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Providing Wireless Bandwidth for High-speed Rail Operations

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Abstract

American railroads are in the process of introducing a wireless network-based control system – commonly referred to as positive train control (PTC) – to share the railroad among multiple trains, worker vehicles, and other support entities. A major challenge with adopting a wireless based communication systems for high-speed rail (HSR) is the limited bandwidth availability in the USA. The objective of this paper is to analyze the sufficiency of the 220MHz frequency range in supporting PTC-like operations for high-speed trains.

The paper begins with a frequency analysis that shows the advantages of using different modulation schemes and channel bandwidths to gain data rates and supporting signaling and beacon networks that uses PTC packets formats. PTC places limitations on the wireless trains speeds with the number of packets required to establish a connection and a minimum distance between overlapping cells, using proposed packet formats. Additionally, using a guard band that can eliminate the Doppler effect caused by increasing train speeds. For example, using a guard band of 300Hz can eliminate the Doppler shift at speeds less than 400mph.

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Keywords: Positive Train control; Frequency planning; high-speed trains

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1. Introduction

High-speed rail operations will bring significant societal benefits to the regions they serve and to the traveling public in general in the U.S.A. European and Asian high-speed trains use GSM-R, a special-purpose extension of the GSM protocol used for cellular telecommunications. GSM-R supports a unified Communications-Based Train Control (CBTC) system known as the European Rail Traffic Management System (ERTMS). ERTMS supports high-speed rail services in Europe and is being adopted in India and China (1).

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There is a move to introduce high-speed rail services in the West Coast of the USA, similar to the North-Eastern corridor, between Boston and Washington D.C. Class-one freight railroad companies (BNSF, NS, CSX and UP) and the main high-speed passenger railway company, Amtrak are collaborating on providing an interoperable Communication Based Train Control (CBTC) system, using their E-VTMS (Enhanced Vessel Traffic Management System) (2), originally designed by BNSF. American railroads use the 220MHz frequency range [217-219MHz for the uplink and 221-222MHz for the downlink] for rail signalling.

We answer the main question of computing the maximum attainable speed using the 220MHz frequency band for ERTMS-like signaling mechanisms for American high-speed trains. The rest of the paper is organized as follows. Section 2 describes the PTC architecture and PTC message formats, as our computations are based on this model. Section 3 discusses the frequency analysis that was carried out to see how the available frequency band should be divided to support train operations. Section 4 discusses related work and Section 5 provides conclusions.

2. PTC System

2.1. PTC Architecture

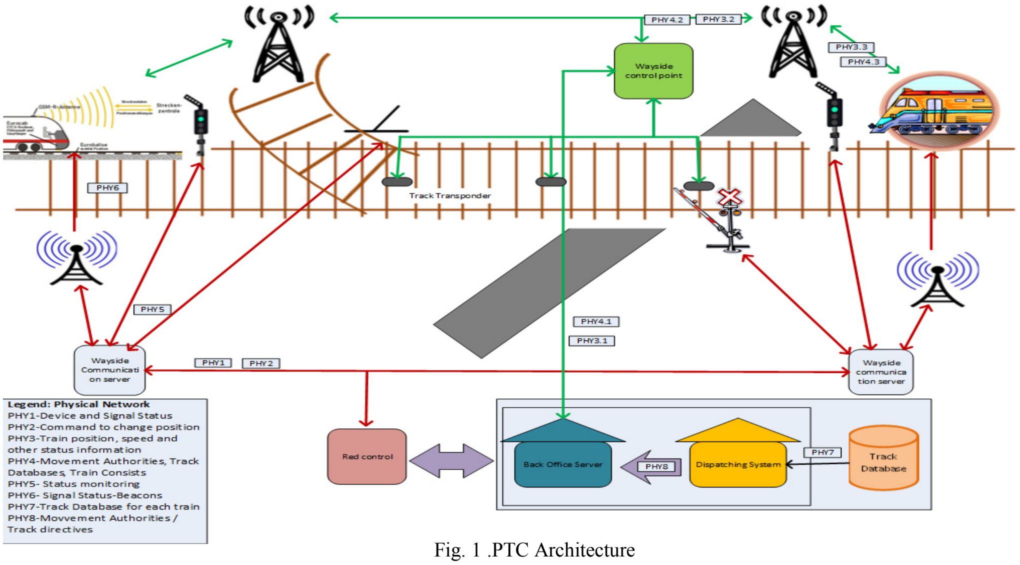


Fig. 1 .PTC Architecture

Fig.1 shows the main components of the proposed 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 connecting the back offices that are in charge of managing the track segment. The logical connectivity of this part is shown as the "green network". With the exception that Amtrak's uses ACSES2, a track-mounted transponders to convey movement authorities using a four-aspect signal encoding, it is ideal for an integrated system to only use wireless communications. In addition to this envisioned PTC system, existing externally mounted and in-cab signals provide movement authority and track condition notifications, including but not limited to switch positions using wayside devices. This existing signal network is shown at the bottom of Fig. 1 as the "red network". Where in-cab signalling is available, the red network may use wireless communications, track mounted sensors (as in Amtrak's Northeast corridor) or provide wired external signals. In either case, movements can be controlled 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 analyse bandwidth requirements for high-speed traffic. Given existing agreement between the railroads to use EVTMS we use EVTMS as the PTC system that will be used in high-speed rail operations in the U.S.A.

2.2. PTC Messages

Table 1(a). WIU Status Message Format (3) (b) Signalling Message Format (4)

(a)

Field	Size	Description
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	Generated by WIU
VDIV	32 bits	HMAC

(b)

Field	Size (Bytes)	Description
Protocol Version	1	Version of EMP header
Message Type (ID)	2	As noted in the definition of each message in this ICD
Message Version	1	As noted in the definition of each message in this ICD
Flags	1	Timestamp Format, No encryption. No compression, Data Integrity
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
Variable Header Size	1	Defined by length of source and destination addresses
Time to Live	2	Quality of Service and Time to Live
Routing QoS	2	Quality of Service and Time to Live
Source	64 max	
Destination	64 max	
Data Integrity	4	Truncated Keyed Hashed Message Authentication Code.

PTC traffic consists of two main types of messages. They are,

a) **Messages that belong to the WIU network:** Broadcasts WIUStatus. Message numbers are 5100 and 5101. Message format is shown in Table 1(a).
   - Beacon Request: Sent by a train 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.
   - 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 exclude message payload fields. (3)

b) **The messages that belong to the signaling network:** These are the control messages sent from the back office to the train and the train to the back office. The message format is shown in Table 1(b).
   - Messages from the train to the back office- Message type from 01000 to 01123
   - Messages from the back office to the train-Message type from 02000 to 02122 (4)

3. Frequency Analysis

3.1. Calculating the Guard band

Due to the potential speed of trains, the well-known Doppler shift should be addressed. The guard band is a vacated portion of the spectrum to allow for potential frequency shift due to Doppler, protecting the neighboring channel from interference. To ensure its functionality, the guard band should be at least as twice the value of the calculated Doppler frequency shift. The frequency shift is calculated using Equation (1):

$$\frac{\Delta f}{f} = \frac{V_t}{C} \tag{1}$$

We varied the speeds from 50mph to 400mph and calculated the corresponding Doppler shift. As shown in Fig. 2(a), 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 recognizing the potential for slight variations set the final guard band size to 300Hz.

3.2. Calculating maximum number of packets per channel

Train operations occupy 217-219MHz for the uplink and 221-222MHz for the downlink. A channel is 25 kHz wide and uses DQPSK modulation. The base and locomotive radios can support data rates up to 32 kbps, while the wayside radio can support data rates up to 16 kbps. The maximum WIU message size is 2040 bits (see Table 1(a)) and the maximum signalling message size is 1216 bits (see Table 1(b)). We used these maximum packet sizes and calculated the minimum number of packets per second that a channel can use. This result is tabulated in Table 2(a). It shows that with the current PTC system with 32 kbps data rate signal channel can use up to 26 packets per second and beacon channel can transmit up to 15 packets per second.

Table 2(a). Minimum possible packets per channel per second for signalling network and beacon network (b) Channel capacities with different bandwidth and modulation schemes

(a)

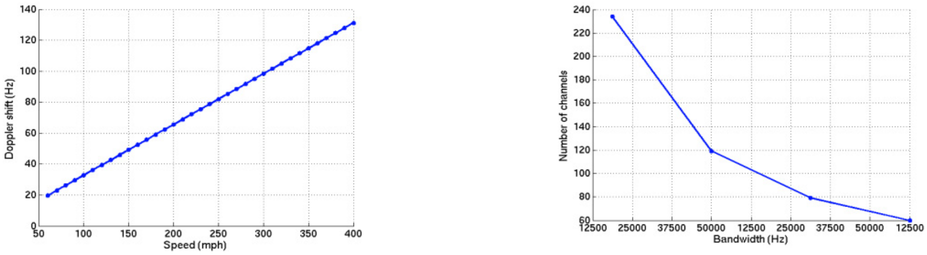
Bit rate (kbps)	Signal network	Beacon network
16	13	7
32	26	15
48	39	23
64	52	31
80	65	39

(b)

Bandwidth (kHz)	BPSK	QPSK	8QAM
12.5	8kbps	16kbps	24kbps
25	16kbps	32kbps	48kbps
37.5	24kbps	48kbps	72kbps
50	32kbps	64kbps	96kbps

Then we analyzed how the bitrates change with the bandwidth and the modulation scheme and for selected bit rates we calculated the number of packets each channel can handle per second. If the roll off of the filter is α, Symbol rate is S then the occupied bandwidth (B) can be calculated using equation 2.(5). For α=0.5 is the variation of channel capacities with different bandwidths and modulation schemes is shown in Table 2(b).

$$B = S*(1+\alpha) \qquad (2)$$



(a) (b)

Fig. 2. (a) The Doppler Shift (Hz) Vs. speed (mph) (b) Variation of channels with bandwidth

3.3. Calculating maximum number of packets

The number of channels that can be allocated using 3MHz band can be calculated by using equation (3). B is the channel bandwidth in kHz and g is the guard band in kHz. n is the number of channels.

$$n*B+(n+1)*g=3MHz \qquad n=\frac{(3000-g)}{(B+g)} \qquad (3)$$

3.4. Frequency allocation for Control and Beacon WIU)

Channels can be allocated for control and signal messaging dynamically depending on the number of trains the control points have to serve and the number of WIUs that are located closer to the control point. Each WIU that is in the same area should have a different channel so that the channels will neither interfere with each other nor with the control channel. The movement authority should be given from control point to next control point as shown in Fig. 3(a). This adds an extension to the block based movement authority granting proposed in (6). The distance between two control points depend on the maximum transmit power allowed, received power that the receiver can handle and the propagation characteristics, because the train should be able to maintain the communication with the control point until it is handed over to the next control point. The control point should allocate two channels for the uplink and the downlink. Typically in a single track line the number of trains that the control point has to serve is one. This number can be increased depending on the number of parallel tracks and train intersections.

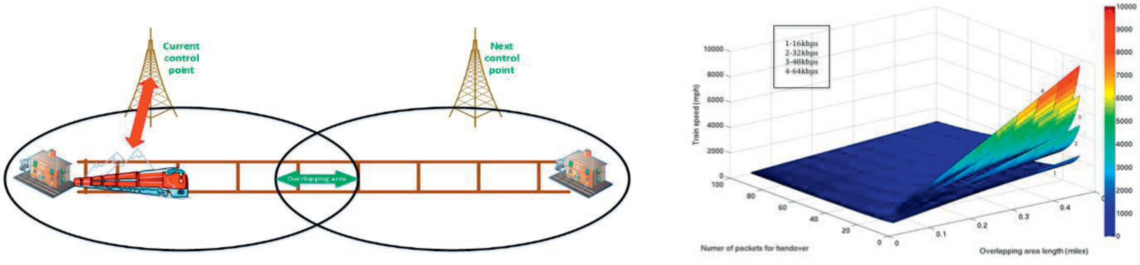
The distance between two WIUs depends on the safety-critical infrastructure existing along the train route. Each WIU requires one channel to broadcast the beaconing messages. WIUs only broadcast individual status. The wayside status messages should arrive at the locomotive in a timely manner such that it has enough time to apply brakes and come to a complete stop before it approaches the stop point.

3.5. Calculating the maximum possible speed

The train should be able to complete the handover process from the current control point to the next control point before it go away from the coverage area of the current control point. If we assume that trains trigger handovers when the signal strength from next control point is stronger than the current one, handover process should complete within the time train moves through the overlapping area. If the overlap distance between the two control cells is x, control packet size is p, bit rate is b and train travels in a constant velocity v and the number of handover messages required is n, distance required to exchange handover messages d in seconds can be obtained from equation 4.

$$d = \frac{n * p}{b} * v \qquad\qquad d < x \tag{4}$$

We varied the number of packets from 0 -100 and overlapping distance from 100-1000m(in steps of 100m) and size of a control packet is considered as 1216bits.We obtained the maximum possible train speed that the system can support for different data rates. The results are shown in Fig. 3(b). This packet number was varied to simulate differing network conditions. The number of packets may change from location to location due to the fact that it requires packet retransmission if the channel is lossy and has interference. This will take the overhead of the air interface protocol into account.



(a) (b)

Fig. 3. (a) Train communication with control points (b) Maximum possible speed with the overlapping distance and number of handover packets

With the current PTC implementation for a train to operate over 400mph of speed the number of packets to establish for proper connection establishment and handover should be less than 20 and the overlapping area should be greater than 600m. If the medium encounters less loss and therefore does not need packet transmission, it would be possible to operate at such speeds. But due to the overhead in the air interface protocol it is highly unlikely that current system can support train speeds more than 400mph. Therefore if we need to implement PTC like operations for high-speed trains a higher data rate should be used. For the same channel bandwidth this can be achieved by increasing the modulation scheme.

4. Related work

Significant research exists in the area of providing wireless communication for train operations. But most of them focus the wireless bandwidth management for providing wireless services such as Internet access inside trains.

In (7) Lin and Chang discuss conceptual/ functional level architectural design of communication and entertainment services for onboard high-speed public transportation systems. In their approach, the transport system becomes an entity of the mobile network and their connection with the infrastructure is interfaced through either a land terrestrial microwave or a satellite communication system. In (8) Kanafani et. al discuss architecture to provide Internet access on trains using WiFi and WiMAX protocols. They also describe a survey conducted on trains managed by CCJPA by offering trial Internet based on low bandwidth communication infrastructure.

These approaches cannot be directly applied for the wireless bandwidth management of signal and control network of the trains, because these networks are safety critical and should be more reliable. Further, to support high-speed operations the wireless link should support sufficient data rates with a low latency. There are technologies such as DSRC – WAVE (Dedicated Short Range Communication and Wireless Access in Vehicular Environment), WiMAX; and MBWA (Mobile Broadband Wireless Access) that are used in high speed operations. These standards usually support up to 250Km/h speeds(9). The analysis we propose is significant because of its focus on estimating wireless spectrum needs for high-speed rail operations provided existing PTC systems were to be used for the same purpose to near speeds of 400mph.

5. Conclusions

We present design details for a proposed wireless based high-speed rail system. We did a frequency analysis to determine how the available frequency band should be divided to support safe train operations. Guard band is selected to accommodate the Doppler shift due to fast train movements. We then calculated the maximum possible train speed for different cell overlapping lengths and different number of packets to establish the handover.

Our results show that given the limited channel bandwidth, current PTC implementation cannot support high-speed train operations all the way up to 400 mph. By increasing the data rate by increasing the channel bandwidth or modulation order PTC system can support increased speeds provided an overlay system such as E-VTMS can satisfy safety concerns. But increasing the channel bandwidth will limit the number of trains a control point can support at a given time and increasing the modulation order requires more signal to noise ratio at the receiver for proper signal extraction.

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