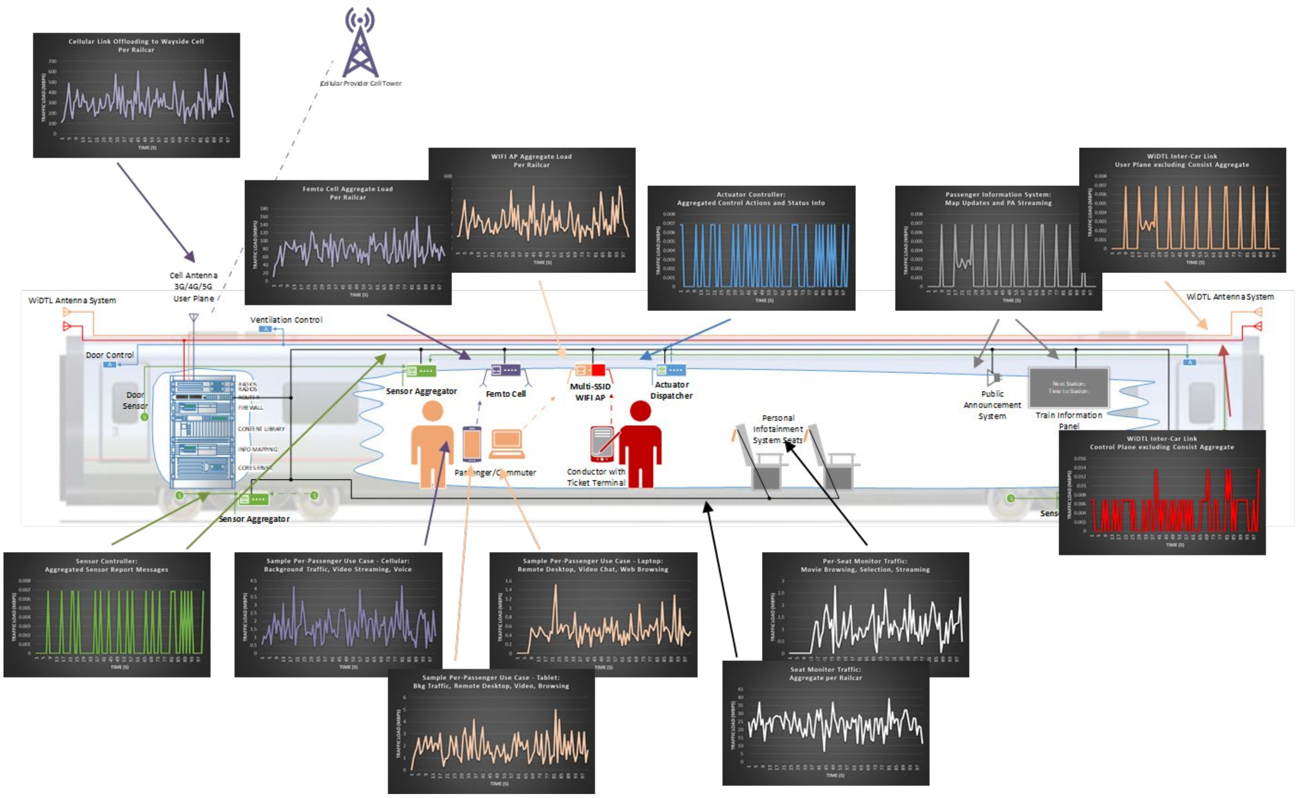
U.S. Department of Transportation

Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Wireless Digital Train Line for Passenger Trains



DOT/FRA/ORD-20/12

Final Report
March 2020

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE March 2020		3. REPORT TYPE AND DATES COVERED Technical Report Aug 2015–March 2019
4. TITLE AND SUBTITLE Wireless Digital Train Line for Passenger Trains			5. FUNDING NUMBERS FR-RRD-0065-15-01-00
6. AUTHOR(S) Hamid Sharif			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Board of Regents of the University of Nebraska for the University of Nebraska-Lincoln 3835 Holdrege Street Lincoln, Nebraska 68583			8. PERFORMING ORGANIZATION REPORT NUMBER
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			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-20/12
11. SUPPLEMENTARY NOTES COR: Tarek Omar			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA eLibrary.			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) This research project evaluated current wireless communication standards used by high-speed passenger rail services around the globe and determined, based on those findings, an architecture design suitable for U.S. high-speed rail implementations that addresses application requirements, overcomes limitations, and unifies several disparate communication services onboard passenger trains. The developed architecture was evaluated for its performance and feasibility using a new computer simulation toolset. The findings from this project were supportive of the architecture and pave the way toward real-world system testing during a follow-up phase.			
14. SUBJECT TERMS Digital train line, wireless connectivity, 5G, WiDTL, user/control plane, high-speed rail, passenger rail service			15. NUMBER OF PAGES 28
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

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

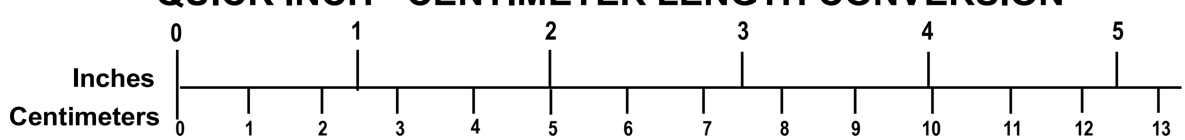
VOLUME (APPROXIMATE)

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

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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

From August 2015 through March 2019, the Advanced Telecommunications Engineering Laboratory (TEL) at the University of Nebraska designed and evaluated a new networking architecture for high-speed passenger trains, and through the use of a new computer simulation platform, established the performance advantages and feasibility of this architecture.

TEL researchers' evaluation of the current state-of-the-art showed that it is not capable of supporting the anticipated demands for performance, latency, security, and reliability that high-speed rail services require.

The purpose of this effort was to study and develop a networking architecture that addresses all of the disparate challenges and requirements faced when considering passenger service needs, onboard system requirements, and technology capabilities.

TEL's architecture both addresses these and establishes itself as future-proof by decoupling all onboard train technologies from each other and enabling targeted technology evolutions to be implemented through upgrades when needed.

The developed architecture combines unique features, such as the proposed user/control plane separation, a new wireless digital trainline approach, an adaptive approach to balancing reliability and performance, and the ability to address virtually all onboard and wayside communications requirements through a single unified architecture. It utilizes these features to achieve targeted performance goals, such as low latency for train control functions or high throughput for content-rich passenger services.

While TEL's work showed the great potential in simulation trials, additional testing will be conducted using real-world devices and deployments in phase 2 of this ongoing research effort. This will include lab and field testing. The results of these tests will be used to increase the accuracy of the computer simulations and to scale-up the scenario size that can be used within the simulator.

1. Introduction

This Advanced Telecommunications Engineering Laboratory (TEL) project focused on studying how wireless technologies could be utilized for high-speed rail applications while addressing a host of requirements, including enhanced passenger services and innovating how train systems are interconnected. This project presented a unique opportunity to leverage TEL's expertise and long collaboration with the rail industry in North America.

1.1 Background

With the advent of diesel locomotives in the railroad industry came a significant shift toward a technology-integrated method of operations. The need to coordinate and control multiple units and railcars in a train consist gave rise to the train line system via a connector and cable assembly. A similar approach can be used on passenger trains to provide data to displays about upcoming stops, or to support a public announcement system, operate doors, etc. In such a configuration, a signaling and control bus is established along the entire train, from the locomotive through all the passenger railcars. This is currently achieved via a bulky connecting cable that carries between 24 and 64 different analog signals, each dedicated to a single specific function. This signaling and data bus distributes commands from the train conductor or engineer to trailing locomotives, passenger cars, etc.

However, the current system is a multi-pin connector that, as stated above, relies on analog signal lines, each dedicated to specific train functions. In many cases, DC voltage levels indicate desired values for specific parameters. This approach is maintenance-intensive, costly, bulky, and error-prone. It requires shielding to prevent potential noise problems and errors in transmitting accurate command and control information from occurring. This approach also limits expandability. All 27 pins are assigned to dedicated functions, such as the throttle, emergency sand operation, brake warnings, headlights, alarm bell operation, etc. Furthermore, the need for cabling increases maintenance costs and creates points of failure for this system. All of these limitations highlight the need to create a new approach for trainline communication.

1.2 Objectives

With the planned efforts to establish a nationwide high-speed passenger rail service, as well as expanding the passenger rail services across the country, the key to success lies in efficient train operations and passenger safety—as well as value-add services for passengers.

Various railroad industry groups and government representatives are currently working together to upgrade the industry standards of the analog train line system to a wired digital communication system. This service is called digital train line, or DTL. In this first project phase the focus is on developing DTL into a working, industry-wide replacement of the old analog trainline system and to further advance this approach into the concept of wireless DTL, or WiDTL. There are numerous issues that need to be resolved, from cabling and connectors, to protocol and application support, to integration with legacy systems and supporting their continued operation during the transition phase.

This was the focus also of TEL’s activities during this initial project phase, leveraging expertise in wired and wireless networks, as well as protocol design, system evaluation, and integration to the railroad technology groups working on DTL.

1.3 Overall Approach

TEL’s approach to this initial phase was to first review the current state-of-the-art and efforts underway, and connect with the responsible industry groups and stakeholders. TEL then utilized this connection to aid in ongoing efforts, review requirements, suggest changes, and develop the concept of WiDTL. WiDTL does require extensive evaluation, and the company’s primary contribution lies in the development of a computer simulation tool that can help the rail industry in evaluating candidate technologies for WiDTL applications. TEL used this tool in this research effort to gauge the feasibility of the overall platform design.

1.4 Scope

In this work, the primary focus is on the use of DTL and WiDTL in passenger rail services. It thus does not cover freight rail services, but the technology does support application in the freight rail sector.

1.5 Organization of the Report

The next several sections describe all of the core efforts related to TEL’s work with DTL and WiDTL. This includes outreach activities to the stakeholders in this effort (Section 2), review of the current state of the art in high-speed passenger train wireless connectivity (Section 3), design of WiDTL (Section 4), and performance evaluation efforts (Section 5).

2. Stakeholder Engagement and Industry Participation

For our research to be truly applicable to addressing rail industry issues, it is vital for our efforts to include regular and frequent communications with all relevant parties. This includes a variety of domains, from our project sponsor to equipment manufacturers and rail service operators. Therefore, we focused on engaging with these stakeholders.

2.1 Stakeholder Groups

For this project we identified two key groups and the primary stakeholders:

On the freight railroad side, the Association of American Railroad's (AAR's) Locomotive Committee formed the Locomotive Consist Control (LCC) Technical Advisory Group (TAG). LCC TAG is responsible for overseeing the efforts on the freight railroad industry side and ensuring compliance with 49 CFR Part 229, Subpart E.

These efforts are focused on using Ethernet technology to connect locomotives. A field demonstration of two different approaches was planned for October 2015 at TTC.

However, this demonstration was mostly focused on mechanical aspects of the connection and was not open to non-industry members, and thus TEL unfortunately could not attend.

Among the people contacted on the AAR side were:

- AAR: Bob Kollmar, Nader Ebeid
- BNSF: Jim Barrett, James Brady
- CN: Carlos da Roza, Cory Wyka
- CSX: Alex Latchaw
- EMD: Allen Mitchel, Ben Raeder, Wayne Rudolph
- GE: Mark Kraeling, Patty Lacy, Eric Vorndran
- MCC: Rachel Milcic, Tim Potter
- NS: Bruce Backus, Richard New, Tim Wymer
- UPRR: Raymond Peterson, Tom Vaiskunas
- Wabtec: Ted Allwardt

On the passenger rail side, the effort is directed through the Next Generation Equipment Committee (NGEC). The NGEC was created in response to the Passenger Rail Investment and Improvement Act (PRIIA) of 2008, H.R.6003, where in Title III Section 305 it instructs Amtrak to "establish a Next Generation Corridor Equipment Pool Committee to design, develop specifications for, and procure standardized next-generation corridor equipment." [1, 2]

The NGEC was not fixed on a wired solution and was interested in pursuing the possibility of a wireless approach to DTL.

The list of people contacted on the Amtrak side included:

- Eric Curtit, Missouri DOT
- Mario Bergeron, Amtrak

- Tammy Nicholson, Iowa DOT
- Ray Hessinger, New York DOT
- Darrell Smith, Amtrak
- John Oimoen, Illinois DOT

2.2 Meeting and Conference Call Participation

Each group organized weekly or biweekly conference calls to inform members of ongoing efforts and progress. TEL representatives were invited to join these calls and report on the progress of our efforts. They continued this engagement throughout the entire project phase.

On October 6, 2015, AAR's Railway Electronics Standards Committee (RESC) had a full committee meeting. This event was co-hosted with the AREMA 2015 Railway Interchange Annual Conference, October 4–7, 2015, in Minneapolis, MN.

The event schedule included discussions and status updates on the AAR's efforts on DTL, and hence provided an ideal opportunity to connect with railroad personnel and stakeholders in DTL.

TEL representatives' participation there was very successful. They made several connections that were instrumental throughout this project phase.

Below are several photos from the event and the AREMA conference.

Figure 1. AREMA conference show floor engagements

Figure 2. AREMA conference show floor

Figure 3. Vendor booth showcasing train communication system

The team also attended the SafeRail 2016 event, held together with the PTC World Congress, from March 22–23, 2016 in Washington, DC. This event brought together a wide array of equipment vendors, some of which are also engaged in the development of DTL and are industry participants on the AAR and NGEC conference calls.

The team had the opportunity to meet with these vendors and explored their efforts and potential collaborations in this endeavor. Overall, TEL's participation in this event was a success and the team returned with many novel insights. The team continued its engagements with stakeholders throughout this project phase, and gained invaluable insights that helped shape TEL efforts and focus its research.

3. Technology Review of High-Speed Passenger Train Wireless Connectivity

Through one of our first engagements with the stakeholders on this research topic it became clear that a comprehensive analysis of existing technologies was required in order to present the current state-of-the-art to the railroad community. We published our findings in peer reviewed scientific articles, including in [3].

Hence the TEL team's first research task focused on collating information from a range of scientific publications about the wireless communication technologies in use by high-speed rail operators around the world. From the information the team compiled, it generated a high-level overview, shown in the following table.

Specifically, train operations are surveyed in [4]. GSM-R and related technologies were analyzed in [5-9], Wireless LAN technologies in [10-13], 4G LTE and LTE-R in [9-14]. Radio-over-fiber (RoF) was analyzed extensively in [15-18], leaky coaxial cable in [19, 20], and satellite communication in [21, 22, 45].

Table 1. Overview of high-speed train systems and associated key wireless technologies

High Speed Trains	Country	Key Cities & Routes	Avg. Speed (km/hr.)/Max. Speed (km/hr.)	Key Wireless Technologies Used
TGV-POS (SNCF)	France	Basel, Zurich, Vallorbe, Lausanne	320/574.8	ETCS-2/Satellite
CRH380A & AL (China Railway Corporation)	China	Shanghai-Hangzhou Shanghai-Nanjing	300/487.3	GSM-R
AVE Class 103 (RENFE)	Spain	Madrid, Taragona	310/403.7	GSM-R (ETCS-2)
ICE 3 class 403, 406 (Deutsche Bahn, Nederlandse Spoorwegen)	Germany	Frankfurt, Paris	330/368	GSM-R, Radiating cable (LCX), Wi-Fi
ETR 500 (Trenitalia)	Italy	Rome, Naples, Florence, Bologna	300/362	Radiating cables, Wi-Fi, GSM-R
KTX-I	South Korea	Seoul, Busan	330	ATC (Automatic Train Control), Wi-Fi
Eurostar (GNER, SNCF)	France, Spain, England	Brussels, Lille, London.	300/334.7	Wi-Fi, WIMAX, ETCS-2
N700 Shinkansen (JR West, JR Central, JR Kyushu)	Japan	Tokyo, Osaka, Tokaido-Sanyo	275/332	LCX
THSR 700T	Taiwan, China	Taoyuan, Hsinchu, Taichung	300	RoF, WIMAX
Acela (Amtrak)	USA	Washington, Baltimore, New York	240/265	Wi-Fi, GSM-R
Pendolino	Finland	Helsinki, Tampere	250	Flash-OFDM, WIMAX

Based on this information, the team proceeded to evaluate these wireless technologies for various performance parameters. This analysis was based on available information and theoretical performance envelope studies. The results are shown in the figure below. From that information representatives could then conduct an application-driven analysis: How well does each technology support different end-user applications, such as video-streaming, teleworking for commuter passengers, web browsing, etc. For this analysis team members assumed ridership levels in accordance with published statistics and expected use case scenarios for planned U.S.-based high-speed rail services.

Table 2. Analysis of different wireless technologies in use by high-speed rail services

Parameters	Wireless Technologies										
	GSM-R	P25	TETRA	802.11	WIMAX	3G	LTE-R	RoF	LCX	Satellite	FLASH-OFDM
Working Frequency	800 - 900 MHz	700 MHz	~400 MHz	2.4/5.8 GHz	2.3/2.4/2.5/3.5 GHz	800/910 MHz 2.1 GHz	Variable 400 - 3.5 GHz	Variable	Variable	Limited	450 MHz and variable
Data Rate	5 - 10 Kbps	40 - 100 Kbps	5 - 10 Kbps	>10 Mbps	>30 Mbps	>2 Mbps (stationary) >384 Kbps (Mobile)	>10 Mbps	1 - 10 Gbps	1 - 10 Mbps	>2 Mbps	>2 Mbps
IP Support	Not standalone	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Handover Mechanism	Open standard (till 500 km/h)	Open standard	Open standard	Proprietary	Open standard/High handover	Open standard	Open	Open;	Open	Depends	Proprietary;
Modulation/ Multiplexing	GMSK -TDMA	4FSK	DQPSK-TD MA	QPSK, QAM	BPSK, QPSK 16 QAM	PSK	QPSK, 16 - 64 QAM (OFDM, SCFDMA)	QPSK, 16QAM-OFD M	Standard and OFDM	FSK-PSK	OFDM
Maturity	Mature, supporteduntil 2025	Mature in US	Mature	Mature	Mature, lead to WIMAX 2	Mature	Emerging and offered	Concepts like “moving cell”	Matured (N700)	Matured but costly	Matured
Market Support	Until 2025	US	Yes/almost obsolete	Yes	Yes, decreasing	Yes, but moving to LTE	Yes, building standards	Matured	Japan, Europe	Yes, in Europe Thalys, SNCF	Yes, Flarion

In all scenarios the conclusion was the same: Current technologies do not sufficiently support the demand generated by the expected ridership levels coupled with the current penetration level of mobile devices and applications.

Another key research area of interest is Cognitive Radios. These are software-driven radio solutions that instead of optimized fixed-function chipsets rely on programmable high-performance digital signal processing chipsets. This enables them to adapt on the fly to changes in their RF environment and communication requirements. Some of the research in this area is documented in [24-26]. Another key area of research activity is found in the RF challenges, with channel propagation research conducted in [27-29], handover for high-speed trains being analyzed in [30-37], and various other challenges and approaches being presented in [38-45].

From studying all of these efforts we can learn that there are two primary architectures for end-to-end connectivity between passengers and the internet:

1) There are Wi-Fi access point and/or small cell base stations installed within the passenger railcars. All passengers’ mobile devices connect to those. The aggregate traffic from all passenger—plus all onboard—systems needing to communicate off-train, is then sent through an onboard cellular radio to the nearest base station trackside. This simplifies connection management because all passengers stay connected to the onboard equipment during their ride.

2) Each passenger on the train directly connects via cellular to the nearest trackside base station. This simplifies the onboard network architecture, but hinders the performance of each end-user because now each device individually needs to manage frequent

connection changes whenever the train moves from one base station coverage area to the next—a process called handover.

In both of these scenarios, however, the cumulative traffic load onto the shared wireless medium between train and track-side cellular base station is approximately the same. Hence, an approximate analysis of the expected application load support can easily be conducted.

The following graph first shows the expected total throughput capacity of a 4G LTE trackside base station. This analysis assumes operation in the 2 GHz frequency band and a transmit power of 86 dBm.

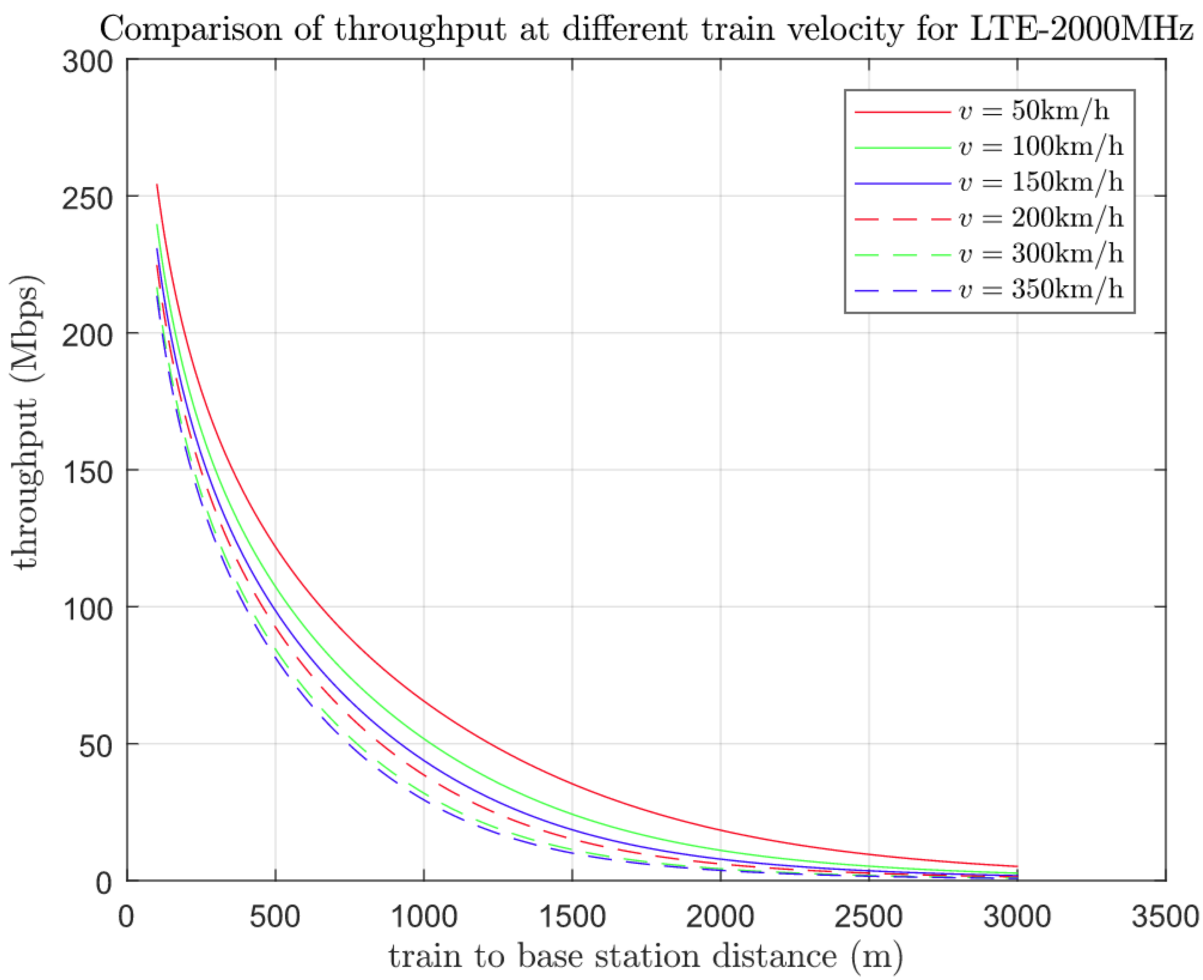


Figure 4. 4G LTE performance at 2 GHz and 86 dBm transmit power

While the maximum throughput is quite high, at over 200 Mbps, that performance degrades rapidly with increasing distance from the base station. At 2000 m from the base station, the maximum performance has dropped to less than 25 Mbps. Note that this represents the capacity shared by all riders.

When this is expressed as, for example, the number of concurrent Netflix streaming sessions, it becomes clear that this is insufficient performance.

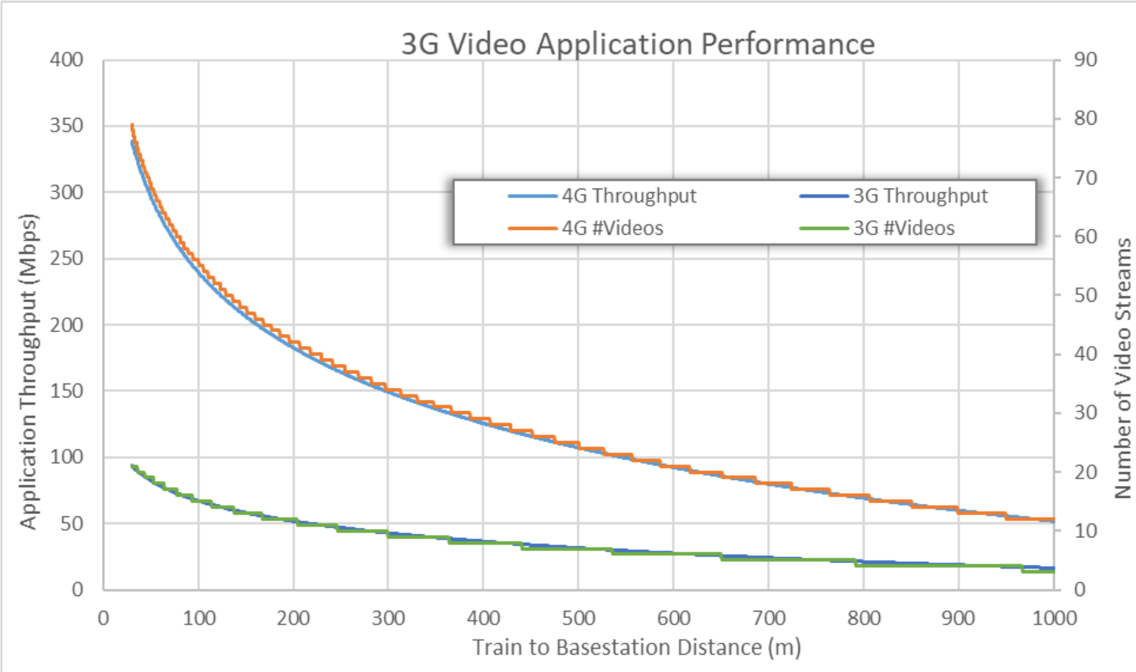


Figure 5. Comparison of 3G and 4G performance and their effective video stream support

It was clear from these numbers that current technologies would barely support current demand, and would definitely not be a future-proof choice, or even scale with the anticipated growth in demand over the next few years.

Hence, the focus shifted to a new architecture utilizing novel technologies. This became the next research focus: After collecting all the requirements, researchers designed a new architecture that addressed the various demands from different aspects of high-speed rail systems:

- Passenger services needed to support a myriad of applications, from video streaming and telework for commuters to rich infotainment offerings, ticket purchases, and more.
    - These services focus on high performance and security, but do not require low latency or high robustness.
    - Any traffic fitting this category was labeled “user plane” traffic.
- Onboard systems must be able to report data reliably and in a timely fashion. They must be able to communicate with each other as well as with offboard systems, dispatch centers, and more.
    - Secure data transmissions are required, as is ultra-low latency, but these services do not require high throughput performance.
    - Any services under this category were grouped into the “control plane” traffic category.

There are competing demands between user and control plane traffic. Addressing these is a challenging endeavor.

In the end, the suggested architecture for future onboard systems is summarized by Figure 6 and Figure 7, below. In this architecture, all networking activity is coordinated and routed through an onboard networking closet. It effectively is a translator between different networking technologies and an aggregator of traffic. All network traffic—from passengers and equipment alike—routes through the network closet, and from there takes one of two paths:

1. If it is destined to an off-board receiver, such as an internet service, the dispatch center, or other trackside equipment, it will be sent through the cellular link to the nearest cell tower.
2. If it is destined to another onboard device or passenger, it may be routed through the wireless digital trainline (WiDTL) connection that exists between adjoining railcars. This WiDTL interconnect spans the entire length of the train. It is split into the aforementioned user and control plane interfaces that enable this architecture to fulfill all specific traffic demands on latency, reliability, security, performance, etc.

This architecture is replicated in each passenger railcar, and also—in a modified form—the power car, as shown in the following figure. On the power car, passenger-centric services are not required, but additional interfaces exist for the train engineer to control train systems, review trackside system status information obtained wirelessly, obtain precise location data from track-mounted balises, observe the PTC system status, etc.

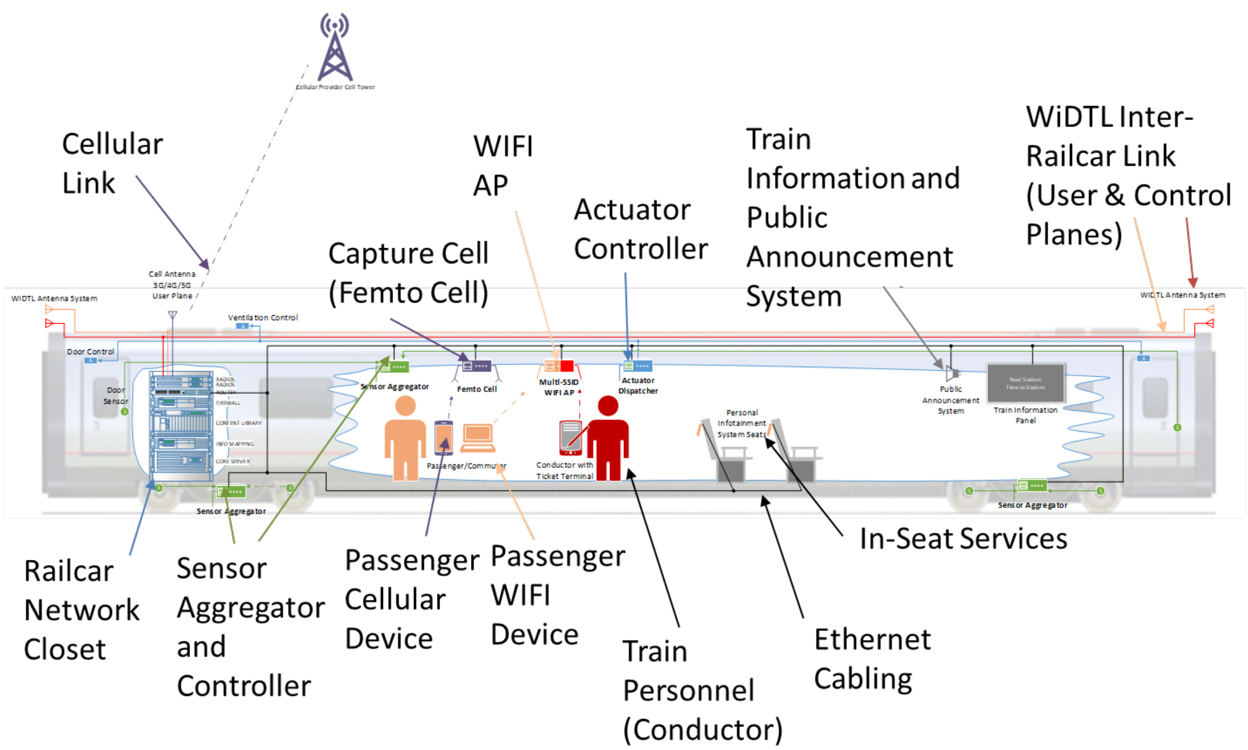


Figure 6. Proposed passenger railcar networking architecture

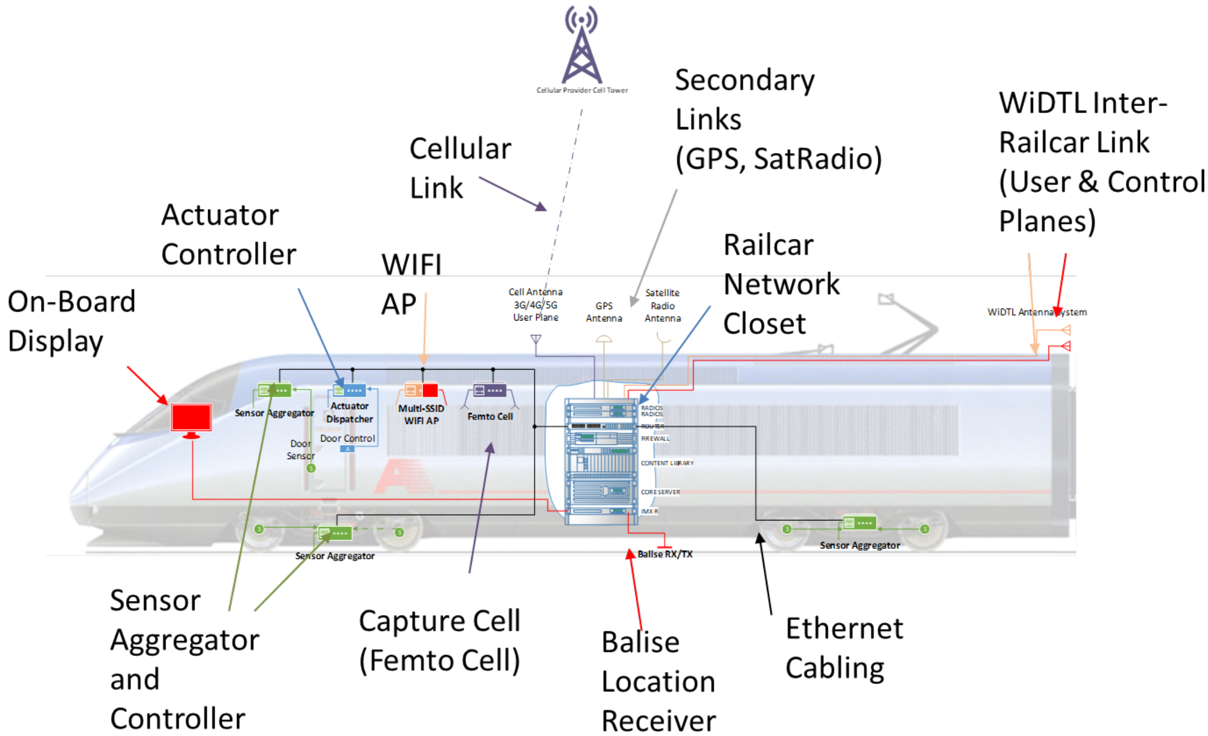


Figure 7. Proposed power car networking architecture

This architecture provides several key advantages:

- Railcars are atomic units; that is, within a single railcar, connections are independent of connections between railcars or from railcars to the internet. This allows railcar-internal cabling to be used and shifts the focus on how to interface railcars with each other and with wayside infrastructure.
- Users are expected to carry a variety of personal devices connecting to the internet in different ways. Researchers principally grouped these connections into onboard Wi-Fi and onboard cellular traffic. Cellular traffic in this architecture is aggregated by each railcar's capture base station. Traffic is then tagged and delivered through a networking closet on each railcar to the remaining infrastructure. Network closets are equipped with a variety of radio technologies and it is here that the heart of this architecture resides.
- It addresses the need for a revision to the current trainline system. While current efforts are underway to transition to DTL, this still represents a wired approach, suffering from similar limitations as the current analog trainline system. The envisioned WiDTL, on the other hand, would alleviate many, if not all, of these limitations.
- It addresses the various competing requirements of different networking activities onboard high-speed passenger trains by providing physically and logically distinct network pathways for the data, each addressing the specific requirement independently of the other network paths.

- It is future-proof because no network path depends on specific technology being employed. As such, it can grow by transitioning, for example, from 4G to 5G to 6G when available or required. This transition path is key to ensuring economic viability of this system while ensuring that performance demands are met.

4. Network Simulation of Proposed Architecture

To evaluate the specific capabilities of this architecture, TEL staffers needed to conduct computer simulations of the employed technologies. Unfortunately, no simulator currently supports all these technologies. Hence, researchers endeavored to integrate needed capabilities into an existing open-source network simulation platform called ns-3. Within this package, a number of key technologies have already been implemented. Others are missing and needed to be added. Furthermore, some of the implemented features lack the fidelity desired for the simulation environment.

TEL envisioned this tool to be useful for the greater railroad community as well, to enable network engineers to quickly and easily evaluate specific scenarios during deployment planning and technology selection.

TEL integrated or improved the following capabilities:

- Full support for user/control plane separation according to the proposed UCDA (user/control plane decoupled architecture) scheme
- Support for current 4G cellular technology
- Support for 5G physical layer simulations, including mmWave technology above 6 GHz
- Fully realized handover scheme support in simulator
- Support for environmental features such as hills, bridges, tunnels, and cuttings
- Support for new channel models (WINNER II D2a, free space, CIR, ABG, COST231, ITU-T)
- Support for single/dual/multi-link scenarios
- Scenario-based PHY channel models (individual models for different scenarios)
- Support for in-train femto cells
- Support for in-train Wi-Fi
- Enhanced framing and synchronization
- Enhanced control signaling

Researchers then incorporated control of all these features into a simple-to-use scripting approach that allows engineers a template-driven approach to simulations that simply requires the modification of a few script values to realize specific simulation scenarios.

They utilized this tool to study a wide range of aspects of the proposed architecture. Below are several results obtained. Researchers evaluated this architecture essentially as viewed from data sources through aggregation to the corresponding ingress/egress points to develop an estimate of required network performance at each link. Below are some of the results collected.

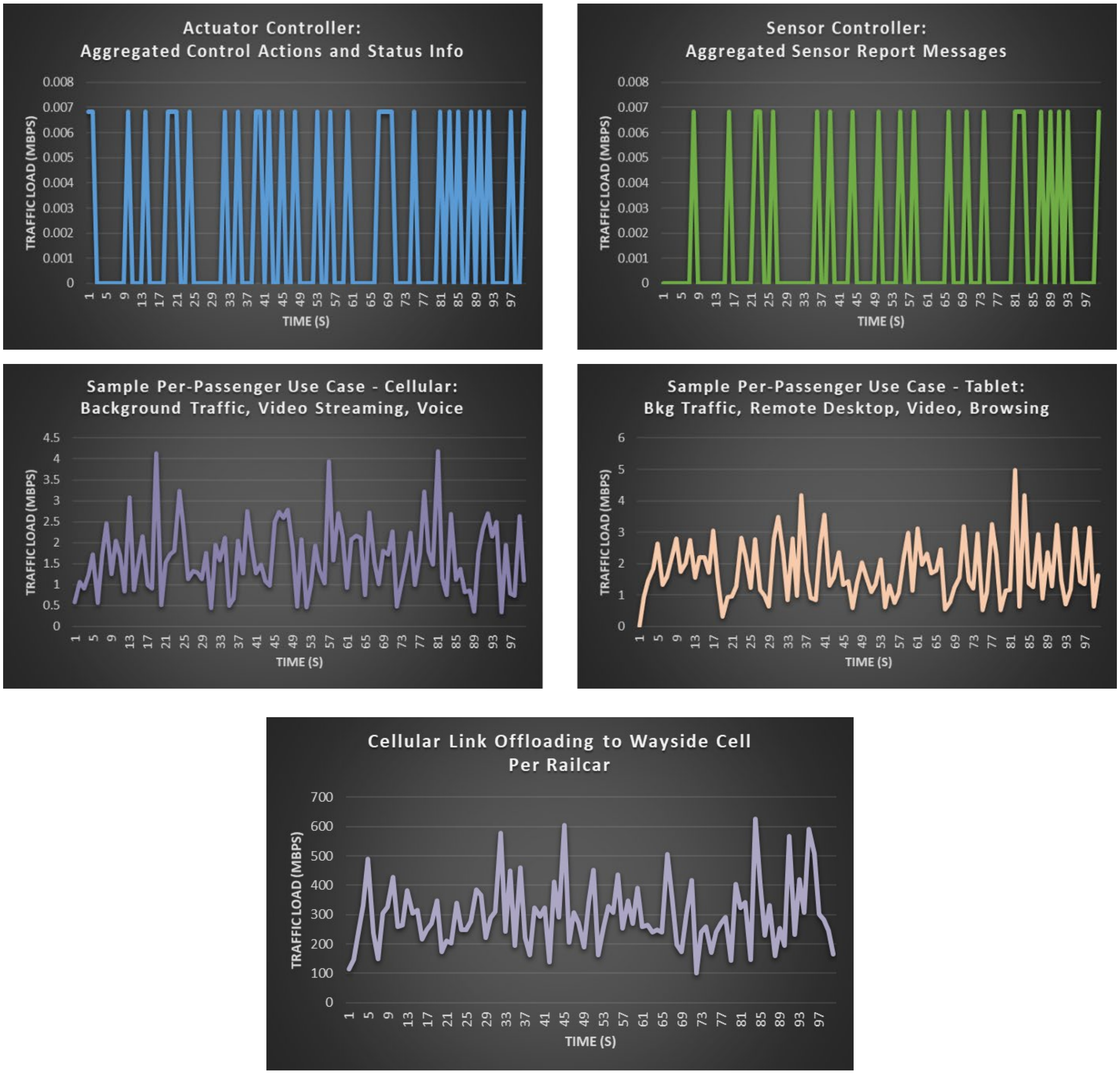


Figure 8. From sources to sinks: Simulation results from different study points within the architecture

Simulation studies with this architecture showed a significant increase in overall performance that this architecture enabled. The interplay between different technologies can also be observed. With the support for different application profile, this simulation tool can also be used to study capacity demands for passenger services, end-to-end latency for critical train control functions, and so much more.

For example, Figure 9 shows the results of one of the handover analysis scenarios. In this case, researchers simulated a single train at various different velocities when operating using 4G LTE at 900 MHz. The simulation considers two base stations about 2.5 km apart and evaluates the handover failure probability at different locations—different distances from base station 1 in order to study not only when handovers occur but also how likely they are to succeed, given that with increased distance from a base station the probability of successful communication also decreases.

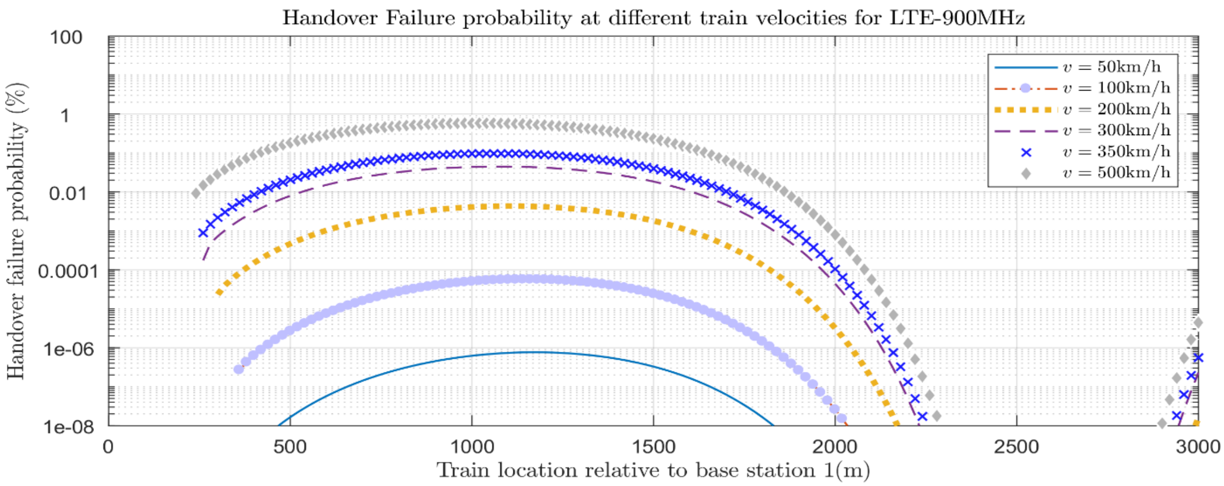


Figure 9. Handover failure probability simulation results

These results show that the highest failure probability occurs roughly in the middle, between both base stations, which is also the area where most handover schemes decide to start the handover process. Therefore, this illustrates the need to evaluate handover schemes to find more suitable approaches for use with high-speed rail deployments.

5. Conclusion

At the core of this initial phase of TEL's work in wireless communication for high-speed passenger rail services was the review of the current state-of-the-art, determination of its benefits and drawbacks, and then researching ways to overcome these limitations.

TEL believes that it accomplished this goal through an architecture that incorporates novel features such as user/control plane separation and new technologies, such as 5G, into a single cohesive architecture.

To establish performance metrics of this architecture, TEL developed a new computer simulation environment based on ns-3 that enables easy scenario-driven technology evaluation. It incorporates a host of new features and improvements of existing capabilities. Driven by simple template-based scripts, it enables complex scenarios to be constructed and evaluated.

The results we obtained are based on the computer network simulator we developed, which show the great potential for our proposed system architecture.

TEL is currently in the process of establishing the phase 2 part of this project. The principal goal of the second phase is to conduct actual device tests and field tests to validate the simulation results. Additionally, through the collected data from device tests TEL can improve the fidelity of its computer simulation results, which also aids in the process of scaling up the simulation to larger scenarios, such as the simulation of an entire high-speed rail corridor segment, or areas of high density such as Chicago-area rail services.

TEL is also planning field testing of 5G technologies in rail applications, using the test facilities at the Transportation Technology Center in Pueblo, CO. This state-of-the-art testing facility enables real-world tests on actual train systems. Its environment is ideally suited for this study. To the best of the researchers' knowledge, this would be the first 5G test of its kind for high-speed rail applications.

6. References

[1] 110th Congress (2007–2008). H.R.6003 - Passenger Rail Investment and Improvement Act of 2008.

[2] PRIIA. Section 305 Statute. American Association of State Highway Transportation Officials (AASHTO), http://www.highspeed-rail.org/Documents/305%20Exec/305_statute.pdf

[3] S. Banerjee, M. Hempel, & H. Sharif (2016). A Survey of Wireless Communication Technologies & Their Performance for High Speed Railways. *Journal of Transportation Technologies, Scientific Research Publishing (SCIRP), 6,* 15–29.

[4] Fokum, Daniel T., Frost, & Victor, S. (2010). A Survey on Methods for Broadband Internet Access on Trains. *IEEE Communications Surveys & Tutorials, 12*(2), 171–185. http://dx.doi.org/10.1109/SURV.2010.021110.00060

[5] Shafiullah, GM., Gyasi-Agyei, A., & Wolfs, P. (2007). Survey of Wireless Communications Applications in the Railway Industry, *Proceedings of the 2nd International Conference on IEEE Wireless Broadband and Ultra band Communication, Sydney.* http://dx.doi.org/10.1109/auswireless.2007.74

[6] Li Yan, & Xuming Fang. (2013). Decoupled wireless network architecture for high-speed railway. *2013 International Workshop on High Mobility Wireless Communications (HMWC),* 96–100, Shanghai. http://dx.doi.org/10.1109/HMWC.2013.6710300

[7] Yan, L., Fang, X., & Fang, Y. (2015). Control and data signaling decoupled architecture for railway wireless networks. *IEEE Wireless Communications, 22*(1), 103–111. http://dx.doi.org/10.1109/MWC.2015.7054725

[8] ERTMS. (2005). SUBSET-093: GSM-R Interfaces; Class 1 requirements.

[9] Sniady, A., & Soler, J. (2014). LTE for Railways: Impact on Performance of ETCS Railway Signaling. *IEEE Vehicle Technology Magazine, 9*(2), 69–77.

[10] Sniady, A., & Soler, J. (2013). Performance of LTE in High Speed Railway Scenarios. 5th International Workshop, Nets4Cars/Nets4Trains. Springer Berlin Heidelberg, 211–222, 7865.

[11] Bertout, A., & Bernard, E. (2012). Next Generation Of Railways And Metros Wireless Communication Systems. *ASPECT,* Institution of Railways Signal Engineers.

[12] Ghannoum, H., & Sanz, D. (2013). Internet Onboard: Technical Analysis.5th International Workshop, Nets4Cars/Nets4Trains. Villeneuve d'Ascq, France. http://dx.doi.org/10.1007/978-3-642-37974-1_2

[13] Salaberria, I., Perallos, A., Azpilicueta, L., Falcone, F., Carballedo, R., Angulo, I., et al. (2014). Ubiquitous Connected Train Based on Train-to-Ground and Intra-Wagon Communications Capable of Providing on Trip Customized Digital Services for Passengers. *Sensors, 14*(5), 8003–8025. http://dx.doi.org/10.3390/s140508003

[14] Shrestha, P., Hempel, M., Sharif, H., & Mehrvarzi, S. (2013). A comparative analysis of Mobile WiMAX 2.5 GHz and 3.65 GHz for freight railroad applications. 2013 9Th

International Conference On Innovations In Information Technology (IIT), Abu Dhabi. https://dx.doi.org/10.1109/innovations.2013.6544416

[15] Pleros, N., Vyrsokinos, K., Tsagkaris, K., & Tselikas, N. (2009). A 60 GHz Radio-Over-Fiber Network Architecture for Seam-less Communication with High Mobility. *J. Lightwave Technol., 27*(12), 1957–1967. http://dx.doi.org/10.1109/JLT.2009.2022505

[16] Lannoo, B., Colle, D., Pickavet, M., & Demeester, P. (2007). Radio-over-fiber-based solution to provide broadband in-ternet access to train passengers [Topics in Optical Communications]. *IEEE Commun. Mag., 45*(2), 56–62. http://dx.doi.org/10.1109/MCOM.2007.313395

[17] De Greve, F., Lannoo, B., Peters, L., Van Leeuwen, T., Van Quickenborne, F., & Colle, D. et al. (2005). FAMOUS: A Network Architecture for Delivering Multimedia Services to FAst MOving USers. *Wireless Personal Communication, 33*(3-4), 281-304. http://dx.doi.org/10.1007/s11277-005-0573-2

[18] Han,T., & Ansari, N. (2015) RADIATE: radio over fiber as an antenna extender for high-speed train communications. *IEEE Wireless Communications, 22*(1), 130–137.

[19] Terada, M., & Teraoka, F. (2012). Providing a high-speed train with a broadband and fault tolerant IPv4/6 NEMO environment. 2012 IEEE Globecom Workshops, Anaheim, CA. http://dx.doi.org/10.1109/GLOCOMW.2012.6477723

[20] Guan, J., & Zhou, K. (2013). Analysis of the radiation field distribution characteristics of the LTE-R leakage coaxial cable in the high-speed train. 2013, 5th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies For Wireless Communications, Chengdu. http://dx.doi.org/10.1109/MAPE.2013.6689857

[21] Sanz, D. Satellite Technologies for Broadband Internet Access On Board High Speed Train. SNCF-Direction De'innovation Et De La Researche, Paris.

[22] Kruijff, M., Dumville, M., Hutchinson, M., & Ginati, A. Intelligent Railways via Integrated Satellite Services (IRISS). IAC-11-B5.2.7.

[23] European Space Agency (ESA), ARTES Applications, Integrated Railways Via Integrated Satellite Systems (IRISS). https://artes-apps.esa.int/projects/iriss

[24] Amanna, A., Gadhiok, M., Price, M., Reed, J., Siriwongpairat, W., & Himsoon, T. (2010). Railway Cognitive Radio. *IEEE Vehicle Technology Magazine, 5*(3), 82–89. http://dx.doi.org/10.1109/MVT.2010.938275

[25] Amanna, A., Ali, D., Gadhiok, M., Price, M., & Reed, J. (2012). Cognitive radio engine parametric optimization utilizing Taguchi analysis. EURASIP Journal on Wireless Communications & Networks, 2012(1), 5. http://dx.doi.org/10.1186/1687-1499-2012-5

[26] Bebineau, M., Masson, E., Cocheril, Y., Kalakech, A., Ghys, JP., Dayoub, I., et al. (2014) Cognitive Radio for High Speed Railway through Dynamic and Opportunistic spectrum Reuse, Transport Research Arena, Paris.

[27] Li, J., & Zhao, Y. (2012). Radio environment map-based cognitive Doppler spread compensation algorithms for high-speed rail broadband mobile communications. *EURASIP Journal of Wireless Communication Network.* http://dx.doi.org/10.1186/1687-1499-2012-263

[28] Luan, Fengyu, Zhang, Yan, Xiao, Limin, Zhou, Chunhui, Zhou, & Shidong. (2013), Fading Characteristics of Wireless Channel on High-Speed Railway in Hilly Terrain Scenario. *International Journal of Antennas and Propagation*. Hindawi Publishing Corporation, Vol. 2013, Article ID 378407. http://dx.doi.org/10.1155/2013/378407

[29] Tseng, Ming-Chien, Cheng, Ming-Hung. (2012) Experimental Study of Fading Characteristics for Wireless Communications in High-Speed Railway Environments. *Proceedings for IEEE Antennas and Propagation Society International Symposium (APSURSI).* Chicago. http://dx.doi.org/10.1109/aps.2012.6348848

[30] Li, J., Tian, L., Zhou, Y., & Shi, J. (2012). An adaptive handover trigger scheme for wireless communications on high speed rail. IEEE International Conference on Communications (ICC), Ottawa, 5185–5189. http://dx.doi.org/10.1109/icc.2012.6364484

[31] Xu, Q., Ji, H., Li, X., & Zhang, H. (2015). Admission Control Scheme for Service Dropping Performance Improvement in High-Speed Railway Communication Systems. *IEEE Transactions on Vehicular Technology.* http://dx.doi.org/10.1109/TVT.2015.2458512

[32] Zhou, Y., & Ai, B. (2014). A position-based access scheme for high-speed railway communications. 2014 IEEE International Conference On Signal Processing, Communications And Computing (ICSPCC), Guilin. http://dx.doi.org/10.1109/ICSPCC.2014.6986265

[33] Zhao, Y., Li, X., & Ji, H. (2012). Radio admission control scheme for high-speed railway communication with MIMO antennas. 2012 IEEE International Conference on Communications (ICC), Ottawa. http://dx.doi.org/10.1109/TWC.2010.05.081548

[34] Kwan, R., Arnott, R., & Kubota, M. (2010). On Radio Admission Control for LTE Systems. 2010 IEEE 72nd Vehicular Technology Conference, Ottawa,. http://dx.doi.org/10.1109/VETECF.2010.5594566

[35] Tian, L., Li, J., Huang, Y., Shi, J., & Zhou, J. (2012). Seamless Dual-Link Handover Scheme in Broadband Wireless Communication Systems for High-Speed Rail. IEEE Journals on Selected Areas of Communication, 30(4), 708–718. http://dx.doi.org/10.1109/JSAC.2012.120505

[36] Luo, W., Fang, X., Cheng, M., Zhao, Y. (2013) Efficient Multiple-Group Multiple-Antenna (MGMA) Scheme for High-Speed Railway Viaducts. *IEEE Transactions of Vehicle Technology, 62*(6), 2558–2569. http://dx.doi.org/10.1109/TVT.2013.2244106

[37] Radio Frequency Systems. (2009, August). Solutions for High-Speed Rail and Expressway Wireless Coverage in China.

[38] Guan, K., Zhong, Z., & Ai, B. (2011) Assessment of LTE-R Using High Speed Railway Channel Model. Third International Conference on Communications and Mobile Computing, Qingdao. http://dx.doi.org/10.1109/cmc.2011.34

[39] Zhou, T., Tao, C., Liu, L., Qiu, J., & Sun, R. (2012). High-speed railway channel measurements and characterizations: a re-view. *Journal of Modern Transportation, 20*(4), 199–205. http://dx.doi.org/10.1007/BF03325799

[40] EIRENE. (2014). Functional Requirement Specification, Ver 7.4, Ref. UIC code 950.

[41] Federal Railroad Administration. (2013). Railway Cognitive Radio to Enhance Safety, Security, and Performance of Positive Train Control. [DOT/FRA/ORD-13/09]. Washington, DC: U.S. Department of Transportation.

[42] Ai, B., Cheng, X., Kurner, T., Zhong, Z., Guan, K., He, R., et al. (2014). Challenges toward Wireless Communications for High-Speed Railway. *IEEE Transactions on Intelligent Transportation System, 15*(5), 2143–2158. http://dx.doi.org/10.1109/TITS.2014.2310771

[43] Karimi, O., Liu, J., & Wang, C. (2012). Seamless Wireless Connectivity for Multimedia Services in High Speed Trains. *IEEE Journal on Selected Areas in Communications, 30*(4), 729–739. http://dx.doi.org/10.1109/JSAC.2012.120507

[44] Chen, H. (2007). *The next generation CDMA technologies.* Chichester, England: John Wiley. http://dx.doi.org/10.1002/9780470022962

[45] Federal Railroad Administration. (2012). Rail-CR: Railroad Cognitive Radio [RR 12-17]. Washington, DC: U.S. Department of Transportation.

Abbreviations and Acronyms

TEL	Advanced Telecommunications Engineering Laboratory at UNL
AREMA	American Railway Engineering and Maintenance-of-Way Association
AAR	Association of American Railroads
DTL	Digital Trainline
FRA	Federal Railroad Administration
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
LTE	Long-Term Evolution
NGEC	Next Generation Equipment Committee
PHY	Physical Layer
UNL	University of Nebraska-Lincoln
UCDA	User/Control Plan Decoupled Architecture
WiDTL	Wireless Digital Trainline