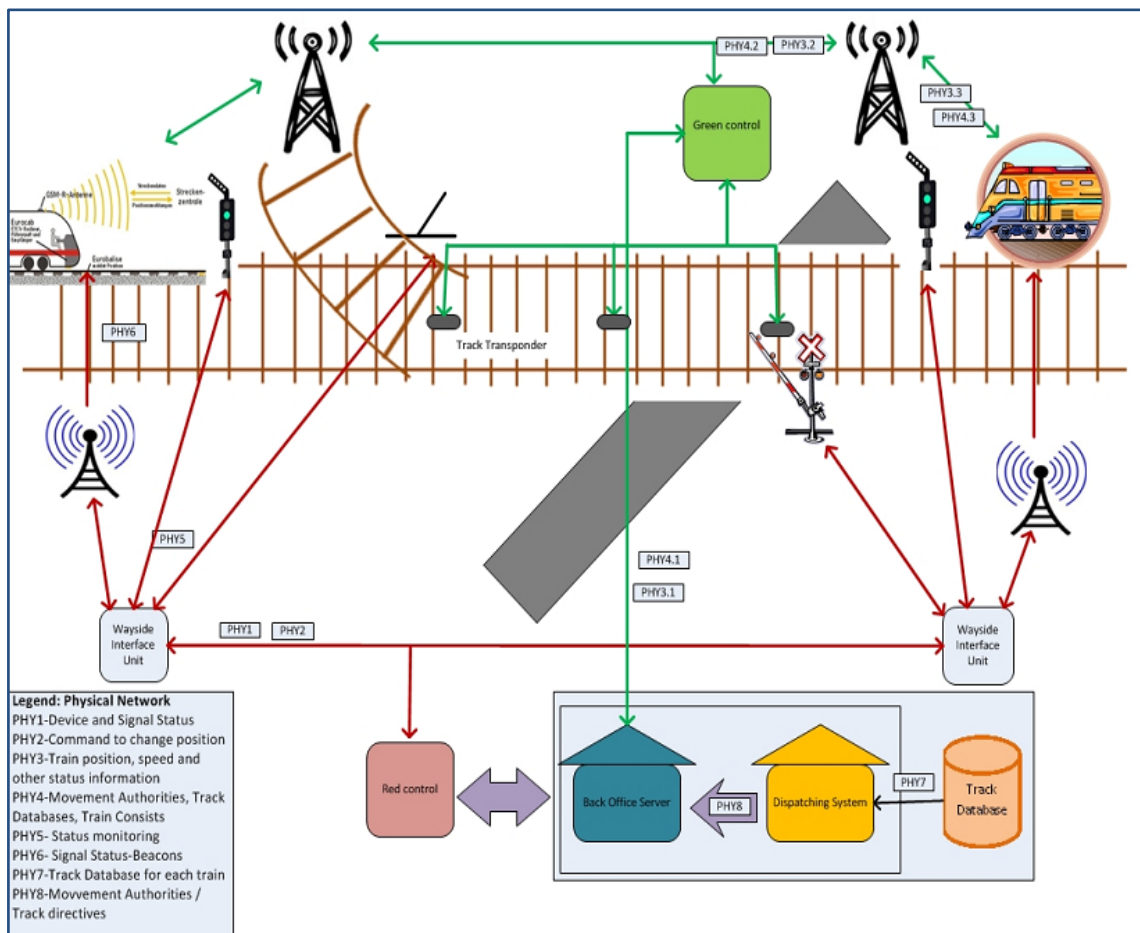




U.S. Department of  
Transportation  
**Federal Railroad  
Administration**

# Providing Wireless Bandwidth for High-speed Rail Operations

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



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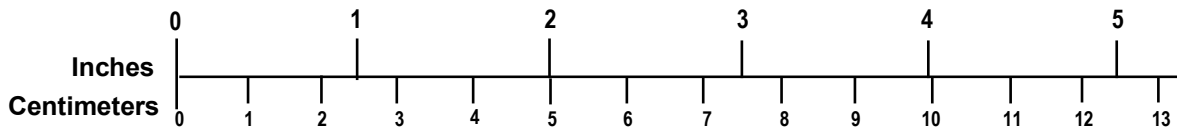
# METRIC/ENGLISH CONVERSION FACTORS

## ENGLISH TO METRIC

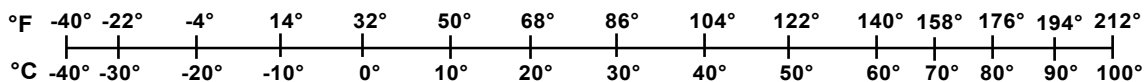
## METRIC TO ENGLISH

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<p><b>TEMPERATURE (EXACT)</b></p> <p><math>[(x-32)(5/9)]\text{ }^{\circ}\text{F} = y\text{ }^{\circ}\text{C}</math></p>	<p><b>TEMPERATURE (EXACT)</b></p> <p><math>[(9/5)y + 32]\text{ }^{\circ}\text{C} = x\text{ }^{\circ}\text{F}</math></p>

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## Executive Summary

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Operational high-speed trains, which are generally located in Europe and Asia, are controlled with wireless communication systems. The U.S. Class 1 railroads and the Federal Railroad Administration (FRA), have been developing a Positive Train Control (PTC) system to control trains in the United States. To operate safely, trains controlled by wireless communications systems must maintain seamless connections with control centers and infrastructure placed near the tracks. To maintain seamless connectivity, the wireless radio system that supports the network must provide cellular coverage over rail tracks, with bandwidth that can accommodate all transactions.

In this project, George Mason University, with the assistance of Siemens Research, conducted an investigation to ascertain the maximum attainable speed of American high-speed trains if PTC was used to provide communication assistance. The study has found that a channel capacity of 64 Kbps under the Binary Phase Shift Keying (BPSK) modulation schema will allow high-speed trains to attain speeds of 400 mph, provided that the number of packets required to switch from one tower to the next is less than 500. The study shows the effect of these parameters:

- Multipath fading has the most dominant factor in losing signal strength, and as a solution; it is recommended to place wayside interface radios closer to each other.
- Received signal strength can change due to vegetation in some areas. Given the geographical location and month of the year, it is possible to compute signal fading due to vegetation.
- Additionally, the study has found that the effect of signal strength fading due to precipitation can be computed and is generally minimal.

Given that train arrivals can be known in advance, bandwidth allocation for high-speed trains is an appropriate area for dynamic channel allocation and power management for signaling and wayside information using cognitive radio technology. This step, with a more detailed cell planning, can lead to finer grained geography-specific bandwidth estimates for high-speed trains.

The results of this study were also compared with traffic traces from the European Rail Traffic Management System (ERTMS); however, the comparison did not reveal much information on bandwidth management aspects of PTC-like high-speed trains control systems, mainly due to fundamental architectural differences between PTC and ERTMS. For example, ERTMS-controlled trains continuously maintain two Global Systems for Mobile Communications – Railway (GSM-R) connections that mostly consist of *keep-alive* messages. Also, ERTMS communicates the track database using radio links dynamically while PTC is designed to load the track database prior to dispatching a train.

The work described in this report can be directly applied to California's ongoing efforts to introduce high-speed trains and the efforts to increase rail speeds in the northeastern corridor. Exact Wayside Interface Unit (WIU) densities and train timetables can be applied to specialize the findings of this study to appropriate locations.

# 1. Introduction

---

In Europe and elsewhere (such as Asia), wireless media provides signal information and track warrants to trains so that the engineers can navigate in a safe and timely manner. U.S. railroads are in the process of introducing a wireless-network based control system, commonly referred to as Positive Train Control (PTC), which was mandated to be operational by 2015 by the Rail Safety Improvement Act of 2008 (RISA 2008). The primary objective of PTC systems is to ensure safety by granting authority for a specified train to occupy a specific track segment, enforcing speed limits and other restrictions, ensuring switches are aligned in the correct position, and protecting railroad workers.

## 1.1 Background

European and Asian high-speed trains use GSM-R, a special-purpose extension of the GSM protocol used for cellular telecommunications, to send PTC-like communications for controlling trains. This supports a unified Communications-Based Train Control (CBTC) system known as the European Rail Traffic Management System (ERTMS). It satisfies similar objectives as PTC and is based on a purpose-built communications protocol (GSM-R), ERTMS supports high-speed rail services in Europe and is being adopted in India and China. Given that U.S. railroads are going to adopt PTC or an improved version of the system, it has become necessary to determine if PTC can be utilized to attain the same functionality (i.e., speeds) as ERTMS controlled trains. Since ERTMS has more bandwidth allocated to its usage in contrast to PTC systems (with a 220 MHz bandwidth spectrum), investigating this issue is important.

## 1.2 Objectives

This project investigated the possibility of providing wireless communication for ERTMS-like signaling mechanisms for U.S. high-speed trains. The most important issue was the differences between the capabilities of the frequencies for rail operations in the United States and the frequencies used by GSM-R in other parts of the world. In Europe, GSM-R is transmitted over frequencies ranging from 800 MHz to 900 MHz, while the United States has less bandwidth available and in a lower-frequency spectrum.

This project was carried out in two phases. In the first phase, a frequency analysis was done to determine how the available frequency band should be divided to support the train operations. For varying bit rates, modulation schemes, and number of packets per handshake, models were developed to calculate the number of trains that a WIU can handle and the maximum speed the train can operate at. In the second phase, a detailed link budget analysis was developed to calculate the receive power level. Given that high-speed lines have not been built in the United States yet, we used Southern California Regional Rail Authority (SCRRA) lines in Southern California and the Coast Starlight light rail line as case studies for our analysis. The locations of WIUs, points along the train line, and the terrain features were determined using existing maps, all of which were applied to calculate estimates of receive power for train communications.

### **1.3 Overall Approach**

This report considers the PTC message structure and estimates the bandwidth requirements needed to transmit these messages in a timely manner. This estimate is used with the radio power specifications to compute how the transmission fades under different environmental conditions. This information was used to create linear radio cells that are capable of providing wireless coverage with overlapping regions between adjacent cells. Given that a sufficient guard band was taken to avoid interference, the maximum number of trains that can be supported and the maximum speed attainable by high-speed trains were computed.

### **1.4 Scope**

This report is preliminary and is based on published parameters of PTC systems, 220 MHz frequency allocations, as well as the documentation and performance results that were obtained from ERTMS. The project did not implement or prototype the proposed systems.

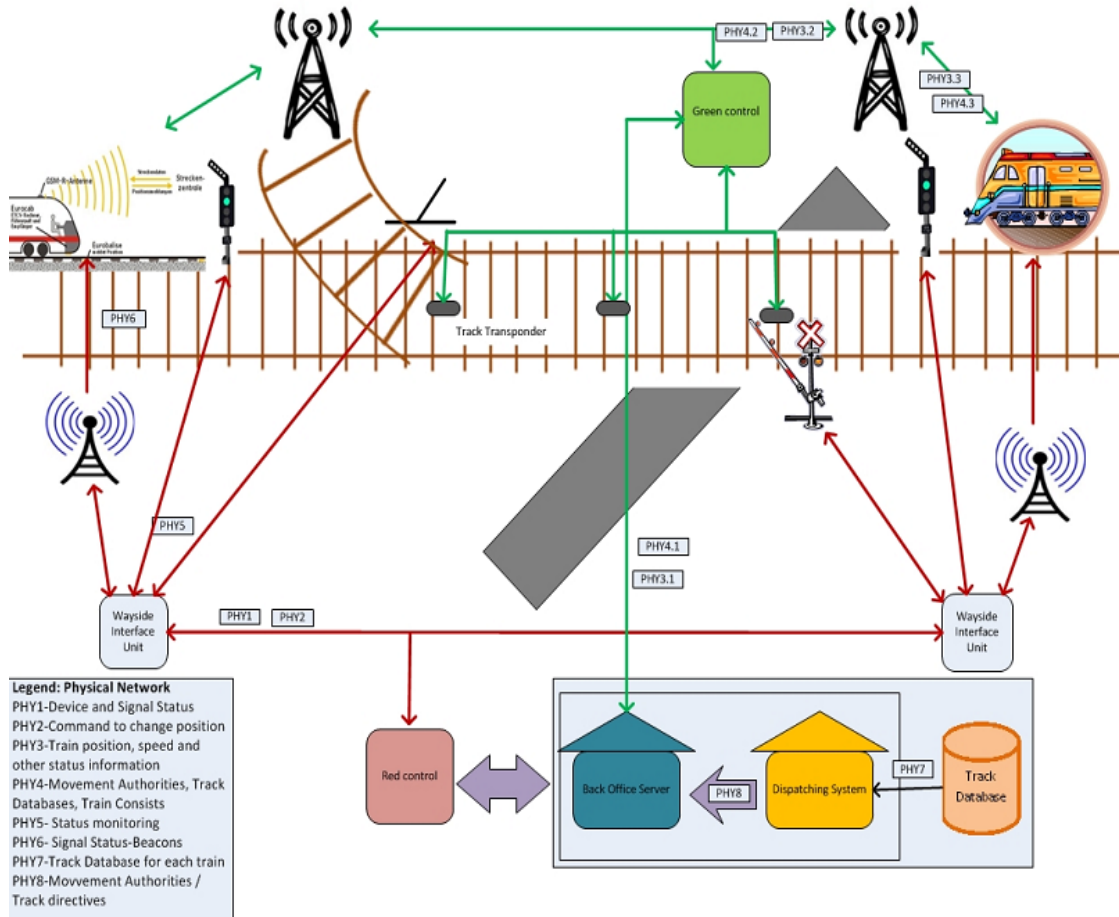
### **1.5 Organization of the Report**

The remainder of the report is organized into five sections: Section 2 provides a brief introduction to PTC and the packet formats proposed for PTC transmissions; Section 3 analyzes the bandwidth requirements for high-speed passenger trains and freight trains travelling at current speeds; Section 4 provides a link budget analysis for the transmission requirements; and Section 5 analyzes potential radio interferences. Section 6 has our concluding comments and provides suggestions for future studies.

## 2. Positive Train Control Systems

This section describes the proposed PTC system and its communication subsystem specifications, including network packet sizes, their payloads, and the timing characteristics of the payloads.

### 2.1 PTC Architecture



**Figure 1. Generic PTC Systems**

Figure 1 shows the main components of a generic PTC system. As shown at the top half of the diagram, on-track train movements are governed using authorities communicated through a system of networks that connect the back offices in charge of managing the track segment. The logical connectivity of this part is shown as the “green network.”

It is ideal for an integrated system to only use wireless communications, with the exception of Amtrak’s use of ACSES2 track-mounted transponders to convey movement authorities with a four-aspect signal system encoding. If Amtrak was to move to ERTMS, then the network that connects the transponders would probably use the wireless transmission system. In addition to the planned PTC system, existing externally-mounted and in-cab signals provide movement signaling and track condition notifications, including but not limited to switch positions that use wayside devices. The bottom of Figure 1 displays this existing signal network in red and where in-cab signaling is available, this network may use wireless communications, track mounted

sensors (as in Amtrak’s Northeast corridor), or provide wired external signals. In either case, controlling movements can be achieved using signals and existing voice-based radio communication. In the ideal situation, with the full implementation of PTC as a vital system, the red network should be merged with the green network using the same wireless protocols. We use this logical view as a basis to analyze our proposed wireless bandwidth requirements for PTC and non-PTC traffic. Given the agreement between the railroads, ERTMS will be the PTC system that will be used in high-speed rail operations in the U.S.

## 2.2 Pertinent PTC Message Structures

Table 1 shows the message structure of the proposed PTC system. These packet characteristics were used to determine the wireless network’s bandwidth needs for high-speed trains.

**Table 1. Signaling Message Format [1]**

<b>Field</b>	<b>Size (Bytes)</b>	<b>Description</b>
Protocol Version	1	Version of EmNetS Network Management Protocol (EMP) header
Message Type (ID)	2	As noted in the definition of each message in this Interface Control Document (ICD)
Message Version	1	As noted in the definition of each message in this ICD
Flags	1	Timestamp Format: Coordinated Universal Time (UTC) No encryption No compression Data Integrity: Application-specific data integrity value used
Data Length	3	As noted in the definition of each message in this ICD
Message Number	4	Application Message Sequence Number
Message Time	4	UTC timestamp of message creation by sending application
Variable Header Size	1	Defined by length of source and destination addresses
Time to Live	2	As defined in section 1.10 Quality of Service and Time to Live
Routing QoS	2	As defined in section 1.10 Quality of Service and Time to Live
Source	64 max	See section 1.3.2 EMP Source and Destination Fields
Destination	64 max	See section 1.3.2 EMP Source and Destination Fields
Data Integrity	4	Truncated Keyed Hashed Message Authentication Code. See section 1.3.3 EMP Data Integrity Field

PTC traffic consists of two main types of messages:

1. The messages that belong to the signaling network. They are the control messages from the back office to the train and from the train to the back office. The message format is shown in Table 1.
  - a. Messages from the train to the back office - Message type from 01000 to 01123
  - b. Messages from the back office to the train - Message type from 02000 to 02122 [1]
2. Messages that belong to the WIU network.
  - a. WIUStatus: Message numbers 5100 and 5101
  - b. Beacon Request: This message is sent to request a WIU to begin periodic transmission of WIUStatus messages. Message type number is 5200. The message format is similar to WIUStatus message, but it does not include message payload fields.
  - c. GetWIUStatus: This message is sent to indicate a request for a WIU to immediately return a WIUStatus. Message type number 5201. The message format is similar to WIUStatus message, but it does not include message payload fields.

The format of the Wayside Interface Unit (WIU) messages is given in Table 2.

**Table 2. Wayside Interface Message Format [2]**

<b>Field</b>	<b>Size</b>	<b>Description</b>
WIU address	40 bits	ATCS Type address
Beacon TTL	1 bit	Beacon expiration
Vital message type	6 bits	Defined by WIU
Vital message version	5 bits	
mod 16 times	4 bits	Modified timestamp
Message sequence number	8 bits	0-255 binary
Device status	1-1944 bits	Device status generated by WIU
VDIV	32 bits	HMAc vital data integrity value

### 3. Frequency Analysis for High-Speed Trains

This section analyzes how the 200 MHz frequency band can be used by high-speed trains. In the United States, the uplink frequency bands are 217-219 MHz and the download frequency bands are 221-222 MHz. The project used the 3 MHz bandwidth to create channels with neighboring channels separated by guard bands (a vacated portion of the spectrum that allows for frequency shift due to Doppler effect, protecting the neighboring channel from interference). These channels can be either statically or dynamically allocated between the two networks according to the needs of the PTC traffic.

#### 3.1 Calculating the Required Guard Band

Due to the potential speed of the train, the well-known phenomena of the Doppler effect should be addressed. To ensure that the guard band functions properly, it should be at least twice the value of the calculated Doppler frequency shift. The frequency shift is calculated using Equation (1):

$$\Delta f/f = v_t/C \quad (1)$$

Where:  $v_t$  is the travelling speed,  $\Delta f$  is the frequency shift,  $f$  is the operating frequency and  $C$  is the speed of the light.

As Equation (1) shows, the frequency shift is linearly proportional to the speed of the train. We assumed a maximum train speed of 400 mph and calculated the Doppler shift to be 131Hz. We then doubled that value to 262Hz and set the final guard band size to 300Hz to consider the potential for slight variations. Figure 2 displays the results of these computations using equation (1) in graphical form.

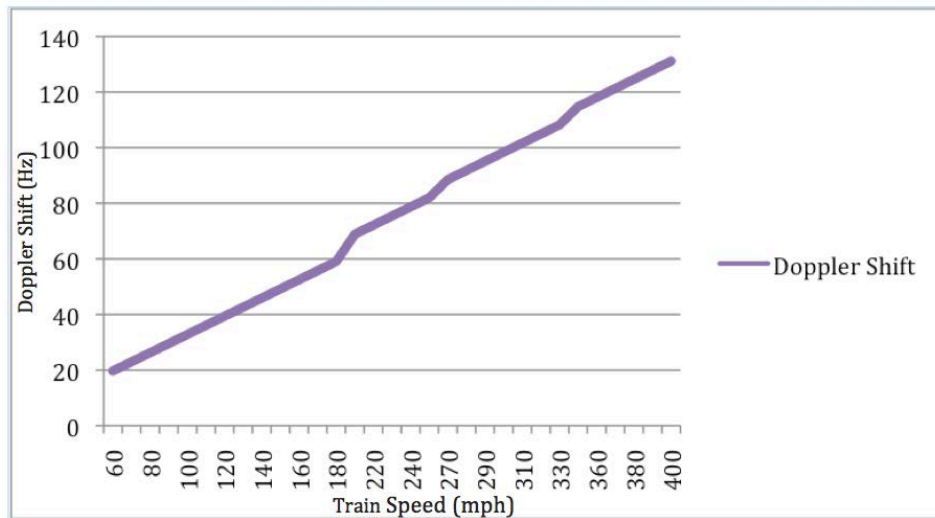


Figure 2. Doppler Shift (Hz) vs. Speed (mph)



**Final Recommendation:** The guard band should be 300kHz to support up to 400mph.

### 3.2 Calculating the Channel Bandwidth

In wireless communications, 64kbps is the basic data rate and multiples of that data rate is used to develop channel capacities. Therefore we used data rates to define channels from 64kbps to 384kbps in steps of 64kbps to recognize the relationship between available bandwidth and higher data rates. Furthermore, for each channel, the bandwidth is calculated using Equation (2):

$$\text{Occupied filter Bandwidth} = \text{Symbol rate} \times (1 + \alpha) \quad (2)$$

In equation (2),  $\alpha$  is the roll off of the filter. Computed results are shown in Table 5.

### 3.3 Calculating the maximum number of packets per channel per second

The maximum WIU message size is 2040 bits (see Table 2) and the maximum signaling message size is 1216 bits long (see Table 1). The maximum packet sizes are used to calculate the number of packets for each channel. For this calculation, we considered that the available frequency band is divided into three channels (two for the control network and one for the WIU network). Based on this allocation, the number of packets transmitted per second is shown in Table 3.

**Table 3. Minimum possible packet amount per a channel per second for signaling network and beaconing network**

Channel Capacity (kbps)	Number of signaling packets per channel per second	Number of WIU packets per channel per second
64	53	31
128	105	63
192	158	94
256	211	125
320	263	157
384	316	188

### 3.4 Calculating the maximum number of channels

The number of channels that can be allocated using a 3 MHz band is calculated with Equation (3):

$$n \times \text{channel bandwidth} + (n+1) \times \text{guard band} = 3 \text{ MHz} \quad (3)$$

Where  $n$  is the number of channels, Equation (3) is rearranged to find  $n$  as shown in Equation (4).

$$n = (3000 - \text{guard band(kHz)}) / (\text{channel bandwidth(kHz)} + \text{guard band(kHz)}) \quad (4)$$

For different modulation schemes and bit rates, the required bandwidth is calculated using equation (2). Using those values, we calculated the number of channels that 3 MHz band can support using equation (4). The results are shown in Table 4.

**Table 4. Bandwidth of channels and the no of channels with different channel rates and Modulation schemes (a) Binary Phase-Shift Keying (BPSK) (b) Quadrature Phase Shift Keying (QPSK) (c) 8QAM (form of digital Quadature Amplitude Modulation) (d) 16QAM (form of digital Quadature Amplitude Modulation) (e) Summary**

(a)

Channel Capacity (kbps)	Symbol rate	Bandwidth (kHz) alpha=0.3	Number of channels
64	64	83.2	36
128	128	166.4	18
192	192	249.6	12
256	256	332.8	9
320	320	416	7
384	384	499.2	6

(b)

Channel Capacity (kbps)	Symbol rate	Bandwidth (kHz) alpha=0.3	Number of channels
64	32	41.6	72
128	64	83.2	36
192	96	124.8	24
256	128	166.4	18
320	160	208	14
384	192	249.6	12

(c)

<b>Channel Capacity (kbps)</b>	<b>Symbol rate</b>	<b>Bandwidth (kHz) alpha=0.3</b>	<b>Number of channels</b>
64	21.333333 33	27.73333333	107
128	42.666666 67	55.46666667	54
192	64	83.2	36
256	85.333333 33	110.9333333	27
320	106.66666 67	138.6666667	22
384	128	166.4	18

(d)

<b>Channel Capacity (kbps)</b>	<b>Symbol rate</b>	<b>Bandwidth (kHz) alpha=0.3</b>	<b>Number of channels</b>
64	16	20.8	142
128	32	41.6	72
192	48	62.4	48
256	64	83.2	36
320	80	104	29
384	96	124.8	24

(e)

<b>Channel Capacity (kbps)</b>	<b>BPSK</b>	<b>QPSK</b>	<b>8QAM</b>	<b>16QAM</b>
64	36	72	107	142
128	18	36	54	72
192	12	24	36	48
256	9	18	27	36
320	7	14	22	29
384	6	12	18	24

The Matlab model (shown in Figure 3) calculates the Doppler shift for different speeds and the number of possible frequency channels for different bit rates and different modulation schemes. Lines 4-13 calculate and plot the Doppler shift with speed. Lines 14-31 calculate and plot the

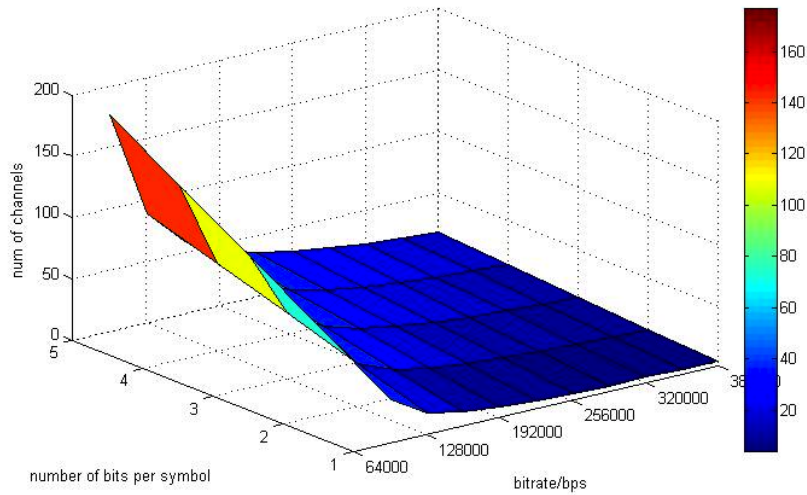
number of channels available for different bitrates and different bits per symbol as shown in Figure 4. The number of bits per symbol depends on the modulation scheme used.

```

1. clear all
2. close all
3. % calculate doppler shift
4. f=220*10^6;
5. C=3*10^8;
6. for i=1:35
7. v(i)=(50+i*10)*1609.344/3600;
8. del_f(i)=v(i)*f/C;
9. end
10. figure(1)
11. plot(v,del_f);
12. xlabel('speed');
13. ylabel('doppler shift');
14. %calculate the number of possible channels with channel capacity and
15. %modulation schemes
16. guard_band=300;
17. alpha=0.3;
18. i=1:6;
19. bitrate=64000*i;
20. bitrate_mat= repmat(bitrate,5,1);
21. bits_per_symbol=1:5;
22. bits_per_symbol_mat=repmat(bits_per_symbol',1,6);
23. occupied_bw=(bitrate_mat./bits_per_symbol_mat)*(1+alpha);
24. n=round((3000*1000-guard_band)./(occupied_bw+ guard_band));
25. figure(2)
26. surf(n);
27. colorbar;
28. set(gca, 'XTickLabel', bitrate);
29. xlabel('bitrate(bps)');
30. ylabel('number of bits per symbol');
31. zlabel('number of channels');

```

**Figure 3. Matlab model to calculate the number of channels**



**Figure 4. Variation of number of channel with bit rate and number of bits per symbol**

### **Final Recommendation:**

Based on the results from section 3.3 and 3.4, a good channel capacity to support PTC operations is 64kbps. The number of control channels and WIU channels can be selected depending on the area's traffic density.

### **3.5 Calculating the Required Receive Power at the demodulator**

For different modulation schemes, the minimum required Signal-to-Noise Ratio (SNR) at the demodulator is calculated using equation (5):

$$M = (1+S/N)^{0.5} \quad (5)$$

Where: S is the signal level, N is the noise level and M is the number of bits per symbol.

This equation can be rearranged to find the minimum required SNR for different modulation schemes. For example, if the modulation scheme is BPSK, a symbol carries 2 bits. Therefore M is 2. If we substitute that Equation (5) we can get the minimum SNR required for that modulation scheme. Table 5 shows the minimum required SNR for different modulation schemes.

**Table 5. Minimum required Signal to Noise Ratio for different modulation schemes**

<b>Modulation scheme</b>	<b>Number of bits per symbol(M)</b>	<b>Minimum SNR</b>	<b>SNR(DB- in Decibel)</b>
BPSK	2	3	5
GMSK	2	3	5
QPSK	4	15	12
8-QAM	8	63	18
16-QAM	16	255	25

If total noise temperature is 120 K, the minimum required RX power level for different filter bandwidths is shown in Table 6.

For different filter bandwidths, the noise level is calculated using Equation (6). and the calculated noise level is shown in the column 3 of Table 6. These values together with the minimum SNR values calculated in Table 5 are used to calculate the signal level at the receiver (as shown in column 5. Column 6 shows the signal level in dB)

$$\text{Noise power level} = k \times T \times B \quad (6)$$

Where:

K = Boltzmann constant ( $1.38 \times 10^{-23}$ ) kg s<sup>-2</sup> K<sup>-1</sup>

T = Noise temperature

B = Filter Bandwidth

<b>Modulation Scheme</b>	<b>Noise Bandwidth (kHz)</b>	<b>Noise level</b>	<b>SNR</b>	<b>Signal level at RX</b>	<b>Signal level at RX-dB</b>
BPSK	128	2.11968E-16	3	6.35904E-16	-151.97
BPSK	256	4.23936E-16	3	1.27181E-15	-148.96
BPSK	384	6.35904E-16	3	1.90771E-15	-147.19
BPSK	512	8.47872E-16	3	2.54362E-15	-145.95
QPSK	64	1.05984E-16	15	1.58976E-15	-147.99
QPSK	128	2.11968E-16	15	3.17952E-15	-144.98
QPSK	192	3.17952E-16	15	4.76928E-15	-143.22

QPSK	256	4.23936E-16	15	6.35904E-15	-141.97
8-QAM	42.66666667	7.0656E-17	63	4.45133E-15	-143.52
8-QAM	85.33333333	1.41312E-16	63	8.90266E-15	-140.5
8-QAM	128	2.11968E-16	63	1.3354E-14	-138.74
8-QAM	170.6666667	2.82624E-16	63	1.78053E-14	-137.49

**Table 6. Minimum required signal level at the receiver for different filter bandwidths**

### **Final Recommendation:**

A lower order modulation scheme is recommended, mainly because it requires low signal to noise ratio at the demodulator and implementing them is simple compared to higher order modulation schemes. BPSK provides 36 channels to share between both control and WIU networks with channel capacity at 64kpbs. Therefore, BPSK is suitable to support PTC operations.

### **3.6 Frequency allocation for control and beacon (WIU) channels**

Channel allocation for control and signal messaging, can be done dynamically depending on the number of trains the control points have to serve and the number of WIUs that are located near the control point. Every WIU in the same area should have a different channel such that the channels will neither interfere with each other nor with the control message channel.

A control point requires two channels for uplink and downlink communication and each point should be at the entry to any block. In a single track line, the number of trains that a control point has to serve is typically one, and this number can be increased depending on the number of parallel tracks. The distance between two control points should allow any train, at any moment, to talk with one control point and perform a seamless handover from one control point to the next without dropping the connection. Therefore when calculating the distance between two control points, received power level and additional safety criteria should be considered. In our initial design, the received power was the factor that limited the distance between two control points.

There are a greater number of WIUs than control points and the distance between two WIUs depends on the safety-critical infrastructure along the train route. Each WIU requires one channel to broadcast the beaconing messages. WIUs only broadcast individual status; therefore the number of channels required for the beacon network is independent of the speed of the train.

### **3.7 Calculating the maximum possible distance between two control points**

The Egli model [4] was used to calculate the maximum possible distance between the train and the control point. The minimum possible received power that the demodulator can handle is obtained from Table 7 and the distance can be calculated for a given transmit power. The Egli



model is a terrain model that provides the relationship between transmit power, received power and the distance for cellular communication where one antenna is fixed and another is mobile. This model accounts for the effect of multipath but does not consider attenuation due to vegetation and precipitation. Another limitation with this model is that it predicts the loss as a whole and cannot subdivide the loss into specific types. Since the control points are located closer to the track, the distance the train should travel to establish a connection with the control point is assumed to be twice the minimum required distance between the train and the control point in order to receive signal with sufficient signal to noise ratio .

### 3.8 Computing the maximum possible train speed

To establish the restriction for train speed, we determined how long it would take for a set number of packets to establish the connection between the train and its approaching control point. The number of packets was varied to simulate different network conditions. The corresponding time values that were produced, compared with various train speeds, can be used to set maximum possible distances between control points. For safe train operation, our hypothesis is that the train should complete proper handover and handshake between the next control point at least within the point it passes one control point, because the train needs a reliable connection before it receives dispatching messages. The number of packets may change from location to location due to the fact that it requires packet retransmission if the channel cause bit errors and has interference, which can occur in rail operations.

Therefore the project modeled the maximum possible speed that the train can travel, given the number of packets for handover, the bit rate, and the number of bits per symbol. The number of bits per symbol depends on the modulation scheme used.

If the number of handshake messages is  $n$ , the train and WIU should exchange at least ( $n \times packet\_size$ ) to complete the handshake. For the maximum signaling packet size of 1216 bits the handshake time  $t$  is,

$$t = n \times 1216 / \text{symbol rate} \quad (7)$$

The maximum possible speed that a train can travel can be calculated by the ratio between the maximum possible distance and the time needed to complete handshake.

$$\text{Speed max} = n \times 1216 / \text{symbol rate} \times \text{distance\_max} \quad (8)$$

The above model is implemented in Matlab and the figures for the maximum possible speed have been generated. Figure 6 shows how the maximum possible train speed varies based on the number of bits per symbol, bit error rate and number of packets.

The important elements of the Matlab model (see Figure 5) are as follows:

- Lines 13-22 calculate the noise level at the receiver.
- Line 24-25 calculate the minimum signal to noise ratio the receiver can handle
- Line 26 calculates the minimum receive power the demodulator can handle
- Line 24-37 calculates the maximum possible distance between the train and the control point using Egli model
- Lines 46-51 calculates time required to complete handover and handshake. Line 52 calculates the maximum speed possible.

## **Final Recommendation**

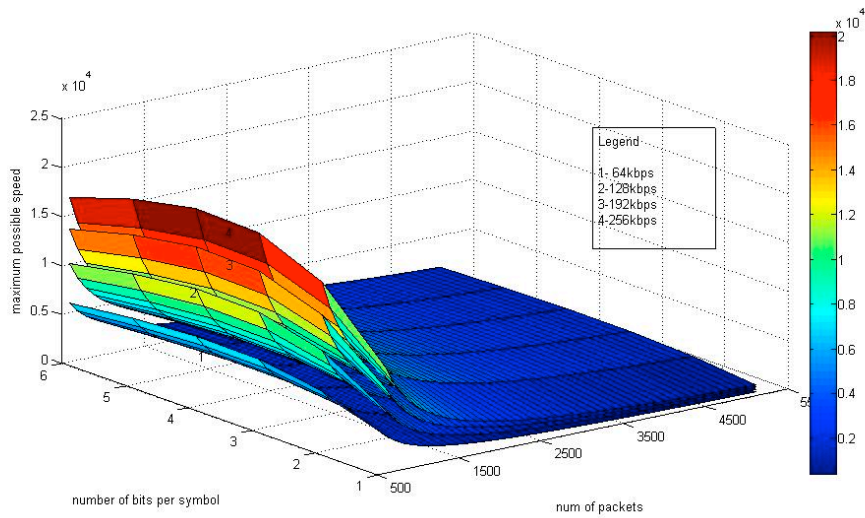
If the channel capacity is 64kbps and the number of packets needed to establish a connection is less than 500, a PTC system can support up to 400mps train speeds in the United States.

```

1. clear all
2. close all
3. %consider total noise temperature is 120K,
4. %boltzman constant =1.38 *10^-23 kg s-2 K-1
5. %Bandwidth 128kHz -512kHz
6. %Consider modulation scheme is GMSK -1 bit/symbol
7. %Noise power level
8.
9. % For GMSK the minimum SNR the receiver can handle
10. %M=(1+S/N)^0.5
11. %S/N=M^2 -1
12. %num of packets
13. p_sz=[500:100:5000];
14. s=size(p_sz,2);
15. n=1:6; %num of bits per symbol
16. n1= repmat(n,[4,1,s]);
17. C=[128*10^3;256*10^3;384*10^3;512*10^3];
18. C= repmat(C,[1,6,s]);
19. k=1.38 *10^-23;
20. T=120;
21. N=k.*T.*C./n1;
22. M=2.^n1;
23. SNR=M.^2-1;
24. RX=SNR.*N;
25. Gm=1;
26. Gb=1;
27. TX=10;
28. Hm=5;
29. Hb=10;
30. f=220;
31. %conside Hm=5m Hb=10m TX=10W f=220MHz Gb=1 Gm=1
32. %using Egli model
33. %RX=0.668*Gb*Gm*[Hb*Hm/d62]^2*[40/f]^2 *TX
34. d4=0.668*Gb*Gm*(Hb*Hm)^2*(40/f)^2*TX./RX;
35. d=d4.^(0.25);
36. %channel capacity
37. % C=[128*10^3;256*10^3;384*10^3;512*10^3];
38. num_pkt= repmat(p_sz,[4,1,6]);
39. num_pkt1=permute( num_pkt,[1 3 2]);
40. %calculate the speed for different bitrates & num of packets
41. t=num_pkt1.*1216./(C.*n1);
42. v=d./t;
43. hold all
44. x=n';
45. y=C(:,1,1);
46. z=num_pkt(1, :, 1)';
47. figure
48. hold all
49. surf(squeeze(v(1, :, :)));
50. surf(squeeze(v(2, :, :)));
51. surf(squeeze(v(3, :, :)));
52. surf(squeeze(v(4, :, :)));
53. xticklabels =500:1000:5500;
54. set(gca, 'XTickLabel', xticklabels);
55. grid on
56. xlabel('num of packets');
57. ylabel('number of bits per symbol');

```

**Figure 5. Matlab model to calculate the maximum possible speed**



**Figure 6. Maximum possible speed with different bitrates, modulation schemes and number of packets**

### 3.9 Summary of Findings

To support up to 400mph train speed:

- Channel capacity – 64kbps
- Modulation scheme –BPSK
- Doppler shift – 300Hz
- Number of packets to establish a connection is less than 500

## 4. Link Budget Analysis

---

This study also did a detailed link budget analysis to show how radio signal power loss values change along a rail line. As case studies, geographical data of two existing rail lines on the West coast were used, namely the SCRRRA lines comprising the greater Los Angeles area and Amtrak's Coast Starlight connecting Sacramento, CA to Portland, OR. Using publically available rail maps and timetables, we developed a Matlab model to calculate Path loss, Multipath fading, Vegetation loss, Precipitation loss and the received power. Link budget analysis for a particular path is given by equation (9):

$$Rx\ power\ (P_{rx}) = P_{tx} + G_{tx} + G_{rx} - L_{tx} - L_{rx} - L_{mp} - L_p - L_r - L_m - L_f \quad (9)$$

Where:

- $P_{tx}$  = Tx power
- $G_{tx}$  = Tx antenna gain
- $R_{tx}$  = Rx antenna gain,
- $L_{tx}$  = TX feed loss
- $L_{rx}$  = RX feed loss
- $L_{mp}$  = Antenna miss pointing losses
- $L_p$  = Free space loss
- $L_r$  = Rain attenuation
- $L_m$  = Multi path effects
- $L_f$  = foliage effects

Each of the components in equation (9) is analyzed, as described below, to determine how power losses and gains can affect the radio links under consideration.

### 4.1 Transmission Power

Power ratings from the Meteocomm radio equipment specifications are shown below;, where the operating power of the antenna is limited by its height from the ground.

- 0m to 150m -500W
- 150m to 225m -250W
- 225m to 300m -125W
- 300m to 450m -60W
- 450m to 600m -20W

### 4.2 Antenna Gain

This depends on the antenna that is used. Each antenna should have low directivity. If an isotropic antenna is used, the gain will be 1.

### 4.3 Feed Loss

When feed loss occurs, it happens at feed runs between the high power amplifier and the transmitting antenna at the transmitting end as well as the receive antenna and the high power amplifier at the receiving end. The values depend on the length of the feeding cable and its material; for a feed made of 12 ft. coaxial cable CL-50086, the feed loss is 1 dB.

#### 4.4 Antenna Mispointing Loss

When low directional antennas are used, the antenna mispointing loss is negligible so this factor can be excluded from our calculations.

#### 4.5 Free Space Loss

Free space loss is proportional to the distance between the antennas ( $d$ ) and the transmit frequency ( $f$ ) and it is given by equation (10).

$$\text{Free Space loss} = 32.4 - 20 \log(d) - 20 \log(f) \quad (10)$$

#### 4.6 Rain Attenuation:

The signal attenuation due to rain fade was computed using equation (11).

$$L_{pre} = 10^{1.203 \log(f) - 2.290} R^{1.703 - 0.493 \log(f)} \quad (11)$$

Where:

- $L_{pre}$  is the attenuation due to rain fade,
- $f$  is the frequency in GHz, and
- $R$  is the rain density in mm/hr.

#### 4.7 Multipath Fading:

Multipath fading is caused by the phase differences between the waves (direct wave and the reflected waves from the obstacles) that are arriving at the receiving antenna. In urban areas, where multiple obstacles are present, multipath fading will adversely affect the signal. It is possible that many reflected waves from buildings and other structures diffract with the main signal. The Okumura-Hata model [5] given by equation (11) was used to compute the multipath fading of the radio signal:

$$L_{ob} = 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_B - C_H + [44.9 - 6.55 \log_{10} h_B] \log_{10} d \quad (12)$$

In equation (12),  $L_{ob}$  is the loss caused by obstacles in dB,  $f$  is the frequency in MHz,  $h_B$  is the height of the fixed transmitter,  $C_H$  is an antenna height correction factor, and  $d$  is the distance between transmitter and receiver in kilometers. The antenna height correction factor is calculated based on the urban area density [9]. For a small to medium sized city it is given by equation (13).

$$C_H = 0.8 + (1.1 \log_{10} f - 0.7) h_M - 1.56 \log_{10} f \quad (13)$$

Equation (14) was used to compute the loss due to obstacles for large cities.

$$C_H = 8.29 (\log_{10} (1.54 h_M))^2 - 1.1, \text{ if } 150 < f < 200 \quad (14)$$

$$C_H = 3.2 (\log_{10} (11.75 h_M))^2 - 4.97, \text{ if } 200 < f < 1500 \quad (15)$$

#### 4.8 Doppler Effect:

The guard band value was selected in order to avoid the affect from Doppler fading.

Consequently, we excluded the Doppler effect from the link budget calculation.

#### 4.9 Vegetation

Rain and wind can cause the propagation channel to vary when heavy foliage is present. This is a predictable geographic phenomenon due to known routes on specific rail lines. The increase in loss due to propagation through trees is calculated with the exponential decay model presented by LaGrone [6], seen in equation (16).

$$L_{veg} = 0.26 * f^{0.77} * Df \quad (16)$$

Where:

$L_{veg}$  is the loss caused by vegetation,

$f$  is the frequency in GHz, and

$Df$  is the foliage depth in meters.

To develop a link budget analysis model, vegetation data was obtained from existing maps and a spreadsheet was created for chosen points along the rail line, closest WIU locations, vegetation details, rain details, urbanization, transmit power, mobile antenna height and fixed antenna height. A Matlab model was developed for reading the spreadsheets, calculating the loss values and calculating the receive power using link budget calculations, shown in Figure 7:

- Line 4-9 reads values from the spreadsheet to a matrix.
- Line 11-30 extracts the relevant data for every train location.
- Line 32-36 calculates the distance between the train and the WIU given the latitude and longitude.
- Line 37-45 calculates the precipitation loss, vegetation loss, and multipath fading. Line 46 calculates the received power using link budget calculations.

```

1. clear all
2. close all
3. file=input('Enter file name');
4. [type,sheetname]=xlsinfo(file);
5. m=size(sheetname,1);
6. [WL,string]=xlsread('WIU.xlsx');
7. for(a=1:m)
8. Sheet=char(sheetname(1,a));
9. TR1=xlsread(file,Sheet);
10. TR=[TR1(:,2) TR1(:,3) TR1(:,4) TR1(:,5) TR1(:,6) TR1(:,9) TR1(:,10) TR1(:,11) TR1(:,12)
    TR1(:,13) TR1(:,14) TR1(:,15) TR1(:,16) TR1(:,27)];
11. f=TR(1,1);
12. plot(WL(:,1),WL(:,2),'*');
13. n=size(TR,1);
14. Gt=0;
15. Gr=0;
16. for( i=1:n)

```

```

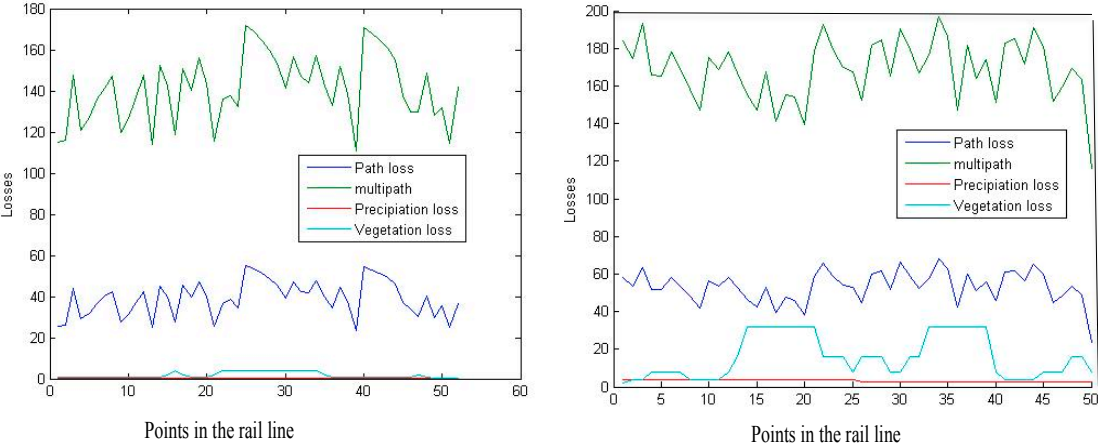
17. x=TR(i,2);
18. y=TR(i,3);
19. wx=TR(i,4);
20. wy=TR(i,5);
21. pprecip=TR(i,6);
22. raindensity=TR(i,7);
23. pveg=TR(i,8);
24. vegdensity=TR(i,9);
25. pobs=TR(i,10);
26. urb=TR(i,11);
27. Hm=TR(i,12);
28. Hb=TR(i,13);
29. Tx=TR(i,14);
30. R=6373;
31. %calculate the distance between the train and the wiu
32. dlat = wx - x;
33. dlon = wy - y;
34. a = (sind(dlat/2))^2 + cosd(wx) * cosd(x) * (sind(dlon/2))^2;
35. c = 2 * atan2( sqrt(a), sqrt(1-a) );
36. d(i) = R * c ;
37. Lprep(i)=(10^(1.203*log10(f/1000)-2.290))*(raindensity^(1.703-0.493*log10(f/1000)));
38. Lveg(i)=0.26*((f/1000)^0.77)*vegdensity;
39. if(urb==0)
40. Ch=0.8+(1.1*log10(f)-0.7)*Hm-1.56*log10(f);
41. else
42. Ch=3.2*((log10(11.75*Hm))^2)-4.9;
43. end
44. Lob(i)=69.55+26.16*log10(f)-13.82*log10(Hb)-Ch+(44.9-6.55*log10(Hb))*log10(d(i));
45. Lpath(i)=32.4-20*log10(d(i))-20*log10(f);
46. Rx(i)=Tx+Gt+Gr-Lprep(i)-Lveg(i)-Lob(i)+Lpath(i);
47. end
48. figure
49. plot(Lob)
50. plot(Lpath)
51. plot(Lprep)
52. plot(Lveg)
53. legend('Multipath', 'Path loss','Precipitation loss','Vegetation loss');
54. ylabel('Loss');
55. figure
56. subplot(1,2,1)
57. plot(Rx)
58. ylabel('Receive power level');
59. subplot(1,2,2)
60. hist(Rx,50);
61. ylabel('Histogram');
62. L=[d;Lprep;Lveg;Lob;Lpath;Rx];
63. L=[TR(:,2) TR(:,3) d' Lprep' Lveg' Lob' Lpath' Rx'];
64. col_header={'Lat','Lon','distance(km)','Lprep','Lveg','Lob','Lpath','RX'};    xlsxwrite('coast_result_10
162013',L,Sheet,'B2');
65. xlsxwrite('coast_result_10162013',col_header, Sheet,'B1');
66. end

```

**Figure 7: Matlab Code to Compute the Receive Power**

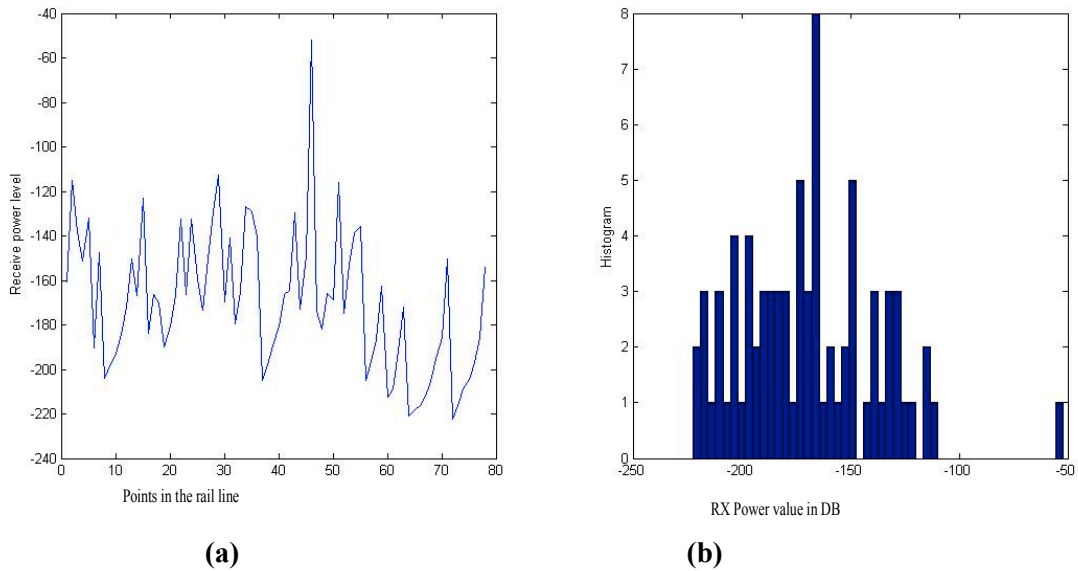


The results of the Matlab simulation are shown in Figure 8, for the two rail lines, and in both cases, multipath fading is the most dominant loss factor. This is mostly because both the two rail lines run across urban areas where a lot of obstacles. The path loss for SCRRA line is around 40dB. For the coastal line it is around 60dB. SCRRA line has low path loss compared to Coastal line because the WIU's in SCRRA are spaced frequently than the Coastal line. We also observed that there is a significant contribution from vegetation to the total loss value in the Coastal line, because it runs through a route with considerable vegetation. For the two rail lines the precipitation loss is very small and has a negligible effect on the total loss.

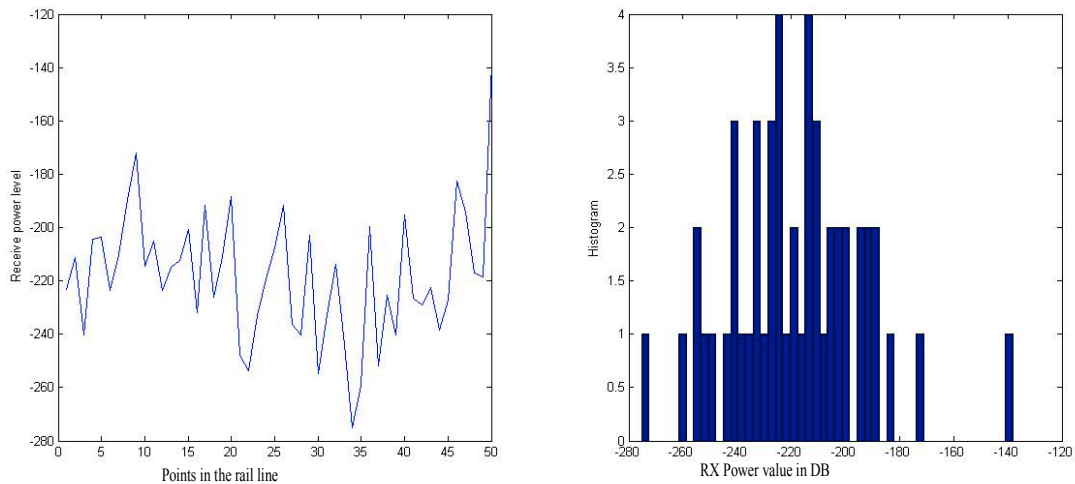


**Figure 8: Loss values (a) along the Orange County rail line in SCRRA  
(b) Loss values along Coast Starlight rail line**

Both Figure 9 and 10 show the variation of received power levels for the two rail lines and the mean received power level for the SCRRA line is -160dB. And the standard deviation for the power level is 24.9093dB. For the coastal rail line, the mean received power level is -216.0107dB and the standard deviation is 27.6678dB.



**Figure 9: (a) Received power values along Orange County rail line in SCRRA  
(b) Histogram for power values**



**Figure 10: (a) Received power values along Coast Starlight rail line  
(b) Histogram for power values**

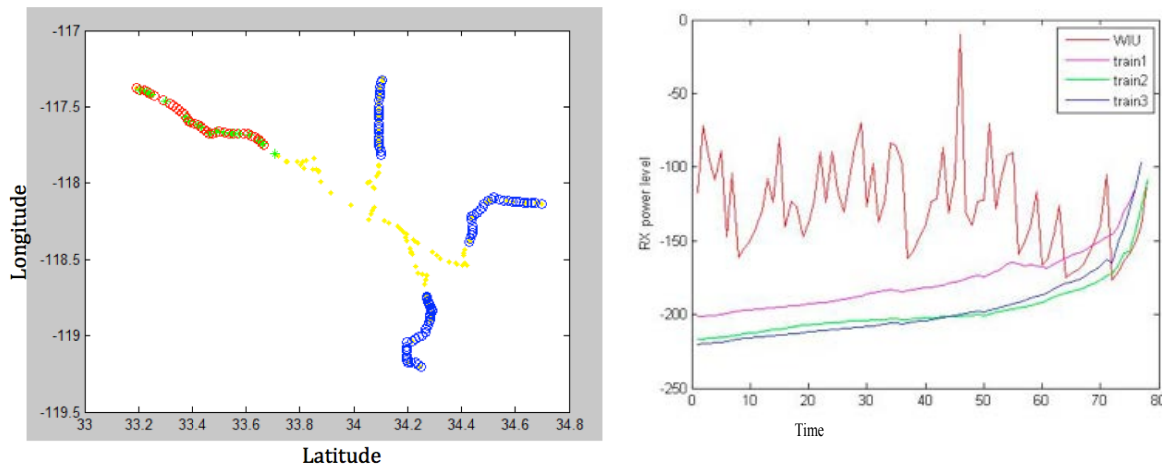
#### 4.10 Summary of Findings

In this section we analyzed how different loss factors can affect the received power level of the train. The SCRRA rail lines and the Coast Starlight rail line were analyzed. The results are,

- Multipath fading is the most serious loss factor. For the two rail lines that we have considered the multipath loss level is more than the path loss.
- Precipitation loss is very less and does not effect receive power level.
- Received power level were:
  - SCRRA – Mean: -160dB Standard deviation: 24.9093dB
  - Coast Starlight – Mean: -216.0107dB Standard deviation: 27.6678dB

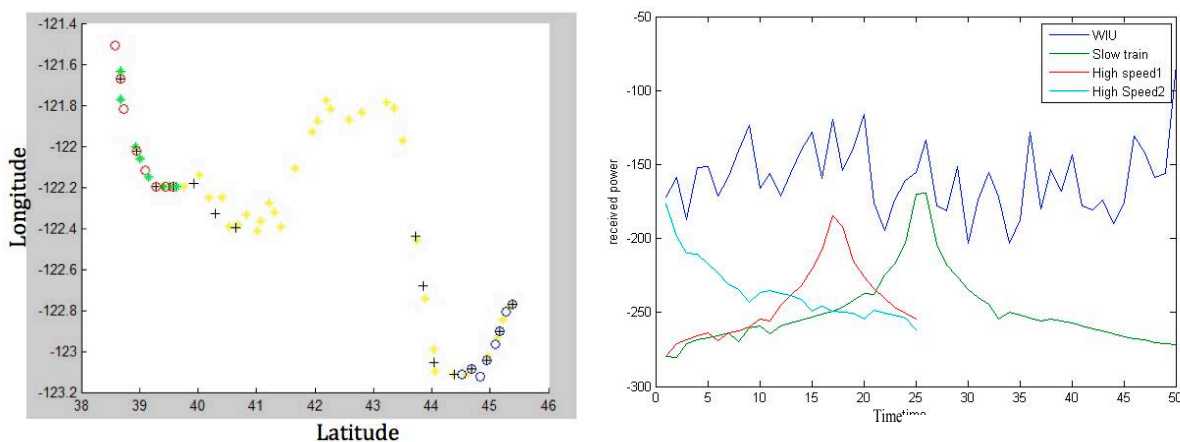
## 5. Interference Analysis

This section discusses how signals from other trains can interfere with the control signal. To determine how interference occurs, we first developed the model for the SCRRA line. This model uses existing timetables to model a scenario where four trains are traveling at the same direction along four rail lines, as shown in Figure 8(a). The targeted train is in red and the other three trains are in blue, while the WIU to train communication is shown in green. The received power from WIU and other three trains were calculated and the results were compared. This model is an extension of the model used to calculate the received power. Here we calculated the receive power from the nearest WIU and all the other trains operate at the same time with the model used to calculate the received power level. Figure 8(b) shows the received power level variations of the WIU and the other three trains. The results showed that there is a significant signal level from other trains when the three trains are getting closer.



**Figure 11: Matlab model for four trains travelling close-by on the SCRRA line**

**(a) Simulation (b) Received power level**



**Figure 12: Matlab model for two high-speed trains and two slow trains on Coast Starlight line**

**(a) Simulation (b) Received power level**

Similar analysis were done for the Coast Starlight train line, where a hypothetical scenario was considered with two slow trains and two high speed trains start at the same time and run in opposite directions. In this scenario, the speeds of the high-speed trains are twice the speed of the slow trains and the simulation is shown in Figure 9(a). The targeted train is in red, the nearest WIU is in green, and the slow train running in the opposite direction is shown as blue circles. Black crosses indicate the locations of the two high-speed trains. We calculated and compared the received power levels and the results indicated that when a train gets closer, the received power from the train increases. Thus, cause interference is possible if the frequency is not properly allocated.

The results from the SCRRA and Coast Starlight rail line analyses show that there can be significant interference from neighboring trains if the frequency is not chosen carefully. To avoid interference, the following measures can be taken:

- Identify whether the two trains run close to each other at any time during their respective journeys. If not, the two trains can use same or closer frequency channels. But if the two trains run close to each other, the frequency of the two train channels must be far from each other.
- Reduce the transmit power level so that the area where there is a potential interference is limited.
- Use dynamic channel allocation schemes. If channel is affected by interference, the channel would be switched to a frequency where there is no interference.

## **5.1 Summary of Findings**

In this section, we analyzed the interference effect from other trains.

- When two trains operate close to each other, the frequency channels for each train should be far away from each other.
- In potential interference areas, the transmit power should be reduced.
- Dynamic channel allocations schemes can ensure that if a channel is affected by interference, an interference free channel is chosen.

## 6. Conclusion

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For efficient PTC operations on high-speed lines, the channel capacity of 64 Kbps and the BPSK modulation scheme are sufficient. However, if the number of packets for connection is greater than 500, a higher order modulation scheme should be used. Also, the Doppler shift should be greater than 300 Hz and the number of packets to establish a connection should be less than 500.

If the conditions in the opening paragraph are met, high-speed trains can travel at speeds up to 400 mph. Well-separated frequency channels should be assigned to trains that will operate in close proximity. Additionally, in potential interference areas, the transmit power should be reduced. Dynamic channel allocations schemes can be adapted so that if a channel is affected by interference, it is capable of selecting an interference free channel.

Multipath fading is the most significant adverse influence to receive power for the required PTC communications between train and control point. Path loss is also a dominant loss factor. To reduce this, WIUs and control points should be placed more frequently. This effort may also reduce the impact of multipath fading. In some geographic areas, trains encounter areas of dense vegetation that requires consideration. However, this is a fairly predictable phenomenon (unlike precipitation) and proactive mitigation measures can be taken to ensure PTC communications.

Contribution from precipitation loss is negligible. Although certain areas of the United States will offer climatic conditions that vary significantly from the case-studies used in our analysis, the frequency range of PTC (~220 MHz) is naturally resilient to precipitation based on its wavelength. However, transition to a higher spectrum range—such as satellite technologies – will require further study.

### 6.1 Recommendations for Future Investigations

- If packet details for ERTMS are provided, a similar analysis could be conducted for ERTMS. This will allow a more robust comparison between frequency management of PTC and ERTMS.
- Developing a signaling mechanism for dynamic channel allocation. When the communication channel of the train is affected by interference, the train can switch its communication channel to an interference free channel. However, there must be an associated exchange with the control point to disclose that the communication channel has been changed.

## 7. References

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## **Abbreviations and Acronyms**

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BLE	Brotherhood of Locomotive Engineers
CFR	Code of Federal Regulations
FMVSS	Federal Motor Vehicle Safety Standards
MBTA	Massachusetts Bay Transit Authority
OSHA	Occupational Safety and Health Administration
UTU	United Transportation Union