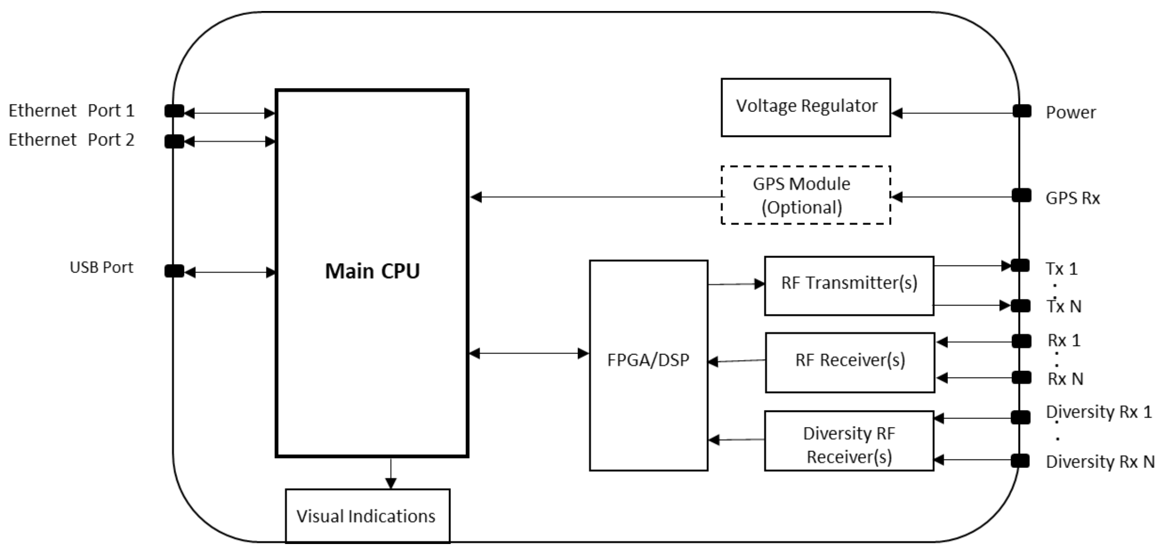
U.S. Department of Transportation

Federal Railroad Administration

Railroad Software-Defined Radio

Office of Research, Development, and Technology
Washington, DC 20590



DOT/FRA/ORD-20//39

Final Report
September 2020

<table>
<tr><td colspan="4">REPORT DOCUMENTATION PAGE</td><td colspan="2">Form Approved
OMB No. 0704-0188</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="2">1. AGENCY USE ONLY</td><td colspan="2">2. REPORT DATE
September 2020</td><td colspan="2">3. REPORT TYPE AND DATES COVERED
Technical Report</td></tr>
<tr><td colspan="4">4. TITLE AND SUBTITLE
Railroad Software-Defined Radio</td><td colspan="2" rowspan="2">5. FUNDING NUMBERS
Task Order 42</td></tr>
<tr><td colspan="4">6. AUTHOR(S)
Sarat Eruvuru, Alan Polivka, Bivesh Paudyal</td></tr>
<tr><td colspan="4">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Transportation Technology Center, Inc.
55500 DOT Road
Pueblo, CO 81001</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="4">9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development, and Technology
Washington, DC 20590</td><td colspan="2">10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-20/39</td></tr>
<tr><td colspan="6">11. SUPPLEMENTARY NOTES
COR: Jared Withers</td></tr>
<tr><td colspan="4">12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA eLibrary.</td><td colspan="2">12b. DISTRIBUTION CODE</td></tr>
<tr><td colspan="6">13. ABSTRACT (Maximum 200 words)
Transportation Technology Center, Inc. assessed the potential use of a software-defined radio to meet the current and future wireless communication needs of the U.S. railroad industry. FRA funded this project due to the high level of complexity involved in developing requirements and a preferred design approach for such a radio. The project required extensive research, survey, and trade studies of a technology area that has not been widely implemented beyond military applications.</td></tr>
<tr><td colspan="5" rowspan="2">14. SUBJECT TERMS
Railroad wireless communications, software-defined radio, technology survey, system requirements specification (SysRS), component requirements, trade-off analysis.</td><td>15. NUMBER OF PAGES
125</td></tr>
<tr><td>16. PRICE CODE</td></tr>
<tr><td>17. SECURITY CLASSIFICATION OF REPORT
Unclassified</td><td colspan="2">18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified</td><td colspan="2">19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified</td><td>20. LIMITATION OF ABSTRACT</td></tr>
</table>

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by
ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

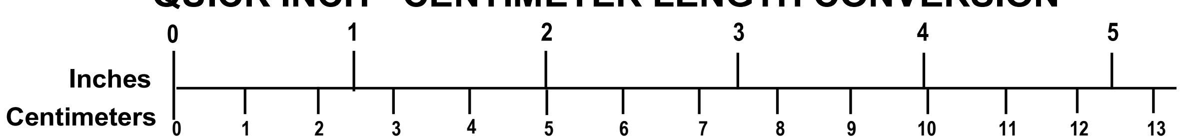
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

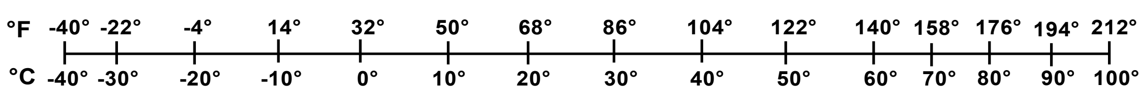
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Contents

Illustrations

Tables

Executive Summary

Transportation Technology Center, Inc. (TTCI) assessed the potential use of a software-defined radio (SDR) to meet current and future wireless communication needs of the U.S. railroad industry. The Federal Railroad Administration (FRA) funded this project due to the complexities of developing requirements and a preferred design approach for such a radio. The project required extensive research, survey, and trade studies of a technology area that has not been widely implemented beyond military applications.

Project results included the following:

- The TTCI research team developed a comprehensive SDR system requirements specification (SysRS) with inputs from the project's railroad advisory group.
- Technology surveys identified currently available SDR system and component technologies and the team compared them against key railroad requirements.
- Researchers defined and evaluated several candidate SDR hardware architectures and subsystem architectures against key criteria to determine the suitability of each candidate for meeting the wireless communications needs of each type of railroad platform. Trade study evaluations addressed cost, performance, and other characteristics of the various candidates.
- The team made modularity recommendations to improve availability and maintainability.
- Key requirements were developed for the most critical SDR hardware components.
- TTCI issued requests for information (RFIs) to determine cost and feasibility of the most critical SDR components requiring development.
- The team assessed the feasibility of using an SDR versus conventional dedicated radios versus a combination thereof for various railroad platforms.
- The team then made recommendations for follow-up work.

The results indicated that SDR technology is an attractive, feasible, and potentially affordable solution for meeting the needs of railroads, especially for use on platforms requiring multi-channel and multi-application wireless communications. The SysRS project document TTCI developed can be used as the technical basis for an organization to procure an SDR for railroad use. Researchers did not find a commercial-off-the-shelf (COTS) SDR that would satisfy all or even a sufficient subset of the railroads' requirements. Certain architectures offered significant advantages over others, due to specific characteristics of the railroad applications. Smart modular partitioning of the design can allow the SDR to keep operating with reduced performance after various component failures and also reduce the cost of repairs. All components required to build an SDR for railroad use were available either as COTS items or through supplier development based on existing technologies.

1. Introduction

The FRA funded TTCI to develop requirements and key trade studies for an SDR that can meet current and future wireless communication needs of the U.S. railroad industry. FRA funded this project due to the complexities involved in developing comprehensive requirements of such a radio, which requires extensive research, survey, and feasibility study of a technology area that has not been widely implemented beyond military applications.

1.1 Background

Railroads have numerous and ever-growing needs for wireless applications to support safe and efficient operations. The platforms and applications include handheld devices, locomotive data and voice radios, base stations, wayside interface units (WIUs), hi-rail vehicles, head-of-train/end-of-train communication links, distributed power, and unmanned aerial systems (UAS), among others. Currently, several types of radios and frequency bands are used to support the various applications and platforms.

Benefits of a software-defined radio (SDR) include the following:

- Reduced hardware count—one SDR could provide the capability of multiple radios currently in use, reducing overall hardware count and the need to support multiple, disparate radio types.
- Migration support—when migrating an application from one protocol, waveform, and/or frequency band to another, a single SDR could accommodate both versions (old and new), e.g., as a train passes from territory equipped with the prior radio sites to territory equipped with the new ones.
- Dynamic adaptability—ability to adapt to a changing environment and/or availability of spectrum, especially as a mobile moves from one area to another. This could include the ability to recognize and avoid interference with other communications channels in use.
- Upgradeability and flexibility for future expansion—SDRs can be modified to expand their capability and to support changing or new wireless communication requirements without having to replace hardware in many cases. Communications characteristics could be altered by downloading and running new SDR software at will, including over-the-air reprogramming if desired.
- Sparing and reliability—an SDR would provide the ability for one radio to replace many other radio types in the event of a particular radio’s failure or obsolescence. This can reduce the logistics cost of having to stock spares for each individual type of (dedicated) radio. Or it can increase reliability by facilitating the addition of a standby radio on each platform in cases where it might not have been previously practical.

1.2 Objectives

The overall short-term (current project) and long-term (potential future projects) objectives of this SDR development work are to:

- Define the overall requirements for an industry-standard SDR for use in railway applications.

- Perform trade studies to select preferred overall architecture and type of solution for each major component (e.g., power amplifier, antenna, front end, modulator, demodulator), including reliability considerations.
- Generate specifications for key characteristics of each major component to support development.
- Develop and test prototypes of the major components.

1.3 Scope

SDR development was planned to be implemented in multiple phases. Phase 1 (the subject of this report) included developing and documenting railroad SDR system requirements, architecture, key component requirements, capabilities, and verifying assumptions with railroad stakeholders.

Future phases (if funded) will include prototyping, testing, and evaluating individual SDR components. The Conclusion section of this report provides near-term follow-on recommendations.

To achieve the Phase 1 research objectives described above, eight major tasks were conducted:

Task 1. Project Management: This was an ongoing task throughout the entire project. TTCI applied required resources and tools to adequately manage the project.

Task 2. Stakeholder Engagement: This was also an ongoing task throughout the entire project.

Task 3. Document Railroad SDR System Requirements: TTCI worked with project stakeholders to identify the operational applications for a railroad SDR and document the system-level operating and interface requirements for each application.

Task 4. Develop Railroad SDR System Architecture Documentation: TTCI developed candidate SDR system-level architectures based on the results of Tasks 2 and 3. These architectures were reviewed by the stakeholders.

Task 5. Technology Survey: TTCI performed a literature search, held discussions with suppliers, and issued requests for information (RFI) to determine what relevant technologies and products currently exist vs. what would require development.

Task 6. Document Railroad SDR Component Requirements: TTCI documented key component-level technical and performance requirements. However, complete component-level requirements documents were out of scope.

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

1.4 Overall Approach

TTCI took the following approach for each task:

- For Tasks 1 and 2, TTCI established a stakeholder advisory group (AG) composed of FRA, railroads, and Meteorcomm, and established communication channels as appropriate. Periodic calls, email exchanges and other communication methods were used to promote the exchange of information, achieve the resolution of issues, and make required decisions. TTCI 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, TTCI used information from another FRA-funded effort, the Wireless Communications Roadmap (WCR) project, and also gathered inputs from the railroads to identify their operational needs, potential applications, and system limitations for a SDR. TTCI developed system-level operating and interface requirements. TTCI wrote a system requirements specification and submitted it to the AG for review and approval.
- Under Task 4, TTCI developed system architecture documentation based on the results of Tasks 2 and 3 and developed trade studies to evaluate different architectures for the SDR system. Also, TTCI produced high-level architecture documentation at the completion of the task, as part of the final report.
- Under Task 5, TTCI developed a technology comparison study for complete commercial off-the-shelf (COTS) SDRs. TTCI performed technology surveys of COTS components and, in cases where complete commercial solutions were not available, RFIs were issued to determine feasibility and the effort required to engineer the components for an SDR.
- Under Task 6, TTCI established key technical and performance requirements for the individual components, with flow down of the system-level requirements. TTCI produced high-level component requirements that were reviewed by the AG.

As a final task, TTCI prepared an FRA Technical Report on the work performed, analysis, recommendations, and results.

1.5 Organization of the Report

This report is organized in seven major sections:

1. Introduction: Provides an overall description of the project objectives and the work conducted.
2. SDR System Requirements: Provides an overview of how SDR system requirements were developed.
3. SDR System Architecture: Provides details on SDR system architecture and architectural trade study.
4. Technology Survey: Provides details on surveys performed on different components and technologies to be used in an SDR.
5. SDR Component Requirements: Provides details on how component requirements were developed.
6. Conclusion and Recommendations for Follow-on Work

Appendices: Additional details on SDR system requirements, cost trade studies, and component requirements.

2. SDR System Requirements

A system requirements specification (SysRS) documents the characteristics that a system must have to perform all of the necessary functions. The SDR SysRS consists of functional and non-functional requirements. Non-functional requirements include performance, safety, security, regulatory, system effectiveness, environmental, packaging, and interface requirements.

TTCI documented the SDR functional and non-functional requirements in a comprehensive document shown in Appendix A.

The functional requirements were developed based on inputs from the WCR project, in which TTCI gathered and documented all identified current railroad use cases, platforms, and future wireless application needs. The functional requirements are provided in Section A3 of Appendix A. In addition, TTCI gathered inputs from the AG about their operational needs that were not captured in the WCR project and any system characteristics or limitations that needed to be addressed in the SysRS.

The non-functional requirements were developed based on the existing specifications of the different railroad radio systems shown in Sections A4 through A12 of Appendix A. For requirements that are common among different platforms or applications, TTCI generally assumed the most conservative specifications of all the existing radio systems. TTCI followed the requirements for electronics suitable for stringent locomotive environments, as shown in Section A11 of Appendix A.

The SDR packaging requirements are addressed in Section A11 of Appendix A. The packaging and certain interface requirements were developed per Association of American Railroads (AAR) Manual of Standards and Recommended Practices (MSRPs) and American Railway Engineering and Maintenance-of-Way Association (AREMA) standards. In addition, TTCI developed potential SDR architectures with modularity as an option for packaging for increased availability, as illustrated in Section 4 of this report. TTCI also developed interface requirements for the SDR to be able to interface with users and other system/sub-systems as necessary.

The SysRS document establishes "baseline" requirements for the SDR. However, there are some requirements that are yet to be defined at this stage of the project. Also, there are some requirements that are not specified, but rather, are left for the suppliers to offer the optimal trade of performance versus cost, to the extent possible. As a result, the SysRS is not overly restrictive for the vendors/suppliers developing the SDR or components that go into the SDR.

For the detailed system requirements, refer to Appendix A.

3. SDR System Architecture

This section provides an overview of how various subsystems or components form the SDR system in terms of packaging, interconnections and component dependencies. In addition, this section also illustrates how some of the subsystems can be realized in multiple ways using different architectures.

Figure 3-1 illustrates the SDR block diagram. Note that external filters, duplexer, and T/R switches are not shown.

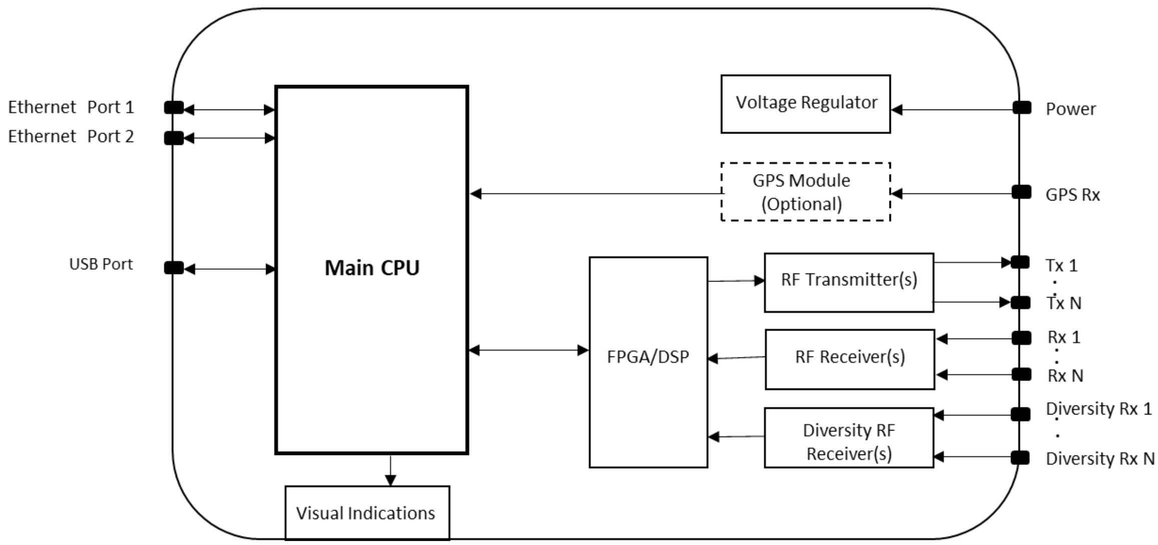


Figure 3-1: SDR block diagram

The SDR system comprises four subsystems:

- Transmitter
- Receiver
- Field programmable gate array (FPGA) and digital signal processing (DSP)
- Main central processing unit (CPU)

The SDR transmitter and receiver together can be referred to as a SDR transceiver.

The SDR may or may not use an intermediate frequency (IF) stage. Whether to use an IF stage is an implementation decision beyond the scope of this project. For the purposes of this study it was assumed that no IF stage is used, although the diagrams show that the same modulator and demodulator architectures could support either approach.

3.1 SDR Architecture Components

3.1.1 SDR Transmitter

The SDR transmitter is further divided into two subsystems:

- Modulator
- Transmit back-end

For the figures in Section 3.1.1, the following acronyms are used for the components defined below:

- DSP—Digital Signal Processing
- FPG —Field Programmable Gate Array
- D/A—Digital to Analog Converter
- LPF—Low Power Filter
- LO—Local Oscillator
- PA—Power Amplifier
- SYNTH—Synthesizer

3.1.1.1 Modulator

A modulator in a wireless communications system performs modulation in which an information stream (analog or digital) is superimposed onto a carrier or intermediate frequency that can be physically transmitted.

For an SDR there are several different ways of implementing a modulator that can be divided into two categories—wideband and band-limited. A single wideband modulator, as illustrated in Figure 3-2, supports all the railroad frequency bands, whereas the band-limited modulators, as illustrated in Figure 3-3 through Figure 3-5, have multiple branches to support all the necessary railroad frequency bands. In addition, there is also a hybrid modulator architecture, as illustrated in Figure 3-6, where a wideband software-defined modulator supports 160 MHz, 220 MHz bands and dedicated radios can be used for 450 MHz, 900 MHz bands.

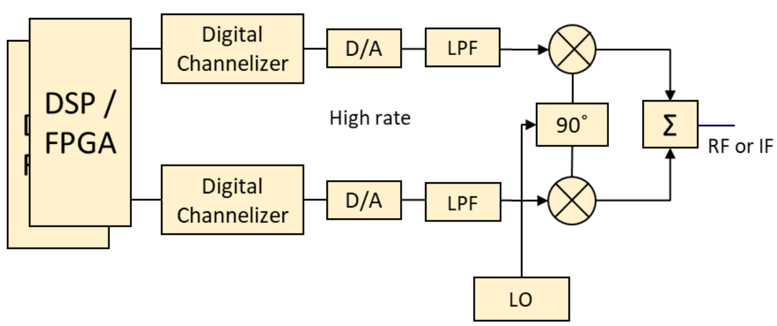


Figure 3-2: Wide-band I/Q modulator (Modulator Architecture No. 1)

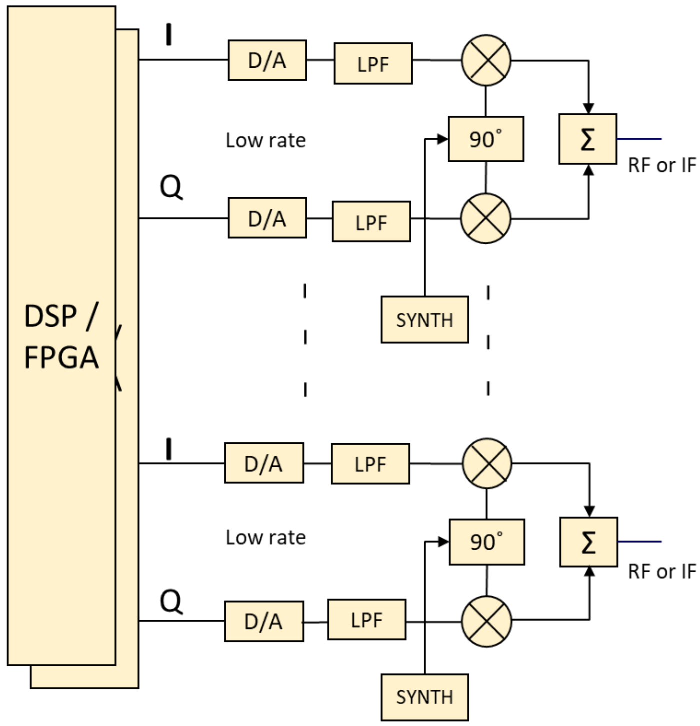


Figure 3-3: Band-limited modulator with an individual branch per carrier (Modulator Architecture No. 2)

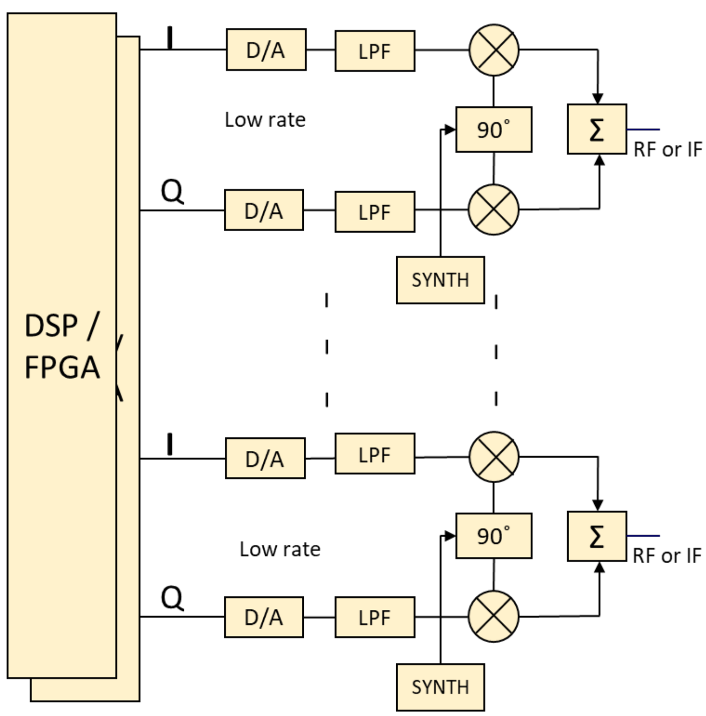


Figure 3-4: Band-limited modulator with individual branches per frequency band (Modulator Architecture No. 3)

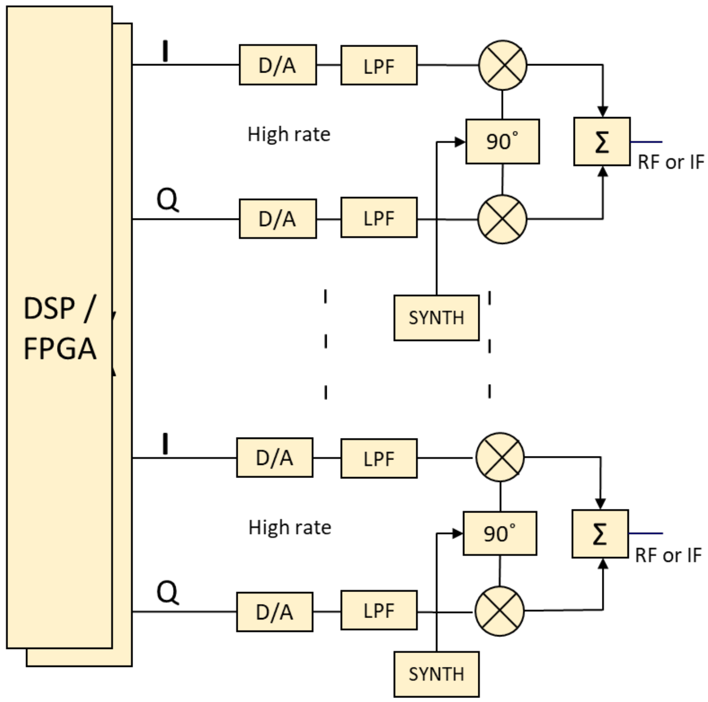


Figure 3-5: Band-limited modulator with individual branches supporting multiple carriers per frequency band (Modulator Architecture No. 4)

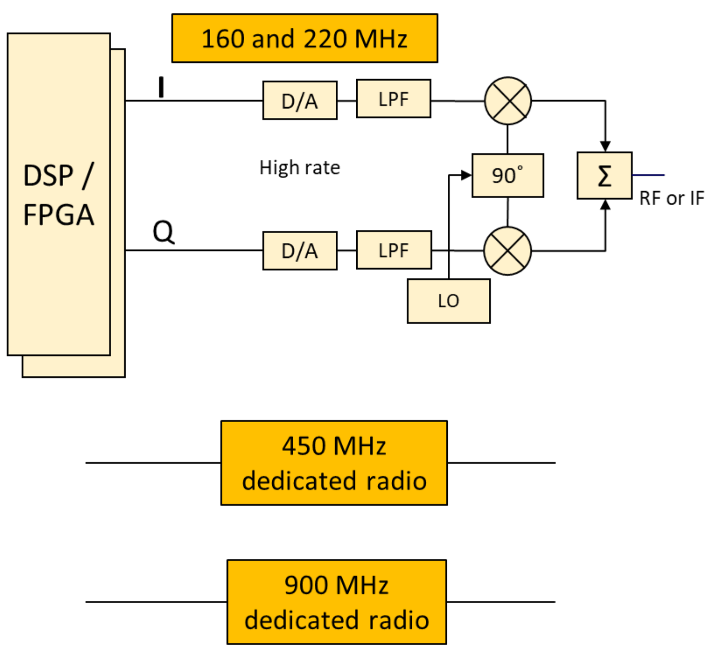


Figure 3-6: Wideband software-defined modulator for 160 and 220 MHz; dedicated radios for 450 and 900 MHz (Modulator Architecture No. 5)

Figure 3-3 through Figure 3-5 show two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

3.1.1.2 Transmitter Back-End

The transmitter back-end consists of the amplification and filtering of signals generated by the modulator. Note that the antenna system, which includes switches, multiplexing/de-multiplexing devices and antennas, are common components to both the transmitter back-end and receiver front-end. As explained in Section 3.1.1.1, transmitter back-end architectures can also be divided into two main categories—wideband and band-limited. In addition, there is also a hybrid back-end architecture, as illustrated in Figure 3-12, to exclusively support the hybrid modulator architecture, as illustrated in Figure 3-6.

Figure 3-7 through Figure 3-12 illustrate all the transmitter back-end architectures.

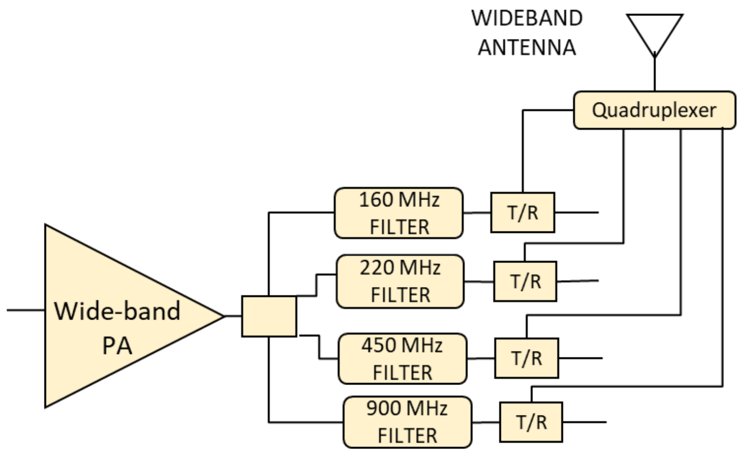


Figure 3-7: Back-end with wide-band modulator input to a wide-band PA, multi-bandpass filters and wideband antenna (Tx Back-End Architecture No. 1)

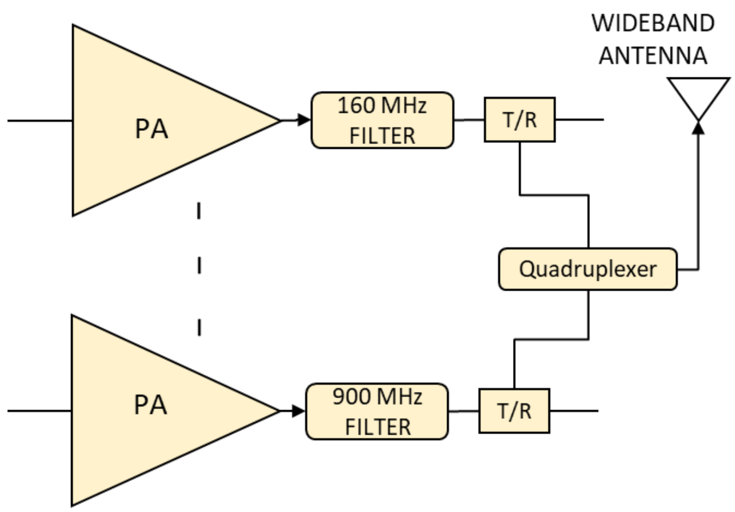


Figure 3-8: Back-end with band-limited modulators input to band-limited PAs, band-pass filters and wide-band antenna (Tx Back-End Architecture No. 2)

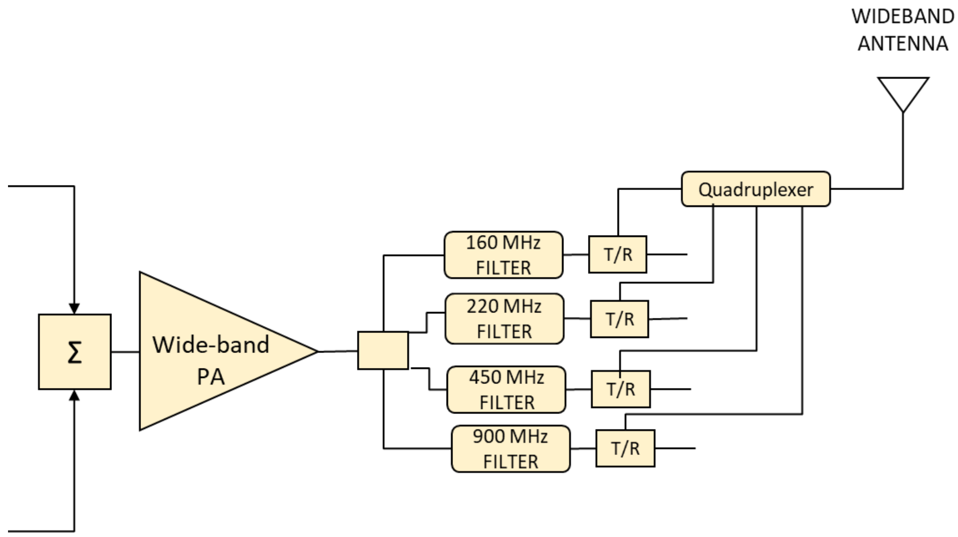


Figure 3-9: Back-end with band-limited modulators inputs combined into a wide-band PA, multi-bandpass filters and wideband antenna (Tx Back-End Architecture No. 3)

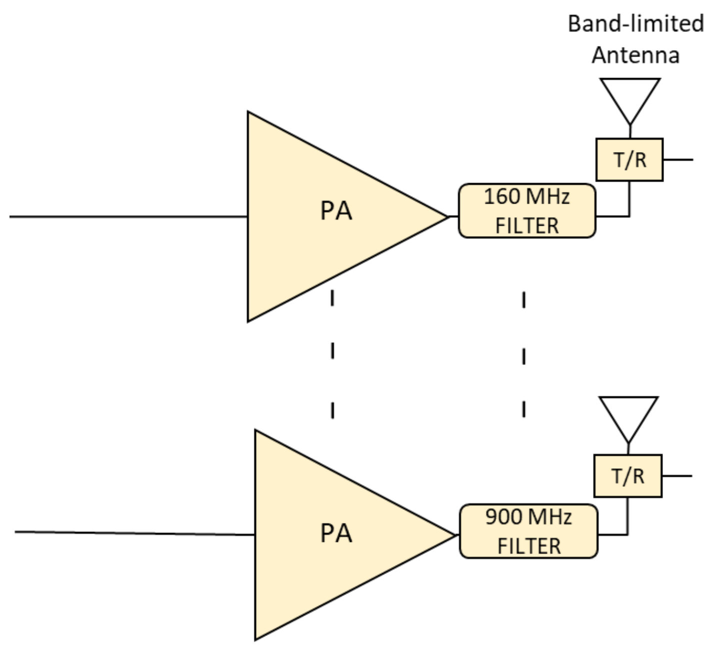


Figure 3-10: Back-end with band-limited modulators inputs to band-limited PAs, bandpass filters, and band-limited antennas (Tx Back-End Architecture No. 4)

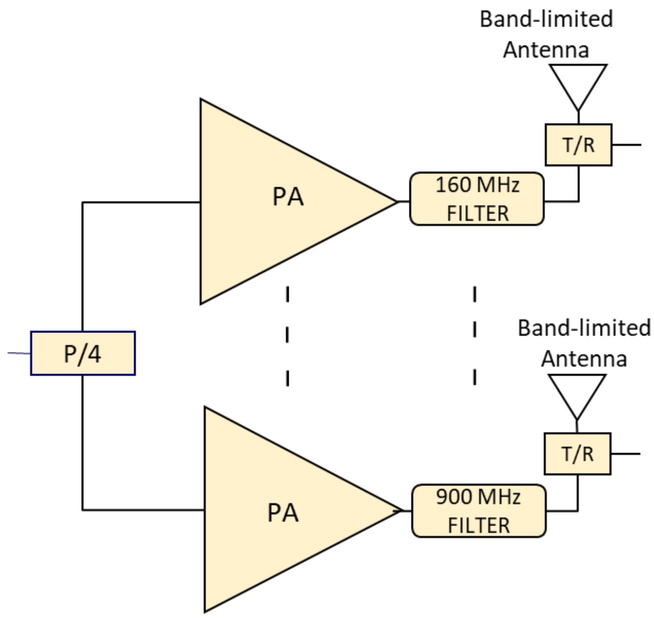


Figure 3-11: Back-end with wide-band modulator input split between band-limited PAs, multi-bandpass filters, and band-limited antenna (Tx Back-End Architecture No. 5)

Figure 3-10 and Figure 3-11 show two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

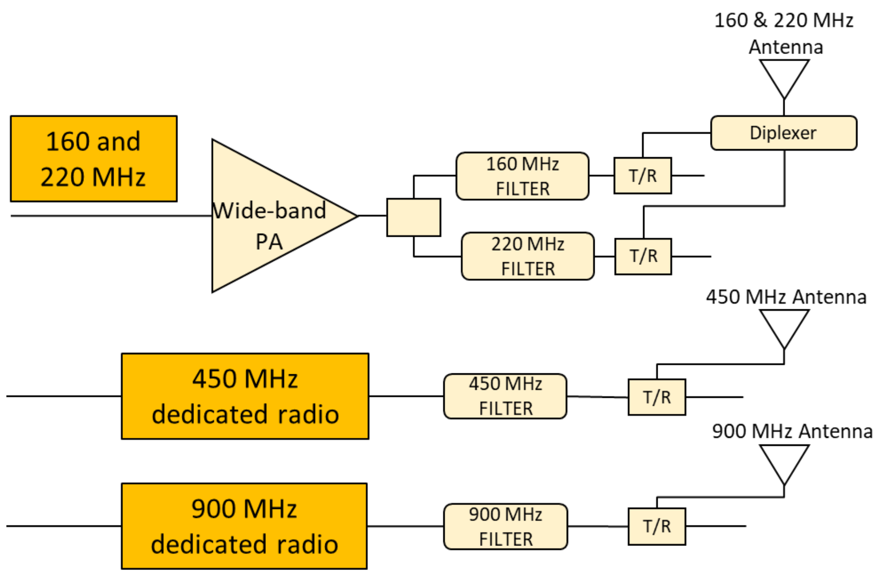


Figure 3-12: Back-end wideband PA, multi-bandpass filters, and wide-band antenna for 160-220 wide-band modulator; bandpass filters and band-limited antennas for dedicated radios (Tx Back-End Architecture No. 6)

An additional transmitter architecture was considered, consisting of four wideband modulators and four wideband transmitter back-ends. The benefit of this architecture would be increased fault tolerance, since failure of any one modulator or transmitter back-end would not cause a loss of transmit capability for that band—it would just require time-sharing of three transmitters among four bands. Furthermore, the PA would not be subject to the extreme intermodulation requirement of Tx Back-End Architecture No. 1. However, due to the complexity (high cost and size) of the high-power filters, switching, and summing network required, this architecture was not further evaluated.

3.1.2 SDR Receiver

Like the SDR transmitter, the SDR receiver is also further divided into two subsystems:

- Demodulator
- Receiver front-end

For the figures in Section 3.1.2, the following acronyms are used for the components defined below:

- A/D—Analog to Digital Converter
- LNA—Low Noise Amplifier
- VGA—Variable Gain Amplifier

3.1.2.1 Demodulator

A demodulator in a wireless communications system performs demodulation in which the original information stream (analog or digital) is extracted from the modulated carrier signal.

As in the SDR transmitter, there are also several different ways of implementing a demodulator, divided into two categories—wideband and band-limited.

Figure 3-13 through Figure 3-17 illustrate all the demodulator architectures.

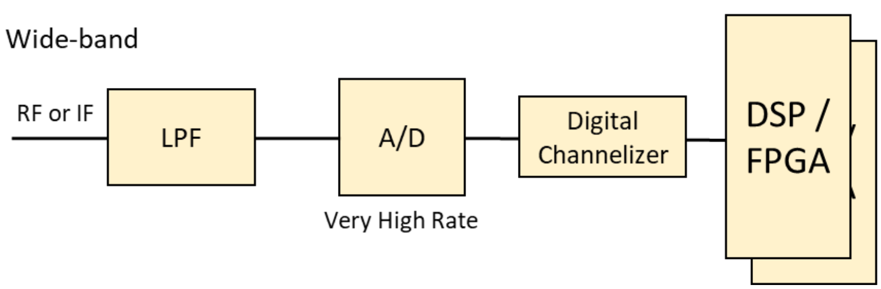


Figure 3-13: Direct digital conversion (DDC) wide-band demodulator (Demodulator Architecture No. 1)

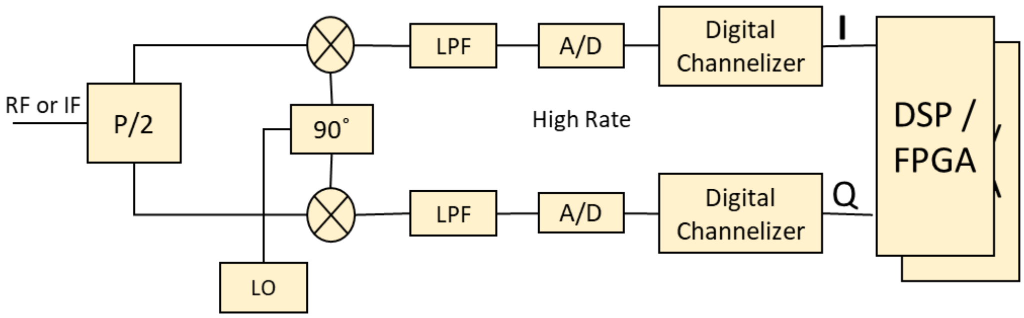


Figure 3-14: Wide-band I/Q demodulator (Demodulator Architecture No. 2)

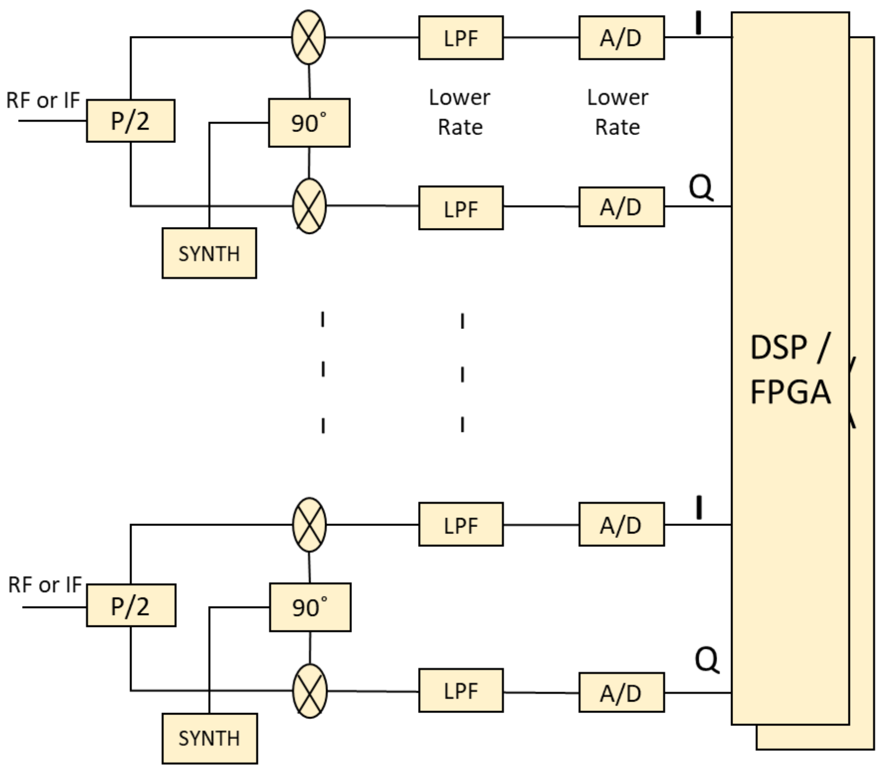


Figure 3-15: Band-limited demodulator per carrier (Demodulator Architecture No. 3)

Figure 3-15 and Figure 3-16 show two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

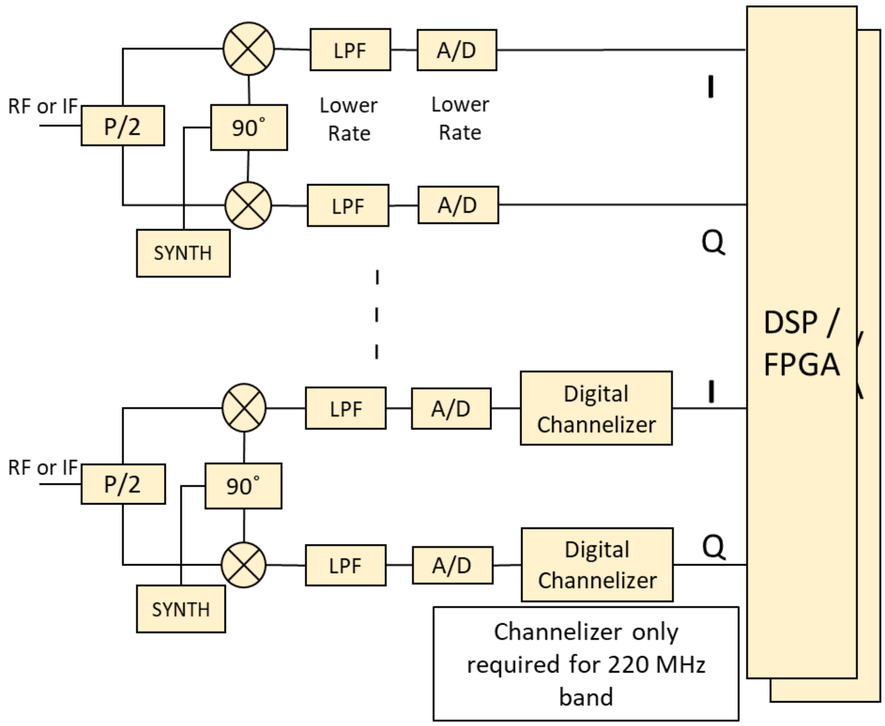


Figure 3-16: Band-limited demodulator per frequency band (Demodulator Architecture No. 4)

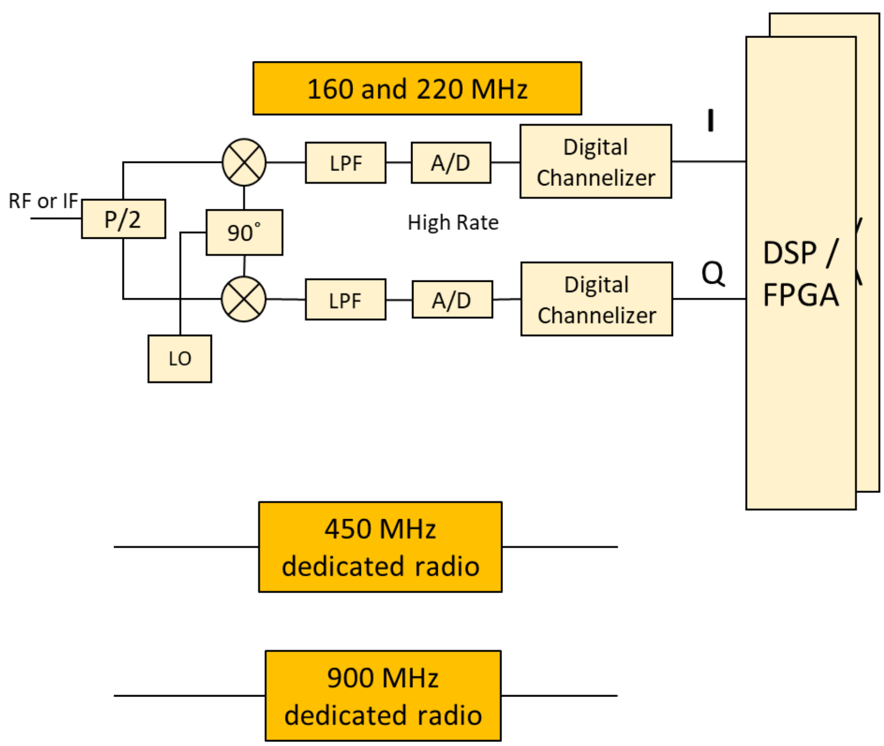


Figure 3-17: Wide-band software-defined demodulator for 160 MHz and 220 MHz; dedicated radios for 450 MHz and 900 MHz (Demodulator Architecture No. 5)

3.1.2.2 *Receiver Front-end*

The receiver front-end consists of filtering and amplification of the signals that need to be demodulated. Figure 3-18 through Figure 3-22 illustrates all the receiver front-end architectures. Note that the antenna system, as illustrated in Figure 3-18 through Figure 3-22, which consists of antennas, multiplexing/de-multiplexing devices, and T/R switches, are same as illustrated in Figure 3-7 through Figure 3-12 of Section 3.1.1.2.

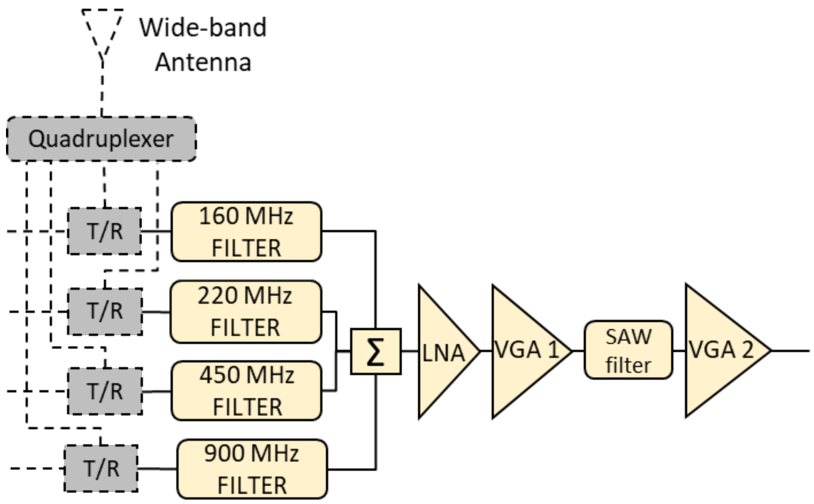


Figure 3-18: Wide-band front-end with wideband antenna, multi-bandpass filters input to a wide-band demodulator (Rx Front-End Architecture No. 1)

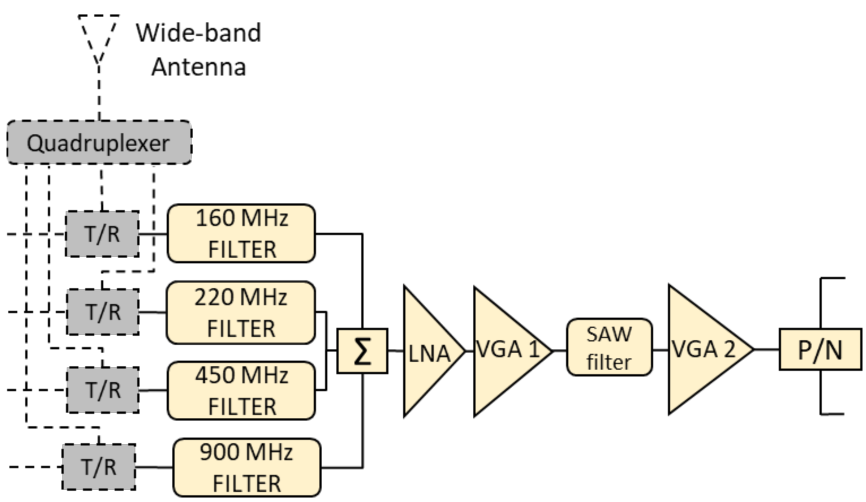


Figure 3-19: Wide-band front-end with wideband antenna, multi-bandpass filters split into multiple band-limited demodulators (Rx Front-End Architecture No 2)

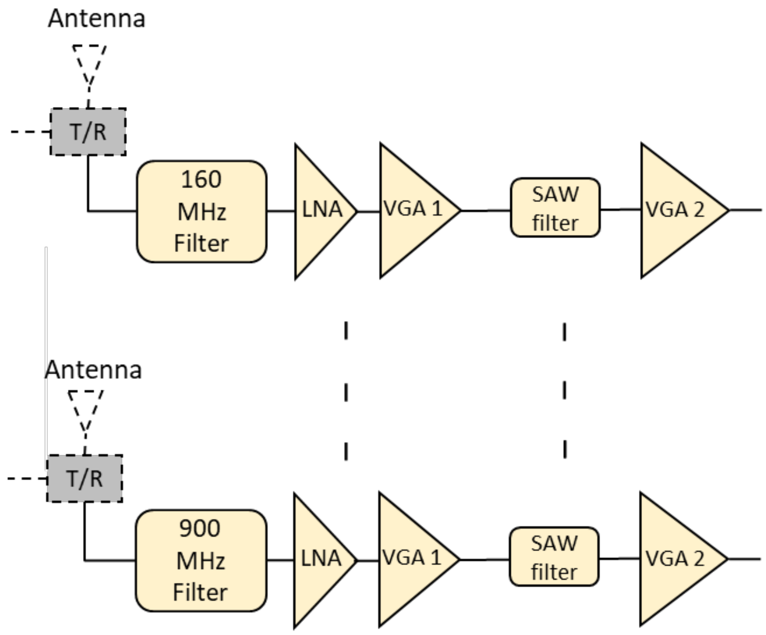


Figure 3-20: Band-limited front-ends with band-limited antennas, bandpass filters input to individual band-limited demodulators (Rx Front-End Architecture No. 3)

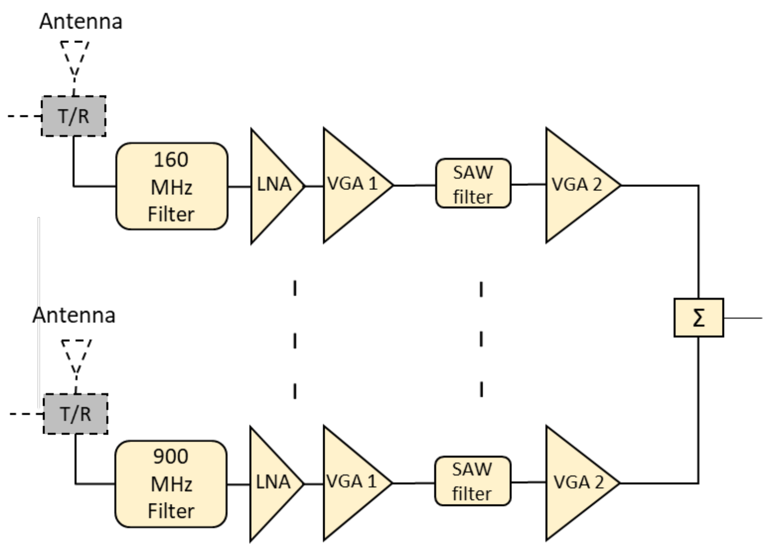


Figure 3-21: Band-limited Front-ends with band-limited antennas, bandpass filters combine into a wide-band demodulator (Rx Front-End Architecture No. 4)

Figure 3-20 and Figure 3-21 show two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

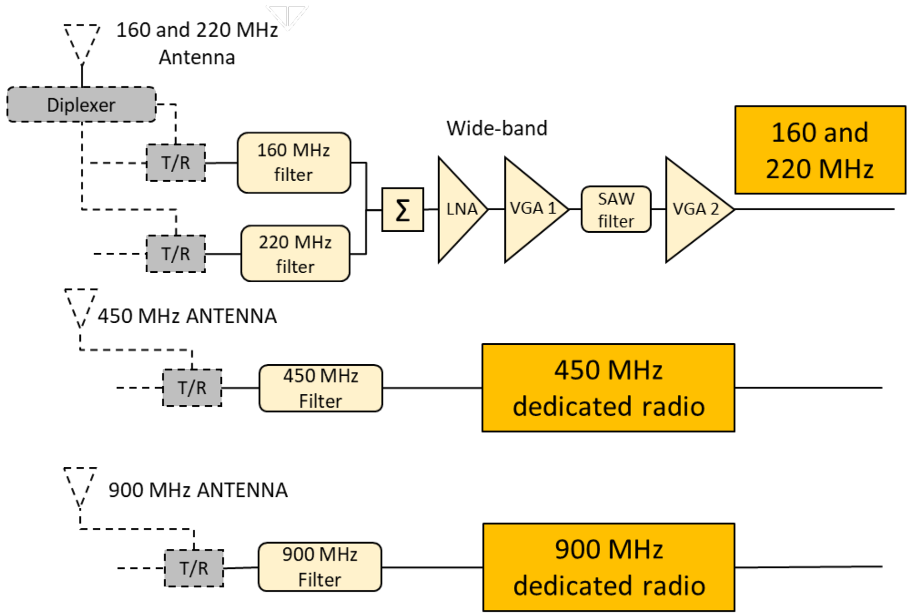


Figure 3-22: Wide-band front-end with wide-band antenna for 160-220 wide-band demodulator, multi-bandpass filters; bandpass filters and band-limited antennas for dedicated radios (Rx Front-End Architecture No. 5)

3.1.3 SDR Field Programmable Gate Array and Digital Signal Processing

3.1.3.1 Field Programmable Gate Array (FPGA)

FPGAs are semiconductor devices that consist of configurable static random access memory (SRAM), configurable logic blocks/logic array blocks (CLBs/LABs), and input/output (I/O) blocks, connected via programmable interconnects. FPGAs can be reprogrammed to desired application or functionality requirements even after the product has been installed in the field. This feature distinguishes FPGAs from application-specific integrated circuits (ASICs), which are custom-manufactured for specific design tasks.

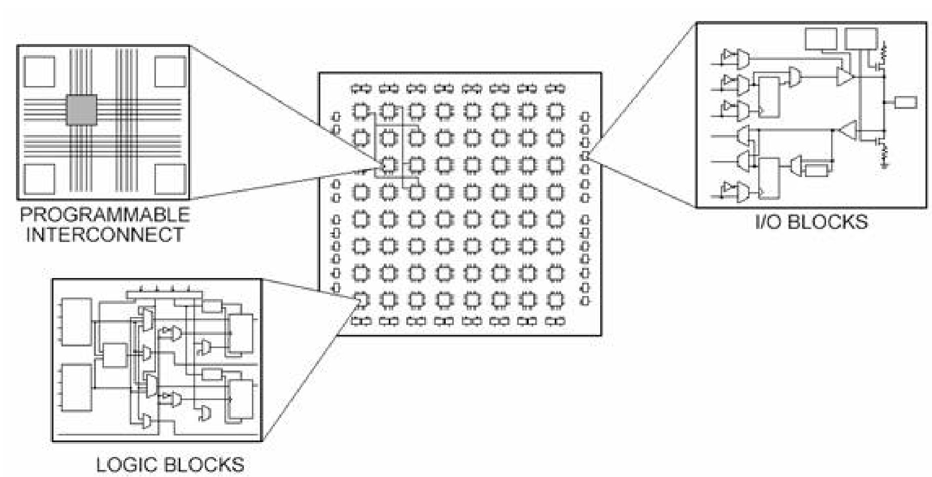


Figure 3-23: FPGA building blocks

FPGAs are needed to support channelization for the SDR transceiver. Further details on channelization can be found in Section 4.3.5.

3.1.3.2 Digital Signal Processor

A DSP is a type of microprocessor that is designed specifically to process digital signals efficiently. In the SDR, DSPs are used for tasks involving digital modulation/demodulation, forward error correction, and the encoding and decoding of digital signals to support various applications. Refer to Section 4.4.4 for the DSP chosen for the SDR system architecture trade study purposes.

3.1.4 SDR Main Central Processing Unit

The main CPU consists of a core processor, RAM, and flash memory, which manages all of the SDR functions. Refer to Section 4.4.4 for details on the specific CPU model chosen for the SDR system architecture trade study purposes.

The FPGA, DSP, main CPU, packaging, and other interface requirements will remain fundamentally the same across all the transceiver architectures illustrated in Sections 3.1.1.1, 3.1.1.2, 3.1.2.1 and 3.1.2.2.

3.2 SDR Architectural Trade Study

This section covers the extensive trade studies performed to determine the preferred SDR subsystem architecture to implement.

Trade studies are decision-making support tools 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 [1]. By providing the trade study inputs/assumptions as well as results, the trade studies can be revised as necessary to accommodate potential changes in the inputs, assumptions, and weightings.

Trade studies were performed for seven SDR platforms:

1. Locomotive
2. Base Station
3. Wayside
4. Hi-Rail
5. Handheld
6. End-of-Train (EOT)
7. Unmanned Aircraft System (UAS)

For each platform, the trade study was further divided into four categories according to subsystem—modulator, transmitter back-end, demodulator, and receiver front-end. The trade study table consisted of several decision-making criteria which were rated across all identified architectural solutions. Each decision-making criterion was given a weight in percentage that varied across categories and platforms, as the importance of the criteria changed with category and platform.

The ratings for the criteria were given on a scale of 0, 1, 3, and 9; 0 is not feasible, 1 is worst, 3 is moderate and 9 is best. Also, there were platforms where some architectures were not applicable, where the ratings were given N/A.

Potential architectural solutions were judged by their overall score produced at the end of each trade study. The overall score for each subsystem architecture was generated by summing the product, rating times weighting, for each criterion. The overall scores were color-coded, red being the worst score and green the best, as a visual aid to more easily compare the scores.

3.2.1 Definitions for Evaluation Criteria

The evaluation criteria used in the trade studies included:

1. Ability to add frequency bands and channels without hardware (HW) modifications.
2. Ability to add channels without HW modification.
3. Ability to support carrier aggregation (CA).
4. Availability—evaluates the availability of an architecture on a high-level
5. Current Draw/Heat Dissipation—evaluates how much current each architecture draws which also tells how much heat dissipation occurs. Heat dissipation is proportional to current drawn.
6. Scalability by Platform—evaluates the ability of a complex SDR architecture for a platform like Locomotive or Base Station, to be scalable to other platforms (requiring a less complex SDR, e.g., fewer simultaneous carriers or bands) like HOT, handheld, or UAS.
7. Out-of-Band Duplexing—evaluates how well an architecture can support out-of-band duplexing so that the SDR can simultaneously transmit and receive on different bands.
8. Unit Size—evaluates the approximate size of each architecture.
9. Unit Cost—evaluates the approximate cost estimation of each architecture.

Ease of Federal Communications Commission (FCC) certification was not included among the evaluation criteria in the trade tables because it scores the same across all platforms.

3.2.2 Locomotive Trade Studies

Refer to the figures in Sections 3.1.1.1, 3.1.1.2, 3.1.2.1 and 3.1.2.2 to better understand the ratings and differences across all the architectural solutions in Table 1 through Table 4.

Table 1 through Table 4 show the results of the locomotive platform trade studies.

Table 1: Trade study for modulator architectures—Locomotive SDR

Criteria	Weighting	Wide-band Architecture	Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	15	9	1	1	3	3
Scalability by Platform	10	1	9	9	9	9
Current Draw/Heat Dissipation	5	1	3	3	3	3
Ability to Support Carrier Aggregation	15	9	9	9	9	3
Availability	20	1	9	9	9	3
Unit Size	10	9	3	3	3	1
Unit Cost	25	9	9	9	9	3
Total	100					
Score		620	690	690	720	340

Note: Scalability by Platform is rated high ("9") for Architectures 2-5 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 2: Trade study for transmitter back-end architectures—Locomotive SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 3	Arch 2	Arch 4	Arch 5	Arch 6
Ability to Add Frequency Bands without HW Modification	15	0	0	1	1	1	3
Ability to Add Channels without HW Modification	10	0	0	9	9	9	3
Scalability by Platform	10	0	0	9	9	9	9
Current Draw/Heat Dissipation	10	0	0	9	9	9	3
Availability	15	0	0	3	3	3	1
Unit Size	15	0	0	9	9	9	1
Unit Cost	25	0	0	9	9	9	3
Total	100						
Score		0	0	690	690	690	330

Note: Scalability by Platform is rated high ("9") for Architectures 2 and 4-6 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 3: Trade study for demodulator architectures—Locomotive SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to add frequency bands and channels without HW modification	10	9	9	1	1	3
Out-of-band duplexing	15	9	9	3	3	3
Ability to support Carrier Aggregation	15	9	9	9	9	3
Scalability by platform	10	1	1	9	9	3
Current Draw/Heat Dissipation	5	1	3	1	9	3
Availability	15	1	1	9	3	1
Unit Size	5	9	3	1	3	1
Unit Cost	25	1	3	3	9	3
Total	100					
Score		460	490	500	610	260

Table 4: Trade study for receiver front-end architectures—Locomotive SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands without HW Modification	10	9	9	1	1	3
Ability to Add Channels without HW Modification	10	9	9	9	9	3
Susceptibility to Intermodulation (IMD)	10	1	1	9	9	9
Scalability by Platform	10	1	1	9	9	9
Current Draw/Heat Dissipation	5	1	1	3	3	3
Availability	15	1	1	3	3	1
Unit Size	15	9	3	3	3	1
Unit Cost	25	9	9	9	9	1
Total	100					
Score		580	490	610	610	310

To summarize, band-limited architectures scored better than wide-band architectures. If all the highest scored band-limited architectures across transmitter and receiver are put together, the resulting SDR system will look like the architecture illustrated in Figure 3-24, Section 3.3.1 of this report.

3.2.3 Base Station Trade Studies

Trade study results for locomotive and base station were identical. Both platforms had almost the same requirements, except for the stringent environmental requirements of a locomotive, so similar solutions are recommended for both the platforms. Refer to Section 3.2.2 for trade study results for base station platform.

3.2.4 Wayside Trade Studies

Refer to the figures in Sections 3.1.1.1, 3.1.1.2, 3.1.2.1 and 3.1.2.2 to better understand the ratings and differences across all the architectural solutions in Table 5 through Table 8.

Table 5 through Table 8 show the results of the locomotive platform trade studies.

Table 5: Trade study for modulator architectures—Wayside SDR

Criteria	**Weighting**	**Wide-band Architecture**	**Multiple Band-limited Architecture**			**Hybrid**
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	15	9	1	1	3	N/A
Scalability by Platform	15	1	9	9	9	N/A
Current Draw/Heat Dissipation	15	1	3	3	3	N/A
Availability	15	1	3	3	3	N/A
Unit Size	10	1	9	9	9	N/A
Unit Cost	30	9	9	9	9	N/A
Total	100					
Score		460	600	600	630	N/A

Note: Scalability by Platform is rated high (“9”) for Architectures 2-4 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 6: Trade study for transmitter back-end architectures—Wayside SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 3	Arch 2	Arch 4	Arch 5	Arch 6
Ability to Add Frequency Bands without HW Modification	10	0	0	1	1	1	N/A
Ability to Add Channels without HW Modification	10	0	0	9	9	9	N/A
Scalability by Platform	10	0	0	1	1	1	N/A
Current Draw/Heat Dissipation	15	0	0	3	3	3	N/A
Availability	15	0	0	1	1	1	N/A
Unit Size	10	0	0	9	9	9	N/A
Unit Cost	30	0	0	9	9	9	N/A
Total	100						
Score		0	0	530	530	530	N/A

Note: Scalability by Platform is rated high ("9") for Architectures 2, 4 and 5 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 7: Trade study for demodulator architectures—Wayside SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add frequency Bands and Channels without HW Modification	10	9	9	1	1	N/A
Out-of-Band Duplexing	10	9	9	3	3	N/A
Ability to Support Carrier Aggregation	5	9	9	9	9	N/A
Scalability by Platform	10	1	1	9	9	N/A
Current Draw/Heat Dissipation	15	1	3	9	9	N/A
Availability	15	1	1	9	9	N/A
Unit Size	10	3	3	9	9	N/A
Unit Cost	25	1	3	9	9	N/A
Total	100					
Score		320	400	760	760	N/A

Table 8: Trade study for receiver front-end architectures—Wayside SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands without HW Modification	10	9	9	1	1	N/A
Ability to Add Channels without HW Modification	10	9	9	9	9	N/A
Scalability by Platform	10	1	1	9	9	N/A
Current Draw/Heat Dissipation	15	1	1	3	3	N/A
Availability	15	1	1	3	3	N/A
Unit Size	10	3	3	9	9	N/A
Unit Cost	30	9	9	9	9	N/A
Total	100					
Score		520	520	640	640	N/A

3.2.5 Hi-Rail Trade Studies

Refer to the figures in Sections 3.1.1.1, 3.1.1.2, 3.1.2.1 and 3.1.2.2 to better understand the ratings and differences across all the architectural solutions in Table 9 through Table 12.

Table 9 through Table 12 show the results of the locomotive platform trade studies.

Table 9: Trade study for modulator architectures—Hi-Rail SDR

Criteria	Weighting	Wide-band Architecture	Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	15	9	1	1	3	3
Scalability by Platform	15	1	9	9	9	9
Current Draw/Heat Dissipation	5	1	3	9	9	3
Availability	15	1	3	3	3	1
Unit Size	20	1	9	9	9	9
Unit Cost	30	9	9	9	9	9
Total	100					
Score		460	660	690	720	660

Note: Scalability by Platform is rated high ("9") for Architectures 2-5 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 10: Trade study for transmitter back-end architectures—Hi-Rail SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 3	Arch 2	Arch 4	Arch 5	Arch 6
Ability to Add Frequency Bands without HW Modification	10	0	0	1	1	1	3
Ability to Add Channels without HW Modification	10	0	0	9	9	9	3
Scalability by Platform	10	0	0	1	1	1	3
Current Draw/Heat Dissipation	10	0	0	3	3	3	3
Availability	15	0	0	3	3	3	1
Unit Size	15	0	0	9	9	9	3
Unit Cost	30	0	0	9	9	9	3
Total	100						
Score		0	0	590	590	590	270

Note: Scalability by Platform is rated high ("9") for Architectures 2 and 4-6 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 11: Trade study for demodulator architectures—Hi-Rail SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	15	9	9	1	1	3
Out-of-Band Duplexing	10	9	9	3	3	3
Scalability by Platform	10	1	1	9	9	3
Current Draw/Heat Dissipation	5	1	3	9	9	3
Availability	15	1	1	9	9	1
Unit Size	20	3	3	9	9	3
Unit Cost	25	1	3	9	9	3
Total	100					
Score		340	400	720	720	270

Table 12: Trade study for receiver front-end architectures—Hi-Rail SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency bands without HW Modification	10	9	9	1	1	3
Ability to Add Channels without HW Modification	10	9	9	9	9	3
Scalability by Platform	15	1	1	9	9	3
Current Draw/Heat Dissipation	5	1	1	3	3	3
Availability	15	1	1	3	3	1
Unit Size	20	3	3	9	9	3
Unit Cost	25	9	9	9	9	9
Total	100					
Score		500	500	700	700	420

3.2.6 Handheld Trade Studies

Refer to the figures in Sections 3.1.1.1, 3.1.1.2, 3.1.2.1 and 3.1.2.2 to better understand the ratings and differences across all the architectural solutions in Table 13 through Table 16.

Table 13 through Table 16 show the results of the locomotive platform trade studies.

Table 13: Trade study for modulator architectures—Handheld SDR

Criteria	Weighting	Wide-band Architecture	Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	10	9	1	1	3	N/A
Scalability by Platform	10	1	9	9	9	N/A
Current Draw/Heat Dissipation	15	1	3	9	9	N/A
Availability	10	1	3	3	3	N/A
Unit Size	25	1	9	9	9	N/A
Unit Cost	30	9	9	9	9	N/A
Total	100					
Score		420	670	760	780	N /A

Note: Scalability by Platform is rated high ("9") for Architectures 2-4 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 14: Trade study for transmitter back-end architectures—Handheld SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture			Hybrid
	%	Arch 1	Arch 3	Arch 2	Arch 4	Arch 5	Arch 6
Ability to Add Frequency Bands without HW Modification	5	0	0	1	1	1	N/A
Ability to Add Channels without HW Modification	5	0	0	9	9	9	N/A
Scalability by Platform	5	0	0	1	1	1	N/A
Current Draw/Heat Dissipation	15	0	0	3	3	3	N/A
Availability	10	0	0	1	1	1	N/A
Unit Size	30	0	0	9	9	9	N/A
Unit Cost	30	0	0	9	9	9	N/A
Total	100						
Score		0	0	650	650	650	N /A

Note: Scalability by Platform is rated high ("9") for Architectures 2, 4 and 5 based on the assumption that the SDR design is modularized such that only hardware for the necessary bands is included for each type of platform.

Table 15: Trade study for demodulator architectures—Handheld SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands and Channels without HW Modification	10	9	9	1	1	N/A
Out-of-Band Duplexing	10	9	9	3	3	N/A
Scalability by Platform	10	1	1	9	9	N/A
Current Draw/Heat Dissipation	10	1	3	9	9	N/A
Availability	10	1	1	9	9	N/A
Unit Size	20	3	3	9	9	N/A
Unit Cost	30	1	3	9	9	N/A
Total	100					
Score		300	380	760	760	N /A

Table 16: Trade study for receiver front-end architectures—Handheld SDR

Criteria	Weighting	Wide-band Architecture		Multiple Band-limited Architecture		Hybrid
	%	Arch 1	Arch 2	Arch 3	Arch 4	Arch 5
Ability to Add Frequency Bands without HW Modification	10	9	9	1	1	N/A
Ability to Add Channels without HW Modification	10	9	9	9	9	N/A
Scalability by Platform	10	1	1	9	9	N/A
Current Draw/Heat Dissipation	10	1	1	3	3	N/A
Availability	10	1	1	3	3	N/A
Unit Size	20	3	3	9	9	N/A
Unit Cost	30	9	9	9	9	N/A
Total	100					
Score		540	540	700	700	N /A

3.2.7 EOT Trade Studies

Trade study results for Handheld and EOT platforms were identical. Both platforms had almost the same requirements, except for the stringent environmental requirements for EOT platform, so similar solutions are recommended for both platforms. Refer to Section 3.2.6 for trade study results for EOT platform.

3.2.8 UAS Trade Studies

Trade study results for handheld and UAS platforms were identical. Both platforms had the same requirements, so similar solutions are recommended for both platforms. Refer to Section 3.2.6 for trade study results for UAS platform.

3.3 Potential SDR System Architectures

Based on the architectural trade studies explained in Section 3.2, TTCI has developed two potential SDR system architectures—bandlimited and quasi-wideband.

3.3.1 Band-limited SDR System Architecture

The band-limited system architecture illustrated in Figure 3-24 was developed using transmitter and receiver architectures that scored highest in the architectural trade studies. Figure 3-24 shows two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

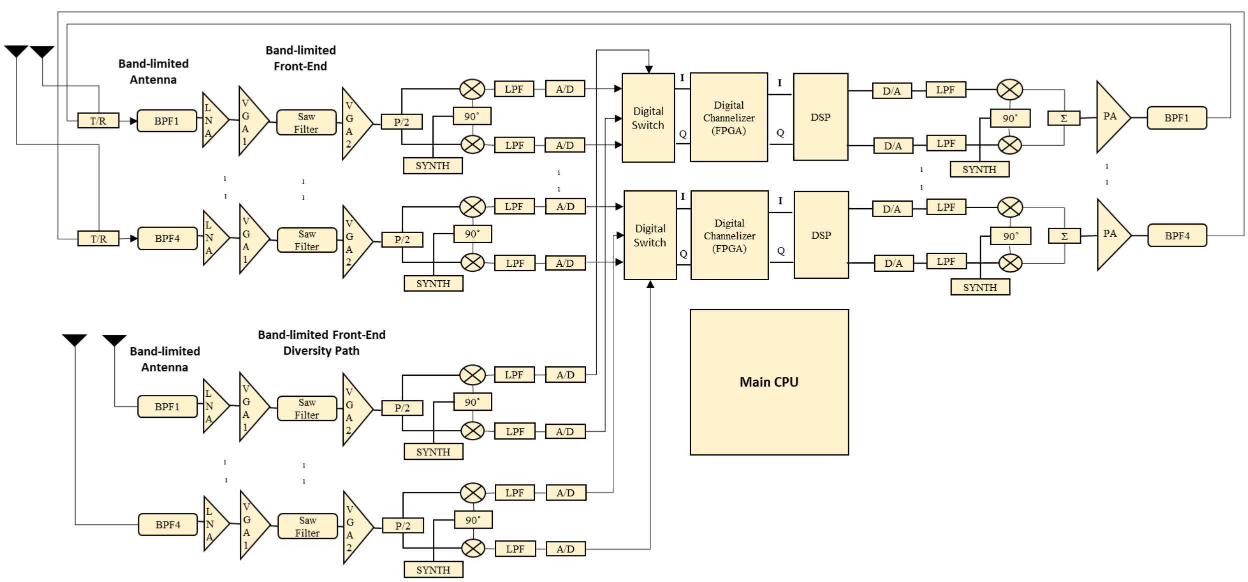


Figure 3-24: Potential band-limited SDR system architecture

A general concern in any system architecture is reliability. In this specific SDR system architecture, failure of one component can lead to a replacement of the entire radio, which can be very costly for maintenance. As a result, TTCI recommends that the band-limited SDR system architecture be modularized to allow soft failures (albeit, not 100 percent fault tolerance) and more efficient maintenance at minimal additional cost by the smart partitioning of hardware as an alternative to adding full redundancy.

Figure 3-25 illustrates a modularized SDR transceiver and Figure 3-26 illustrates one way in which the entire SDR system can be modularized. Note that CPU and FPGA/DSP modules might be combined into one single module or they might remain separate (as shown) with the ability for either CPU module to communicate with either FPGS/DSP module for additional fault tolerance. Also note that all FPGA/DSP hardware modules would be identical and all CPU hardware modules (i.e., primary and secondary) would be identical. All transceiver modules were identical except for their RF center frequencies. If an IF is used, all IF modules can be identical.

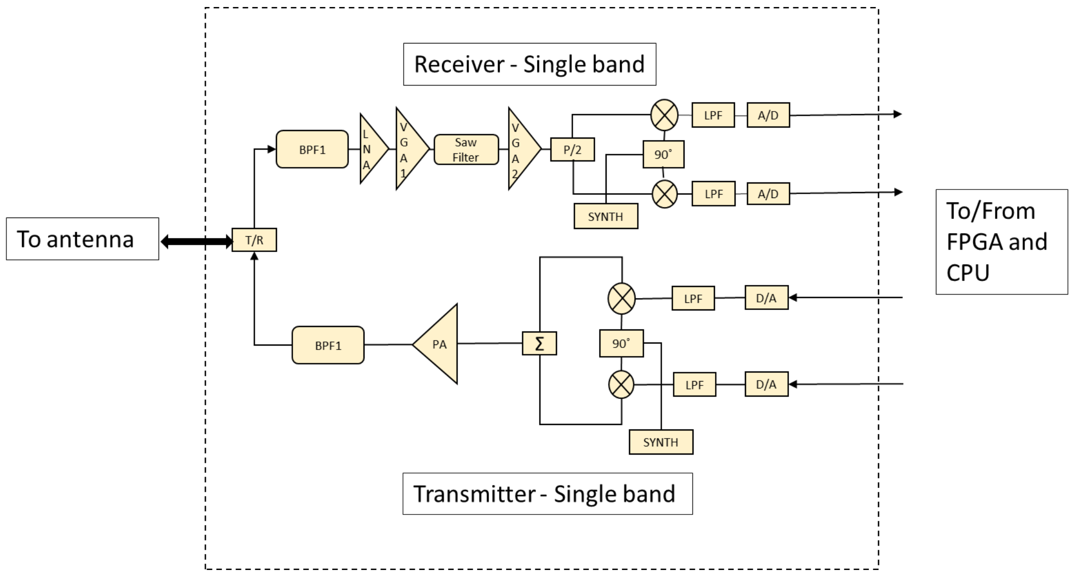


Figure 3-25: Modularized bandlimited SDR transceiver

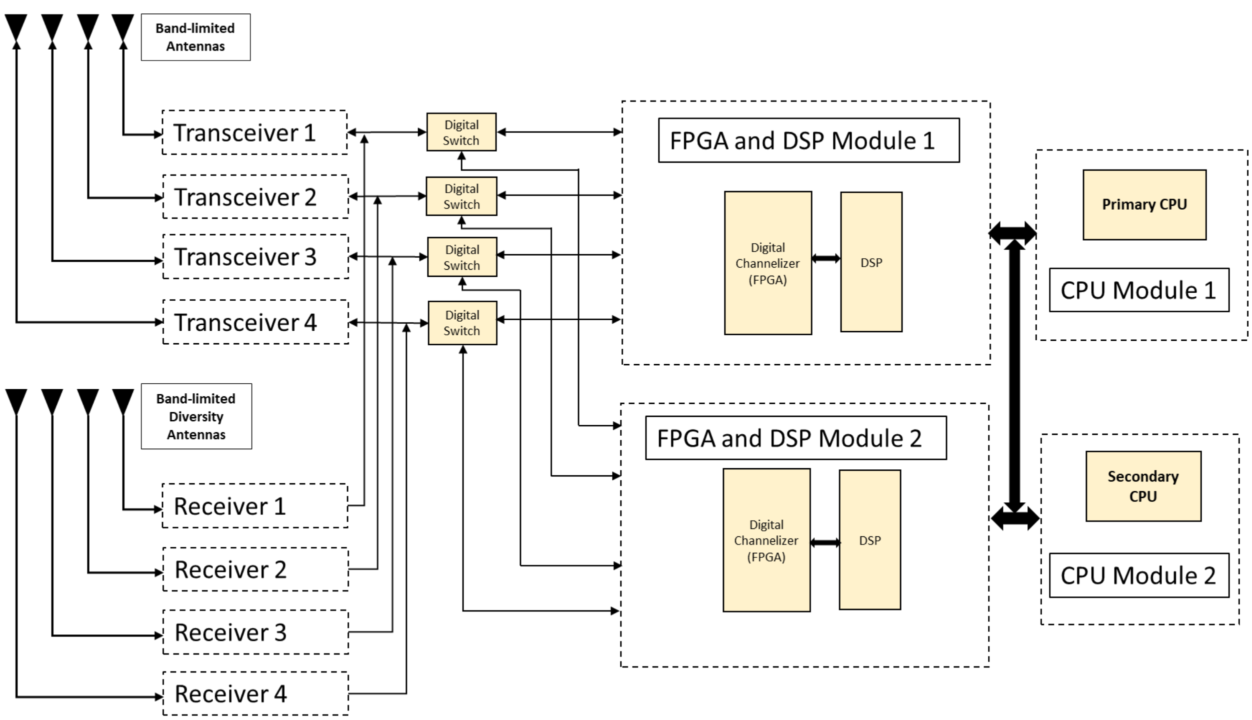


Figure 3-26: Modularized bandlimited SDR system architecture

3.3.2 Quasi-Wideband System Architecture

The quasi-wideband system architecture, as illustrated in Figure 3-27, was developed as an alternative option to the band-limited system architecture. Figure 3-27 shows two nearly identical hardware paths, one per band. For a four-band SDR, four hardware paths would be required. For a single-band SDR, only one hardware path is required.

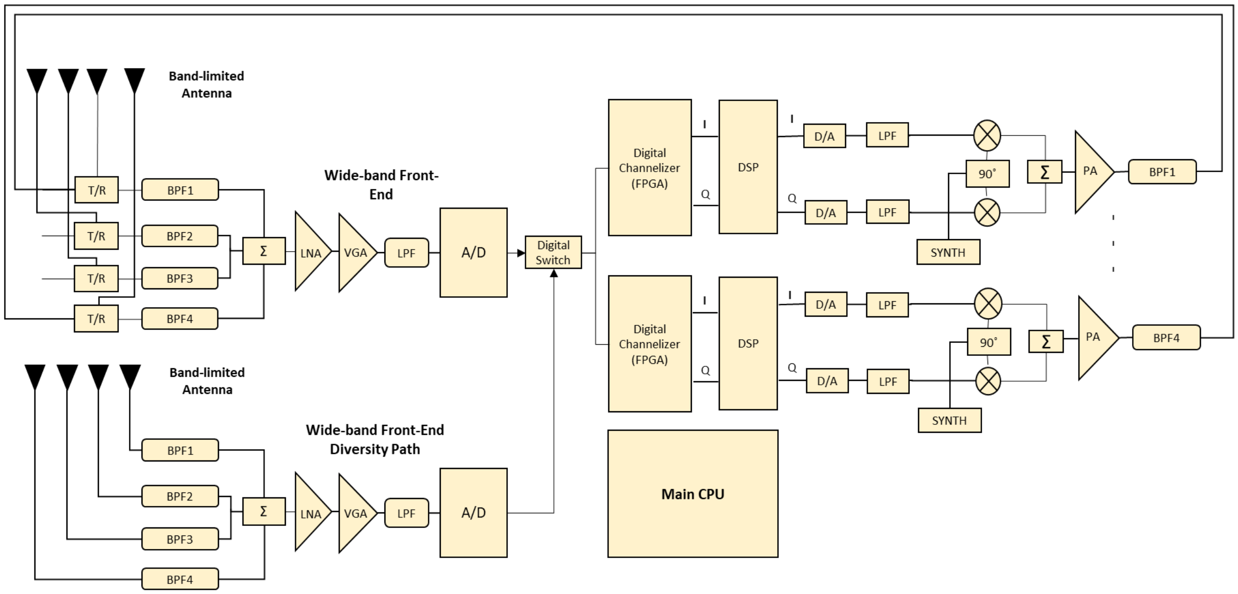


Figure 3-27: Potential quasi-wideband SDR system architecture

Similar to the explanation on modularization for the band limited SDR architecture in Section 3.3.1, the quasi-wideband SDR system architecture can be modularized to allow soft failures and more efficient maintenance at minimal additional cost by smart partitioning of hardware as an alternative to adding full redundancy.

Figure 3-28 illustrates a modularized SDR transceiver and Figure 3-29 illustrates one way in which the entire SDR system can be modularized.

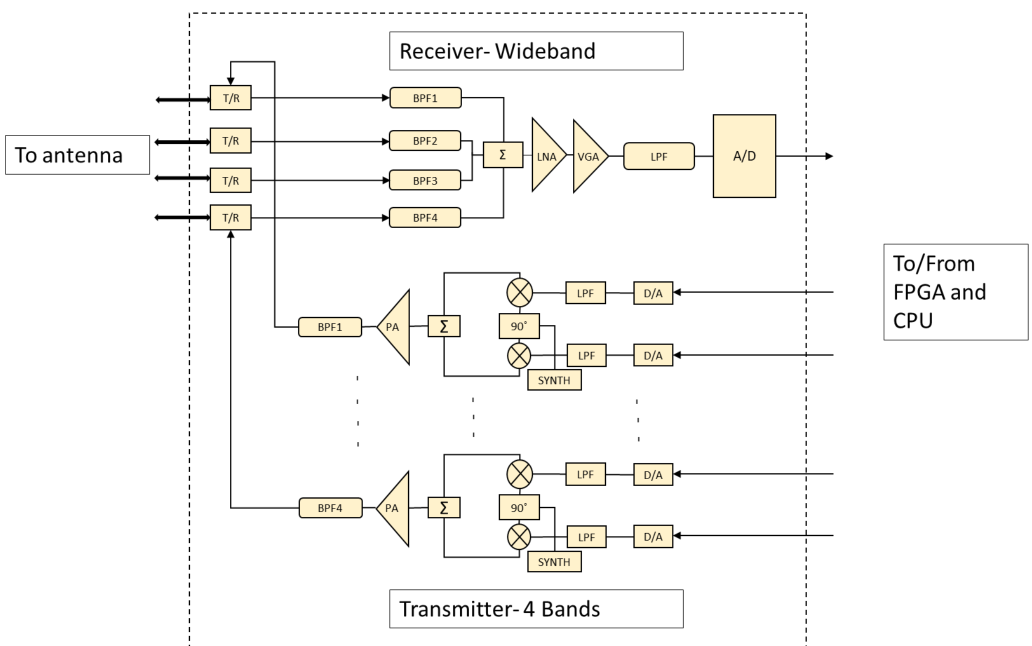


Figure 3-28: Modularized quasi-wideband SDR transceiver

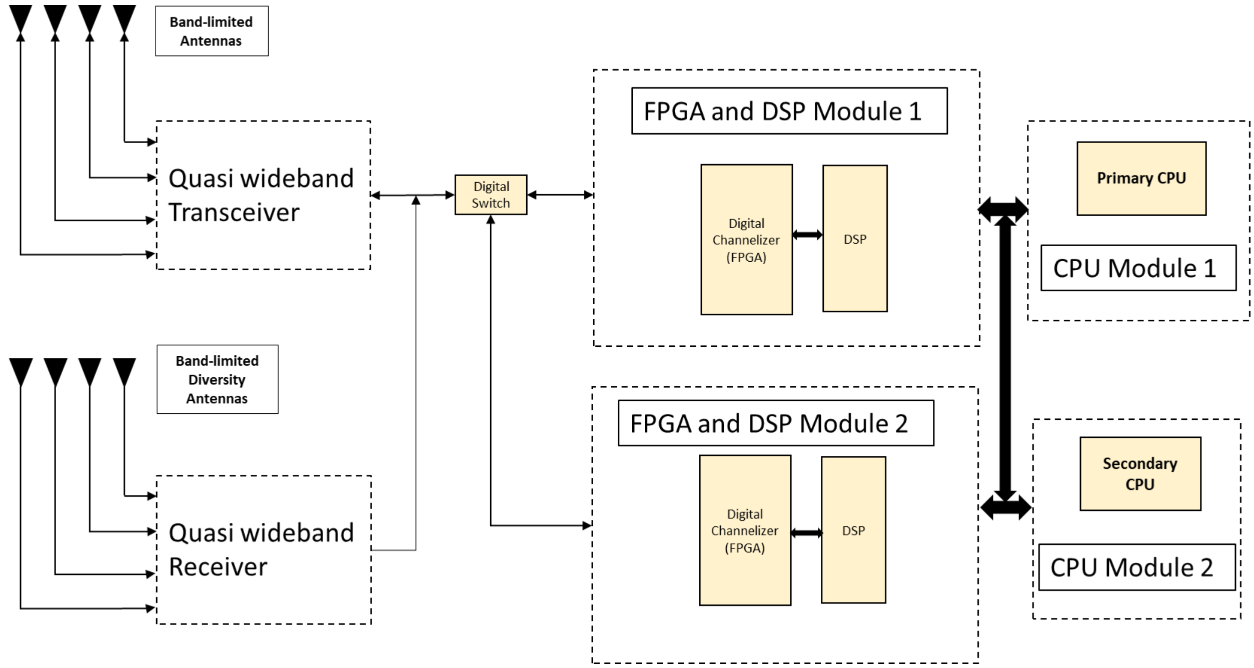


Figure 3-29: Modularized quasi-wideband SDR system architecture

3.4 SDR vs. Dedicated Radios Trade Study

This section explains the trade study developed to compare SDR against the dedicated radios that are currently being used by the railroads.

This trade study was performed only on three railroad platforms—locomotive, base station and wayside. The trade study table consisted of several decision-making criteria which were rated across potential SDR system architectures and dedicated radios. The ratings were given on a scale of 1 to 10; 1 being the worst and 10 the best. Potential radio solutions were judged by their overall score produced at the end of the trade study. The overall scores were color-coded, red being the worst score and green the best, as a visual aid to more easily compare the scores.

Table 17 shows the trade study results for SDR versus dedicated radios.

Table 17: Trade study for SDR versus dedicated radios

Criteria	Dedicated Radio	Band-Limited SDR*	Quasi-Wideband SDR **
Dynamic Modulation, Protocol & Data Rate	2	10	10
Can Add Frequency Bands without HW Modification	0	0	5
Can Add Channels without HW Modification	2	10	10
Supports Carrier Aggregation & Frequency Diversity	2	10	10
Spectrum Sensing (Cognitive)	2	10	10
Supports Antenna Diversity	2	10	10
Availability	3	8	5
Unit Size	5	7	6
Unit Cost (Locomotive)	1	10	5
Unit Cost (Base Station)	7	10	5
Unit Cost (Wayside)	10	5	0
NRE	10	0	0
Total Score (Locomotive)	30	75	71
Total Score (Base Station)	35	75	66
Total Score (Waysides)	45	80	61

* as shown in Figure 4-24; ** as shown in Figure 4-27

Items in the Dedicated Radio column with a rating of 2 were based on the understanding that the existing PTC radio can accommodate these features but dedicated radios for the other four types of platforms (Hi-Rail, Handheld, EOT, UAS) do not.

To summarize, the SDR scored better than dedicated radios across all three platforms, especially the band-limited SDR system. However, railroads should compare the SDR cost estimates, as shown in Appendix C, to the cost of their dedicated radios for the other four platforms to evaluate if SDR implementation would be cost-effective.

4. Technology Survey

This section provides details on surveys performed on different components and technologies to be used in an SDR.

4.1 COTS SDR

One of the first tasks performed on this project was to survey the market to identify commercially available SDRs. TTCI was able to identify and gather specifications for 13 different COTS SDRs from 9 different vendors. TTCI compared the available specifications against the SysRS document to see if any of the COTS SDRs was a close match, if not a complete match.

All 13 COTS SDRs were found to be inadequate regarding one or more of the key system requirements. More specifically, at least one of the key requirements—functional requirements (e.g., ability to support voice communication, RF frequency range, number of simultaneous channels), performance requirements (e.g., adaptive modulation, ADC/DAC resolution), component requirements (e.g., maximum input power level at the receiver) and environmental requirements (e.g., operating temperature range)—was not met by each SDR identified.

To summarize the survey, no COTS SDR was found that would satisfy all, or even a sufficient subset, of the major railroads' requirements. Consequently, development is required.

4.2 Carrier Aggregation

Carrier aggregation (CA) is the process of combining multiple carriers or channels together to increase the overall bandwidth and hence increase the data rate of transmission. Different bandwidth efficient modulation (BEM) schemes may be used to further increase the data rate of transmission. The concept of CA was introduced commercially in 2013 on 4G Long Term Evolution (LTE)-Advanced networks. CA is one of the main features that facilitated LTE-Advanced to truly meet the requirements for 4G such as peak data rates of at least 1 Gbps.

The concept of carrier aggregation is illustrated in Figure 4-1. Each aggregated carrier is referred to as a component carrier (CC) in CA.

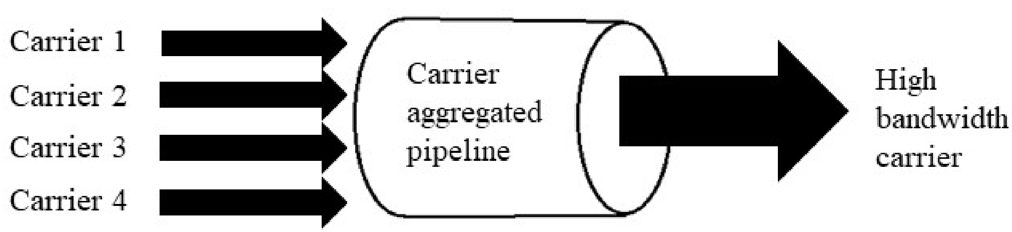


Figure 4-1: Concept of carrier aggregation

There are three types of carrier aggregation:

1. Intra-band contiguous
2. Intra-band non-contiguous
3. Inter-band non-contiguous

In intra-band contiguous CA, CCs, or channels which are adjacent to each other, are aggregated to form a larger bandwidth carrier within the same band. In intra-band non-contiguous CA, CCs not adjacent are aggregated within the same band. And in inter-band non-contiguous CA, CCs from different frequency bands are combined. Figure 4-2 depicts different types of CA.

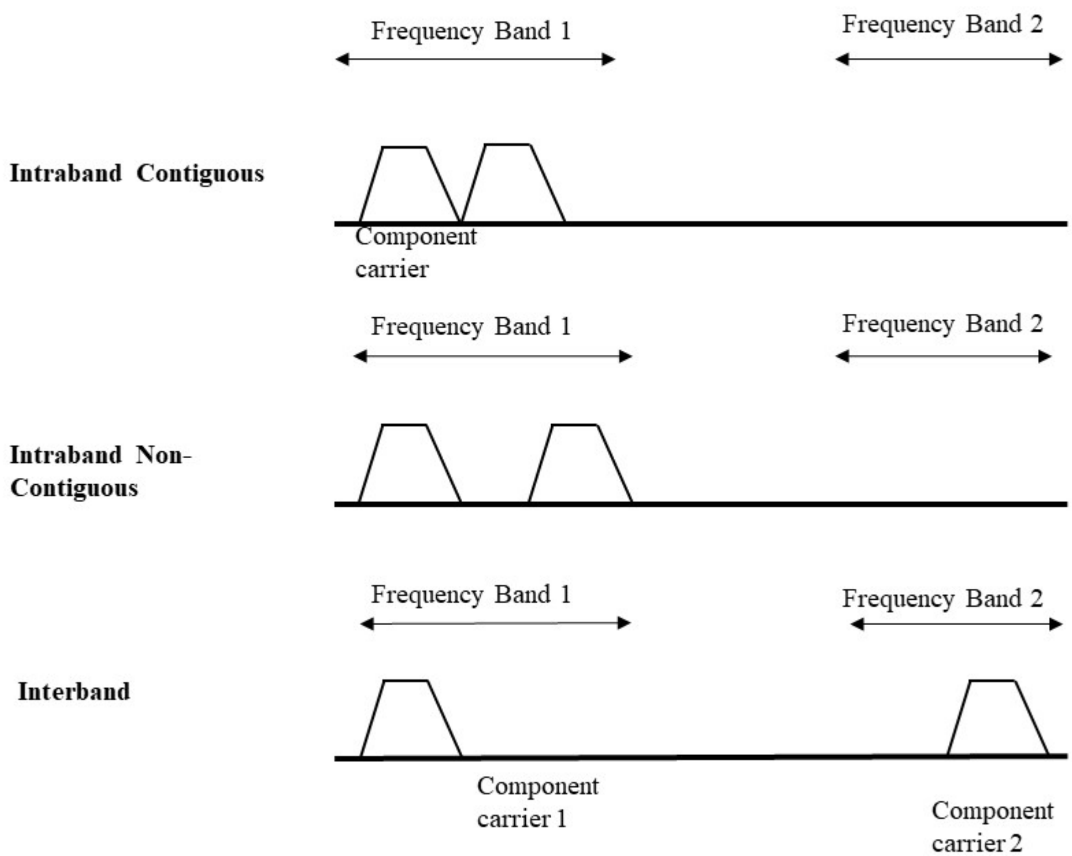


Figure 4-2: Types of Carrier Aggregation

4.2.1 Carrier Aggregation for Railroad SDR

One of the main objectives of the railroad SDR is the efficient utilization of the overall railroad radio spectrum. The unavailability of continuous frequency spectrum in the railroad bands is one of the limiting factors for achieving high data rates. The railroad spectrum is scattered in four bands: 160 MHz, 220 MHz, 450MHz, and 900 MHz. Any unused channels could potentially be aggregated together within the same band or among different bands to form a larger bandwidth carrier to support high data rate applications. Table 18 illustrates the number of available channels and bandwidth, some of which could be aggregated depending upon conditions in the railroad frequency spectrum.

Table 18: Number of available channels and bandwidth in railroad spectrum

Band	Current Application	Total Bandwidth (kHz)	Maximum Contiguous Bandwidth (kHz)	Number of Channels	Channel Bandwidths (kHz)
160 MHz	Voice	1380	1380	92	12.5
220 MHz	PTC	650[1]	75	26	25
220 MHz	RCL	80	40	16	5
450 MHz	EOT/HOT	364.5	75	26	6 kHz/ 11.25 kHz[2]
900 MHz	ATCS	150	0	12	12.5

Notes:

1. The total bandwidth for 220 MHz spectrum also includes regional channels. 450 MHz spectrum.
2. 450 MHz spectrum has channels with bandwidths of 6 kHz and 11.25 kHz.

Frequency spectrum in the 160 MHz band might offer the best opportunity for intra-band carrier aggregation in railroad SDR. The other possibility might be inter-band CA between channels in different bands for the optimal utilization of the frequency resources. Additional spectrum may be acquired by railroads, in which case additional possibilities might exist for CA, e.g., using orthogonal frequency division multiplexing (OFDM).

OFDM is a multi-carrier transmission system in which digital data to be transmitted is encoded in a number of closely spaced multiple carriers that are orthogonal to each other. These closely spaced, narrow signals are called sub-carriers. Because of the orthogonality of the subcarriers, the information can be received without interference. One of the main advantages of using OFDM is immunity to frequency selective fading. If one sub-carrier suffers from fading, then the data can still be recovered from other sub-carriers. The possibility for accommodating OFDM in the SDR is addressed in Section 5, Appendix B, and Appendix C.

4.3 Channelizer

One of the key functions of the railroad SDR is to support multiple channels across multiple bands or within a single band. To perform the task of extracting and isolating the independent communication channels from the wideband signal for follow-on baseband processing, a channelizer is used.

There are various methods used for channelization in SDRs. The method to be used in the SDR must be efficient and require less FPGA area for covering all of the bands or channels within a band. Some of the most popular channelization techniques available are digital down conversion, frequency domain filtering, and polyphase FFT filter banks [2] [3].

4.3.1 Digital Down Conversion (DDC)

DDC is a technique of converting a wideband signal into a baseband signal. This is one of the traditional techniques of channelization. In this technique, the wideband signal may be sampled for analog-to-digital conversion in a way that is analogous to the conventional analog process of being mixed with a locally generated carrier near the carrier frequency of interest. Or the RF signal may be down-converted to complex (I and Q) multi-channel wideband baseband signals. The signal is then converted by the channelizer to individual baseband I and Q channels, each of which is filtered and downsampled to extract a single baseband channel from the wideband signal. Decimation performs the operation of downsampling the signal. Using this method, each channel can be configured independently. If a limited number of channels, non-contiguous and differing in bandwidth, are to be selected from the wideband signal then this method offers a flexible and efficient way for channelization.

The general block diagram of a DDC channelizer is illustrated in Figure 4-3.

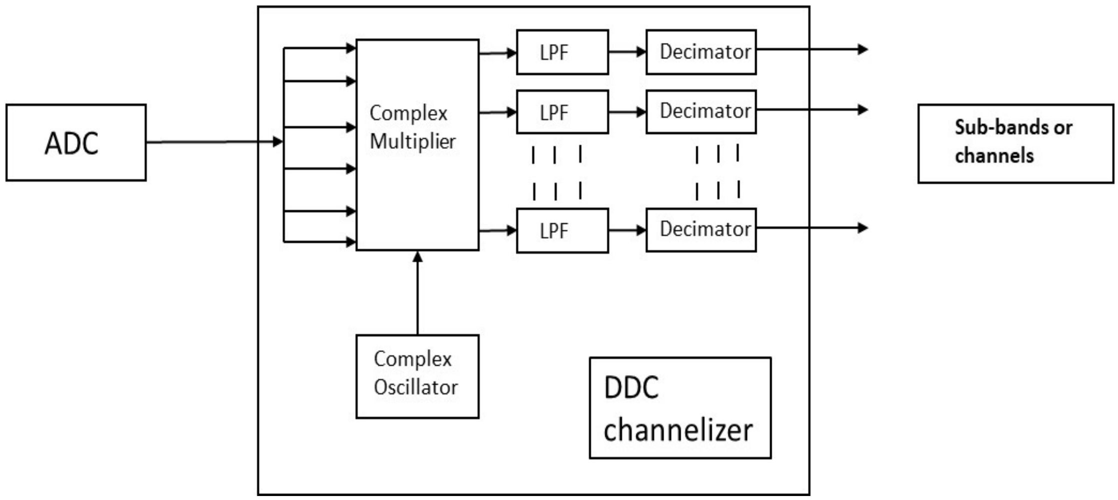


Figure 4-3: General block diagram of DDC channelizer

4.3.2 *Fast Fourier Transform (FFT) Channelizer*

These types of channelizers are the simple and attractive choice for channelization where speed is the main requirement and not performance. An FFT channelizer is a fast implementation of a discrete Fourier transform (DFT). This method of channelization results in significant side lobes in the adjacent channels. The spectral leakage degrades the capability of the receiver to demodulate or detect the weak signals in the presence of the strong interfering signals in adjacent channels. It is particularly suitable for situations in which there are a large number of contiguous, equally-spaced channels without great difference in level between the strongest and weakest channel [4].

4.3.3 *Polyphase FFT Filter Bank (PFFB) Channelizer*

This method is an improvement over FFT-based channelization, utilizing a combination of finite impulse response (FIR) filters and FFT for channelization. A polyphase filter serves as a bandpass filter for each channel to be extracted. A polyphase filtering-based approach overcomes the problem of spectral leakage that is inherent in FFT-based conversion. FIR filters are used for implementation of polyphase filters in the channelizer. The advantage of using an FIR filter is its stability.

The general block diagram of a PFFB channelizer is illustrated in Figure 4-4.

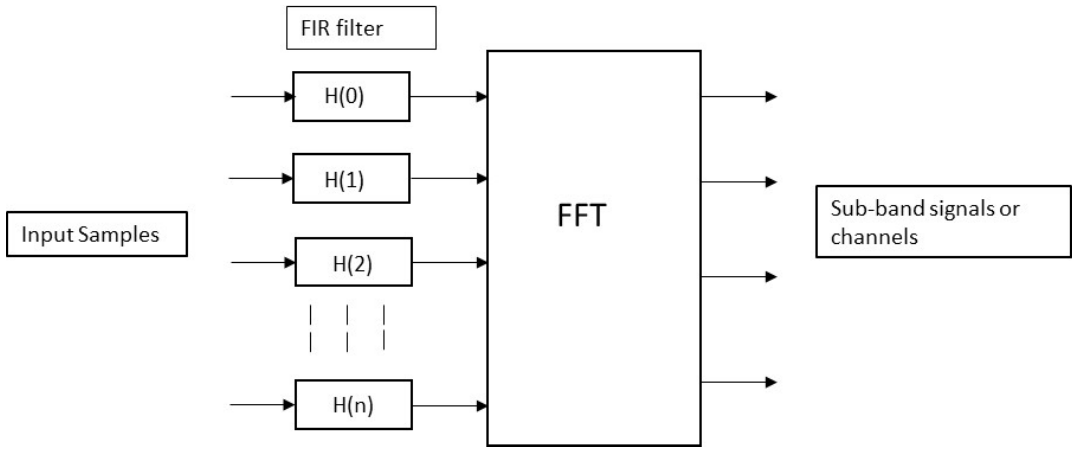


Figure 4-4: Polyphase FFT Filter Bank Channelizer

Since this technique uses FFT for channelization, it is most efficient if the number of channels to be extracted is an integer power of 2. This method is best suited for applications where the number of channels is large and where channels are contiguous and of equal bandwidth.

4.3.4 Selection of Channelizing Technique in Railroad SDR

For selecting a channelization approach for the railroad SDR, the channelization method should be efficient in addressing the following characteristics of channels:

1. The channels to be extracted in the railroad receivers are scattered in four different bands and are not necessarily contiguous in nature.
2. There is a relatively small number of channels to be channelized.
3. The channels are of variable bandwidth.
4. There can be large signals present on nearby channels while needing to receive a weak signal.

DDC was identified as a good approach based on the characteristics of the channels in the railroad SDR. Among all the techniques, DDC is efficient when the required number of channels are few, channels are non-continually distributed, and have differing bandwidths. Another advantage of using the DDC approach over other techniques is the re-configurability of the channels. Addition or removal of channels can be easily done using the DDC approach.

Note, however, that DDC is an appropriate preliminary choice for the objectives of this project. The number of channels to be demodulated in the locomotive and base station SDRs is near the threshold of what is optimal for DDC versus PFFB. It is beyond the scope of this project to make the final implementation decision on the type of channelizer. The general conclusions of the project should be largely unaffected by this choice.

4.3.5 Implementation DDC Channelizers using FPGA

DDC channelizers can be implemented in an FPGA using very high speed integrated circuit hardware description language (VHDL). VHDL is an IEEE standard and is used for describing the behavior and structure of electronic circuits [5].

Xilinx and Altera are two major FPGA suppliers, based on market share. There are several FPGAs available in the market for selection based on the number of configurable logic blocks

(CLB) for DDC operation. A CLB is the fundamental component in Xilinx FPGAs for performing combinational and sequential operations. In Altera's FPGA, logic array block (LAB) is the equivalent of CLB. A large FPGA, like Xilinx XC2V6000, can support approximately six wideband DDC channels or eighteen narrowband DDC channels simultaneously. Table 19 shows the approximate number of wideband and narrowband DDC channels that can be supported by the specified Xilinx and Altera FPGA devices based on the number of CLBs [3].

Table 19: Number of wideband and narrowband DDC channels supported by FPGAs

Manufacturer	FPGA Model	Number of wideband DDC channels supported (approximate)	Number of narrowband DDC channels supported (approximate)	LAB/CLB
Xilinx	XC2V6000	6	18	8,448
Xilinx	XC5VSX95T-2FF1136I	5	15	7,360
Altera	Arria II GX-EP2AGX190EF29C6N	5	16	7,612
Altera	Cyclone III -EP3C120F484I7N	5	15	7,443

Across all SDR platforms and all railroad frequency bands, the maximum number of channels that need to be simultaneously transmitted and received by a single SDR are 4 and 26, respectively, which are mostly narrowband in nature. According to requirement (f) in Section A3 of Appendix A, the SDR shall be capable of simultaneously transmitting and receiving signals that are asynchronous with one another in different bands.

Assuming that the SDR satisfies the above requirement, at a maximum the railroad SDR will simultaneously transmit and receive a total of only 26 channels and not 30 channels. As a result, two counts of any one of the FPGAs shown in Table 19 are sufficient to implement a DDC channelizer. However, due to cost sensitivity of the SDR implementation, the lowest cost option among the candidates shown in Table 19, Altera's Cyclone III -EP3C120F484I7N, was selected as the baseline for the SDR trade studies.

4.4 SDR Components

SDR components can be divided into analog and digital parts. Analog components include antennas, preselect filters, low noise amplifiers (LNAs), variable gain amplifiers (VGAs), bandpass filters (BPFs), low pass filters (LPFs), and power amplifiers (PAs). Digital components include the field programmable gate array (FPGA), the digital signal processor (DSP), and main central processing unit (CPU). Analog-to-digital converters (ADC) and digital-to-analog converters (DAC) are used as conversion devices.

Figure 4-5 illustrates the categorization, as explained in the paragraph above, of SDR components.

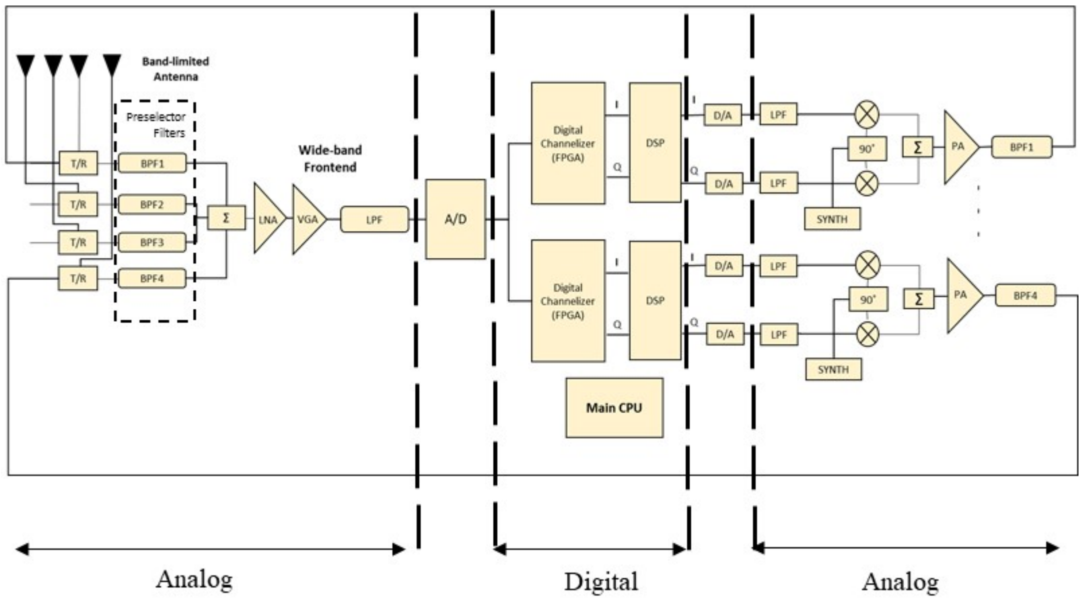


Figure 4-5: Potential SDR architecture design showing DDC channelizer

An intensive component technology survey was carried out to identify COTS components suitable for implementing a railroad SDR. An RFI was issued for each component for which no commercially available option met the requirements for the railroad SDR. Design proposals and pricing quotes were collected from the equipment manufacturers and this information was used in identifying the preferred potential architectures feasible for implementation in the railroad SDR.

In some cases, the component considered for the trade study purposes of this project did not precisely meet every requirement (e.g., exact center frequency or bandwidth), but was close enough that it was reasonable to assume a similar component could be obtained to meet the exact requirements at the time an actual railroad SDR might be designed.

Multiple components and sources were found for each component to avoid the possibility of using outlier data. Costs were typically averaged among the multiple candidates for each required component. Appendix C shows deatiled costs estimates for all the components listed in this section.

4.4.1 Analog Front End

Components in the analog front end were selected to optimize compliance with requirements developed in the front-end component requirement section.

Table 20 lists all the COTS products considered for receiver front end.

Table 20: COTS products for receiver front end

Manufacturer	Component type	Part number	Frequency range (MHz)
Sinclair	Preselector filter	FP20401B-2-1	150-160
Sinclair	Preselector filter	FP20401B-4-1	220-222
STI-CO	Preselector filter	FILT-NB-UHF-COM	450-460
Sinclair	Preselector filter	FP30401B-2-1	440-470
PMI	Preselector filter	8C937D8375-10-CD-SFF	937.8375 (center frequency)
Sinclair	Preselector filter	PH4060C-3	898.5 (center frequency)
Analog Devices	LNA	HMC639ST89 / 639ST89E	0.2-4,000
Analog Devices	LNA	HMC599ST89	50-1,000
MACOM	LNA	MAAL-011136	45-1,218
Microsemi	SAW filter	TFS 456AL	446.75-465.25
Microsemi	SAW filter	TFS 935	929-941
API Technologies	SAW filter	SF0943BA02541S	925-960
Analog Devices	VGA	ADL5330	10-3,000
Analog Devices	VGA	HMC742ALP5E	70-4,000

4.4.2 IQ Modulator and Demodulator

Table 21 lists all the COTS components considered for the IQ modulator and IQ demodulator. The components were selected based on the operating frequency range.

Table 21: COTS products for IQ modulator and demodulator

Manufacturer	Component type	Part number	Frequency range (MHz)
Analog Devices	IQ modulator	ADL5386	50-2,200
Analog Devices	IQ modulator	HMC1097LP4E	100-6,000
Analog Devices	IQ modulator	AD8345	140-1,000
Linear Technologies	IQ modulator	LTC5599	30-1,300
Linear Technologies	IQ modulator	LTC5598	5-1,600
Texas Instruments	IQ modulator	TRF3701	140-1,500
Texas Instruments	IQ modulator	TRF370417	50-6,000
Analog Devices	Synthesizer/LO	ADF4351	35-4,400
Integrated Device Technology	Synthesizer/LO	8V97051	35-4,400
Texas Instruments	Synthesizer/LO	LMX2581	50-3,760
Analog Devices	IQ demodulator	AD8348	50-1,000
Analog Devices	IQ demodulator	AD5387	30-2,000
Analog Devices	IQ demodulator	ADRF6850	100-1,000
Linear Technology	IQ demodulator	LTC5584	30-1,400
Mini Circuits	Low pass filter	SALF-78	0-100
Analog Devices	Low pass filter	HMC1023	0-72

4.4.3 Data Converters

ADCs and DACs were selected based on dynamic range and sampling rate to satisfy the Nyquist sampling rate.

Table 22 and Table 23 lists all the COTS products considered for data converters.

Table 22: COTS products for DAC

Manufacturer	Component type	Part number	Update rate (MSPS)	Bit resolution (bits)
Texas Instruments	DAC	THS5661AIPW	125	12
Texas Instruments	DAC	DAC38RF97	6,000	14
Texas Instruments	DAC	DAC904E	200	14
Texas Instruments	DAC	DAC900	165	10
Analog Devices	DAC	AD9780	500	12
Analog Devices	DAC	AD9706BCPZ	175	12

Table 23: COTS products for ADC

Manufacturer	Component type	Part number	Sample rate (MSPS)	Bit resolution (bits)
Texas Instruments	ADC	ADC3244	125	14
Texas Instruments	ADC	ADS4229	250	12
Texas Instruments	ADC	ADS42JB49	250	14
Analog Devices	ADC	AD9250-250	250	14
Texas Instruments	ADC	ADC32RF42	1,500	14
Analog Devices	ADC	AD9691	1,250	14
Analog Devices	ADC	AD9208	3,000	14
Texas Instruments	ADC	ADC32RF45	3,000	14

4.4.4 Digital Components

Digital components comprise FPGAs, DSP and the CPU. Table 24 lists all the COTS products cosnidered for digital components.

Table 24: COTS products for FPGA, DSP and CPU

Manufacturer	Component type	Part number
Intel/Altera	FPGA	EP3C25F256I7N Logic Cells: 25K
Intel/Altera	FPGA	EP3C120F484I7N Logic Cells: 120K
Texas Instrument	DSP	TMS320C6747DZKBA3
DSP Board		
Cypress	Flash	S29GL128P90TFIR10
Cypress	Flash	S29GL128P90TFIR10
Micron	RAM	MT46H32M16LFBF-6 AAT
CPU		
NXP Semiconductors	Main CPU	Coldfire MCF54455 Evaluation board

4.4.5 Request for Information for SDR Components

COTS components available in the current market didn't meet the requirements for transmitter back-end components, such as power amplifiers and filters. As a result, multiple RFIs were issued to several equipment manufacturers to obtain budgetary prices for developing PAs and filters that meet the requirements mentioned in Appendix B. Due to the proprietary nature of the quotes provided by the vendors, individual vendor pricing is not shown.

Table 25 shows the manufacturers that provided quotes in response to RFIs issued by TTCI.

Table 25: Manufacturers that provided quotes for RFIs issued for PAs and filters

Manufacturer	Component
dbSpectra	Filters
Empower RF	Power amplifier
Excelwave Technologies	Filters
Infinte Electronics	Power amplifier and filters
RFS World	Filters
Triad RF	Power amplifier

5. SDR Component Requirements

5.1 Power Amplifier

The power amplifier (PA) is one of the main components in the SDR transmitter and generally the most expensive portion of the entire SDR. Power amplifiers are used to amplify signals to a required level, before transmission through an antenna into the air, to compensate for the propagation loss between transmitter and receiver. Under small signal conditions, amplifiers may operate as a linear device. But under typical high-power configuration approaching the maximum output level, amplifiers generally become nonlinear. [6]

There were two implementations of power amplifiers (PAs) in the proposed architectures: a wide-band implementation and a band-limited implementation.

The wideband PA must be able to operate in all four bands simultaneously to support BEM schemes. Below is the list of bands proposed for the railroad SDR:

- 160-162 MHz
- 219.5-222 MHz
- 450-460 MHz
- 896-890 MHz

The alternative to a wideband PA is to provide a separate, single-carrier PA for each of the four bands. Requirements for both designs (wide-band versus four band-limited PAs) have been developed.

To support high data rate applications in the architectures, the need for BEM schemes is essential. The proposed PAs must be able to operate linearly and efficiently for the below-listed modulation schemes:

- Π/4-shifted differential quadrature phase shift keying (DQPSK) (minimum requirement)
- 64-quadrature amplitude modulation (QAM) (preferable)
- OFDM (preferable)

The higher-order modulations (64-QAM and OFDM) allow a significantly higher data rate for a given channel bandwidth than Π/4-shifted DQPSK, but they require greater linearity. This makes the PA considerably more expensive for the higher-order modulations. This issue is further compounded by the fact that the higher-order modulations require greater E_b/N_o (the ratio of energy per bit (E_b) to the spectral noise density (N_o)) for the same bit error rate performance as Π/4-shifted DQPSK at a given range. For this reason, requirements were developed for two different versions of the PA, depending upon whether the highest order of modulation supported by the SDR is to be OFDM or just Π/4-shifted DQPSK. In both cases, the PA was designed to accommodate the same average output power. The need for increased linearity was considered, but not the need for a higher E_b/N_o. That choice was made because the increase in cost, size, weight, and power consumption of the PA is so significant (to accommodate the higher linearity requirement of OFDM), that the higher E_b/N_o requirement might be accommodated by designing the network for shorter range, rather than further increasing the PA output power level.

There were two main challenges in selecting the right PA for implementation in SDR:

- Peak-to-average power ratio (PAPR)

- Intermodulation distortion (IMD)

5.1.1 Peak-to-Average Power Ratio

With higher-order modulation schemes comes the challenge of accommodating PAPR, a crucial factor in defining linearity for a PA. PAPR is defined as the ratio between maximum power and the average power of the signal envelope. PAPR is different for different modulation schemes, as presented in Table 26. For sufficiently linear operation, PAs typically need to operate with some back-off or headroom from the 1 dB compression point (P1dB) The amount of back-off required is determined by the PAPR of the modulation scheme and the nonlinear characteristic of the PA near its peak output level. P1dB indicates the power level that causes the gain of the amplifier to drop by 1 dB from the normal linear gain. If the input power is increased much beyond P1dB, then the amplifier goes into saturation with no further increase in output power.

Table 26 illustrates various requirements for the PA based on different modulation schemes.

Table 26: PAPR and P1dB requirement per band

Modulation	PAPR (dB)	Peak Power for a 20W Avg. Signal (Watts) - Locomotive	Required Minimum PA Output P1dB (Watts) - Locomotive	Peak Power for a 30W Avg. Signal (Watts) - Base Station	Required Minimum PA Output P1dB (Watts) — Base Station
Π/4 DQPSK	3.8	50	50	75	75
OFDM	10	200	200	300	300

For the composite signal, with signals in all four bands transmitted simultaneously, the headroom requirement of the PA increases, as illustrated in Table 27 [1].

Table 27: PAPR and P1dB requirement for composite signals

Modulation	PAPR (dB)	PAPR for composite signal (dB)	Number of carriers in composite signal	Avg. power per carrier (W)	Total avg. power of composite signal (W)	Total avg. power of composite signal (dBm)	P1dB of PA (dBm), minimum, with back-off
Π/4 DQPSK	3.8	6	4	30	120	51	57
OFDM	10	13	4	30	120	51	64

5.1.2 Intermodulation Distortion

Another factor affecting the performance requirements for the wideband PA is intermodulation distortion (IMD). IMD signals are generated in non-linear devices because of the multiplication products that result when two or more signals of different frequencies simultaneously pass through the device. For the four railroad bands, the most severe IMD products affecting the performance of the system are the third-order intermodulation products located at frequencies (2f1-f2) and (2f2-f1), where f1 and f2 are carrier frequencies. In the proposed wideband transmit architecture, the interaction between signals at 219.5 MHz and 896.8875 generated an IMD product at 457.8875 MHz. If the SDR is implemented with a wideband PA, IMD products fall within the passband and can therefore affect signal reception in the 450-460 MHz band.

Figure 5-1 illustrates the potential IMD product generated by a wideband PA.

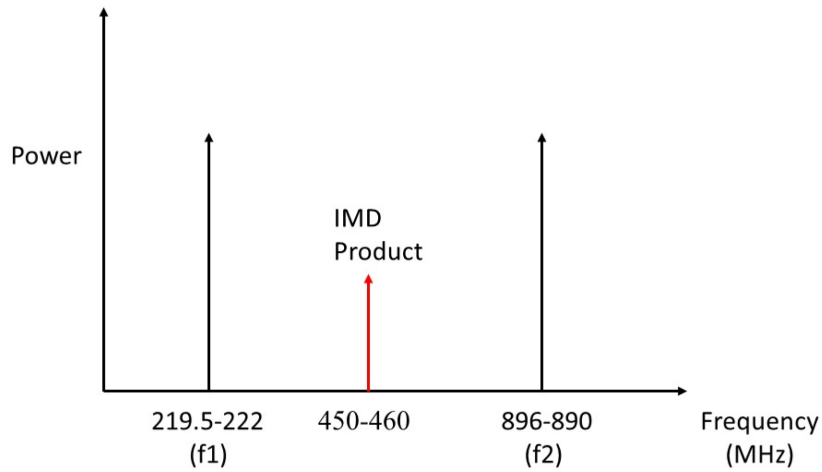


Figure 5-1: Potential IMD product generated by a wideband PA in 450-460 MHz band

The maximum acceptable level of this IMD product in the receiver at 450 MHz frequency band is calculated to be approximately -90dBm.

P_n = thermal noise power in radio front end in the bit rate bandwidth
P_i = power level of IMD product at 450 MHz at PA output
P_{ir}= power level of IMD product in receiver input
Assume,
The typical noise figure (NF) of a 450 MHz radio is around 5 dB
The bit rate of the typical 450 MHz railroad radio is 9,600 baud
Isolation of T/R switch when in R position is typically around 50 dB
Then:
$P_n = -174$ dBm/Hz + NF + 10 log (9,600) = -174 + 5 + 39.8 = -129.2 dBm
P_{ir} should be at least 10 dB lower (e.g., -140 dBm) to minimize degradation of radio performance caused by IMD
Pi must be less than -140 dBm + 50= -90 dBm

5.1.3 PA requirements Based on PAPR and IMD

Taking into consideration the PAPR and IMD issues, requirements for a wideband PA and band-limited PA for Π/4 DQPSK and OFDM modulation schemes are presented in Appendix B.

From the calculation presented in Section 5.1.2, the IMD requirement for a wideband PA that simultaneously handles all four railroad bands is extremely difficult to meet. Based on the feedback and responses from the equipment vendors, IMD requirements for wideband PA can't be met, which makes the wideband PA impractical for implementation in transmit architectures. Note that IMD products can be produced in any nonlinear device, not just the PA. If there is a poor connection anywhere between the PA and the antenna, IMD products may result. So even if a sufficiently linear wideband PA could be affordably produced, the IMD problem can still occur. This problem can be avoided by using a separate PA for each of the four bands.

5.2 Filters

In the proposed SDR architectures, requirements for two types of transmit filters were presented:

- Wide-band transmit filter
- Band-limited transmit filter

Wide-band filters cover all four bands for the simultaneous transmission of signals, whereas band-limited filters provide filtering for transmission in individual bands. Both wide-band and band-limited architectures are developed to support in-band full duplexing in 900 MHz for the base station SDR.

Figure 5-2 illustrates the block diagram of a base station wide-band filter.

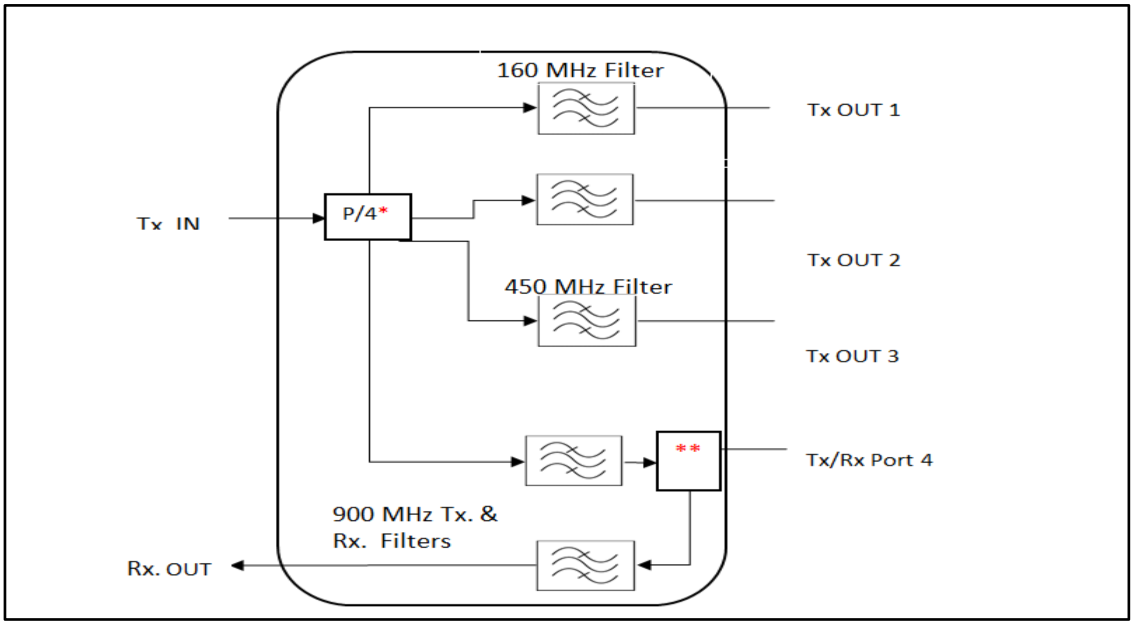


Figure 5-2: Wide-band filter configuration in base station platform

For more details on the requirements developed for transmit filters for the locomotive and base station platforms, refer to Appendix B.

5.2.1 Requirements for Base Station Receive Filter in 900 MHz Band

A cellular base station transmitting in 869-894 MHz might interfere with the railroad receivers operating in 896-898 MHz frequency. Therefore, sufficient filtering must be provided on the 900 MHz receiver's front end to attenuate the signals from the cellular base which is 2 MHz from railroad frequencies. For this, a requirement for 35 dB of attenuation was assumed. Further study may be required to refine this requirement.

Apart from cellular band signal rejection, to avoid being desensed, the 900 MHz receiver must be able to reject signals from all other railroad bands that can be transmitted from the same platform. The other potential interfering frequencies are 44-45 MHz, 160-162 MHz, 217-222 MHz, 450-460 MHz, and 935-937 MHz. The desense threshold for a high quality receiver is typically on the order of -20 dBm. The worst case situation could have 75 watts (48.75 dBm) entering the receiver from a collocated transmitter operating on one or more of the other railroad bands. Therefore, the total isolation required in the receiver from other bands is 68.75 dBm, and with 6 dB of margin, the stopband attenuation proposed in receive filter for 900 MHz band is 75 dB.

5.3 Receiver Front End

The receiver front end is one of the critical subsystems in an SDR. This analog subsystem must be able to successfully process the signals received by the antenna for demodulation and further processing at baseband.

The front-end design is developed to support direct down-conversion of the RF signals as well as to support direct RF processing of the signals. Careful selection of the components needs to be done to preserve the information contained in the signals.

Selectivity, sensitivity, compression point, and dynamic range are the main concerns while designing the front end of the SDR receiver. Selectivity of a receiver is defined as the ability of a receiver to select only the desired signals while rejecting the unwanted signals from the overall spectrum. Sensitivity of a receiver determines the weakest signals that can be received and demodulated by the receiver.

Preselect filters, LNAs, and VGAs are the primary components used in the front end of the SDR. Preselect filters or preselectors are band pass filters used to filter out unwanted signals coming in from the antenna into the receiver. VGAs are used to provide an optimal fixed output level to the circuitry following it.

Below are the factors taken into consideration for developing requirements and for the selection of components in the front end of SDR receiver:

- The overall noise figure in the receiver chain
- The power level of the desense signal at every stage in the front-end

A spreadsheet (a snapshot of which is illustrated in Table 28) was developed to select and refine the components used in the front-end of the receiver based on requirements for gain, dynamic range, compression point, and noise figure (NF).

Table 28: Band-limited receiver front-end design calculations

		Different stages in receiver front end									Dynamic Range
		Filter1		**LNA**		**VGA1**		**Filter2**		**VGA2**	
		Component Specifications (from datasheet)									
Gain, Maximum (dB)		-2.2		13		12		-3		23	89.5
Gain, Minimum (dB)		-2.2		13		-19.5		-3		-35	
Noise Figure (dB)		2.2		2.5		4.5		3		7.8	
Attenuation stop band (dB)		55						60			
P1dB (output) (dBm)				21		21.5					
P1dB (input) (dBm)	43.01		8		9.5		0		-0.3		
Max. Operating Received Inband Signal (dBm)	0		-2.2		10.8		22.8		19.8		
Max. Operating Received Out-of-Band Signal (dBm)	48.75		-8.45		4.55		16.55		-46.45		
		Linear values [10^(dB/10)]									
Gain, Maximum (linear)		0.60		19.95		15.85		0.50		199.53	
Noise Figure (linear)		1.66		1.78		2.82		2.00		6.03	
		Product of gain in succeeding stages									
Gain, Maximum		0.60		12.02		190.55		95.50		19054.61	
		Noise factor in cascade using Friis formula									
Noise Figure (NF)		1.66		2.95		3.10		3.11		3.16	
		Cascade gain and noise figure in dB									
Gain (dB)		-2.2		10.8		22.8		19.8		42.8	
NF (dB)		2.2		4.7		4.92		4.92		5.0	
Max Receiver In-Band Input Level at which Signal Input to Individual Components Exceeds P1dB (dBm)	43.01		10.2		-1.3		8.7		11.4		
Max Input Level, Out-of-Band (dBm)	57		65.2		53.7		63.7		126.4		

Similarly, design considerations for the wideband RF front end is shown in Table 29.

Table 29: Wideband RF front-end design calculations

		Different stages in receiver front-end									Dynamic Range
		Filter1		LNA		VGA1		Filter2		VGA2	
		Component Specifications (from datasheet)									
Gain, Maximum (dB)		-2.2		13		12		-3		23	89.5
Gain, Minimum (dB)		-2.2		13		-19.5		-3		-35	
Noise Figure (dB)		2.2		2.5		4.5		3		7.8	
Attenuation Stop Band (dB)		55						60			
P1dB (output) (dBm)				21		21.5					
P1dB (input) (dBm)	43.01		8		9.5		0		-0.3		
Max. Operating Received Inband Signal (dBm)	6		3.8		16.8		28.8		25.8		
Max. Operating received out-of-band signal (dBm)	53.52		-3.68		9.32		21.32		-41.68		
		Linear values [10^(dB/10)]									
Gain, Maximum (linear)		0.60		19.95		15.85		0.50		199.53	
Noise Figure (linear)		1.66		1.78		2.82		2.00		6.03	
		Product of gain in succeeding stages									
Gain, Maximum		0.60		12.02		190.55		95.50		19054.61	
		Noise factor in cascade using Friis formula									
Noise Figure (NF)		1.66		2.95		3.10		3.11		3.16	
		Cascade gain and noise figure in dB									
Gain (dB)		-2.2		10.8		22.8		19.8		42.8	
NF (dB)		2.2		4.7		4.92		4.92		5.0	
Max Receiver In-Band Input Level at which Signal Input to Individual Components Exceeds P1dB (dBm)	43.01		10.2		-1.3		8.7		11.4		
Max Input Level, Out-of-Band (dBm)	57		65.2		53.7		63.7		126.4		

Tables 28 and 29 above analyze the following cases for both wideband and bandlimited front-ends:

- Overall noise figure of the cascaded components
- Power level of signals propagating in different stages of the front end.
- Maximum receiver in-band and out-of-band input level to individual components to check if this power level exceeds 1 dB compression point (P1 dB) of that component.
- Dynamic range

5.3.1 Overall Noise Figure of the Front End

The noise figure of a device is a measure of how the signal-to-noise ratio is degraded by that device. It is expressed in decibels (dB). The overall noise figure of the cascaded system is calculated using the Friis formula:

Ftotal=F1 + (F2-1)/(G1)+(F3-1)/(G1G2)+(F4-1)/(G1G2G3)
Where, Ftotal (dB)= Overall noise figure of cascaded components
F1 (dB)= Noise figure of component 1
G1 (dB)= Gain from component 1

Table 28 and Table 29 are optimized by selecting COTS components to keep the overall noise figure no greater than 5 dB.

5.3.2 Maximum Desired In-Band Signal Received at Locomotive

The maximum level of the desired in-band signal is specified as 0 dBm based on the calculation of received signal strength indicator (RSSI) in the locomotive using a free space path loss (FSPL) model. Table 30 presents the list of parameters used for calculation of received signal power at a locomotive. Table 31 shows the received power at the locomotive as a function of the horizontal distance between the locomotive and the base station, and the angle of departure from the base station. The vertical radiation pattern of a typical PTC base station antenna is illustrated in Figure 5-3.

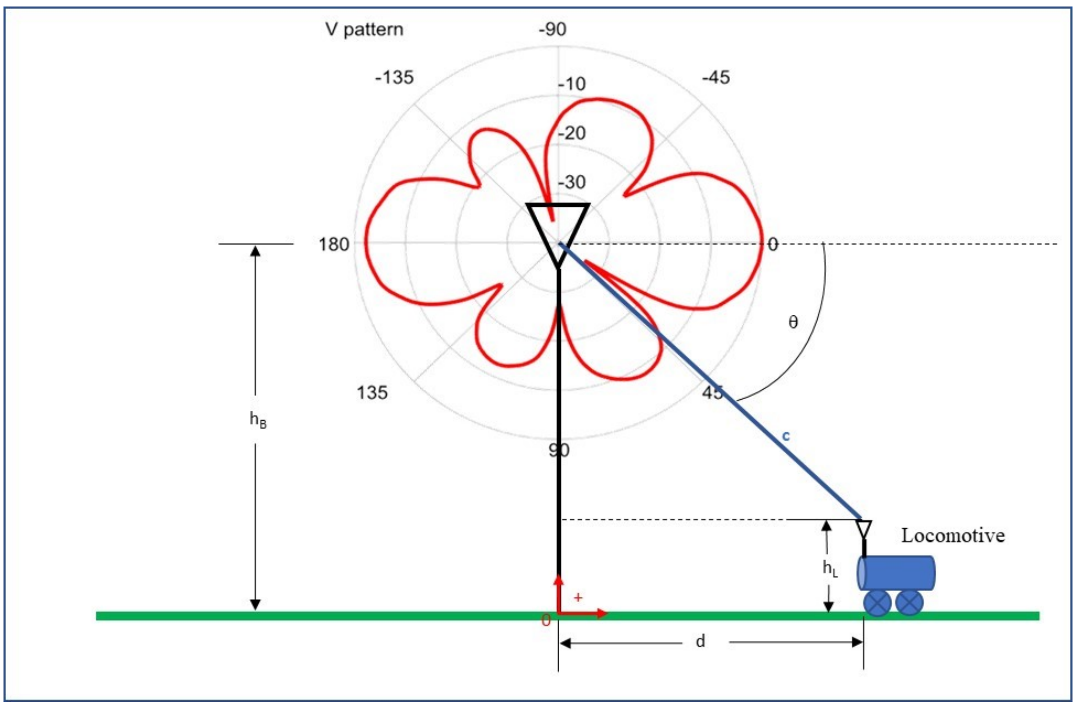


Figure 5-3: Base station antenna vertical radiation pattern

Table 30: Parameters used for calculation of received power at locomotive

Parameters	Value	Unit
Height of base antenna (h_B)	75	ft
Height of locomotive antenna (h_L)	17	ft
Base station peak EIRP	53.9	dBm
Locomotive antenna gain	2.1	dB
Locomotive losses	2.5	dB
Frequency	220	MHz

Table 31: Received peak power at locomotive

Horizontal distance from locomotive to base station (d) (ft)	Θ (degrees)	Antenna gain at Θ (dB)	Distance base antenna-loco antenna (c) (ft)	Peak received power at the locomotive (dBm)
-2000.00	178.34	-2.40	2000	-23.89
-1980.00	178.32	-2.40	1980	-23.81
-380.00	171.32	-3.30	384	-10.47
-370.00	171.09	-3.30	374	-10.24
-360.00	170.85	-3.30	364	-10.01
-350.00	170.59	-3.30	354	-9.77
-340.00	170.32	-3.50	344	-9.72
-330.00	170.03	-3.50	335	-9.47
-320.00	169.73	-3.50	325	-9.21
-170.00	161.16	-6.80	179	-7.36
-160.00	160.07	-7.40	170	-7.49
-110.00	152.2	-13.40	124	-10.76
-100.00	149.89	-15.60	115	-12.33
-70.00	140.36	-24.20	90	-18.84
-50.00	130.76	-15.60	76	-8.75
-40.00	124.59	-13.50	70	-5.93
-30.00	117.35	-12.60	65	-4.37
-20.00	109.03	-13.50	61	-4.73
-10.00	99.78	-16.30	58	-7.17
0.00	90	-27.10	58	-17.84
10.00	80.22	-16.10	58	-6.97
20.00	70.97	-11.10	61	-2.33
30.00	62.65	-8.90	65	-0.67
40.00	55.41	-8.40	70	-0.83
50.00	49.24	-9.60	76	-2.75
90.00	32.8	-27.80	107	-23.86
100.00	30.11	-15.70	115	-12.43
110.00	27.8	-11.80	124	-9.16
150.00	21.14	-5.50	160	-5.10
160.00	19.93	-5.00	170	-5.09
320.00	10.27	-1.30	325	-7.01
330.00	9.97	-1.30	335	-7.27
2000.00	1.66	-0.10	2000	-21.59

Figure 5-4 shows the graphical representation of received power at the locomotive as a function of the horizontal distance between the locomotive and the base station.

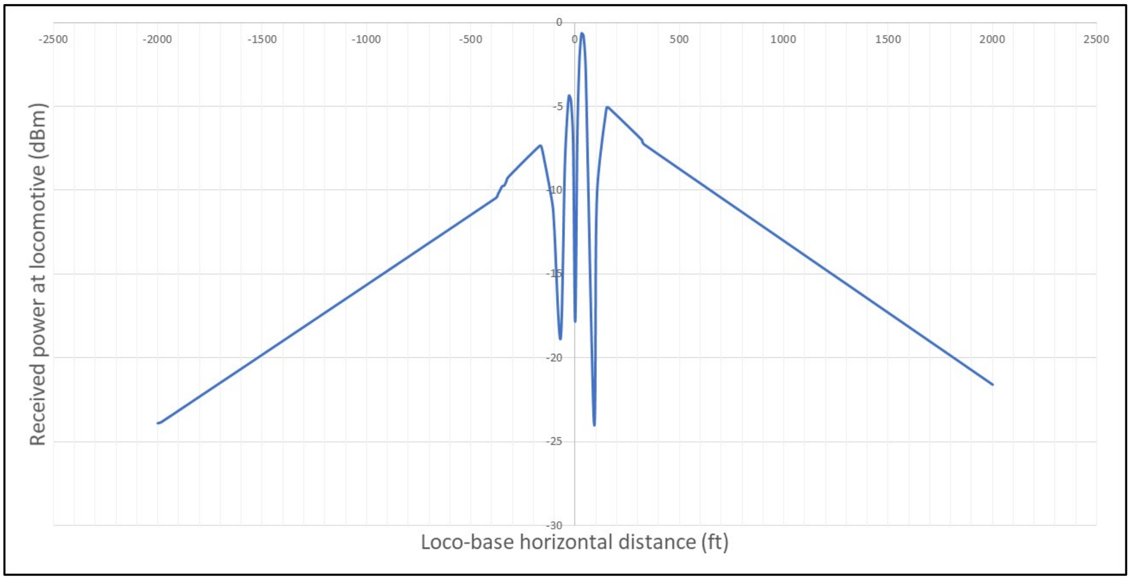


Figure 5-4: Received peak power at locomotive

5.3.3 Maximum Receiver In-Band Input Level

Components are selected based on the maximum power level each component can handle in-band and out-of-band. For in-band signal input consideration, each component must be able to operate within the P1 dB compression point of that component. For out-of-band signal consideration, each component must operate without being damaged.

Table 28 and Table 29 show the requirements for front-end components based on power level.

5.3.4 Dynamic Range

The dynamic range (DR) of a receiver is the range of power of received signals that can be demodulated without reduction in BER versus E_b/N_o performance. Noise figure and linearity set the lower limit and upper limit of dynamic range, respectively.

Table 28 and Table 29 show, for the selected COTS components, the DR of the receiver front end, for both wide-band and band-limited, to be 89.5 dB. While a DR close to 100 dB is desirable, it was identified that higher DR can be achieved without significant increase in cost and complexity of the front-end.

5.4 Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC)

Analog-to-digital converters are used in radio receivers to digitize the analog signal either before or after down conversion by an IQ demodulator. The digitized signal is then filtered and separated by a channelizer into individual channels. Similarly, in radio transmitters, digital-to-analog converters are used to convert digitally coded signals and channels before or after up-conversion and then being fed to filtering and the power amplifier for transmission.

Sampling rate and resolution define the characteristics of a data converter. In general, there is a tradeoff between sampling rate and resolution of an ADC. According to Nyquist, the sampling rate must be at least two times greater than the signal bandwidth. Higher sampling rates offer more bandwidth to be digitized. On the other hand, higher resolution conversion supports higher dynamic range. Dynamic range is the difference between the strongest and weakest signals that can be digitized by the ADC. The dynamic range requirement of a receiver plays a key role in defining the number of bits required in the ADC. [8]

Requirements for the SDR DAC were developed taking into consideration these issues:

- Noise power generated by the DAC
- FCC emission mask requirement

5.4.1 Noise Power Generated by the DAC

The noise power generated by the DAC was calculated and compared with the FCC mask requirement.

For a signal power of 1 V rms and with a load of 50 ohms:

Signal power = 13dBm

The process for calculating the number of bits from a given SNR [2] is as follows:

Given, Signal to Noise Ratio (SNR) = 69 dB,
*Using equation: SNR = 6.02 *b +1.76 dB (Where b = number of bits)*
B = (69-1.76)/6.02
B =11.16943522
Using unitary method,

SNR From website(dB)	Number of bits (b)	SNR for 1 bit (dB)	SNR for 11bits (dB)	SNR for 14 bits (dB)	SNR for 16 bits (dB)
69	11.17	6.18	67.95	86.49	98.84

The process for calculation of the normalized Nyquist band noise power is as follows:

- *For 11 bits converter with 2.5 GSPS sampling rate,*
  SNR = 67.95 dB
  Signal power = 13dBm
  Converter's noise power in Nyquist band = +13dBm-67.95 dB = -54.96 dBm
  10 × log (fsample/2) = 10 × log (2.5 × 10^9/2) = 90.97 dB
  Converter's normalized Nyquist band noise power is:
  -54.96 dBm-90.97 dB = -145.92 dBm/Hz
  The noise power in 25 kHz = -145.92 dBm/Hz + 10 log (25,000) dB= -101.92 dBm
- *For 14 bits converter with 2.5 GSPS sampling rate,*
  Normalized Nyquist band noise power = -164.45 dBm/Hz
  The noise power in 25 kHz = -164.45 dBm/Hz + 10 log (25,000) dB = -120.45 dBm
- *For 16 bits converter with 2.4 GSPS sampling rate,*
  Normalized Nyquist band noise power = -176.63 dBm/Hz
  The noise power in 25 kHz = -176.63 dBm/Hz + 10 log (25,000) dB = - 132.63 dBm

With a gain of 35.7 dB from the PA, the total noise power delivered to the antenna will be:

- *For 11 bits converter with 2.5 GSPS sampling rate,*
  The noise power in 25 kHz = -101.92 dBm + 35.7 dB = -66.2 dBm

- *For 14 bits converter with 2.5 GSPS sampling rate,*
  The noise power in 25 kHz = -120.45 dBm + 35.7 dB = -84.5 dBm
- *For 16 bits converter with 2.4 GSPS sampling rate,*
  The noise power in 25 kHz = - 132.63 dBm + 35.7 dB = -96.9 dBm

5.4.2 FCC Emission Mask Requirement

The FCC mask requirement for the 220 MHz band is the most stringent among all railroad bands and is calculated as shown below:

(30 +10 log (75 watts))- (55+10 Log 75) = -55 watts = -25 dBm

From this calculation, the out-of-band emissions should not be greater than -25 dBm. This value corresponds to the maximum allowable out-of-band emission. For other bands, the noise power output from the DAC is significantly below the FCC mask requirement. Hence, noise power won't violate this requirement.

6. Conclusion and Recommendations for Follow-On Work

The results indicated that SDR technology is an attractive, feasible, and potentially affordable solution for meeting the needs of railroads, especially for use on platforms requiring multi-channel and multi-application wireless communications. The SysRS document developed on the project can be used as the technical basis for an organization to procure an SDR for railroad use. No COTS SDR was found that would satisfy all, or even a sufficient subset of, the railroads' requirements, so development is required. Certain architectures were found to offer significant advantages over others, due to specific characteristics of the railroad applications. Smart modular partitioning of the design can allow the SDR to keep operating with reduced performance after various component failures and also reduce the cost of repairs. All components required to build an SDR for railroad use were found to be available either as COTS items or through supplier development, based on existing technologies.

Detailed recommendations for near-term follow-on projects have are described in the following subsections.

1. Railroad Cognitive Radio Research and Development Project
2. Multi-band and Directional Antenna Research and Development Project

6.1 Railroad Cognitive Radio Research and Development Project

Development of the ability to dynamically assign applications or messages to channels/bands and to aggregate spectrum that may be non-contiguous would help to address the numerous and ever-growing needs for wireless mobile applications to support safe and efficient operations. The objectives of this recommended research are to:

- Investigate methods, equipment, and algorithms for dynamically assigning applications or messages to channels/bands:
    - Spectrum sensing
    - Dynamic spectrum management
    - Adaptive algorithm versus predefined rules, etc.
- Compare different approaches in terms of feasibility and maturity versus railroad needs and potential benefits.
- Investigate methods for Carrier Aggregation (CA):
    - Intra-band CA—aggregating carriers within same frequency band
    - Inter-band CA—aggregating carriers across different frequency bands

6.2 Multi-band and Directional Antenna Research and Development Project

Currently, several different types of radios and frequency bands, requiring several different antennas, are used to support the various railroad wireless communications 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 availability of wireless spectrum are ever-growing challenges.

Development of a multi-band antenna that could be used on a variety of platforms would support the SDR efforts as well as potentially supporting other applications. The potential to combine multiple antennas into one would help to address the challenges discussed above, especially on platforms where space is limited, such as the roof of a locomotive cab. The objectives of this recommended research are to:

- Gather and analyze the requirements associated with multi-band antennas for use on a variety of platforms, considering options, tradeoffs, and applicability to the railroad industry. Considerations would include items such as cost, implementation, maintenance, reliability, etc., and how these items relate to other components of the SDR.
- Perform trade studies to develop the most efficient strategies to allow the railroads to deploy multi-band antennas within their wireless communication networks. This is particularly significant for locomotives, which must communicate with several different systems on different frequency bands.
- Investigate existing technologies that might be applicable or could be modified to be usable.
- Investigate ways to reuse channels in the same area via spatial discrimination to get more capacity from limited available spectrum. Feasibility may vary from one application to the next.

7. References

[1] E. Bertran, Assessment of the peak-to-average power ratio in different channel organization strategies. Springer, vol. 62, no. 2, pp. 363-373, 2016.

[2] Maxim Integrated. 09 September 2002. [Online]. Available: https://www.maximintegrated.com/en/app-notes/index.mvp/id/1197.

[3] W. Zhou. Analog Devices. January 2017. [Online]. Available: http://www.analog.com/en/analog-dialogue/articles/high-definition-low-delay-sdr-based-video-transmission-in-uav-applications.html.

[4] S. M. I. J.-h. J. S. M. I. E. S. F. I. a. J. R. E. M. I. Cheng-Po Liang. Nonlinear Amplifier Effects in Communications Systems. IEEE, 1999.

[5] P. N. N. K. Chetana Dhawale, A REVIEW ON FPGA IMPLEMENTATION OF POLYPHASE FILTER International Journal of Scientific & Engineering Research, vol. 7, no. 2, February-2016.

[6] P. D. L. Stephan Berner. FPGA-Based Filterbank Implementation for Parallel Digital Signal Processing. NASA, 1999.

[7] S. Pithadia, Smart Selection of ADC/DAC Enables Better Design of Software-Defined Radio. Texas Instruments, 2009.

[8] R. M. &. A. P. V. &. E. M.-K. L. &. A. Omondi. Filter Bank Channelizers for Multi-Standard Software Defined Radio Receivers. Journal of Signal Processing Systems, vol. 62, no. 2, 157-171, 2011.

[9] L. Pucker. CHANNELIZATION TECHNIQUES FOR SOFTWARE DEFINED RADIO. 2003.

[10] S. M. R. W. J. L. FAINT. A COMPARISON OF FFT AND POLYPHASE CHANNELIZERS. DEFENCE R&D CANADA - OTTAWA, DEPARTMENT OF NATIONAL DEFENCE OTTAWA, 2003.

[11] X. Z. a. W. W. Y. Guangxiang Yuan. Carrier Aggregation for LTE-Advanced Mobile Communication Systems. IEEE Communications Magazine, vol. 48, no. 2, 2010.

[12] AAR Manual of Standards and Recommended Practices (MSRP) S-9152.V2.1 End of Train Communications.

[13] AAR MSRP S-9153.V1.0 Common Air Interface (CAI-12) Communications for Remote Control Locomotive.

[14] AAR MSRP Section K-3 Wayside Electronics and Mobile Worker Communications Architecture.

[15] AAR MSRP Section K-5 Electronics Environmental Requirements and System Management.

[16] ITC 220 MHz Radio Hardware Specification – Product Release 1.0.

[17] ITCR Base Radio Installation and Field Service Guide – Revision4.0.

[18] ITCR Wayside Radio Installation and Field Service Guide – Revision4.0.

[19] ITCR Locomotive Radio Installation and Field Service Guide – Revision4.0.

[20] FCC Rules and Regulations - Title 47 of the Code of Federal Regulations (CFR).

[21] Baker, Paula J. Whalen, James T., "NASA Independent Verification & Validation (IV&V) Facility [Online]. Available: https://www.nasa.gov/sites/default/files/survey_of_trade_study_methods_-_baker.pdf. [Accessed June 2018].

Appendix A. System Requirements Specification

A1. Introduction and Scope

The scope of this specification document is to define requirements for an SDR intended to meet railroad requirements. The intent is to specify requirements that the SDR designer must meet without specifying internal SDR design details that could unnecessarily constrain the designer's choices. Specifically, this document identifies required characteristics of the generic SDR hardware and its operating system that will support the various waveforms and protocols needed by railroads. It was assumed that any qualified supplier may develop waveform and protocol software to operate on the SDR. The number of potential waveforms and protocols that could be supported is virtually unlimited and needs will change with time, so it is not the purpose of this document to include detailed requirements for waveform and protocol software to be hosted on the SDR. A companion specification addresses antenna requirements.

In order to allow the most cost-effective implementation of the SDR, care has generally been taken to avoid specifying requirements for capabilities that are not essential, such as ability to receive and transmit spread spectrum signals. However, certain requirements have been included beyond what may ultimately be cost effective to achieve. For example, use of an SDR for handheld or EOT applications may be found to be impractical. Such requirements will ultimately be eliminated from this document if trade studies show them to not provide adequate benefit for the cost of including them.

Each section of this document generally contains two parts: narrative text and explicit requirements. The narrative text includes background information, goals, and other supplemental information provided to clarify the requirements. The key words "SHALL," "SHALL NOT," "SHOULD," "SHOULD NOT," "MAY," and "OPTIONAL" in this document are to be interpreted as described below, which is based on IETF RFC 2119.

1. SHALL: This word means that the statement is an absolute requirement of the specification

2. SHALL NOT: This phrase means that the statement is an absolute prohibition of the specification.

3. SHOULD: This word means that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

4. SHOULD NOT: This phrase means that there may exist valid reasons in particular circumstances when the particular behavior is acceptable or even useful, but the full implications should be understood and the case carefully weighed before implementing any behavior described with this label.

5. MAY OPTIONALLY: This phrase means that an item is truly optional. One vendor may choose to include the item because a particular marketplace requires it or because the vendor feels that it enhances the product while another vendor may omit the same item. An implementation which does not include a particular option must be prepared to interoperate with another implementation which does include the option, though perhaps with reduced functionality. In the same vein, an implementation which does include a particular option must be prepared to interoperate with another implementation which

does not include the option (except, of course, for the feature the option provides.)

A2. System Overview

This section of the specification provides a narrative overview of and background on the SDR system. As such, it contains no formal requirements.

For the reasons explained in Section A1, the SDR needs to have the flexibility to communicate using most or all legacy wireless waveforms and protocols currently in use by Class I railroads. Furthermore, to the extent practical, the SDR is to be programmable for additional waveforms, protocols, and operating bands with no or minimal modifications/additions to the SDR hardware. If there are waveforms, protocols, and operating bands that cannot be accommodated with the baseline SDR hardware, they could be accommodated with modular additions.

The SDR is to be capable of dynamically switching between waveforms and protocols, e.g., it might transmit a PTC packet at 220 MHz at one time and then transmit a distributed power message at 450 MHz a few milliseconds later. The SDR is also to be capable of simultaneously transmitting and receiving multiple different waveforms and protocols.

Depending upon the architecture and RF interfaces designed into the SDR, it could transmit and receive over a single wideband antenna or might interface with a separate antenna for each band, which might already exist at the application host platform. Ongoing trade studies aim to resolve this architectural uncertainty.

If the SDR were required to provide distinct legacy interfaces for each possible application, the number of connectors would become excessive. Consequently, the SDR is to interface with the multiple applications at any platform by interfacing with a messaging system.

An example of an SDR application could be as illustrated in Figure A2-1.

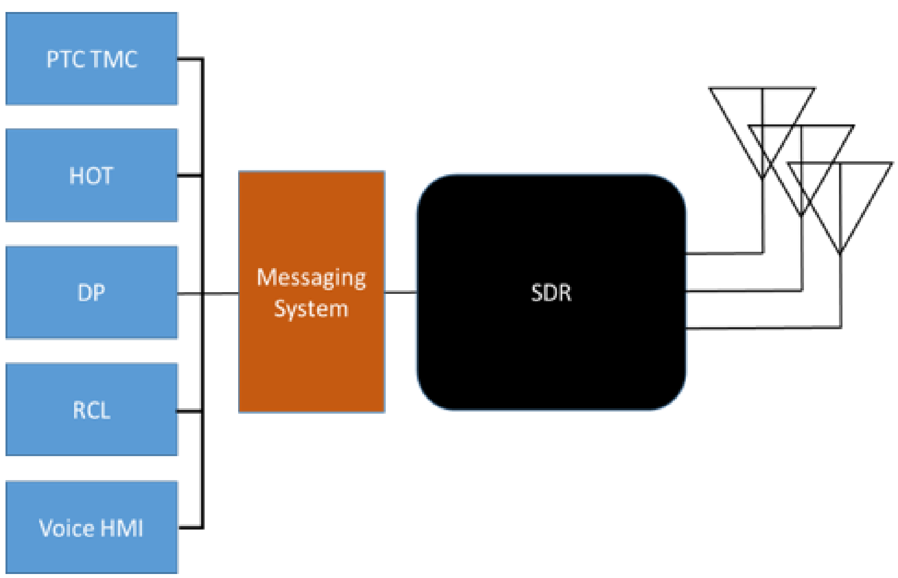


Figure A2-1: Example of how an SDR might be applied on a locomotive

In designing the SDR, its features, capabilities and performance included is to be balanced against unit cost. Otherwise, it might not be cost-effective to use an SDR in applications where a lower cost dedicated radio is available.

A3. Functional Requirements

This section specifies what functions the SDR must perform.

Unless explicitly state otherwise, the requirements listed in this document apply to all radio platforms (locomotive, base, wayside, etc.):

a) The SDR shall be capable of hosting waveform and protocol (including TDMA) software on the RF interfaces that is compatible with the existing radio types specified in Table A3-1 for the specified platforms.

b) The SDR shall be capable of hosting protocol software on the application interface(s) that is compatible with the existing radio types specified in Table A3-2 for the specified platforms.

c) The SDR shall be capable of communicating in the frequency bands specified in Table A3-3 for the specified platforms.

d) The SDR shall be capable of receiving on the number of channels specified in Table A3-4 simultaneously in any combination among the specified operating frequency bands.

e) The SDR shall be capable of transmitting on the number of channels specified in Table A3-4 simultaneously, in any combination among the specified operating frequency bands, without the need for transmitting simultaneously on more than one carrier per band.

f) The SDR shall be capable of simultaneously transmitting and receiving signals that are asynchronous with one another in different bands.

g) The SDR shall accommodate out-of-band full duplex operation.

   Note: Out-of-band full duplexing means the radio can simultaneously transmit and receive on different frequency bands.

h) The SDR shall accommodate in-band full duplex operation over 900 MHz railroad band.

i) The SDR shall accommodate half duplex operation when transmitting and receiving in the same band.

j) The SDR should support "narrowband" analog voice communications with a bandwidth of 12.5 KHz in the railroad VHF voice band.

k) The SDR should be capable of supporting NXDN protocol for voice communications.

l) The SDR shall be capable of hosting software that support mobility, i.e., the ability to autonomously hand-off from one cell to another in accordance with each application's requirements referenced herein, as platform location or other conditions identified in the referenced requirements change.

m) The SDR design should be modular in order to cost-effectively accommodate different requirements for different platforms.

n) The SDR shall be configurable in order to support platforms that require allocation of fewer resources (channels, bands, etc.) without incurring the cost and overhead of the most complex configuration.

o) The SDR shall be capable of hosting software that will synchronize time over-the-air with another radio (e.g., SDR or PTC radio) when GPS is not available or is insufficient.

p) The SDR shall be capable of operating within the specified timing drift rate tolerance when neither GPS nor other radios are available to provide a synchronization reference.

q) The SDR should be capable of hosting software that can route packets or messages when required.

r) The SDR should accommodate high-order modulations (including filtered $\pi/4$ DQPSK) that require linear components.

s) The SDR should be capable of hosting software that performs adaptive modulation depending on channel conditions.

t) The SDR should be capable of hosting software that performs carrier aggregation to support high data-rate applications.

u) The SDR shall be capable of performing block coding and decoding.

v) The SDR shall be capable of performing convolutional coding and decoding.

w) The SDR shall provide a real-time receive signal strength indication (RSSI).

x) The SDR shall be capable of hosting software that supports peer-to-peer communication with another radio in the absence of a base station.

y) The SDR shall support mobility in peer-to-peer communications mode where one or both platforms may be moving.

z) The SDR shall be capable of hosting software that provides priority transmit queuing based on header information in the message from the application.

aa) The SDR should be capable of hosting software that executes a variety of transmit queue scheduling algorithms, including FIFO, LIFO, round robin, and fair share.

bb) The SDR should be capable of hosting ITCM base station, wayside, and locomotive software.

cc) The SDR shall support the ability for a backup radio (in a high-availability configuration, potentially in conjunction with a messaging system), to monitor the primary radio and to take over its identity and messaging tasks if the primary radio fails.

dd) The SDR shall not require external storage to be operational.

ee) The SDR should support removable external storage which can be used to log data.

ff) The SDR shall not be corrupted when power is removed.

Note: For example, the SDR could maintain internal power long enough to do all necessary writes without corrupting memory when external power drops out.

Table A3-1. Minimum required RF interface compatibility with existing radio types

	Platform					
Type of Radio	Loco	Wayside	Base	Handheld	Hi-Rail	UAS
ITC PTC Radio	Y	Y	Y		Y	
ACSES PTC Radio	Y		Y			
Voice Radio	Y		Y	Y	Y	
Embedded Radio						
-Front of Train / End of Train Radio	Y					
-Inter Loco-Consist (DP)	Y					
-RCL 220 MHz Radio	Y			Y		
-RCL 450 MHz Radio	Y			Y		

Table A3-2. Minimum required application interface compatibility with existing applications

	Platform					
Type of Radio	Loco	Wayside	Base	Handheld	Hi-Rail	UAS
ITC PTC Radio	Y	Y	Y		Y	
ACSES PTC Radio	Y		Y			
Voice Radio	Y		Y	Y	Y	
Embedded Radio						
-Front of Train / End of Train Radio	Y					
-Inter Loco-Consist (DP)	Y					
-RCL 220 MHz Radio	Y			Y		
-RCL 450 MHz Radio	Y			Y		

Note: It is likely that most or all the requirements for legacy interfaces will be handled through the ITC Messaging System.

Table A3-3. Minimum required operating frequency bands

	Platform							
Operating Band	Lower Limit (MHz)	Upper Limit (MHz)	Loco	Wayside	Base	Handheld	Hi-Rail	UAS
160 MHz Narrowband (12.5 kHz) Railroad	160.185	161.565	Y	G	Y	Y	Y	
220 MHz PTC-220 and ACSES Bands	217	222	Y	Y	Y		Y	
220 MHz RCL Band	220	222	Y		Y	Y		
450 MHz RCL, DP & EOT Band	452.900	457.875	Y	G	Y	Y		
900 MHz ATCS Band	896.8875	936.9875	Y	Y	Y			Y

G: Goal, not a firm requirement at this time.

Table A3-4. Number of simultaneous channels

Platform	Number of simultaneous Rx channels	Number of simultaneous Rx channels including	Number of simultaneous Tx channels
Loco	15	26	4
Wayside	4	6	1
Base	14	25	4
Handheld	2	2	2
Hi-Rail	2	2	2
UAS	1	1	1

A4. External Interface Requirements

This section specifies SDR interfaces with external users and systems/subsystems.

A4.1 Power Supply Interface

a) The SDR shall operate with the power sources specified in Table A4-1.

b) The SDR shall comply with FCC part 15 Class B for EMI suppression, and comply per S-9401.V1.0 for the acceptable level of transient and surges.

c) The SDR should have a voltage ripple within 200 mV and maximum external current within TBD.

d) The locomotive SDR shall not use a SO-239 connector for power (in order to avoid mistaking it for a clean cab radio connector).

A4.2 RF Interfaces

a) The SDR shall provide the RF ports specified in Table A4-3 to interface with the antenna(s) required for the various frequency bands.

b) The SDR shall not transmit on any ports where the VSWR is higher than 1.5:1.

c) The SDR should be capable of supporting an internal or external GPS receiver to provide timing and location for application requiring it.

d) If the GPS is external, then the SDR shall support an external PPS signal for timing.

e) If GPS is internal to the SDR, the SDR shall include an RF connector to interface with a GPS antenna at 50 ohms.

f) The SDR may optionally include an external connector to provide power from the SDR to the GPS unit for those GPS units requiring a dedicated power connector.

A4.3 Application, System Management, Maintenance, and User Interfaces

a) The SDR shall provide the ports specified in Table A4-4 to interface with applications, systems management, and maintenance devices.

b) The SDR shall support two Ethernet networks, each of which can be used for maintenance or for data flow.

c) The two Ethernet interfaces shall be capable of operating on independent subnets.

d) The two Ethernet interfaces shall be capable of operating on the same subnet.

e) The SDR shall be capable of interfacing with an ELM over Ethernet.

f) The SDR should provide external visual indications of operating status, such as the following indications:

- Power (indication of radio being powered on)
- Fault (flash the power indicator when a fault has been detected currently or recently)
- Standby (indication that radio is in standby mode)

Table A4-1: Power supply interface

Platform	Voltage, nominal (DC)	Voltage, operating range (DC)	Current when receiving (max A)	Current when transmitting & receiving (max A)
Loco	74[1]	45-100[1]	TBD	TBD
Wayside	13.6[1]	10.9-15.5[1]	TBD	TBD
Base	24 or 48[1]	21-27[1]	TBD	TBD
Handheld	TBDBS	TBDBS	TBDBS	TBDBS
Hi-Rail	12	9-16	TBD	TBD
UAS	14 or 28	12-32	TBD	TBD

1 – Values obtained from AREMA manual.

Table A4-2: Voltage Tolerance

Platform	Maximum tolerable input voltage	Input-output isolation	Voltage spike
Loco	130 VDC	500 VDC	5 kV (peak)
Wayside	18 VDC	TBD	TBD
Base	30 VDC or 60 VDC[1]	TBD	TBD
Handheld	TBDBS	TBDBS	TBDBS
Hi-Rail	20 VDC	TBD	TBD
UAS	32 VDC	TBD	TBD

1 - Depending on the supply voltage as illustrated in Table A4-1.

Table A4-3. RF interfaces

Platform	Number of Tx/Rx ports	Number of diversity Rx ports	Connector type	Impedance (ohm)
Loco	15	11	Type N female	50
Wayside	4	2	Type N female	50
Base	14	11	Type N female	50
Handheld	2	0	Type N female	50
Hi-Rail	2	0	Type N female	50
UAS	1	0	Type N female	50

Note: The number of ports in each platform may be consolidated to fewer connectors if a suitable multi-band antenna is available.

Table A4-4. Application, system management and maintenance interfaces

Platform	Number of Ethernet ports	Type of Ethernet connector	Number of external storage sockets
Loco	2	M12	1
Wayside	2	Fiber or RJ45	1
Base	2	RJ45	1
Handheld	1	RJ45	1
Hi-Rail	2	M12	1
UAS	2	M12	1

A5. Performance Requirements

The SDR performance requirements are as follows:

a) The base station and wayside SDR transmit frequency shall be within 0.1 PPM of the assigned frequency for each carrier.

   Note: Per Title 47 CFR Part 90 Section 90.213

b) The locomotive, hi-rail, UAS, and handheld SDR transmit frequency shall be within 1.5 PPM of the assigned frequency for each carrier.

   Note: Per Title 47 CFR Part 90 Section 90.213

c) When GPS or an external timing reference is not available, the SDR timing drift rate shall be no greater than 0.1 PPM for fixed sites and 1.5 PPM for mobiles.

   Note: Per Title 47 CFR Part 90 Section 90.213

   For e.g., if mobile radio is without external reference for 25 minutes while passing through a tunnel then, maximum drift cannot exceed 1.5/(25 minutes)

d) Each transmit channel of the SDR shall accommodate instantaneous application data rates of 32 kb/s and lower.

   Note: This and subsequent requirements is intended to ensure that the SDR hardware is capable of adequate sampling rates, A/D and D/A conversion rates, and processing capacity to support the required maximum data rate.

   Note: The qualifier "instantaneous" is used here to distinguish from average user data rate, which is lower due to specified maximum transmitter duty cycle limitations. E.g., an instantaneous data rate of 32 kb/s transmitted at a duty cycle of 50% would produce an average data rate of 16 kb/s.

   Note: If the SDR is also to accommodate 64QAM-based OFDM in a 125 kHz channel, for example, this requirement would need to be modified to specify an "instantaneous application data rate of 375 kb/s and lower."

Note: If the SDR is also to accommodate video, this requirement would need to be modified to specify an "instantaneous application data rate of X kb/s and lower," where X is the data rate for the quality of video required as specified in Table A5-1 divided by the transmit duty cycle.

e) Each receive channel of the SDR shall accommodate application data rates of 32 kb/s and lower.

Note: If the SDR is also to accommodate 64QAM-based OFDM in a 125 kHz channel, for example, this requirement would need to be modified to specify application data rates of 375 kb/s and lower."

Note: If the SDR is also to accommodate video, this requirement would need to be modified to specify application data rates of X kb/s and lower," where X is the data rate for the quality of video required as specified in Table A5-1 divided by the transmit duty cycle.

f) Each transmit channel of the SDR shall accommodate waveforms with instantaneous symbol rates of 32 kbps and lower.

Note: If the SDR is also to accommodate 64QAM-based OFDM in a 125 kHz channel, for example, this requirement would need to be modified to specify "instantaneous symbol rates of 375 kb/s and lower."

Note: If the SDR is also to accommodate video, this requirement would need to be modified to specify "instantaneous symbol rates of X kb/s and lower," where X is the data rate for the quality of video required as specified in Table A5-1 divided by the transmit duty cycle. The instantaneous symbol rate requirement must be increased to allow for preambles, headers, guard times, forward error correction coding, cyclic prefix, and other overhead as required.

g) Each receive channel of the SDR shall accommodate waveforms with symbol rates of 32 kb/s and lower.

Note: If the SDR is also to accommodate 64QAM-based OFDM in a 125 kHz channel, for example, this requirement would need to be modified to specify "symbol rates of 375 kb/s and lower,"

Note: If the SDR is also to accommodate video, this requirement would need to be modified to specify "symbol rates of X kb/s and lower," where X is the data rate for the quality of video required as specified in Table A5-1 divided by the transmit duty cycle. The symbol rate requirement must be increased to allow for preambles, headers, guard times, forward error correction coding, cyclic prefix, and other overhead as required.

h) Each transmit and receive channel of the SDR shall accommodate waveforms with bandwidths of 25 kHz and lower.

Note: If the SDR is also to accommodate 64QAM-based OFDM in a 125 kHz channel, for example, this requirement would need to be modified to specify "bandwidths of 125 kHz and lower."

Note: If the SDR is also to accommodate video, this requirement would need to be modified to specify "bandwidths of X kHz and lower," where X is the bandwidth required for the user-selected waveform and for the quality of video as specified in Table A5-1 divided by the transmit duty cycle. The bandwidth requirement must be increased to allow for preambles, headers, guard times, forward error correction coding, cyclic prefix, and other overhead as required.

i) The hardware components of the SDR receiver (e.g., RF front end, IF —if included, filters, down converter, amplifiers, and ADC) shall not contribute more than 0.5 dB to overall receiver implementation loss.

   Note: Implementation loss refers to amount of increase in E_b/N_0 above the theoretical amount required to achieve $10^{\wedge -5}$ BER.

j) The hardware components of the SDR transmitter (DAC, up converter, IF —if included, filters, amplifiers, and RF back end) shall not contribute more than 0.5 dB to overall transmitter implementation loss.

   Note: Implementation loss refers to amount of increase in E_b/N_0 above the theoretical amount required to achieve $10^{\wedge -5}$ BER.

k) Each SDR transmit channel shall be capable of keying on and tuning in to the new frequency while meeting the transmitter hardware implementation loss requirement specified herein within 0.1 msec.

l) Each receive channel of the SDR shall be capable of changing carrier frequency and stabilizing to meet the receiver hardware implementation loss requirement specified herein within 0.1 msec.

m) Each SDR transmit channel shall be capable of keying off to meet the maximum output non-transmitting noise level requirement specified herein within 0.1 msec.

n) When not transmitting, each RF port shall output noise power no greater than -134 dBm/Hz.

o) Each transmit and receive channel of the SDR shall accommodate channel steps of 1 kHz and greater.

p) The SDR shall be capable of carrier sensing, e.g., to perform carrier sense multiple access (CSMA).

q) The timestamp provided by the SDR indicating when a packet was transmitted shall represent the time of the first bit appearing at the SDR's Tx RF port within +/- TBD microseconds.

r) The SDR transmitter shall provide an adjacent channel power ratio of at least -60 dBc.

s) The SDR transmitter shall provide an intermodulation attenuation of at least -40 dBc.

t) The SDR shall comply with all the applicable rules in Section 4.0 of S-9401.V1.0.

u) The receiver latency of the SDR hardware shall be no more than TBD msec, where receiver latency is defined as the time from when the last bit of a packet is received by the SDR from the Rx RF port until the first bit of the (first) associated packet header is available at the SDR's application interface.

v) The timestamp provided by the SDR indicating when a packet was received shall represent the time of the first header bit appearing at the SDR's Rx RF port within +/-

TBD microseconds.

w) The SDR should have a desensitization threshold of no less than -20 dBm.

Note: Through testing performed at TTC, the interfering signal level that resulted in desense of the locomotive radio was -20.2 dBm. Further details of the desense test procedure are available from TTCI.

x) The SDR should have adjacent channel selectivity of 70 dB.

y) The SDR shall support demodulation of received signals having carrier and timing Doppler associated with relative platform velocity of 250 mph without exceeding the implementation loss requirement specified herein.

z) The SDR shall demodulate received signals having carrier and timing Doppler associated with relative platform acceleration of 3 g without exceeding the implementation loss requirement specified herein.

aa) The RSSI shall report received signal strength with no more than +/-2 dB error from the actual received signal strength.

bb) The SDR shall provide transmit power output levels within the ranges shown in Table A5-2.

cc) The SDR shall limit the duration of each transmission to avoid exceeding the duty cycles cited in Table A5-2.

dd) The SDR shall handle the transmitter duty cycles at the maximum power levels shown in Table A5-2.

ee) The SDR transmit power level shall be dynamically controllable by a power control algorithm over the range specified in Table A5-2 from minimum TX rms power to maximum TX rms power.

ff) Transmit power level shall be within +/- 0.5 dB of the level specified by an internal or external power control algorithm.

Table A5-1. Bandwidth requirement for video transmission [3]

Format	Compressed Data Rate (Mbps)	64 QAM (Signal BW, MHz)
VGA	2.2	0.4583
720p	6.6	1.375
1080p	14.9	3.1042

Table A5-2. Transmit power levels and duty cycles

Platform	Max Tx Power (W rms)	Min Tx Power (W rms)	Min Step Size for Power Control	Max Duty Cycle	
				Voice	Data
L	20	6	1 dB	TBD	30%
Wayside	10	3	1 dB	TBD	10%
B	30	4	1 dB	TBD	50%
Handheld	5	5	N/A	TBD	TBD
Hi-Rail	20	6	1 dB	TBD	30%
U	20	6	1 dB	TBD	TBD

Note: The values in the table are average powers; peak powers are higher depending on the modulation used.

A6. Safety Requirements

While the SDR may support applications that perform vital functions (e.g., PTC), the SDR itself does not perform any vital functions. Consequently, there are no safety requirements for the SDR.

A7. Security Requirements

Following are the security requirements for the SDR:

a) The SDR shall support encoding and decoding HMACs using certificates that will be installed on the radio to allow maintenance and control messages to be secured.

b) The SDR shall be capable of hosting encryption/decryption software.

Note: This is used today for the transmission and reception of authentication keys for PTC.

A8. System Effectiveness Requirements

This section includes the following subsections addressing their respective topics.

A8.1 Reliability and Availability Requirements

a) The SDR should have a mean time to failure (MTTF) as listed in Table A8-1.

b) The SDR should support a high availability configuration with two radios, one acting as an offline spare.

c) The SDR should have a modular design to support soft failure modes and reduce maintenance costs.

d) The SDR should have a startup time of 30 seconds for a spare radio or modular reconfiguration when used in a high availability configuration.

e) The SDR design should avoid any single points of failure to the extent feasible.

A8.2 Maintainability Requirements

a) The SDR shall support internal logging of statistics, including those identified in Table A8-2.

b) The SDR shall accept and communicate periodic messages reporting health of various onboard systems or wayside devices received from ISMP agents running on the platform applications.

c) The SDR shall support local maintenance.

Note: Local maintenance could be an operation a field technician performs wherever the radio is installed, for example.

d) The SDR shall allow a diagnostic tool to connect for local maintenance.

e) The SDR should support the following functions on the maintenance port:

- Cycle (reboot) the SDR.
- Perform a loopback test.
- Reset all counters / logs.
- Display alarms.
- Display summary statistics.
- Display detailed statistics.

f) The SDR should support the following alarms:

- Low voltage
- High VSWR
- Low forward power
- No GPS PPS
- High temperature
- Failed self-test
- Detected component failures
- Detected upgrade failures

g) The SDR shall, configurably, be able to periodically report its health/status (including alarms) to ISMP.

h) The SDR should support a web server with browser based maintenance functions that can be accessed either through the network or locally via the Ethernet connection.

i) The SDR shall support local keying by a maintenance technician.

j) The SDR should support a sniffer mode where it will listen to local traffic and output information about what it hears.

k) The SDR shall support the ability to roll back to the previous (N-1 or N-2) version of configuration parameters, scripts, and firmware.

l) The SDR shall support the ability to load configuration parameters and script data in a file from a locally attached laptop.

m) The SDR shall support the ability to load configuration parameters and script data in a file downloaded via an ITP or IP network connection.

n) The SDR shall support the download of new configuration parameters, scripts, and firmware remotely from over the air.

o) The SDR shall support the activation of new configuration parameters, scripts, and firmware remotely from over the air.

p) The SDR shall require the secure authentication of a user who is attempting remote configuration.

q) The SDR shall include non-volatile memory for storing configuration parameters and radio identification.

r) The SDR shall require a secure authentication of a user who is attempting local configuration of a SDR.

s) The SDR shall support a way to reset a configuration (including the password) in the case that passwords have been lost.

Table A8-1: Mean time to failure requirements of SDR

Mean Time to Failure (MTTF)					
Loco	Wayside	Base	Handheld	Hi-Rail	UAS
50,000 hrs.	50,000 hrs.	50,000 hrs.	50,000 hrs.	50,000 hrs.	50,000 hrs.

Table A8-2: Minimum logging requirements of SDR

The SDR should support internal logging of permanent statistics including: - Up-time - Time of last configuration change - Last user login info
The SDR should support internal logging of summary statistics for 5 days of operation including: - Cumulative message traffic over the ports and air interface (both message numbers and cumulative data volume transmitted). - # of errors/alarms detected - Last I/O port status change
The SDR should support internal logging of detailed events (for each message or on a cyclic basis as appropriate) for at least 1 day of operation including: - Source address - Reflected power - Forward power - Sync pattern received - Port errors/resets detected - Nominal and keyed DC voltage - Any other errors/alarms detected - GPS # of satellites - RSSI - Noise floor

A9. Extensibility Requirements

Any accommodations for future expansion in capacity, functionality, performance, etc., are addressed in this section:

a) The SDR should accommodate software and firmware defining additional waveforms, protocols, TDMA frame formats, and link access method beyond those existing ones referenced herein for backward compatibility.

b) The SDR should have the ability to host 3rd party software processes (e.g., modulation, demodulation and protocols), on a Linux processor.

c) The SDR shall support the download of new configuration parameters, scripts, and firmware remotely from over the air.

d) SDR shall support the activation of new configuration parameters, scripts, and firmware remotely from over the air.

e) The SDR shall require the secure authentication of a user who is trying to attempt remote configuration.

A10. Regulatory Requirements

a) The SDR shall comply with applicable requirements in Parts 2, 15, 80, and 90 of

FCC rules, including those listed in Table A10-1.

b) The SDR shall comply with applicable requirements in SRSP 500, 501, 504, 509, and 512 of Industry Canada requirements.

Table A10-1: Required FCC compliance

FCC FREQUENCY ALLOCATIONS AND RADIO TREATY MATTERS; GENERAL RULES AND REGULATIONS
The SDR design shall conform to FCC allocation, assignment, and use of radio frequency rules.
The SDR design shall conform to FCC emissions rules.
The SDR design shall conform to FCC marketing of radio frequency devices rules.
The SDR design shall conform to FCC equipment authorization procedures rules.
FCC RADIO FREQUENCY DEVICES rules
The SDR design shall conform to FCC general procedure rules.
The SDR design shall conform to FCC unintentional radiators rules.
PRIVATE LAND MOBILE RADIO SERVICES rules
The SDR design shall conform to FCC general information rules.
The SDR design shall conform to FCC general technical standards rules.
The SDR design shall conform to FCC non-voice and other specialized operations rules.
The SDR design shall conform to FCC standards for special frequencies or frequency bands rules.
The SDR design shall conform to FCC operating requirements rules.
The SDR design shall conform to FCC transmitter control rules.
The SDR design shall conform to FCC developmental operation rules.
The SDR design shall conform to FCC regulations governing licensing and use of frequencies in the rules for each specified operating band.

A11. Environmental and Physical Requirements

Following are the environmental and physical requirements for the SDR:

a) For wayside applications, the SDR shall meet all requirements specified herein when operating in the environment specified by AAR S-5702 for wayside bungalows.

b) For vehicle applications, the SDR shall meet all requirements specified herein when operating in the environment specified by AAR S-5702 for vehicle interior cabs.

c) For base station applications, the SDR shall meet all requirements specified herein when operating in the environment specified by AAR S-5702 for wayside control rooms.

d) For handheld applications, the SDR shall meet all requirements specified herein when operating in the environment specified by MIL-STD-810G.

e) For airborne applications, the SDR shall meet all requirements specified herein when operating in the environment specified by CE 101/102 (TBD), MIL-STD-460/465 and MIL-STD-1275E.

f) For wayside applications, the SDR shall meet all requirements specified herein when operating over the temperature range of -40°C to +70°C.

g) For vehicle applications, the SDR shall meet all requirements specified herein when operating over the temperature range of -40°C to +70°C.

h) For base station applications, the SDR shall meet all requirements specified herein when operating over the temperature range of -30°C to +70°C.

i) The SDR shall meet the physical size requirements specified in Table A11-1.

j) The locomotive SDR shall conform to LSI standards for packaging.

Table A11-1. Physical characteristics

Platform	Volume (max)	Weight (max)	Mounting provisions
Loco	TBD	TBD	TBD
Wayside	TBD	TBD	TBD
Base	TBD	TBD	TBD
Handheld	TBD	TBD	TBD
Hi-Rail	TBD	TBD	TBD
UAS	TBD	TBD	TBD

A12. Other Requirements

The SDR should include enough processing capacity, RAM, non-volatile memory, ADC/DAC rates, etc., to accommodate all the waveforms and other functions per requirements.

Appendix B. Component Requirements

B1. Power Amplifier Requirements

This section provides the requirements for both wide-band and band-limited PAs.

Table B1-1: Requirements for a wide-band PA

PA Requirements	Based on PAPR of 13 dB[1] (OFDM)	Based on PAPR of 6 dB[2] (Π/4 DQPSK)	Units
Frequency range	160 - 960	160-960	MHz
Band 1	160-162	160-162	MHz
Band 2	219.5 - 222	219.5 - 222	MHz
Band 3	450 - 460	450 - 460	MHz
Band 4	896-960	896-960	MHz
Min. input power per carrier (avg., not peak) *	0	0	dBm
Max. input power per carrier (avg., not peak)	+10	+10	dBm
Max input power per carrier for no damage	+20	+20	dBm
Gain*	35	35	dB
1 dB compression point, min.	+64	+57	dBm
3rd order IMD Tone 1: 219.5 -222 MHz @ 45 dBm avg., Tone 2: 896.8875 - 936.9875MHz @ 45 dBm avg.	-90	-90	dBm
Duty cycle per carrier, asynchronous with one another	50	50	%
RF connector type	N-type	N-type	
Operating temperature range	-30 to +70	-30 to +70	°C
Operating humidity	0 to 95	0 to 95	%RH

* Alternatively, PA can have an electronically adjustable gain range of 25 to 35 dB, in which case each input carrier level would be fixed at +10 dBm.
PA must remain stable over the 10 dB range of output powers per carrier.

1. Each carrier has a PAPR of 10 dB but when combined the composite carrier has a PAPR of 13 dB, i.e., a peak power level of 2,500 W.

2. Each carrier has a PAPR of 4 dB but when combined the composite carrier has a PAPR of 6 dB, i.e., a peak power level of 500 W.

Table B1-1: Requirements for 160 MHz band-limited PA

PA for a PAPR of 10 dB (OFDM)	**Value**	**Units**
Frequency range	160-162	MHz
Min. input power per carrier (avg., not peak) *	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max. input power per carrier for no damage	+20	dBm
Gain*	35	dB
1 dB compression point, min.	+55	dBm
PA for a PAPR of 4 dB (Π/4 DQPSK)	Value	Units
Frequency range	160-162	MHz
Min. input power per carrier (avg., not peak) *	0	dBm
Max. input Power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain*	35	dB
1 dB compression point, min.	+49	dBm
Requirements for both PAs (OFDM & Π/4 DQPSK)		
Duty cycle	50	%
RF connector type	N-type	
Operating temperature range	-30 to +70	°C
Operating humidity	0 to 95	%RH

* Alternatively, PA can have an electronically adjustable gain range of 25 to 35 dB, in which case each input carrier level would be fixed at +10 dBm.
Supplier should propose the lower cost alternative.
PA must remain stable over the 10 dB range of output powers per carrier.

Table B1-2: Requirements for 220 MHz band-limited PA

PA for a PAPR of 10 dB (OFDM)	**Value**	**Units**
Frequency range	219.5 - 222	MHz
Min. input power per carrier (Avg., not peak) *	0	dBm
Max. input power per carrier (Avg., not peak)	+10	dBm
Max. input power per carrier for no damage	+20	dBm
Gain*	35	dB
1 dB compression point, min.	+55	dBm
PA for a PAPR of 4 dB (Π/4 DQPSK)	Value	Units
Frequency range	219.5 - 222	MHz
Min. input power per carrier (avg., not peak) *	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain*	35	dB
1 dB compression point, min.	+49	dBm
Requirements for both PAs (OFDM & Π/4 DQPSK)		
Duty cycle	50	%
RF connector type	N-type	
Operating temperature range	-30 to +70	°C
Operating humidity	0 to 95	%RH

* Alternatively, PA can have an electronically adjustable gain range of 25 to 35 dB, in which case each input carrier level would be fixed at +10 dBm.
Supplier should propose the lower cost alternative.
PA must remain stable over the 10 dB range of output powers per carrier.

Table B1-3: Requirements for 450 MHz band-limited PA

PA for a PAPR of 10 dB (OFDM)	**Value**	**Units**
Frequency range	450 - 460	MHz
Min. input power per carrier (avg., not peak)	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain	35	dB
1 dB compression point, min.	+55	dBm
PA for a PAPR of 4 dB (Π/4 DQPSK)	Value	Units
Frequency range	450 - 460	MHz
Min. input power per carrier (avg., not peak)	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain	35	dB
1 dB compression point, min.	+49	dBm
Requirements for both PAs (OFDM & Π/4 DQPSK)		
Duty cycle	50	%
RF connector type	N-type	
Operating temperature range	-30 to +70	°C
Operating humidity	0 to 95	%RH

Table B1-4: Requirements for 900 MHz band-limited PA

PA for a PAPR of 10 dB (OFDM)	**Value**	**Units**
Frequency range	896-960	MHz
Min. input power per carrier (avg., not peak)	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain	35	dB
1 dB compression point, min.	+55	dBm
PA for a PAPR of 4 dB (Π/4 DQPSK)	Value	Units
Frequency range	896-960	MHz
Min. input power per carrier (avg., not peak)	0	dBm
Max. input power per carrier (avg., not peak)	+10	dBm
Max input power per carrier for no damage	+20	dBm
Gain	35	dB
1 dB compression point, min.	+49	dBm
Requirements for both PAs (OFDM & Π/4 DQPSK)		
Duty cycle	50	%
RF connector type	N-type	
Operating temperature range	-30 to +70	°C
Operating humidity	0 to 95	%RH

B2. Transmit Filter Requirements

This section contains the requirements for both wide-band and band-limited transmit filter.

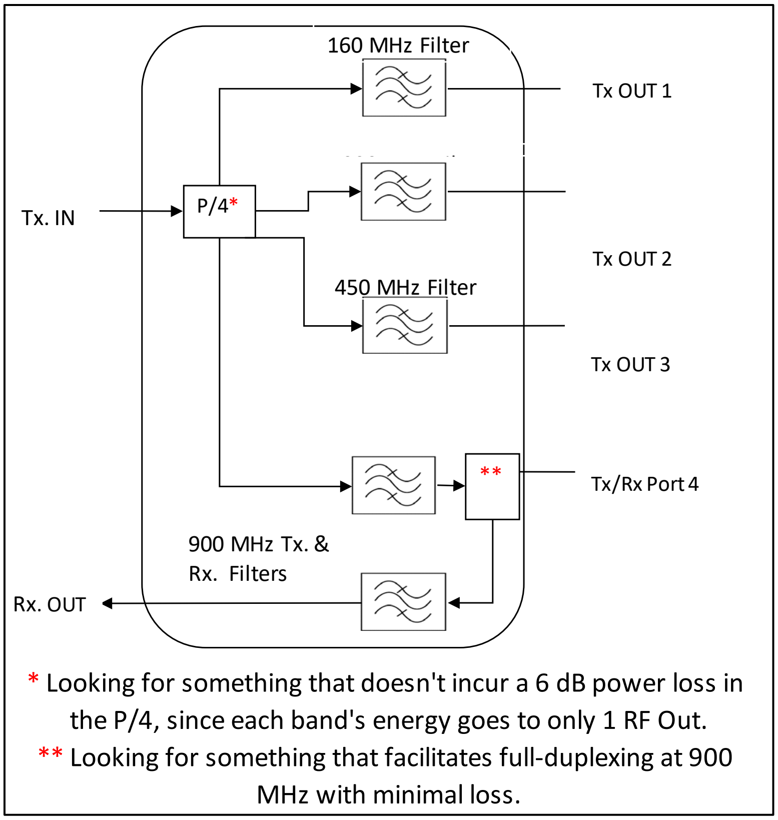
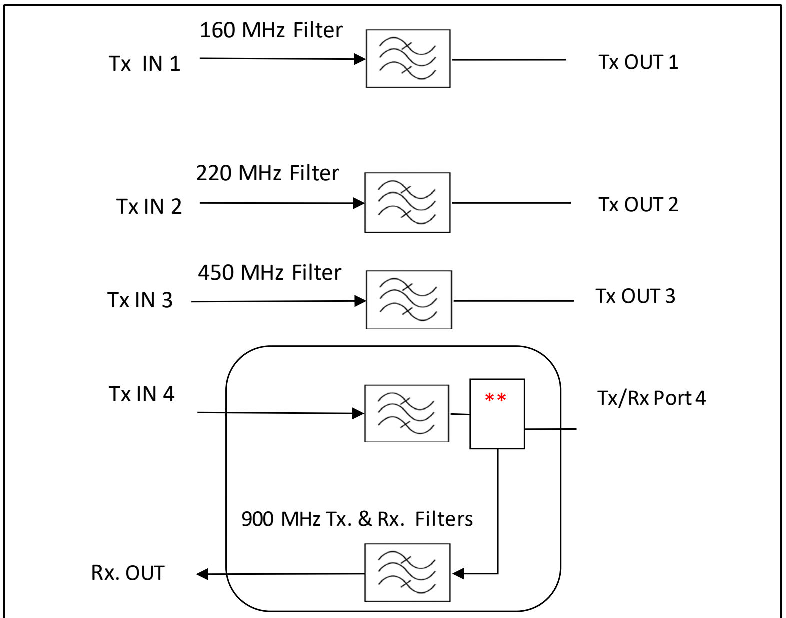


Figure B2-1: Base station wide-band transmit filter

Table B2-1: Requirements for wide-band transmit filter—Base station SDR

	160 MHz Tx. Filter	220 MHz Tx. Filter	450 MHz Tx. 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	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other
VSWR	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better
Insertion Loss (dB)	< 2	< 2	< 2	< 2	< 2
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)	15	15	15	15	Stopbands 1-5: 75 dB Stopband 6: 35 dB
Impedance (Ω)	50	50	50	50	50
Temperature Range (°C)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)
Humidity (non-condensing)	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%
Vibration	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm
	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G
	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G
Dimensions (WxDxH)	Specific requirements for the filter size will be defined by the individual railroads purchasing equipment. For this specification, it is recommended that the filters be implemented to be as compact as possible.				



Looking for Individual filters but open to the idea of combined filter if there is a size and/or cost benefit.

** Looking for something that facilitates full-duplexing at 900 MHz with minimal loss.

Figure B2-2: Base station band-limited transmit filter

Table B2-2: SDR requirements for band limited transmit filter in the base station

	160 MHz Tx. Filter	220 MHz Tx. Filter	450 MHz Tx. 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	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other
VSWR	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better
Insertion Loss (dB)	< 2	< 2	< 2	< 2	< 2
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)	15	15	15	15	Stopbands 1-5 : 75 dB Stopband 6: 35 dB
Impedance (Ω)	50	50	50	50	50
Temperature Range (°C)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)
Humidity (non-condensing)	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%	Max. = 95% ; Min. = 40%
Vibration	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm
	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G
	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	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.				

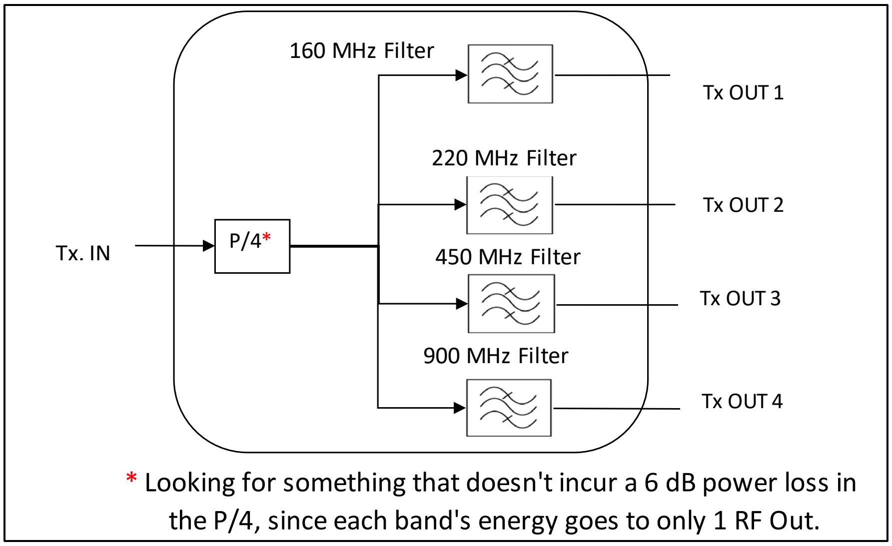


Figure B2-3: Locomotive wide-band transmit filter

Table B2-3: Requirements for wide-band transmit filter—locomotive SDR

	160 MHz Tx. Filter	220 MHz Tx. Filter	450 MHz Tx. Filter	900 MHz Tx. Filter
Specifications	**Value**	**Value**	**Value**	**Value**
Frequency Range (MHz)	Passband: 160 - 162	Passband: 219.5-222	Passband: 450-460	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
Connector Type	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other
VSWR	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better
Insertion Loss (dB)	< 2	< 2	< 2	< 2
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: 935-937
Stopband Attenuation (dB)	15	15	15	15
Impedance (Ω)	50	50	50	50
Temperature Range (°C)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)
Humidity (non-condensing)	Max. = 95%; Min. = 40%	Max. = 95%; Min. = 40%	Max. = 95%; Min. = 40%	Max = 95%; Min = 40%
Vibration	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm
	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G	10 to 200 Hz = 1.5 G
	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	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.			

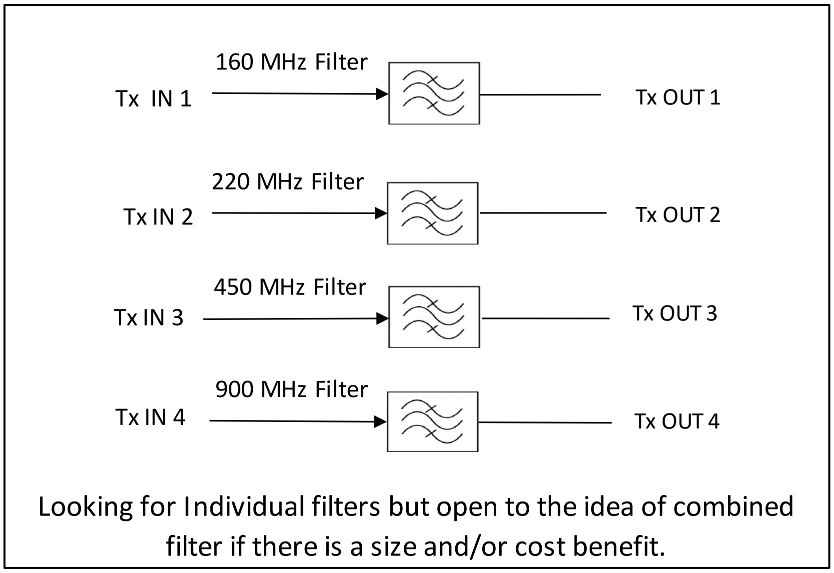


Figure B2-4: Locomotive band-limited transmit filter

Table B2-4: Requirements for band-limited transmit filter—locomotive SDR

	160 MHz Tx. Filter	220 MHz Tx. Filter	450 MHz Tx. Filter	900 MHz Tx. Filter
Specifications	**Value**	**Value**	**Value**	**Value**
Frequency Range (MHz)	Passband: 160 - 162	Passband: 219.5 - 222	Passband: 450 - 460	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
Connector Type	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other	N-type, unless supplier recommends other
VSWR	1.5:1 or better	1.5:1 or better	1.5:1 or better	1.5:1 or better
Insertion Loss (dB)	< 2	< 2	< 2	< 2
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: 935-937
Stopband Attenuation (dB)	15	15	15	15
Impedance (Ω)	50	50	50	50
Temperature Range (°C)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)	-40 to +70 (up to 5 min. at +100 when in a tunnel)
Humidity (non-condensing)	Max. = 95%; Min. = 40%	Max. = 95%; Min. = 40%	Max. = 95%; Min. = 40%	Max. = 95%; Min. = 40%
Vibration	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm	5 to 10 Hz = 7.6 mm
	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G	10 to 200 Hz =1.5 G
	Mech. Shock = 10G	Mech. Shock = 10G	Mech. Shock = 10G	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.			

Appendix C. SDR Cost Estimates

C1. Locomotive SDR Cost Estimate

This section shows the cost estimates developed for the locomotive platform across various SDR architectures, as described and illustrated in Section 3. The actual component manufacturers and model numbers were mentioned in Section 4.4. These cost estimates contain costs derived from quotes provided by vendors for specific components in the transmitter back end and RF front end. The manufacturers, model numbers, and individual costs are not shown for those specific components due to the proprietary nature of the quotes provided by the vendors. Note that there are few cells in the tables where the cost value is indicated as N/A, which means that component is not applicable for that architecture.

Table C1-1: Cost estimate for SDR transmitter in locomotive platform

Components	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
IQ Modulator										
Approx. Average Cost ($)	4	31	4	31	4	31	4	31	1	8
DAC										
Approx. Average Cost ($)	1	131	8	56	8	56	8	133	2	20
Synthesizer/LO										
Approx. Average Cost ($)	1	7	4	28	4	28	4	28	1	7
Power Combiner										
Approx. Average Cost ($)	1	1	4	6	4	6	4	6	1	1
Mixer										
Approx. Average Cost ($)	2	7		N/A		N/A		N/A		N/A
Quad Hybrid										
Approx. Average Cost ($)	1	2		N/A		N/A		N/A		N/A
Combined Cost Estimate ($)		179		121		121		198		36

Table C1-2: Cost estimate for SDR receiver in locomotive platform

Components	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
IQ Demodulator										
Approx. Average Cost ($)		N/A		N/A	26	174	6	40	2	13
ADC (Dual-Channel)										
Approx. Average Cost ($)	2	3,000	2	1,443	26	1,748	6	615	2	205
Channelizer										
Approx. Average Cost ($)	2	1,450	2	1,450		N/A	2	1,450	2	1,450
DSP and DSP Board										
Approx. Total Cost ($)	2	763	2	763	2	763	2	763	2	763
Primary CPU										
Approx. Average Cost ($)	2	700	2	700	2	700	2	700	2	700
Synthesizer (Dual RF Output)										
Approx. Average Cost ($)		N/A	1	7	26	183	6	42	2	14
Filter										
Approx. Average Cost ($)	2	26	4	30	52	384	6	71	4	48
Power Dividers										
Approx. Average Cost ($)		N/A	2	3	26	41	6	8		N/A
Mixer										
Approx. Average Cost ($)		N/A	2	9		N/A		N/A		N/A
Quad Hybrid										
Approx. Average Cost ($)		N/A	2	4		N/A		N/A		N/A
Combined Cost Estimate ($)		5,940		4,409		3,994		3,691		3,194

Table C1-3: Cost estimate for SDR transmitter back-end in locomotive platform

Component	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5	N	Arch 6
PA	Quotes from multiple vendors											
Approx. Average Cost (Π/4 DQPSK) ($)		Not feasible	4	5,838		Not feasible	4	5,838	4	58,38	1	4,900
Approx. Average Cost (OFDM) ($)		Not feasible	1	11,300		Not feasible	4	11,300	4	11,300	1	6,000
Filter	Quotes from multiple vendors											
Approx. Average Cost ($)	1	1,169	1	1,169	1	1,169	1	1,169	1	1,169	1	1,169
Combined Cost Estimate (Π/4 DQPSK) ($)		N/A		7,006		N/A		7,006		7,006		6,069
Combined Cost Estimate (OFDM) ($)		N/A		12,469		N/A		12,469		12,469		7,169

Note: The manufacturers, model numbers, and individual costs are not shown for PAs and filters due to the proprietary nature of the quotes provided by the vendors.

Table C1-4: Cost estimate for SDR receiver front-end in locomotive platform

Component	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
AGC/VGA										
Approx. Average Cost ($)	2	38.08	2	38.08	8	152.32	8	152.32	4	76.16
Filters1	Quotes from multiple vendors									
Approx. Average Cost ($)		3,229		3,229		3,229		3,229		3,229
LNAs										
Approx. Average Cost ($)	4	28.88	4	28.88	8	57.76	8	57.76	2	14.44
Power Combiner/Divider										
Approx. Average Cost ($)		N/A	2	6		N/A	1	3	1	3
Combined Cost Estimate ($)		3,296		3,302		3,439		3,442		3,323

Note: The manufacturers, model numbers, and individual costs are not shown for filters due to the proprietary nature of the quotes provided by the vendors.

Table C1-5 illustrates the potential combinations within transmitter and receiver architectures for locomotive platforms.

Table C1-5: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			**Rx Architectures**	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Note: Refer to Section 3 for Tx and Rx architectures.

Table C1-6 illustrates potential combinations among transmitter and receiver architectures for the locomotive platform. In addition, the table also shows the total cost estimates for various SDR system architectures for Π/4 DQPSK and OFDM modulations.

Table C1-6: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Unit Cost (OFDM) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)[2]	Total Cost Estimate (OFDM) (in $)[2,3]
1	A	7,190	12,650	A	9,380	16,570	22,030
2	A	7,190	12,650	B	7,850	15,040	20,500
3	A	7,190	12,650	C	7,430	14,620	20,080
4	A	7,190	12,650	D	7,130	14,320	19,780
5	B or C	7,130	12,590	A	9,380	16,510	21,970
6	B or C	7,130	12,590	B	7,850	14,980	20,440
7	B or C	7,130	12,590	C	7,430	14,560	20,020
8	B or C	7,130	12,590	D	7,130	14,260	19,720
9	D	7,200	12,670	A	9,380	16,580	22,050
10	D	7,200	12,670	B	7,850	15,050	20,520
11	D	7,200	12,670	C	7,430	14,630	20,100
12	D	7,200	12,670	D	7,130	14,330	19,800
13 [1]	E	6,100	7,200	E	6,520	20,120	21,220

Notes:

1. Price includes approximate cost of 450 and 900 MHz dedicated radios.
2. Price doesn't include cost estimations for antennas.
3. Cost for OFDM assumes PAPR reduction.

C2. Base Station SDR Cost Estimate

This section shows the cost estimates developed for the base station platform across various SDR system architectures as described and illustrated in Section 3. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C2-1: Cost estimate for SDR transmitter in locomotive platform

Components	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
IQ Modulator										
Approx. Average Cost ($)	3	23.37	3	23	3	23	3	23	1	8
DAC										
Approx. Average Cost ($)	1	131	6	42	6	42	6	100	2	20
Synthesizer/LO										
Approx. Average Cost ($)	1	7	3	21	3	21	3	21	1	7
Power Combiner										
Approx. Average Cost ($)	1	1	4	6	4	6	4	6	1	1
Mixer										
Approx. Average Cost ($)	2	7		N/A		N/A		N/A		N/A
Quad Hybrid										
Approx. Average Cost ($)	1	2		N/A		N/A		N/A		N/A
Combined Cost Estimate ($)		171		92		92		150		36

Table C2-2: Cost estimate for SDR receiver in locomotive platform

Components	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
IQ Demodulator										
Approx. Average Cost ($)		N/A		N/A	25	167	5	33	2	13
ADC (Dual-Channel)										
Approx. Average Cost ($)	2	3,000	2	1,443	25	1,681	5	513	2	205
Channelizer										
Approx. Average Cost ($)	2	1,450	2	1,450		N/A	2	1,450	2	1,450
DSP and DSP Board										
Approx. Total Cost ($)	2	763	2	763	2	763	2	763	2	763
Primary CPU										
Approx. Average Cost ($)	2	700	2	700	2	700	2	700	2	700
Synthesizer (Dual RF Output)										
Approx. Average Cost ($)		N/A	1	7	25	176	5	35	2	14
Filter										
Approx. Average Cost ($)	2	26	4	30	50	379	5	60	4	48
Power Dividers										
Approx. Average Cost ($)		N/A	2	3	25	40	5	7		N/A
Mixer										
Approx. Average Cost ($)		N/A	2	9		N/A		N/A		N/A
Quad Hybrid										
Approx. Average Cost ($)		N/A	2	4		N/A		N/A		N/A
Combined Cost Estimate ($)		5,940		4,409		3,906		3,561		3,194

Table C2-3: Cost estimate for SDR transmitter back end in locomotive platform

Component	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5	N	Arch 6
PA	Quotes from multiple vendors											
Approx. Average Cost (Π/4 DQPSK) ($)		N/A	3	4,013		N/A	3	4,013	3	4,013	1	4,900
Approx. Average Cost (OFDM) ($)		N/A	1	8,500		N/A	4	8,500	4	8,500	1	6,000
Filter	Quotes from multiple vendors											
Approx. Average Cost ($)	1	1684	1	1,684	1	1684	1	1,684	1	1,684	1	1,684
Combined Cost Estimate (Π/4 DQPSK) ($)		N/A		5,697		N/A		5,697		5,697		6,584
Combined Cost Estimate (OFDM) ($)		N/A		10,184		N/A		10,184		10,184		7,684

Note: The manufacturers, model numbers and individual costs are not shown for PAs and filters due to the proprietary nature of the quotes provided by the vendors.

Table C2-4: Cost estimate for SDR receiver front end in locomotive platform

Component	N	Arch 1	N	Arch 2	N	Arch 3	N	Arch 4	N	Arch 5
AGC/VGA										
Approx. Average Cost ($)	2	38.08	2	38.08	8	152.32	8	152.32	4	76.16
Filters1	Quotes from multiple vendors									
Approx. Average Cost ($)		1,852		1,852		1,852		1,852		1,852
LNAs										
Approx. Average Cost ($)	4	28.88	4	28.88	8	57.76	8	57.76	2	14.44
Power Combiner/Divider										
Approx. Average Cost ($)		N/A	2	6		N/A	1	3	1	3
Combined Cost Estimate ($)		1,919		1,925		2,062		2,065		1,945

Note: The manufacturers, model numbers, and individual costs are not shown for filters due to the proprietary nature of the quotes provided by the vendors.

Table C2-5 illustrates the potential combinations within transmitter and receiver architectures for the Base Station platform.

Table C2-5: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			Rx Architectures	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Note: Refer to Section 4 for Tx and Rx architectures.

Table C2-6 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK and OFDM modulations.

Table C2-6: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Unit Cost (OFDM) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)[2]	Total Cost Estimate (OFDM) (in $)[2,3]
1	**A**	5,868	10,355	**A**	8,005	13,872	18,360
2	**A**	5,868	10,355	**B**	6,474	12,341	16,829
3	**A**	5,868	10,355	**C**	5,969	11,836	16,324
4	**A**	5,868	10,355	**D**	5,624	11,491	15,979
5	**B or C**	5,788	10,276	**A**	8,005	13,793	18,280
6	**B or C**	5,788	10,276	**B**	6,474	12,262	16,749
7	**B or C**	5,788	10,276	**C**	5,969	11,757	16,245
8	**B or C**	5,788	10,276	**D**	5,624	11,412	15,899
9	**D**	5,847	10,334	**A**	8,005	13,851	18,339
10	**D**	5,847	10,334	**B**	6,474	12,320	16,808
11	**D**	5,847	10,334	**C**	5,969	11,815	16,303
12	**D**	5,847	10,334	**D**	5,624	11,470	15,958
13 [1]	**E**	6,620	7,720	**E**	5,139	14,259	15,359

Notes:

1. Price include approximate cost of 900 MHz dedicated radio.
2. Price doesn't include cost estimations for antennas.
3. Cost for OFDM assumes PAPR reduction.

C3. Wayside SDR Cost Estimate

Unlike the locomotive and base station cost estimates, this section only shows the cost estimates summary for the wayside platform across various SDR system architectures. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C3-1 illustrates the potential combinations within transmitter and receiver architectures for the Wayside platform.

Table C3-1: Combinations of SDR Transmitter and Receiver Architecture

	Tx Architectures			Rx Architectures	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Note:

1. Refer to Section 3 for Tx and Rx architectures.
2. Combination E is not applicable for Wayside platform.

Table C3-2 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK modulation scheme.

Table C3-2: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)
1	**A**	1,012	**A**	5,238	6,250
2	**A**	1,012	**B**	3,717	4,730
3	**A**	1,012	**C**	3,479	4,491
4	**A**	1,012	**D**	2,514	3,526
5	**B or C**	897	**A**	5,238	6,134
6	**B or C**	897	**B**	3,717	4,614
7	**B or C**	897	**C**	3,479	4,376
8	**B or C**	897	**D**	2,514	3,411
9	**D**	897	**A**	5,238	6,134
10	**D**	897	**B**	3,717	4,614
11	**D**	897	**C**	3,479	4,376
12	**D**	897	**D**	2,514	3,411
13	**E**	N/A	**E**	N/A	N/A

Note: Price doesn't include cost estimations for antenna.

C4. Hi-Rail SDR Cost Estimate

Unlike the Locomotive and Base Station cost estimates, this section only shows the cost estimates summary for the hi-rail platform across various SDR system architectures. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C4-1 illustrates the potential combinations within transmitter and receiver architectures for the Hi-Rail platform.

Table C4-1: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			**Rx Architectures**	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Note: Refer to Section 4 for Tx and Rx architectures.

Table C4-2 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK modulation scheme.

Table C4-2: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)
1	**A**	2,021	**A**	5,021	7,042
2	**A**	2,021	**B**	3,480	5,501
3	**A**	2,021	**C**	2,134	4,155
4	**A**	2,021	**D**	2,134	4,155
5	**B or C**	1,955	**A**	5,021	6,976
6	**B or C**	1,955	**B**	3,480	5,435
7	**B or C**	1,955	**C**	2,134	4,089
8	**B or C**	1,955	**D**	2,134	4,089
9	**D**	1,955	**A**	5,021	6,976
10	**D**	1,955	**B**	3,480	5,435
11	**D**	1,955	**C**	2,134	4,089
12	**D**	1,955	**D**	2,134	4,089
13	**E**	5,443	**E**	2,176	7,618

Note: Price doesn't include cost estimations for antenna.

C5. Handheld SDR Cost Estimate

Unlike the locomotive and base station cost estimates, this section only shows the cost estimates summary for the handheld platform across various SDR system architectures. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C5-1 illustrates the potential combinations within transmitter and receiver architectures for the Handheld platform.

Table C5-1: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			**Rx Architectures**	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Note:

1. Refer to Section 3 for Tx and Rx architectures.
2. Combination E is not applicable for Handheld platform.

Table C5-2 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK modulation scheme.

Table C5-2: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)
1	**A**	986	**A**	5,023	6,009
2	**A**	986	**B**	3,482	4,468
3	**A**	986	**C**	2,135	3,121
4	**A**	986	**D**	2,135	3,121
5	**B or C**	920	**A**	5,023	5,943
6	**B or C**	920	**B**	3,482	4,402
7	**B or C**	920	**C**	2,135	3,055
8	**B or C**	920	**D**	2,135	3,055
9	**D**	920	**A**	5,023	5,943
10	**D**	920	**B**	3,482	4,402
11	**D**	920	**C**	2,135	3,055
12	**D**	920	**D**	2,135	3,055
13	**E**	N/A	**E**	N/A	N/A

Note: Price doesn't include cost estimations for antenna.

C6. EOT SDR Cost Estimate

Unlike the locomotive and base station cost estimates, this section only shows the cost estimates summary for the EOT platform across various SDR system architectures. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C6-1 illustrates the potential combinations within transmitter and receiver architectures for the EOT platform.

Table C6-1: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			**Rx Architectures**	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Notes:

1. Refer to Section 4 for Tx and Rx architectures.
2. Combination E is not applicable for EOT platform.

Table C6-2 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK modulation scheme.

Table C6-2: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)
1	**A**	1,093	**A**	4,784	5,877
2	**A**	1,093	**B**	3,236	4,330
3	**A**	1,093	**C**	1,875	2,969
4	**A**	1,093	**D**	1,875	2.969
5	**B or C**	987	**A**	4,784	5,771
6	**B or C**	987	**B**	3,236	4,224
7	**B or C**	987	**C**	1,875	2,863
8	**B or C**	987	**D**	1,875	2,863
9	**D**	987	**A**	4,784	5,771
10	**D**	987	**B**	3,236	4,224
11	**D**	987	**C**	1,875	2,863
12	**D**	987	**D**	1,875	2,863
13	**E**	N/A	**E**	N/A	N/A

Note: Price doesn't include cost estimations for antenna.

C7. UAS SDR Cost Estimate

Unlike the locomotive and base station cost estimates, this section only shows the cost estimates summary for the UAS platform across various SDR system architectures. The actual component manufacturers and model numbers were mentioned in Section 4.4.

Table C7-1 illustrates the potential combinations within transmitter and receiver architectures for the UAS platform.

Table C7-1: Combinations of SDR transmitter and receiver architecture

	Tx Architectures			**Rx Architectures**	
Tx Combination	Modulator Arch	Tx Back-End Arch	**Rx Combination**	Demodulator Arch	RF Front-End Arch
A	1	5	**A**	1	4
B	2	4	**B**	2	4
C	3	4	**C**	3	3
D	4	4	**D**	4	3
E	5	6	**E**	5	5

Notes:

1. Refer to Section 4 for Tx and Rx architectures.
2. Combination E is not applicable for UAS platform.

Table C7-2 shows the total cost estimates for various SDR system architectures for Π/4 DQPSK modulation scheme.

Table C7-2: Combinations of SDR system architecture and cost estimate summary

SDR Combination	Tx Combination	Unit Cost (Π/4 DQPSK) (in $)	Rx Combination	Unit Cost (in $)	Total Cost Estimate (Π/4 DQPSK) (in $)
1	**A**	1,421	**A**	5,312	6,733
2	**A**	1,421	**B**	3,764	5,185
3	**A**	1,421	**C**	2,403	3,824
4	**A**	1,421	**D**	2,403	3,824
5	**B or C**	1,315	**A**	5,312	6,627
6	**B or C**	1,315	**B**	3,764	5,079
7	**B or C**	1,315	**C**	2,403	3,718
8	**B or C**	1,315	**D**	2,403	3,718
9	**D**	1,315	**A**	5,312	6,627
10	**D**	1,315	**B**	3,764	5,079
11	**D**	1,315	**C**	2,403	3,718
12	**D**	1,315	**D**	2,403	3,718
13	**E**	N/A	**E**	N/A	N/A

Note: Price doesn't include cost estimations for antenna.

Abbreviations and Acronyms

Abbreviation or Acronym	**Name**
AAR	Association of American Railroads
ACSES	Advanced Civil Speed Enforcement System
ADC	Analog to Digital Converter
AG	Advisory Group
AGC	Automatic Gain Control
AREMA	American Railway Engineering and Maintenance-of-Way Association
ATCS	Advance Train Control System
BEM	Bandwidth Efficient Modulation
BER	Bit Error Rate
BRC	Belt Railway of Chicago
BW	Bandwidth
CA	Carrier Aggregation
CC	Component Carrier
CFR	Code of Federal Regulations
C/I	Carrier-to-Interference ratio
CIM	Configuration Information Management
COTS	Commercial Off-The-Shelf
CSMA	Carrier Sense Multiple Access
DAC	Digital to Analog Converter
dB	Decibel
dBm	Decibel-Milliwatts
DDC	Digital Down Conversion
DFT	Discrete Fourier Transform
DQPSK	Differential Quadrature phase shift keying
DSP	Digital Signal Processor
EIRP	Equivalent Isotropically Radiated Power
ELM	External Link Manager
EMI	Electromagnetic Interference
EOT	End-of-Train
ERP	Effective Radiated Power
FCC	Federal Communication Commission
FFT	Fast Fourier Transform
FIFO	First In, First Out
FIR	Finite Impulse Response
FPGA	Field-Programmable Gate Arrays
FRA	Federal Railroad Administration
FSPL	Free Space Path Loss
GPS	Global Positioning System
GSPS	Giga-Samples Per Second
HOT	Head-of-Train
HW	Hardware

Abbreviation or Acronym	Name
IEEE	Institute of Electrical and Electronics Engineers
I-ETMS	Interoperable-Electronic Train Management System
IETF	Internet Engineering Task Force
IF	Intermediate Frequency
IMD	Intermodulation Distortion
IP	Internet Protocol
ISMP	InterSwitch Message Protocol
ITC	Interoperable Train Control
ITCC	ITC Communications system
ITCM	ITC Messaging
ITCnet	Interoperable Train Control Network
LIFO	Last In, First Out
LNA	Low Noise Amplifier
LSI	Locomotive System Integration
LTE	Long Term Evolution
Mb/s	Megabits per Second
MB/s	Megabytes per Second
MSPS	Mega-Samples Per Second
MSRP	Manual of Standards and Recommended Practices
MTTF	Mean Time to Failure
NB	Narrowband
NF	Noise Figure
NMS	Network Management System
NRE	Non-Recurring Engineering
OBC	Onboard Computers
OCM	Office Communications Manager
OFDM	Orthogonal Frequency-Division Multiplexing
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PEP	Peak Envelope Power
PFFB	Polyphase FFT Filter Bank
PPM	Parts per Million
PPS	Pulse per Second
PTC	Positive Train Control
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAM	Random Access Memory
RCL	Remote Control Locomotive
RF	Radio Frequency
RFI	Request For Information
RFC	Request For Comments
RSSI	Received Signal Strength Indication
Rx	Receive/Receiver
SDR	Software-Defined Radio

Abbreviation or Acronym	Name
SNR	Signal-to-Noise Ratio
SRAM	Static Random-Access Memory
TBD	To Be Defined
TBDBS	To Be Defined By Supplier
TDMA	Time Division Multiple Access
TMC	Train Management Computer
TO	Task Order
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
Tx	Transmit/Transmitter
UAS	Unmanned Aerial System (drone)
UHF	Ultra-High Frequency
VGA	Variable Gain Amplifier
VHDL	Very high-speed integrated circuit Hardware Description Language
VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
WB	Wideband
WCR	Wireless Communications Roadmap
WIU	Wayside Interface Unit