174 MHz 7.8 @ 219.5-222 MHz 9.5 @ 896-937 MHz					
	VSWR	Comply					
	weight (lbs.)	70					
	dimensions (L x W X D) (in)	246 x 45 x 3					

Table 27. Comparison and compliance matrix of supplier responses to base station multi-band omni/bi-directional antenna RFI

<table>
<tr><th>Platform</th><th>Parameters</th><th>Supplier 1</th><th>Supplier 3</th><th>Supplier 8</th><th>Supplier 10</th><th>Supplier 11</th><th>Supplier 12</th></tr>
<tr><td rowspan="5">Base Station Omni low gain 4-port</td><td>Frequency range (MHz)</td><td>Comply</td><td rowspan="16">Opted out</td><td rowspan="16">Provide a design concept but no specifications</td><td rowspan="16">Response not in compliance with the requested format. Supplier couldn't provide modified response in time to be included in this report.</td><td rowspan="16">Opted out</td><td rowspan="16">Opted out</td></tr>
<tr><td>Gain (dBi) (Min)</td><td>1.6 @ 157 - 174 MHz
5.8 @ 219.5 - 222 MHz
1.8 @ 450-470 MHz
8.4 @ 896-937 MHz</td></tr>
<tr><td>VSWR</td><td>Comply</td></tr>
<tr><td>weight (lb)</td><td>100</td></tr>
<tr><td>dimensions (L x W X D) (in)</td><td>324 x 3</td></tr>
<tr><td rowspan="5">Base Station Bi-dir Low gain 4-port</td><td>Frequency range (MHz)</td><td>Comply</td></tr>
<tr><td>Gain (dBi) (Min)</td><td>4.6 @ 157 - 174 MHz
7.4 @ 219.5 - 222 MHz
5.5 @ 450-470 MHz
8 @ 896-937 MHz</td></tr>
<tr><td>VSWR</td><td>Comply</td></tr>
<tr><td>weight (lb)</td><td>40</td></tr>
<tr><td>dimensions (L x W X D) (in)</td><td>125 x 45 x 3</td></tr>
<tr><td>Base Station Omni high gain 4-port</td><td></td><td>Not practical due to large physical size</td></tr>
<tr><td rowspan="5">Base Station Bi-dir high gain 4-port</td><td>Frequency range (MHz)</td><td>Comply</td></tr>
<tr><td>Gain (dBi) (Min)</td><td>9.4 @ 157 - 174 MHz
9.5 @ 219.5 - 222 MHz
9.8 @ 450-470 MHz
9.5 @ 896-937 MHz</td></tr>
<tr><td>VSWR</td><td>Comply</td></tr>
<tr><td>weight (lb)</td><td>75</td></tr>
<tr><td>dimensions (L x W X D) (in)</td><td>263 x 45 x 3</td></tr>
</table>

5.3 Commercial-off-the-Shelf Dual-band Directional Antennas

The team conducted research for any COTS dual-band directional antenna solutions that met the dual-band directional antenna requirements for base stations and waysides, per Section 3.3. The basic requirement that a COTS solution needed to satisfy, or closely match, was the pair of frequency bands. The survey indicated only single-band directional antennas that matched the individual railroad bands. Based on the input provided by the AG, railroads were already using such single-band directional antennas.

5.3.1 Directional Antenna RFI Responses

As COTS dual-band antenna solutions were not found to be available, the team issued an RFI to multiple suppliers, including those that did not or declined to respond to the multi-band antenna RFI. Researchers asked suppliers to indicate whether they currently had any products that met the antenna requirements. Further, if they did not have existing products, they were asked if they could design practical solutions that met the antenna requirements presented in Section 3.3.

Table 28 is a compliance matrix of supplier responses against key requirements such as frequency range, gain, horizontal 3 dB beam width, minimum sidelobe attenuation, VSWR, weight, and dimensions.

Table 28. Comparison and compliance matrix of supplier responses to dual-band directional antenna RFI for base station and wayside platform

Platform	Parameters	Supplier 1	Supplier 3	Supplier 5	Supplier 8	Supplier 10
Dual-band Directional Base station 1-port	Frequency range (MHz)	Comply	Comply	Comply	Comply	Comply
	Gain (dBi) (Min)	Comply	Comply	Comply	Nearly Comply (7.65; required 8)	Comply
	Horizontal 3 dB beamwidth (degrees)	Comply	Not Comply (80° to 100°; required 60° or lower)	Not Comply (80°; required 60° or lower)	Not comply (106°; required 60° or lower)	Not Comply (95° to 102°; required 30° to 60°)
	Minimum Attenuation (dB) Horizontal pattern Other than main lobe (-45 to -135 degrees & +45 to +135 degrees[1])	Not Comply	Comply	Nearly Comply (10 dB min; required min. of 12 dB)	Not comply	Partially Comply (comply beyond +/- 85° @ 160 MHz; +/- 60° @ 220 MHz;)
	Front-to-Back ratio (dB) Horizontal Pattern	Comply	Comply	Not Comply (15 dB; required 20 dB)	Comply	Comply
	VSWR	Comply	Comply	Nearly Comply (1.75 max; required <1.5)	Comply	Comply
	Weight (lbs.)	Info not provided	16	15	8	20
	Dimensions (L x W X D) (in)	75 x 60 x 24	51 x 36 x 3	135 x 42 x 5	44 x 42 x N/A	95 x 38 x5.5
Dual-band Bi-directional (back-to-back) Base station 1-port	Frequency range (MHz)	Comply	Comply	Comply	Comply	Comply
	Gain (dBi) (Min)	Comply	Comply	Comply	Nearly Comply (7.65; required 8)	Not Comply
	Horizontal 3 dB beamwidth (degrees)	Partially Comply (75° @ 160 MHz, 55° @ 220 MHz; required 60° or lower)	Not Comply (80° to 100°; required 60° or lower)	Not Comply (80°; required 60° or lower)	Comply	Not Comply (95° to 102°; required 30° to 60°)
	Minimum Attenuation (dB) Horizontal pattern Other than main lobe (-45 to -135 degrees & +45 to +135 degrees[1])	Comply	Comply	Nearly Comply (10 dB min; required min. of 12 dB)	Not comply	Partially Comply (comply beyond +/- 85° @ 160 MHz; +/- 60° @ 220 MHz;)
	VSWR	Comply	Comply	Nearly Comply (1.75 max; required <1.5)	Comply	Comply
	Weight (lbs.)	Info not provided	25	30	16	40
	Dimensions (L x W X D) (in)	150 x 42 x 6	51 x 36 x 6	270 x 42 x 5	90 x 42 x N/A	190 x 38 x5.5
Dual-band Directional for Base station colocation 1-port	Frequency range (MHz)	Comply	Comply	Comply	Comply	Comply
	Gain (dBi) (Min)	Comply	Comply	Comply	Comply	Comply
	Horizontal 3 dB beamwidth (degrees)	Partially Comply (80° @ 160 MHz, 60° @ 220 MHz; required 60° or lower)	Not Comply (80° to 100°; required 60° or lower)	Not Comply (80°; required 60° or lower)	Not comply (106°; required 60° or lower)	Not Comply (95° to 102°; required 30° to 60°)
	Minimum Attenuation (dB) Horizontal pattern Other than main lobe (-45 to -135 degrees & +45 to +135 degrees[1])	Nearly Comply (comply beyond +/- 55 degrees)	Comply	Nearly Comply (10 dB min; required min. of 12 dB)	Not comply	Partially Comply (comply beyond +/- 85° @ 160 MHz; +/- 60° @ 220 MHz;)
	Front-to-Back ratio (dB) Horizontal Pattern	Comply	Comply	Not Comply (15 dB; required 20 dB)	Comply	Comply
	Minimum Attenuation (dB) Vertical patterns Other than main lobe (-91 to -100 degrees[1])	Comply	Supplier thinks their design complies but needs to confirm with further testing	Nearly Comply (32 dB min; required 35 dB min)	Comply	Nearly Comply (30 dB min; required 35 dB min)
	VSWR	Comply	Comply	Nearly Comply (1.75 max; required	Comply	Comply
	Weight (lbs.)	Info not provided	16	15	16	20
	Dimensions (L x W X D) (in)	110 x 42 x 6	51 x 36 x 3	135 x 42 x 5	110 x 44 x N/A	95 x 38 x5.5

Note:
1. refer to the illustration provided under Table 13

Based on the supplier responses in Table 28, it appeared that all the suppliers can design dual-band directional antenna solutions, with solutions from Supplier 1 and Supplier 3 complying with most of the key requirements.

Table 29 provides a summary of supplier participation in various RFIs issued by the research team.

Table 29. Summary of supplier participation to various TTCI RFI

Supplier	Responded to Multiplexer RFI	Responded to Multi-band Omni/Bi-directional Antenna RFI	Responded to Dual-band Directional Antenna RFI
Supplier 1	Y	Y	Y
Supplier 2	Y	N/A	N/A

Supplier	Responded to Multiplexer RFI	Responded to Multi-band Omni/Bi-directional Antenna RFI	Responded to Dual-band Directional Antenna RFI
Supplier 3	Y	Y	Y
Supplier 4	Y	N/A	N/A
Supplier 5	Y	N	Y
Supplier 6	N/A	N	N/A
Supplier 7	N/A	N	N/A
Supplier 8	Y	Y	Y
Supplier 9	N/A	N	N
Supplier 10	N/A	Y	Y
Supplier 11	N/A	Y	N/A
Supplier 12	N/A	Y	N/A

N/A – Not applicable due to lack of expertise in this area to respond to the RFIs.

5.4 Smart Antenna Systems

Smart antenna system offerings have primarily grown in the higher frequency bands – partly as candidates to improve capacity for cellular communications driven by exponential growth in data usage. In addition, solutions developed for high frequencies tend to be smaller in size, as the antenna element size and spacing is directly proportional to the RF signal wavelength (λ).

Smart antenna systems are also a growing area in satellite and aerospace communication systems, as they can dynamically adjust to moving platforms like aircraft. For many decades, the U.S. military has been applying smart antenna systems to take advantage of their null steering capabilities to mitigate jamming/ECM attacks by placing smart antenna systems under a controlled reception pattern antenna (CPRA). In addition, military radar and communications applications have taken advantage of null steering in the form of sidelobe cancellation (SLC) to mitigate the effects of an active attacker (jammer) that lies outside a non-array antenna's main lobe.

The key to achieving beam steering, or null steering, is using algorithms that can determine in real time the direction in which a beam must be pointed and then apply different amplitude weighting and phase shifts to individual antenna elements within the array dynamically. Two options for methods of determining the direction in which to point a smart antenna beam are provided in Section 2.5.3. In general, the phase shifts are used to point the beam, and the amplitude weights are used to shape the beam and adjust sidelobe levels. There has been significant research in adaptive beam-forming algorithms, and an in-depth analysis of the adaptive beam forming algorithm was beyond the scope of this project. However, the team did model some basic approaches.

Smart antennas can increase the capacity of communication systems, both in terms of users and data rates, making them attractive particularly for communications systems in which increasing data rates and serving the maximum number of users are priorities.

The team researched COTS solutions for smart antennas that can meet railroad needs. Researchers found some solutions, developed for the 900-MHz band, that railroads can leverage when implementing smart antenna systems. Table 30 presents the survey results for the smart antenna systems. Since there are no mechanically moving parts, phased array antennas tend to be more reliable and more quickly steerable than mechanically steerable antennas. For these reasons, research into smart antennas focused on electronically steerable phased arrays.

Table 30. Supplier survey result for phased array antennas

Parameters	Supplier B	Supplier L	Supplier M	Supplier N	Supplier O
Applicable Platform	Base Station	Mobile	Base Station	Other	Other
Frequency range (GHz)	2.49-2.69	2.4/5.8	2.3-5.85	0.62 - 5.8	2.4/4.9-6.0
Gain (dBi) (Min)	18.2	11 @ 2.45 GHz 15 @ 5.8 GHz	15 @ 2.3 GHz 15-17 @ 5.8 GHz*	3.8 @ 617 - 900 MHz 4.5 @900 - 1800 MHz 4 @ 1.8-5.4 GHz	7.5 @ 2.4 GHz 7.5 @4.9-6 GHz
VSWR	1.43	< 2.5	< 1.5	< 2.5	< 2
Weight (lbs.)	50.27	9	14 (2.3 GHz) 6 (5.8 GHZ)	1	1.2
Dimensions (LxWxD) (inches)	68.x16.x10	15x 10.6	30.43 x 14.65 x 4.72	5.7x5.3x1	7.5 x 7.5 x 1.2
*depending on beamwidth					

5.4.1 Smart Antenna System for Base Station Platforms

The team conducted modeling and simulations in MATLAB® using the sensor array design tool to extract the following information for a phased array antenna for the base station platform:

- Size of the phased array antenna for horizontal and vertical beam widths of 30 degrees and 10 degrees, respectively
- Wind loading exerted on the towers due to the resultant phased array antenna area.

Researchers performed a technology survey on array antennas used in cellular communications to understand the widely used array geometry and element types. Cellular communications often use panel antennas for broadside coverage with cross-polarized elements arranged in vertical columns to maximize gain by reducing elevation beam width. Since a flat, broadside panel array has a limited field of view, they are often deployed three per location at locations requiring 360-degree azimuth coverage, as illustrated in Figure 48.

Figure 48. Example of a typical three-sectored cellular tower with panel antennas

The team used the MATLAB® sensor array design tool to model a M×N uniform rectangular array (URA), where M is number of rows and N is number of columns with individual broadside elements spaced at a half wavelength (λ/2) apart. Based on the results, a 14×4 URA appeared to give the desired beam widths -30 degrees in the horizontal plane and 10 degrees in the vertical plane. Figure 49 illustrates the array geometry and a 3D radiation pattern of a 14×4 URA.

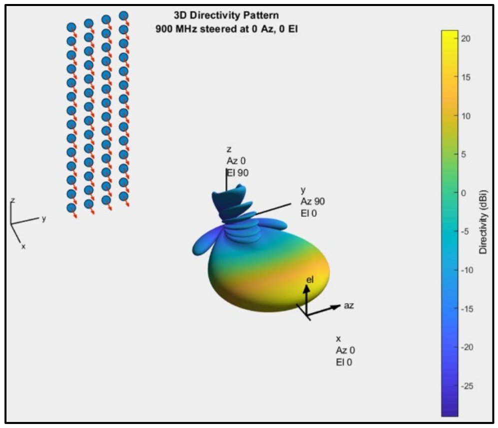

Figure 49. Array geometry and 3D radiation pattern of a 14×4 URA

Additionally, the 14×4 URA model was scaled across various railroad frequency bands to evaluate the size of the array panels. The size of the array increased proportionally as the frequency reduced – the size of the individual array elements and their spacing is directly proportional to the wavelength, λ. The size of the 14×4 URA to operate in the 160 MHz frequency band would be 12.16 meters high and 2.81 meters wide, not including the protective radome and the RF ports. Table 31 lists the sizes of 14×4 URAs for various railroad frequency bands.

Wind loading forces on the towers is a significant challenge when using antennas at these large sizes. As illustrated in Table 31, the team calculated frontal wind loading (direction of wind perpendicular to the face of the antennas) for various antenna sizes across all railroad frequency bands using the methods described in Iqbal, et al. [8] The wind loading of a 14×4 URA was significantly higher compared to the largest folded dipole antenna at 160 MHz. Note that when railroads plan to implement these array antennas, lateral wind loading also needs to be calculated once the depth information of the antenna is available. Also note that the wind loading values shown in Table 31 are for a single 14×4 URA. Depending on the geography and capacity needs, two or more of these antennas may need to be installed on the same tower, which could increase the wind loading impact on the tower.

Table 31. Comparison of electrical and mechanical specifications of base station panel array antennas at various railroad frequency bands

Frequency (MHz)	Length of the array (m)	Width of the array (m)	Half – power beamwidth Horizontal (degrees)	Half –power beamwidth Vertical (degrees)	Gain (dBi)	Area (m^2)	Effective drag area (ft^2)	Wind loading Frontal @ 100mph (lbf)	Wind loading Frontal @ 100mph (kN)
160	12.16	2.81	34	10	20.49	34.17	647.33	5224	23.24
220	8.85	2.04	34	10	20.49	18.05	342.03	2760	12.28
450	4.32	1	34	10	20.49	4.32	81.84	660	2.94
900	2.16	0.5	34	10	20.49	1.08	20.46	165	0.73

Researchers performed a literature survey to understand the wind loading capacity of the typical telecommunications towers (e.g., lattice, monopole, guyed mast). Information suggests that towers, particularly three-legged lattice towers, can support these high wind loads, but the installation is limited to certain heights and particular members within the tower [8]. The team recommends railroads perform independent analysis using structural analysis standards for telecommunication towers per ANSI/TIA-222G standards.

As explained in the following paragraphs, smart antenna systems at base station platforms are not practical in some of the existing railroad bands due to characteristics of the current radio systems.

For the 220 MHz PTC band, smart antenna systems would be very complex because the current PTC radio protocol requires the base station radios to monitor 10 receiving channels at the same time 1) to relay the wayside status messages (WSM) to the back office, and 2) to avoid any packet collisions between F-frame and D-frame traffic.

In areas like the Chicago DUA where smart antenna systems are most applicable, traffic on the 10 receiving channels at the base station radio typically arrives from up to 10 different directions, and a smart antenna system would have to create 10 individual beams. Since all 10 radio receiving channels share the same RF port, 10 electronically tunable bandpass filters could in turn be required between the antenna and the radio.

Today's 160 MHz railroad radios have single-band receivers, making them less complex than the 220 MHz radios, but smart antenna systems are not useful in conjunction with these radios due to the ubiquitous nature of communications. In particular, conventional voice radio base stations must continuously listen in all directions from which a transmission might spontaneously be sent. However, railroads are investigating ways to also support data applications at 160 MHz. A smart antenna system that can support higher data rates by directing a high-gain beam toward a target and can transmit or receive a burst of data could be highly useful along with a more capable radio (yet to be identified).

For 450 MHz fixed sites, smart antenna systems are not applicable generally because base stations are not a significant part of the RF network. Fixed sites exist in 450 MHz at some locations to act as repeaters for peer-to-peer (P2P) communications within the same train consist. Typically, the repeaters are only deployed in areas with challenging terrain or other obstructions that can induce high propagation losses upon the P2P links. A message initiated from the end of a train can be relayed by the repeater to the head of a train. Similarly, 450 MHz repeaters are used to enhance the reliability of links between distributed power locomotives within the same train consist. These types of coverage issues can be resolved with omnidirectional or fixed directional antennas at the repeaters.

For 900 MHz, there are interesting possibilities for use of smart antennas at base stations. With the increased amount of contiguous spectrum made available in the railroad recently, 900 MHz band communication methods similar to those used by 5G cellular systems (and the likelihood of deploying a new radio system to take advantage of it) could be used to communicate bursts of high-rate data over high-gain steerable antenna beams.

5.4.2 Smart Antenna Systems for Wayside Platforms

Currently, most railroads use tilt-down poles at wayside locations for ease of installation and maintenance. The main challenge with these towers is the number of antennae they can support. According to a recent test conducted by one Class I railroad together with a major supplier of the tilt-down towers, such towers reach about 83 percent of their loading capacity when two of the typical folded dipole antennas – weighing about 20 lb each and rated for a lateral thrust of 59 lbf at 100 mph – are installed on the tower. As a result, the team concluded that phased array antennas are not feasible for implementation on the tilt-down towers, as they cannot support the weight and the wind loading exerted by the array antennas at any frequency bands per Table 31.

5.4.3 Smart Antenna Systems for Locomotive Platforms

The team conducted modeling and simulations in MATLAB® using antenna design tools, phased array system toolkits, and custom modeling to extract the following information for a phased array antenna at a locomotive platform:

- Minimum achievable beam widths
- Feasibility of attaining sufficient sidelobe reduction
- Space required to implement the antenna array

The team conducted research into different implementations of array antennas (linear, rectangular, lattice, circular, and spherical) and different types of antenna elements (monopole, dipole, broadside). After multiple simulations, the team concluded that a circular array with dipole elements was well-suited for implementation on a locomotive platform. The main advantage of a circular array is its ability to steer the beam in any direction of the azimuth plane with little variation in beam width and sidelobe levels. In contrast, linear arrays have less than a 180-degree steering range, and broadside arrays can steer the beam in the elevation plane (when mounted horizontally as on a locomotive roof) but have limited steering capability in the azimuth plane.

There are several types of circular array configurations: uniform circular array (UCA), concentric circular array (CCA), and centered element CCA (CECCA). A CCA has multiple concentric rings of elements compared to a single ring in a UCA. A CECCA appears to perform better than a CCA for the same amount of space [2]. A common design approach is to maintain approximately half a wavelength ($\lambda/2$) separation between antenna elements. For a UCA, as the number of elements increases, the radius of the circular arrangement increases to maintain the $\lambda/2$ separation (see Table 32). For a CCA or CECCA, inter-ring spacing is also important – in addition to the spacing between the antenna elements. A 19-element CECCA, for example, can have approximately $\lambda/2$ separation between elements within the same ring as well as between elements in different rings [2]. Researchers focused modeling efforts on N-element UCAs and a 19-element CECCA. Figure 50 illustrates the different array arrangements with varying number of elements for UCA and a 19-element CECCA.

Table 32. Comparison of array size for various array geometries with λ/2 spacing between individual antenna elements

# of elements	Diameter of the array/ λ	Diameter at 900 MHz with λ/2 spacing (m)	Diameter at 900 MHz with λ/4 spacing (m)	Diameter at 450 MHz with λ/2 spacing (m)	Diameter at 450 MHz with λ/4 spacing (m)	Diameter at 220 MHz with λ/2 spacing (m)	Diameter at 220 MHz with λ/4 spacing (m)	Diameter at 160 MHz with λ/2 spacing (m)	Diameter at 160 MHz with λ/4 spacing (m)
8 UCA	1.31	0.44	0.22	0.87	0.435	1.78	0.89	2.45	1.225
10 UCA	1.62	0.54	0.27	1.08	0.54	2.21	1.105	3.03	1.515
12 UCA/ 19 CECCA	1.93	0.64	0.32	1.29	0.645	2.63	1.315	3.62	1.81
16 UCA	2.25	0.75	0.375	1.5	0.75	3.06	1.53	4.21	2.105
18 UCA	2.56	0.85	0.425	1.71	0.855	3.49	1.745	4.8	2.4
20 UCA	2.88	0.96	0.48	1.92	0.96	3.93	1.965	5.4	2.7
24 UCA	3.2	1.07	0.535	2.13	1.065	4.36	2.18	5.99	2.995

The main goal of implementing a UCA or CECCA is to achieve beamforming with the ability to instantaneously steer the beam in azimuth. The team simulated antenna patterns for each of the array arrangements illustrated in Figure 50 to analyze beamforming and the resultant beam widths and sidelobe levels (SLL). Figure 51 compares normalized radiation patterns generated for 8-, 12-, 16-, 20- and 24-element UCAs as well as the 19-element CECCA. In all examples, phase shifts were applied to individual array elements to achieve beamforming at a steering angle of 0 degrees. Some additional steering angles were modeled as well to examine the extent of pattern degradation due to non-ideal orientation.

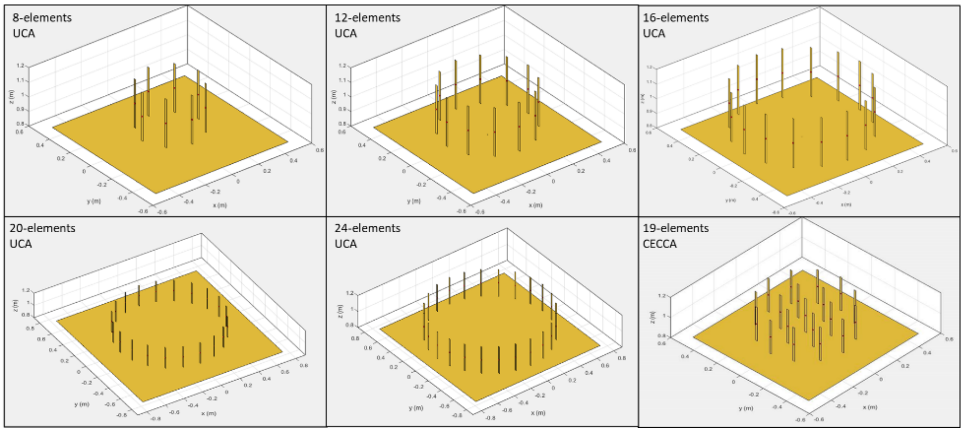

Figure 50. Comparison of dipole array arrangement for 8-, 12-, 16-, 20-, and 24-element UCA and a 19-element CECCA with λ/2 separation between the elements

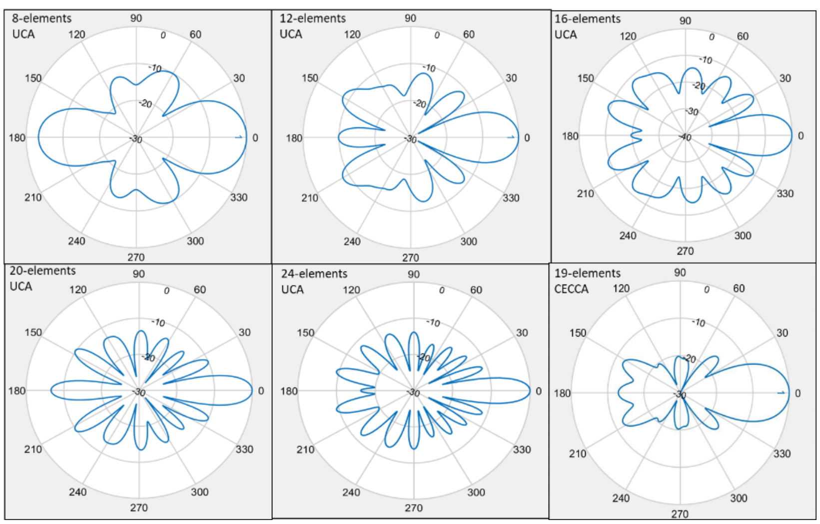

Figure 51. Comparison of normalized radiation patterns for 8-, 12-, 16-, 20-,and 24-element UCAs and a 19-element CECCA phase shifts applied for a beam steered at 0 degree

Although desirable beam widths were achieved, the resultant sidelobes were significant and 20 dB sidelobe attenuation (the baseline goal explained in Section 4.2.3) could not be achieved using phase shifts alone. As a result, the team investigated four tapering algorithms – namely, Dolph-Chebyshev (D-C), triangular, Hamming, and Hanning, to reduce the sidelobe levels. D-C is a widely used tapering algorithm for antenna arrays; however, it is not directly applicable to circular, non-boresight arrays. Researchers performed analysis to correlate (project) the weights produced for a 99-element linear array to that of an N-element UCA.

The D-C weights applied along with phase shifts applied for reducing SLL provided promising results for a 20- and 24-element UCA. However, the reduction in the SLL only reduced the sidelobes nearest to the main lobe and the rest of the sidelobes and back lobes became further degraded, as illustrated in Figure 52. There have been successful attempts at applying D-C tapering for uniform circular arrays [3] [4] [5], which might be applied for smart antenna system development for the railroad industry.

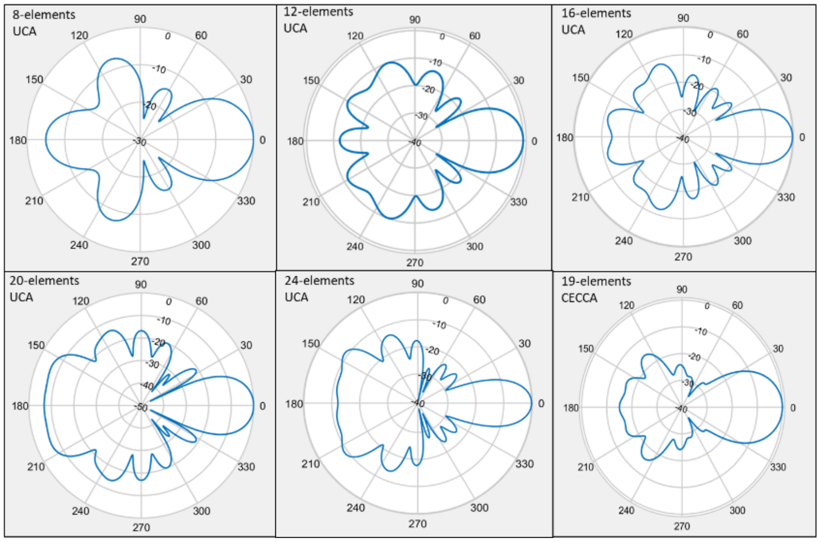

Figure 52. Comparison of normalized radiation patterns for 8-, 12-, 16-, 20-, and 24-element UCA and a 19-element CECCA with tapering and phase shifts applied for a beam steered at 0 degrees

For a CECCA, triangular tapering provides some benefit and the team modeled it using amplitude weights based on the equations in Reza, et al. [2] The results for triangular tapering for a 19-element CECCA have an effect similar to that of D-C tapering for a UCA. The tapering resulted in significant reduction in SLL for the immediate sidelobes but degraded the back lobes (see Figure 52).

Table 33 provides a summary of key MATLAB® simulation results for UCA and CECCA with λ/2 separation between the individual antenna elements.

Table 33. Summary of key results for UCA and CECCA MATLAB® simulations with λ/2 separation between the elements

No. of Elements	Sidelobe Attenuation* (dB)	Gain (dBd)	Tapering Algorithm	Steering Granularity	Half-Power Beam Width (degrees)	Null-to-Null Beam Width (degrees)
8 UCA	14.77	10.59	D-C (single)	45	36	90
12 UCA	13.78	12.78	D-C (single)	30	28	64
16 UCA	17.20	13.90	D-C (double)	22.5	24	54
20 UCA	20.11	12.84	D-C (double)	18	22	52
24 UCA	23.56	13.75	D-C (double)	15	20	50
19 CECCA	25.38	12.73	Triangular	60	30	84

*Not considering the significant back lobes as show in Figure 50.

The research team identified that both the UCAs and the 19-element CECCA had limitations regarding beam equality. For example, an eight-element CCA produced significantly different beam forming results for different beam steering angles. The solution to having beam forming relatively similar in all directions is to increase the number elements for the UCA and the number of rings (and number of elements in each ring) for the CECCA.

To improve the attenuation in the back lobes and to reduce the array size, researchers simulated some of the UCA and CCA arrangements with λ/4 spacing between the elements and created an optimizer tool for finding the best phase and amplitude values for beam steering in any direction. The best result, in terms of sidelobe attenuation and steering granularity, was achieved with a 24-element UCA as illustrated in Figure 53. The size of this array geometry was half the size of the 24-element array with λ/2 as presented in Table 32, and the average sidelobe attenuation achieved was 20 dB. TTCI also simulated arrays with λ/4 element spacing having fewer elements in the UCA. However, the array had limitations to the beam equality; thus, it was not very useful.

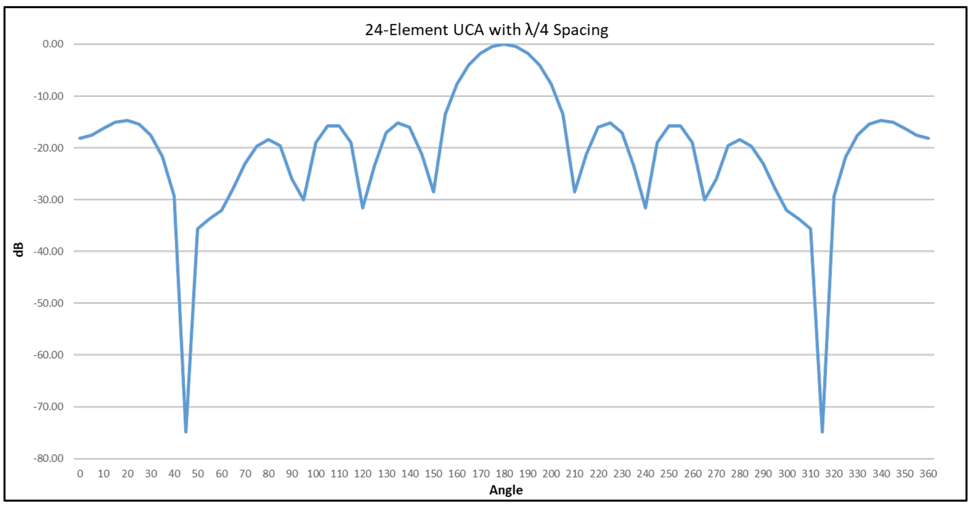

Figure 53. Azimuth radiation pattern for 24-element UCA with λ/4 spacing between individual antenna elements

Table 34 lists some key results from simulating the 24-element UCA with λ/4 spacing between the elements.

Table 34. Key results for a 24-element UCA with λ/4 spacing between individual antenna elements

No. of Elements	Min. Sidelobe Attenuation (dB)	Avg. Sidelobe Attenuation (dB)	Gain (dBd)	Tapering Algorithm	Half-Power Beam Width (degrees)	Null-to-Null Beam Width (degrees)
24-element UCA	14.65	20	11.5	Custom Optimizer	26	62

Based on the simulations, it appeared that a 24-element UCA with λ/4 spacing between individual antenna elements can achieve the goal of an average of 20 dB attenuation across all the sidelobes, including back lobes. As explained in Section 4.2.3 and Table 20, significant capacity benefit can be obtained if the locomotive antenna sidelobes are at least 20 dB below the main lobe gain. However, the space on the roof of a typical locomotive is 70″L×40″W×5″H. The only frequency band that makes a 24-element UCA with a $\lambda/4$ spacing between the elements practical for use on a locomotive roof is 900 MHz, per Table 32.

Although feasible at 900 MHz, installing a phased array antenna system could limit the installation space for and/or negatively affect the performance of the individual antennas needed for other frequency bands at the locomotive platform. Nonetheless, the potential benefits of a phased array antenna at 900 MHz are worthy of further investigation.

6. Tradeoff Analysis

A tradeoff study, also known as a trade study, is a decision-making support tool used to identify the most acceptable technical solution among a set of proposed solutions. By nature, all decisions are subjective and involve risks. Trade studies provide an effective means for addressing this by documenting the decision-making process and inputs/assumptions to enable traceability and repeatability [6]. By providing the trade study inputs/assumptions as well as results, they can be easily reviewed by stakeholders and revised as necessary to accommodate potential changes in the inputs, assumptions, and priorities/weightings.

The research team conducted trade studies to determine the most qualified antenna solution among the different antenna types identified in Section 2.5 for each of the platform types (base station, wayside and locomotive).

The trade study table consists of several decision-making criteria that are rated across all identified antenna solutions for each platform. Each decision-making criterion is given a weight in percentage that varies across platforms, as the relative priorities of the criteria differ from one platform type to another. A weighting of 0 in the trade table means that the evaluation criterion does not apply to that platform.

The ratings for the criteria are given on a scale of 1, 3, and 9 – where 1 is worst, 3 is moderate, and 9 is best. Alternatively, in tables where more granularity is needed, ratings can be selected from values of 1, 3, 9, 27; or from 1, 2, 4, and 8. In any event, trade table entries should be related by a factor of 2 or 3, rather than by equal increments (e.g., 1. 2, 3, 4…) to produce more accurately representative results and to increase the distinction among total scores for candidate solutions.

There are some antenna solutions that are not applicable due to certain constraints within the platform and therefore are given a rating of "N/A" – not applicable. A rating of "NF" means that antenna is not feasible per feedback from the antenna suppliers.

Potential antenna solutions are judged by their overall score produced at the end of each trade study table. The overall score for each antenna solution is generated by summing the product of rating and weight for each criterion. The overall scores are color-coded, with red being the worst score and green being the best, as a visual aid to compare the scores more easily.

The overall scores in the tables represent a preliminary assessment that should be reviewed and revised by any railroad intending to implement advanced antenna technologies. Each railroad should adjust the weightings to best represent its specific priorities, along with adding any further criteria specific to their needs and possible additional information they may have about candidate antenna solutions.

6.1 Definitions of Evaluation Criteria

The evaluation criteria used in the tradeoff tables were as follows:

1. Capacity Improvement – Evaluates various antenna solutions based on their ability to increase the capacity of the network.

2. Incumbent and Quiet Zone Protection – Evaluates various antenna solutions based on the ability the antenna might have to protect incumbent zones and quiet zones specified by FCC.
3. Compatibility with Existing Radios – Such as might be needed for steering antennas, as well as compatibility with multi-channel receivers.
4. Reliability, Availability, and Maintainability
5. Installation Complexity – Involves the difficulty of installing the antenna system in terms of number of individual antennas, size/number of holes, and number of cables, as well as any additional mechanical components required (e.g., for steering the antenna).
6. Network Planning Complexity – Evaluates how the various antenna solutions affect the network planning complexity. This includes frequency planning, time slot planning, and ERP planning, as well as determination of optimum antenna characteristics (e.g., beam width, orientation, and height).
7. Size and Weight – Evaluates the approximate size and weight of various antenna solutions. This is based on available feedback from the suppliers and surveys from the supplier's websites on the antenna specifications for each type of antenna. Size is important on mobile platforms since locomotives and hi-rail vehicles have limited roof space. Base station and wayside towers and poles have limited ability to withstand wind loading as well as limits on how much weight they can support.
8. Cost – Evaluates the estimated total cost of each antenna solution. For multi-band antenna solutions the cost of a multiplexer is also considered.

6.2 Trade Study Tables

Initially, the team developed a generic trade study that incorporated all the antenna solutions identified in Section 2.5, and the range of weighting percentage for the evaluation criteria across all the platforms as illustrated in Table 35. In addition, this generic trade study table indicates the antenna solutions that were deemed NF, based on supplier response to the multi-band antenna requirements RFI as indicated in Table 24. Those antenna solutions were discarded for further evaluation regarding the affected platform(s).

Table 35. Generic trade study table for various antenna solutions

		Omni Directional			Fixed Directional			Mechanically Steerable Antenna			Switched Beam Antenna			Adaptive Array Antenna		
Criteria	**Weighting Range (%)**	**SB**	**DB**	**QB**	**SB**	**DB**	**QB**	**SB**	**DB**	**QB**	**SB**	**DB**	**QB**	**SB**	**DB**	**QB**
Capacity Improvement	35-40															
Incumbent and Quiet zone protection	3-5															
Compatibility with existing radios	15															
RAM	10			NF*			NF			NF			NF			NF
Installation Complexity	5															
Network Planning Complexity	0-10															
Size and Weight	5-15															
Cost	10-15															
Total	100															

Notes:
SB – Single Band; DB – Dual Band; QB – Quad Band
Dual Band: 160 and 220 MHz; Quad band: 160, 220, 450 and 900 MHz
NF: Not feasible based on supplier's feedback
*For locomotive platform two suppliers response indicated that single element quadband omni directional antenna is feasible

To make the comparison between different antenna solutions effective, each platform was provided with its own weights, as the impacts of these evaluation criteria vary across the platforms. For example, size and weight criteria may have more impact upon a locomotive platform than a base station platform. Therefore, size and weight for the locomotive platform was given more weight (15 percent) as compared to that of the base station (5 percent).

Table 36, Table 37, and Table 38 present the trade studies performed across each platform (base station, wayside ,and locomotive) for various antenna solutions. Note that the total scores are color-coded relative to minimum and maximum scores across all three platforms.

Table 36. Example trade study for base station platform for various antenna solutions

		Omni		Fixed Directional		Mechanically Steerable		Switched Beam		Adaptive Array	
Criteria	Weighting (%)	SB	DB	SB	DB	SB	DB	SB	DB	SB	DB
Capacity Improvement	40	1	1	3	3	3	3	9	9	9	9
Incumbent and Quiet zone protection	5	1	1	9	9	9	9	9	9	9	9
Compatibility with existing radios	15	9	9	9	9	1	1	1	1	1	1
RAM	10	9	9	9	9	1	1	3	3	3	3
Installation Complexity	5	9	9	3	3	9	9	9	9	9	9
Network Planning Complexity	5	9	9	1	1	3	3	3	3	3	3
Size and Weight	10	3	9	3	9	1	1	1	1	3	3
Cost	10	9	9	9	9	3	3	1	1	1	1
Total	100	480	540	530	590	290	290	530	530	550	550

Notes:
SB – Single Band; DB – Dual Band
Dual Band: 160 and 220 MHz

Table 37. Example trade study for wayside platform for various antenna solutions

		Omni		Fixed Directional		Mechanically Steerable		Switched Beam		Adaptive Array	
Criteria	Weighting (%)	SB	DB	SB	DB	SB	DB	SB	DB	SB	DB
Capacity Improvement	35	1	1	3	3	3	3	3	3	3	3
Incumbent and Quiet zone protection	5	1	1	9	9	9	9	9	9	9	9
Compatibility with existing radios	15	9	9	9	9	1	1	1	1	1	1
RAM	10	9	9	9	9	1	1	3	3	3	3
Installation Complexity	5	9	9	3	3	3	3	3	3	3	3
Network Planning Complexity	5	9	9	1	1	3	3	3	3	3	3
Size and Weight	10	3	9	3	9	1	1	1	1	1	1
Cost	15	9	9	9	9	3	3	1	1	1	1
Total	100	520	580	560	620	260	260	250	250	250	250

Notes:
SB – Single Band; DB – Dual Band
Dual Band: 160 and 220 MHz

Table 38. Example trade study for locomotive platform for various antenna solutions

		Omni			Fixed Directional	Mechanically Steerable		Switched Beam *		Adaptive Array *	
Criteria	Weighting (%)	SB	DB	QB	N/A	SB	DB	SB	DB	SB	DB
Capacity Improvement	37	1	1	1		3	3	9	9	9	9
Incumbent and Quiet zone protection	3	1	1	1		3	3	3	3	3	3
Compatibility with existing radios	15	9	9	9		1	1	1	1	1	1
RAM	10	9	9	9		1	1	3	3	3	3
Installation Complexity	5	1	3	9		1	1	3	3	3	3
Network Planning Complexity	0										
Size and Weight	15	1	3	9		1	1	1	1	3	3
Cost	15	9	9	9		1	1	1	1	1	1
Total	100	420	460	580		180	180	432	432	462	462

Notes:
SB – Single Band; DB – Dual Band; QB – Quad Band
Dual Band: 160 and 220 MHz; Quad band: 160, 220, 450 and 900 MHz
* This is only practical for 900 MHz and therefore these ratings are based on assuming a 900 MHz array

To summarize the results, the dual-band, fixed directional antenna scored the best at both base station and wayside platforms. However, for the base station platform, omnidirectional or bi-directional antennas were a close second and might be a preferred solution for rural and some mountainous scenarios. For the locomotive platform, the quad-band omnidirectional antenna scored the best result as compared with any other antenna solutions.

The results of these trade study tables are subject to change depending upon vendor designs as well as individual railroad priorities, experience, and evaluation techniques. Therefore, the tables have been labeled "Example." It is recommended that each railroad assign its own weightings and ratings for each of the categories based on their unique needs and environment. A railroad might also want to insert additional criteria.

7. Conclusion and Recommendations

This report provides an assessment of the potential use of multi-band and directional antennas (including smart antenna systems) to meet the current and future wireless communication needs of the U.S. railroad industry. The project required extensive research, survey, and trade studies of some technology areas that are relatively new to the railroad industry. The analysis performed focused on the four dedicated railroad frequency bands at 160 MHz, 220 MHz, 450 MHz, and 900 MHz.

Project results included the following:

- Multiple different antenna requirements were developed for both multi-band omnidirectional, bi-directional, and directional antennas for various railroad platforms.
- A spectrum spatial reuse analysis quantifying the capacity benefits that can be achieved by using directional antennas for various platforms.
- Technology surveys identifying the applicability of multi-band and directional antennas for various platforms.
- Recommendations for antenna solutions applicable to various railroad use cases

The results indicate that multi-band and directional antenna technology is an attractive, feasible, and potentially cost-saving technology for helping to meet the wireless spectrum needs of the railroads. The following conclusions can be drawn from the results of this project.

1. Significant capacity benefits can be achieved by using directional antennas and multiple sectors at some base stations, particularly in urban areas.
2. A multi-band (quad-band or tri-band), single-element antenna solution is only feasible for the mobile (locomotive and hi-rail) platform. A dual-band, single-element antenna solution is possible, however, for base station and wayside platforms.
3. Smart antenna systems that can provide significant capacity benefits are only practical to implement for the 900 MHz railroad frequency band at base stations and locomotives due to size constraints.

7.1 Recommendations

The research team recommends that railroads implement the following, listed in approximate order of priority:

1. RF optimizations at the base station platform, particularly changing to directional antennas with appropriate power reductions, at those sites indicated by the optimization analysis.
2. Cell splitting and sectoring schemes at the appropriate base station platforms, particularly in urban areas, to improve capacity to support next generation train control technologies.
3. Power reductions at wayside platforms without compromising the required coverage on the tracks and performance of wayside-base station communication links.

4. Multi-band (quad-band or tri-band), single element antenna solution on locomotives. Additionally, railroads can choose to implement dual (redundant), multi-band antennas to increase reliability and/or to support diversity reception.
5. Dual-band omnidirectional or bi-directional antenna solutions at wayside platforms where weight and wind-loading improvements are needed to accommodate addition of more bands on a pole or tower.
6. Smart antenna solutions at base station and locomotive platforms for the 900 MHz frequency band, as an alternative to fixed antennas cited in recommendations 1 and/or 4 above.

Additionally, the team developed recommended antenna solutions for various railroad operational use cases, as listed in Table 39.

Table 39. Recommended antenna solutions for various railroad operational use cases

Use case number	Use case	Recommended antenna solutions
1-B	Base station near straight railroad tracks with minimum curves (Urban)	-Fixed directional antennas connected to separate radios in multiple sectors -Smart-antenna systems only at 900 MHz
1-W	Wayside near straight railroad tracks with minimum curves (Urban)	-Fixed directional antennas in back-to-back configuration connected to same radio
1-M	Mobile on straight railroad tracks with minimum curves (Urban)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz
2-B	Base station near railroad tracks with curves and diamond crossings (Urban)	-Dual-band omni/bi-directional -Fixed directional antennas with multiple sectors connected to separate radios -Smart-antenna systems only at 900 MHz
2-W	Wayside near railroad tracks with curves and diamond crossings (Urban)	-Dual-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio
2-M	Mobile on railroad tracks with curves and diamond crossings (Urban)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz
3-B	Base station near straight railroad tracks with minimum curves (Rural)	-Dual-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio
3-W	Wayside near straight railroad tracks with minimum curves (Rural)	-Dual-band omni/bi-directional
3-M	Mobile on straight railroad tracks with minimum curves (Rural)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz
4-B	Base station near railroad tracks with curves and diamond crossings (Rural)	-Dual-band omni/bi-directional
4-W	Wayside near railroad tracks with curves and diamond crossings (Rural)	-Dual-band omni/bi-directional
4-M	Mobile on railroad tracks with curves and diamond crossings (Rural)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz
5-B	Base station near straight railroad tracks with minimum curves (Mountain)	-Dual-band omni/bi-directional -Fixed directional antennas in back-to-back configuration connected to same radio
5-W	Wayside near straight railroad tracks with minimum curves (Mountain)	-Dual-band omni/bi-directional
5-M	Mobile on straight railroad tracks with minimum curves (Mountain)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz
6-B	Base station near curved railroad tracks with limited or no LOS (Mountain)	-Fixed directional antennas in back-to-back configuration connected to same radio
6-W	Wayside near curved railroad tracks with limited or no LOS (Mountain)	-Fixed directional antennas in back-to-back configuration connected to same radio
6-M	Mobile on curved railroad tracks with limited or no LOS (Mountain)	-Quadband omnidirectional -Smart-antenna system only at 900 MHz

Note that the recommendations included in this report are based on the assumptions, criteria, and available information cited. A railroad planning to implement new antenna technologies is advised to review the basis of these recommendations and adjust them as necessary to meet its specific needs and priorities.

8. References

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Abbreviations and Acronyms

ACRONYM	DEFINITION
AG	Advisory Group
B-B	Base-to-Base Interference
BWC	Beam Width Calculator
C/I	Co-channel Carrier-to-Interference Ratio
CCA	Concentric Circular Array
CECCA	Centered Element Concentric Circular Array
CONOPS	Concept of Operations
COTS	Components-of-the-Shelf
DB	Dual Band
D-C	Dolph-Chebyshev
D-frame	Dynamic Frame
DSB	Dynamic Short Broadcast
DUA	Dense Urban Area
F-frame	Fixed Frame
GHz	Gigahertz
IPM	ITCnet Planning Module
ITCnet	Interoperable train control network
kHz	Kilohertz
LOS	Line of Sight
LR	Locomotive Radio
LWRS	Locomotive WSM reception simulator
MHz	Megahertz
MTA	Major Trading Area
N/A	Not Applicable
NF	Not Feasible
PTC	Positive Train Control
QB	Quad-band
RF	Radio Frequency
RFI	Request for Information

ACRONYM	DEFINITION
RSSI	Received Signal Strength Indicator
SB	Single Band
SIR	Signal-to-Interference Ratio
SLL	Sidelobe Level
SSBZ	Safe Short Broadcast Zone
TTCI	Transportation Technology Center, Inc.
UCA	Uniform Circular Array
W-B	Wayside-to-Base
WIU	Wayside Interface Unit
WR	Wayside Radio
WSM	Wayside Status Message
WSRS	Wayside Status Relay Service