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Assessment of Wind Farm Interference Impact on ITC Communications in 220 MHz Frequency Band

Research Technical Report

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Revision History

Revision	Date	Summary of changes
0.1	08/12/2024	Kee Himsoon - First draft
0.2	09/12/2024	Pam Siriwongpairat – Updated content on modeling and field testing
0.3	10/3/2024	Kee H. - Reviewed and updated content
0.4	10/30/2024	Kee H. Added content on test site details
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1.0	12/16/2024	First distribution for review
1.1	12/19/2024	Updated content based on internal reviewers' feedback
1.2	12/23/2024	Revision based on Clark Palmer's comments

Table of Contents

Table of Figures

Table of Tables

1. Executive Summary

The purpose of this project is to assess impact of wind farm interference to interoperable train control (ITC) communication system at 220 MHz. In this project, Meteorcomm's (MCC) Research team performed field measurement at Tehachapi Pass Wind Farm in California, characterized wind farm interference and its impact, proved the existence of wind farm interference, and provided recommendations on mitigation strategies/counter measures to avoid wind farm interference.

Results show that a wind farm deployment could potentially obstruct radio communication links and/or degrades radio RF signal reception by means of lowering signal to noise ratio through several mechanisms and factors such as diffraction, scattering, wind farm density, distance, speed, etc.

Impact analysis was performed based on modeling, and correlated with, data received from field measurement in California.

Below is a summary and associated recommendations:

- Field measurement and modeling confirm existence of wind farm interference to ITC radio operating at 220 MHz.

- Recommended exclusion zones, zone parameters, and assessment requirements are as follows

Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0 - 0.3 miles (0 - 500 meters) from railroad tracks	0.3 miles – 0.6 miles (501 - 1,000 meters) from railroad tracks	0.6 – 1.2 miles (1,001-2,000 meters) from railroad tracks (Within maximum effective radio range)	> 1.2 miles (>2,000 meters) from railroad tracks (Beyond effective radio range)
Assessment Requirements	Safeguarding	Detailed Assessment	Simple Assessment	No Assessment

- Recommended mitigation measures related to wind farm interference effect to ITC radio include a) regulatory change/new guidelines, b) wind turbine/wind farm options, c) modify/improve communication devices or links, and d) terrain screening.

2. Introduction

2.1 Purpose

The purpose of this document is to document MCC’s Research team’s detailed study and impact assessment of wind farm interference to PTC operations using the 220 MHz network. Impact to other railroad operating frequency bands can be explored later based on level of interest or requests from key stakeholders. The outcome of the analysis described in this paper addresses concerns raised by DOT, FRA, and AAR regarding potential impact of wind farm RF interference.

The questions and concerns are related to the possibility of co-locating of large-scale high-density wind farms with PTC communication system infrastructure. Most of the existing wind farm interference studies focus on wind farm interference impact to systems such as radar, air traffic control, microwave link, terrestrial fixed radio links, etc. There are a few assessments for its impact to railroad operations, but these assessments do not focus on impact to PTC operation.

This report addresses these questions and concerns by attempting to prove or disprove the existent of such wind farm interference on PTC communications. In addition, this report provides recommendations related to mitigation strategies or countermeasures to avoid or mitigate such interference if it does exist.

Activities in this assessment included:

- Modeling and characterizing wind farm interference and its behavior
- Field testing to collect field test data, compiling, and correlating the results with those from modeling.

- Conducting an impact study, analysis, and assessment of the obtained results and proving recommendations on courses of action to mitigate/avoid the identified interference issues.

The Tehachapi Pass wind farm in Kern County, California, was chosen as an area under study. Field testing was conducted at Tehachapi Pass wind farm in August 2024.

2.2 Terms and Definitions

Table 1: Terms and Definitions

Term	Definition
AAR	The Association of American Railroads
BER	Bit Error Rate
bps	Bits per second
C/I	Carrier to Interference Ratio
CGR	Current Generation Radio
DQPSK	Differential Quadrature Phase Shift Keying modulation
DOT	Department of Transportation
EMI	Electromagnetic interference
FEC	Forward Error Correction
FR	Full Rate (32 kbps)
FRA	Federal Railway Administration
HR	Half Rate (16 kbps)
ITC	Interoperable Train Control
ITCnet	Air interface protocol used by the ITC 220 MHz radios to communicate with each other
kbps	Kilobits per second
MHz	Mega Hertz
ms	Milliseconds
PER	Packet Error Rate
PTC	Positive Train Control

PTC220	PTC-220 is a consortium held by the seven Class I railroads. It is a spectrum holding company and licensee for various FCC call signs in the 219 and 220/221 MHz bands.
RF	Radio Frequency
RS	Reed-Solomon code
RSSI	Received Signal Strength Indicator, an estimated measurement of how good a radio can detect and receive signals
SNR	Signal to Noise Ratio
VHF	Very High Frequency in the range 30 to 300 megahertz (MHz)
Wind Farm	A group of wind turbines that are used to generate electricity for power grids

2.3 References

[1] “RF Measurement Assessment of Potential Wind Farm Interference to Fixed Links and Scanning Telemetry Devices”, ERA Technology Ltd, March 2009.

[2] “ITCR Physical Layer System Specifications”, Meteorcomm.

[3] “ITCnet CAI Specification”, Meteorcomm.

[4] USGS Wind Farm Database, https://eerscmap.usgs.gov/uswtdb/

[5] Derek Edmonson, “Evaluation Wind Turbine Facilities and Detrimental Impact to ITC”, Meteorcomm Research Forum, 2024.

[6] Kee Himsoon, Pam Siriwongpairat, and Josiah Solomon, “Wind Farm Interference Study”, Meteorcomm Research Forum, 2024.

2.4 Scope

- This study focuses on wind farm interference to train control communications in the 220 MHz band and its ITC radios. Other frequency bands can be considered later as a follow-on study.
- This study considers collected compounded impacts from wind farm interference factors on the radio packet error rate performance. These factors are such as wind farm density, wind turbine structure and material, distance, etc.

- This study's scope of includes:
  - System modeling
  - Field testing, and
  - Impact study, analysis, and assessment

3. System Concept

3.1 ITC Communications

The interoperable train control (ITC) communication system uses 220 MHz radio communications to supply operational data to the locomotive.

A system overview diagram of 220 MHz PTC radio system is shown in Figure 1 below. The wireless interoperable train control network comprises three types of the ITC radios: base radios, locomotive radios, and wayside radios. The radios communicate to each other through 220 MHz wireless network.

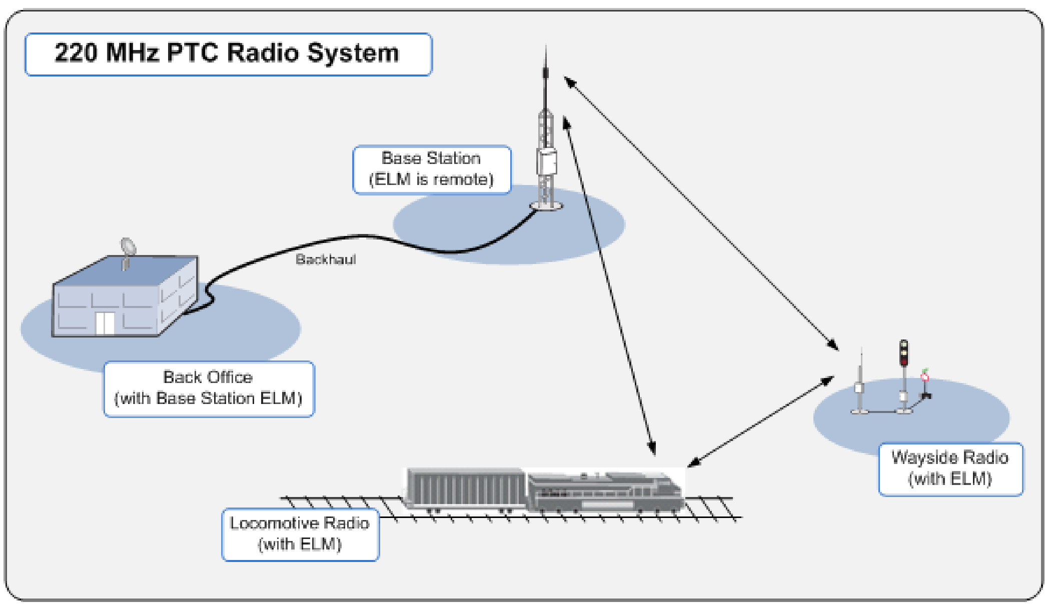


Figure 1: ITC 220 MHz network diagram

Robust and reliable communications over 220 MHz channels is one the most vital components to the success of PTC operations. The 220 MHz ITC communication system utilizes Meteorcomm's proprietary ITCnet® protocol which is designed to ensure reliable wireless communications and sufficient capacity for PTC operation.

The 220 MHz ITCnet air interface protocol utilizes 25 kHz frequency channels in the 220 MHz band for data communications among base, locomotive, and wayside radios. The ITCnet® protocol provides a communication path in both directions between any two connected radios over the 25 kHz ITC channel.

In the 25 kHz channel, the ITC radios employ Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme to provide transmit data rates of 32 kbps (also referred to as full rate) as well as 16 kbps (also referred to as half rate). The ITCnet packet consists of packet header and data which is protected with a forward error correction (FEC) code. ITCnet supports various FECs including Reed-Solomon (RS) and convolutional coding with different coding rates. With DQPSK modulation and 3/4 rate FEC, the ITC radios were shown to provide good RF link quality for PTC communications.

3.2 Wind Farm Interference

For the purposes of this study, a wind farm consists of a group of wind turbines in the same location. The average rotor diameter of new wind turbines in 2023 was over 438 feet. The average height of a wind turbine tower is over 320 feet, and the average length of a wind turbine blade is 210 feet. Figure 2 below shows typical wind turbine dimension and structure with a microwave line of sight Fresnel zone that is disrupted by moving turbine blades.

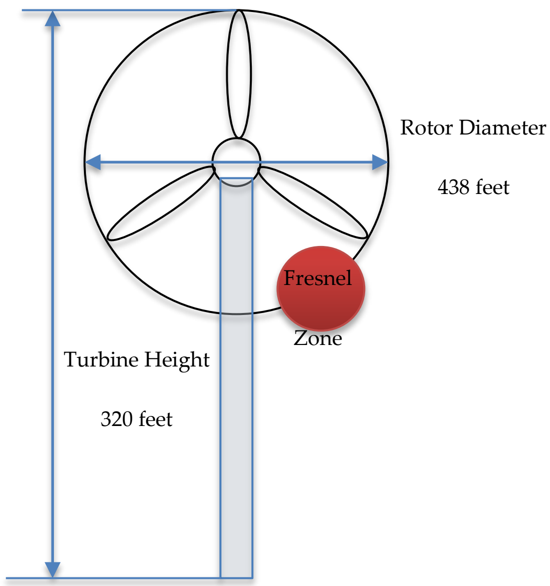


Figure 2: Wind turbine structure

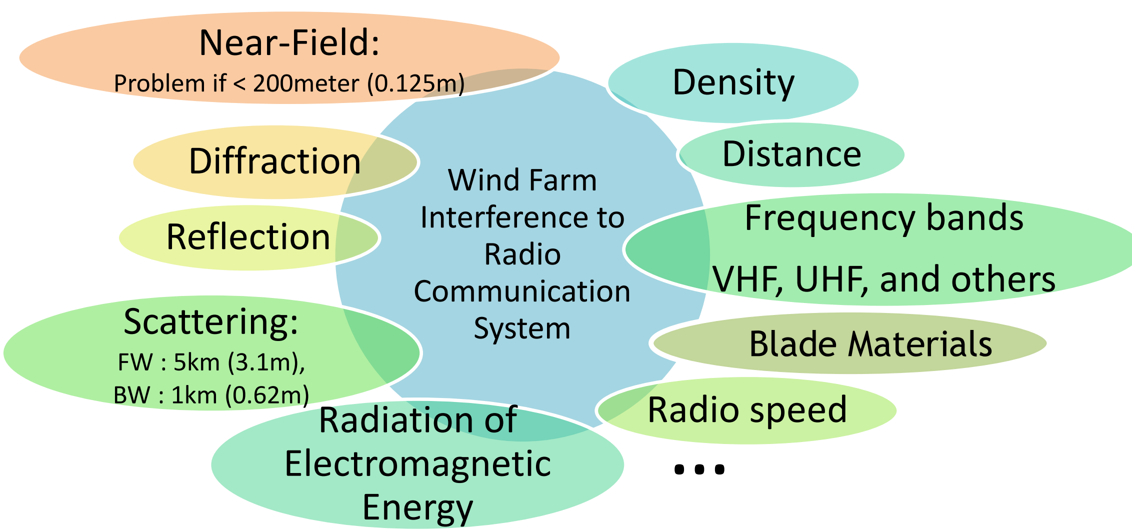


Figure 3: Wind farm interference factors

Figure 3 shows key factors that contribute to wind farm interference. They are briefly explained as follows [5],[6].

3.2.1 Scattering

Scattering refers to the individual reflections from each rotating blade of a wind turbine. Scattered signal (considered interference) can spread across a wider range of Doppler frequencies due to wind turbine blade's movement. Thus, resulting in a dispersed interference pattern. In addition, the blades with large tip speeds cause a significant Doppler profile.

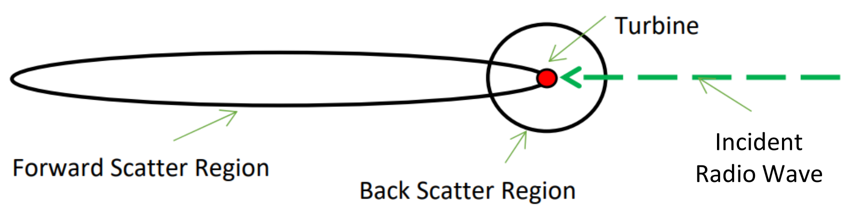


Figure 4: Forward and back scatter signal regions

There are two types of scatter mechanisms, forward and backward scatterings. Regions of forward and backward scatterings are shown in Figure 4 above.

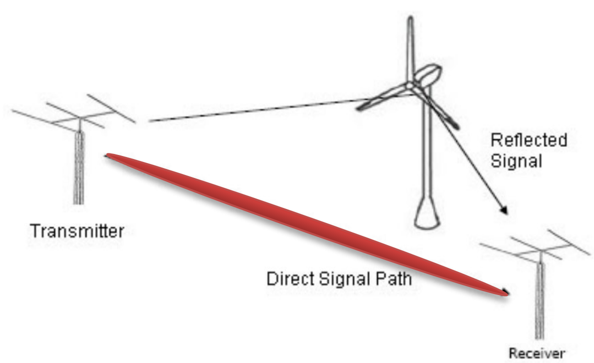


Figure 5: Scattered signal through a wind turbine

A scattered signal impacts the communication performance by causing interference due to a reflected signal at the receiver. Figure 5 above depicts a scattered signal through a wind turbine. The resulting interference reduces the carrier to interference ratio (C/I). When the C/I is lower than what is required to receive a desired signal, it can cause packet loss and degrade the communications system performance.

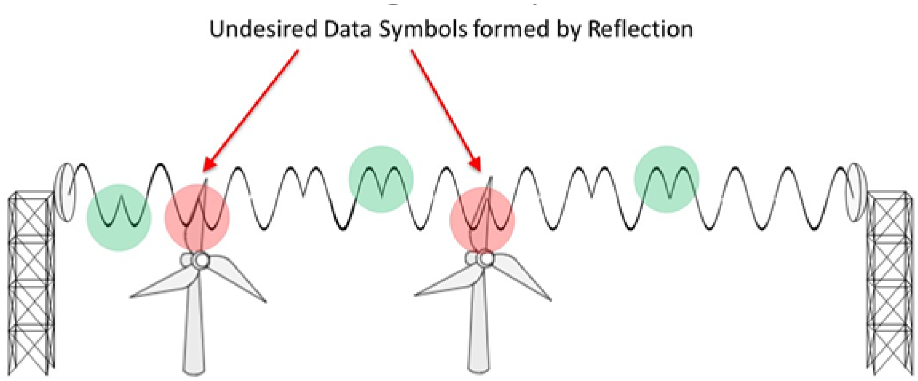


Figure 6: Example of impact from simple reflection [5]

Figure 6 above shows a simple reflection of a non-line-of-sight signal. In this scenario, portions of signals/symbols that are interfered with can be recovered with FEC. This helps to mitigate the impact of the interference. If there are too many corrupted symbols, FEC can be overrun and some of the symbols cannot be recovered, resulting in RF packet loss.

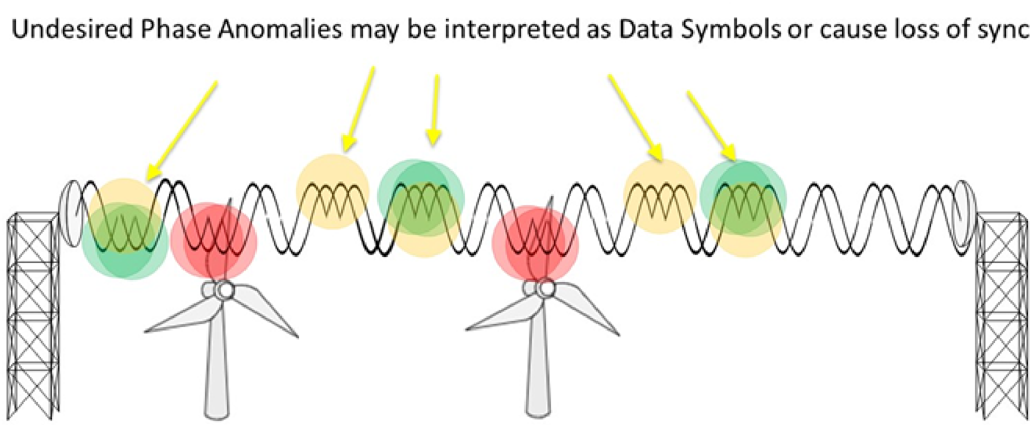


Figure 7: Example of impact from multipath signals [5]

Figure 7 above shows an example when interferers cause phase changes in a desired signal through non-line-of-sight reflected, multipath signals. Such undesired phase anomalies may be interpreted as data symbols or cause loss of synchronization to a received RF packet. This condition is exacerbated by multiple signal paths of varying lengths where the relative amplitudes of the energy along disparate paths do not meet C/I requirements. This will be treated as co-channel interference from radio point of view.

3.2.2 Diffraction

Diffraction effects, caused by signal reflection at the wind farm rotor edges, occur in the forward scattering zone where the turbine obstructs the path between transmitter and receiver. Significant diffraction may occur for high frequency link with a turbine located closer to one end (i.e. near an antenna) of such a radio link.

3.2.3 Clutter

Clutter is the collective effect of numerous scattered signals from wind turbines. The resulting unwanted echoes may reduce detection capability due to the overwhelming and complex interfering signal. Clutter results in significant impact to radar operation due to increasing of probability of fault detection.

3.2.4 Near-Field Effects

Near-field effects occur when the wind farm is installed sufficiently close to a terrestrial radio antenna. The turbine's physical presence very near to a near-field region of a terrestrial radio antenna can significantly distort desired signal reception. Near-field effects result in a quick drop in power with distance, especially at VHF band (30-300MHz). Prediction of near-field effects can be complex due to many factors such as antenna pattern, turbine geometry, and surrounding terrain. To minimize near-field effects, a large buffer zone around a terrestrial radio antenna is required in the installation of wind farm infrastructure.

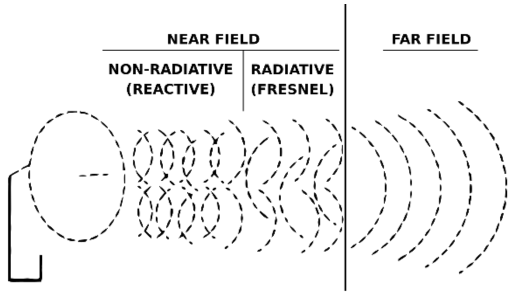


Figure 8: Near-field effects

3.2.5 Wind Turbine Density

Wind turbine density refers to number of wind turbines and how densely they are installed within a given area (see Figure 9 below). High wind turbine density is highly likely to cause interference to communication signals that operates within wind farm’s vicinity. This is a result of the combined effects of many rotating blades and huge metal structures that reflect and/or obstruct electromagnetic waves. Therefore, co-locating large-scale high-density wind farms with terrestrial radio infrastructure requires proper planning to avoid potential interference.

(a) Low Density

(b) High Density

Figure 9: Wind turbine density (a) Low density and (b) High density [5]

3.2.6 Desensitization

Desensitization is a case that a radio receiver becomes less sensitive to incoming signals due to the presence of wind farm reflected and cluttered interfering signal. This causes the radio to detect weaker or lower quality of incoming radio signals in vicinity of the wind farm. Worst case scenario would be complete loss of signal reception in certain areas.

3.2.7 Frequency of Radio Signal

Wind farms can potentially interfere with radio signals across a wide frequency range by causing signal fading. Wind farm interference has the most significant impact at higher frequencies, especially the microwave band which covers 1 GHz to 10 GHz. Radio signal wavelength in the microwave band is shorter and more susceptible to scattering by the blades.

Lower frequency radio signals, in VHF and UHF bands (1.5GHz-18GHz), are generally less susceptible to interference from wind turbines. Among VHF and UHF bands, terrestrial radio systems operating at UHF bands are more susceptible as a higher frequency is prone to stronger reflection. For UHF, there is possibility of 2-15dB signal loss for 1% of the operating time. This may need suitable exclusion zones to allow coexistence of wind farms and terrestrial radios.

3.2.8 Electromagnetic Interference (EMI)

Wind turbine components can generate electromagnetic radiation that interfere to radio spectrum. Such components can cause the following interference mechanisms:

- Micro-Arcing caused by stator/rotor commutator interface
- Macro-Arcing caused by aging and hardware breakdown
- Wide Band EMI caused by conflagration during catastrophic failure

3.2.9 Wind Farm Blade Materials

Different kinds of wind farm blade materials; metal, composite, and fiberglass, can influence scattered signal level. Due to unique transmissive and refractive indexes for each type of material, metallic blade causes higher scattered signal. Composite or fiberglass blades, result in scattered signal levels 6-10 dB lower.

4. Assessment Approach

This section describes the approach used to assess the impact of wind farm interference on ITC communications over 220 MHz band.

4.1 Assessment Process

To assess the impact of wind farm interference on the ITC communication system, the MCC Research team developed a model of ITC communications system in the presence of wind farm interference, carried out field measurements, analyzed the measurement data, and fine-tuned the model based on the analyzed measurement data. After fine-tuning, the model was utilized to predict wind farm interference on the ITC communication system in different scenarios.

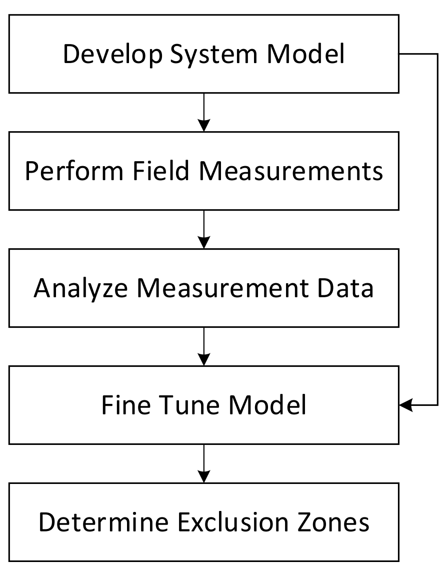


Figure 10: Wind farm interference impact assessment process

The assessment process is summarized in Figure 10 above. In the following subsections, this document presents the area of study, describes the system model, and then describes the measurement methodology.

4.2 Area of Study

In this study, we selected Tehachapi Pass wind farm which is one of the first large-scale wind farms installed in the US. Tehachapi Pass wind farm is in Mojave, California, as shown in Figure 11 and Figure 12 below. There 3,400 wind turbines in this location to produce around 710 megawatts (950,000 hp).

The rotor hub height for the four Tehachapi turbines is 75 feet above ground level. The blades are 7 meters (or 23 feet) in length, so the overall height of the turbines is under 100 feet.

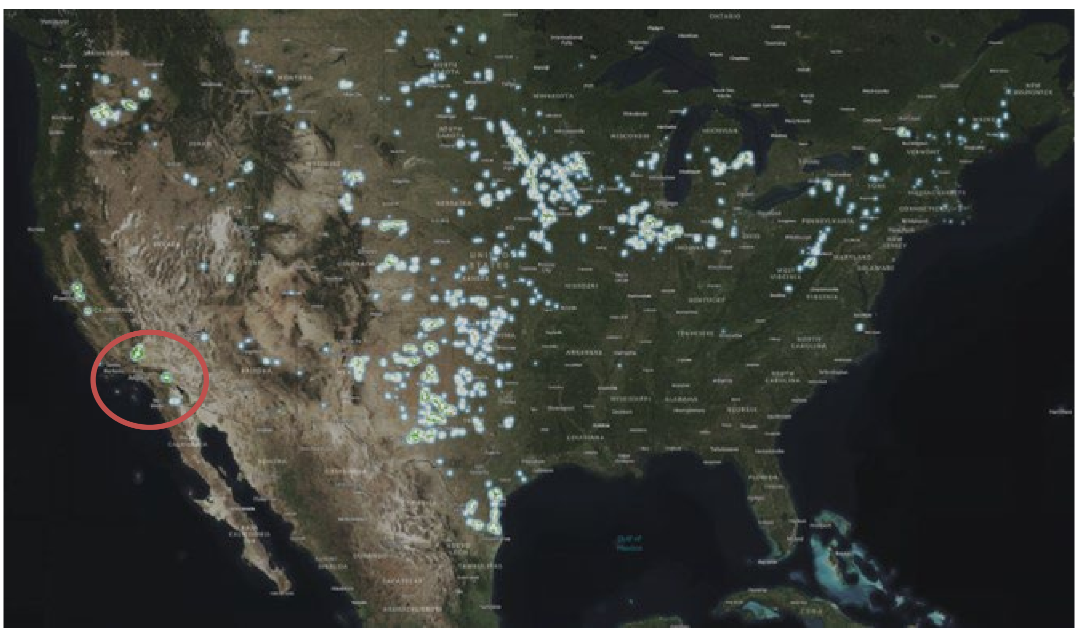


Figure 11: High-level view of the Wind Turbine Farms in US with the study area in California circled in red

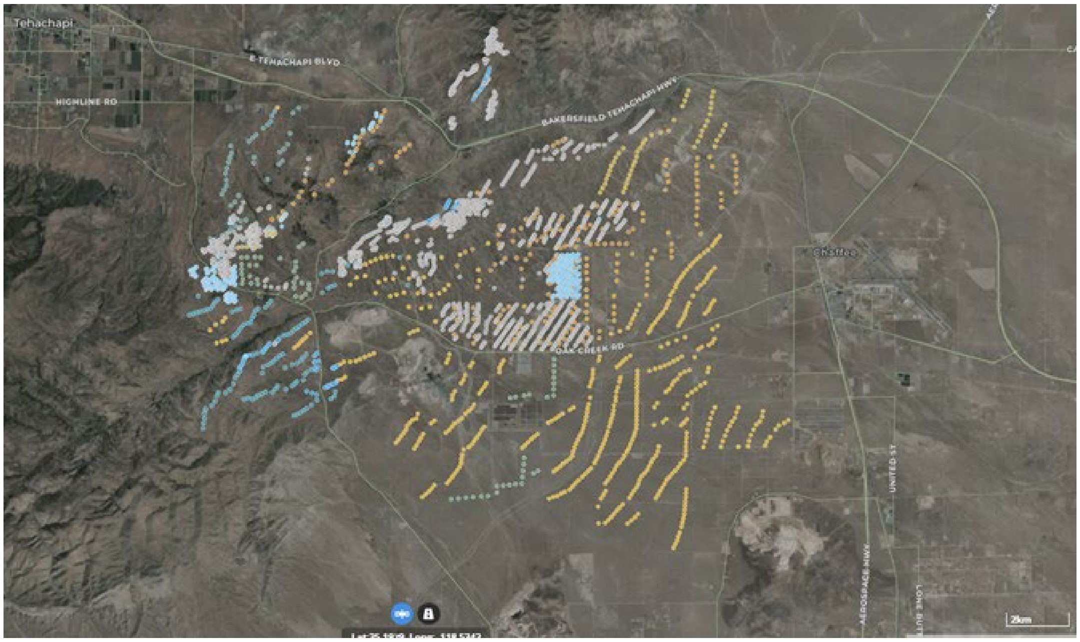
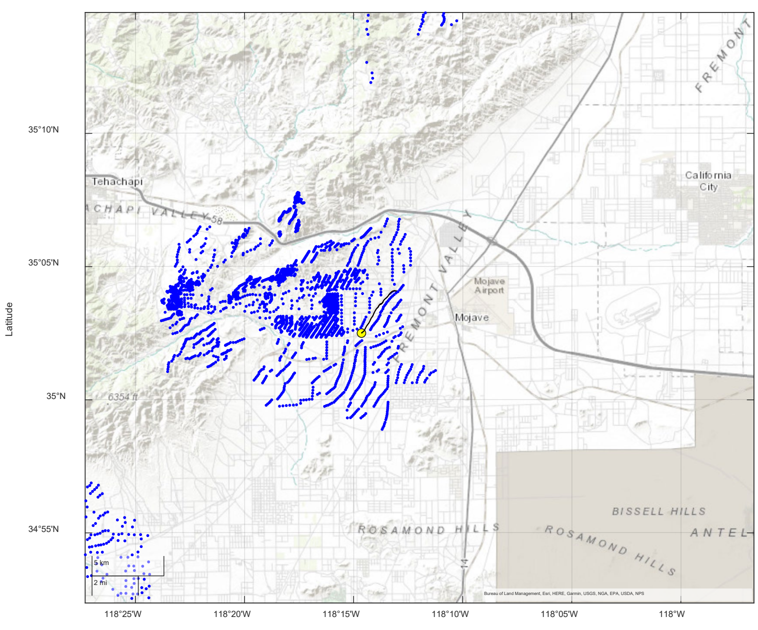
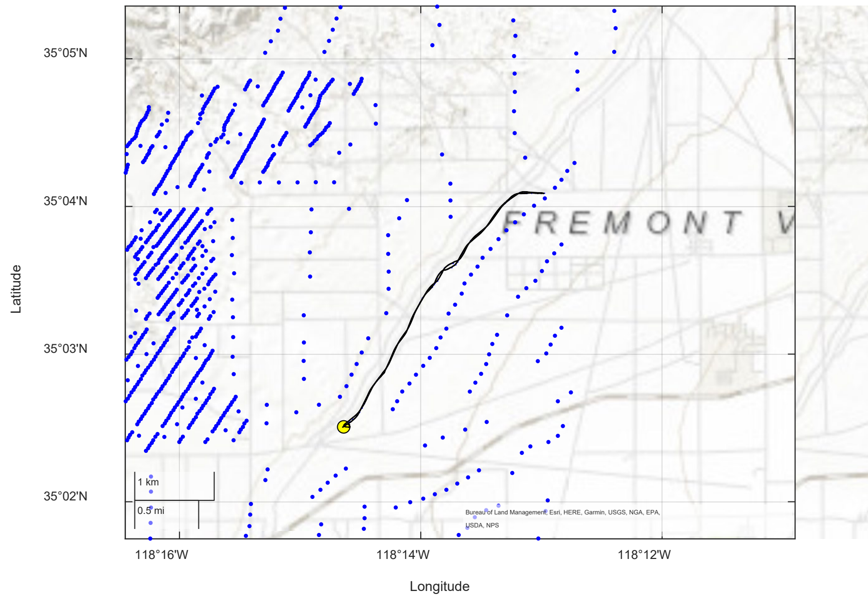


Figure 12: Area of study - Tehachapi Pass Wind Farm in Mojave, California



a) High level overview



b) Zoom in view

Figure 13: Arial view of wind farm study location in Tehachapi Pass wind farm, Kern County, California. a) High level overview and b) Zoom in view

Figure 13a and Figure 13b above show the selected route of the study whose results are provided in this document. Figure 13a shows a high-level overview of the area, and Figure 13b shows a zoom-in view. In the figures above, the location of transmit radio is represented by yellow dot, the locations of the receive radio along the selected route are represented by black dots, and the wind turbines are represented by blue dots.

From the two figures above (Figure 13a and 13b), the transmit radio is at a fixed location, while the receive radio moves to different locations along the 2.4-mile route away from the transmit radio location and the returning back to the starting location.

Along the selected route, there are about 10 wind turbines per mile on one side of the trail with the wind turbines about 0.2 miles (~0.3 km) from the trail.

4.3 System Model

Figure 14 below shows the diagram of the ITC communications system model in the presence of wind farm interference. The communications system model comprises a transmit radio, 220 MHz channel with wind farm interference, and a receive radio.

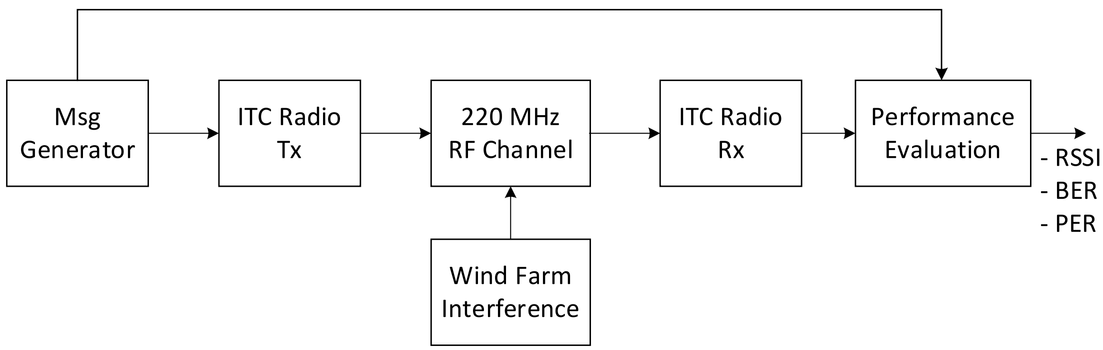


Figure 14: Diagram of ITC communications system model

The locations of wind turbines, transmit radio, and receive radios described in Section 4.2 are based on the actual locations in the area of study. At each receive location, the model compares the transmitted and received data and determines bit error rate (BER) and packet error rate (PER) performance.

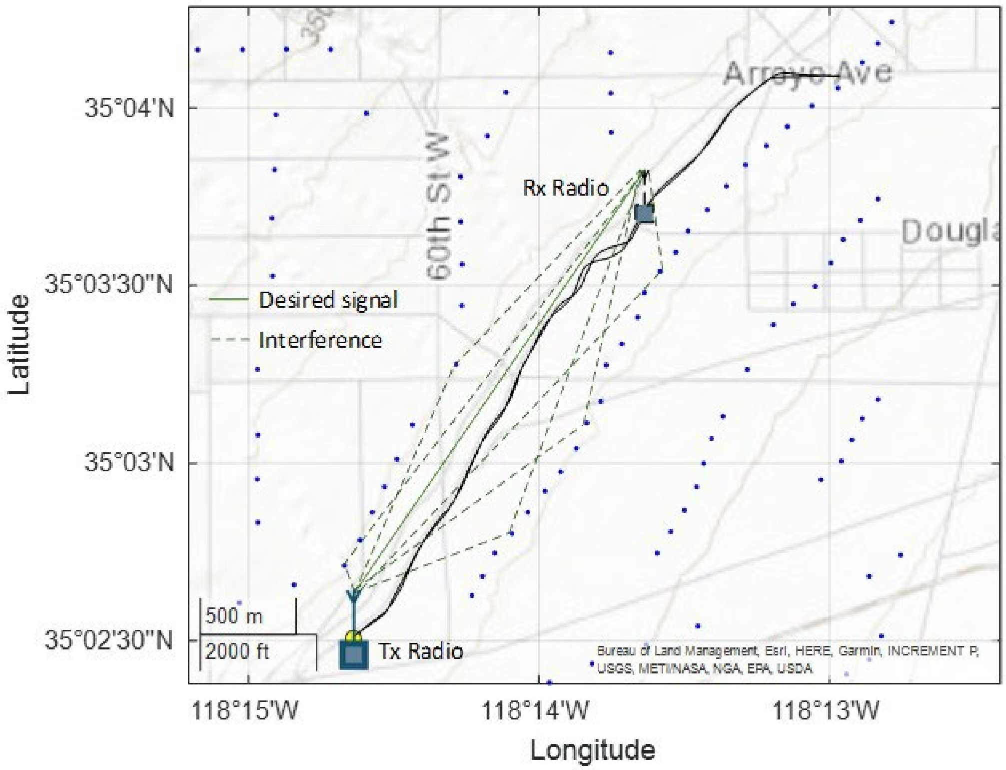


Figure 15: Model of ITC communications in the presence of wind farm interference

Figure 15 above shows the model of received signal at a receiving location. As shown in Figure 15, the received signal at each receive location comprises the desired signal and wind farm interference. The signal strength of the desired signal and interference can be determined as follows.

At a receiving location R, the signal strength of the desired signal, $P_{T\text{-}R}$, can be calculated as

$$P_{T\text{-}R} = EIRP - L_{T\text{-}R}$$

where EIRP (dBm) is equivalent isotropical radiated power of the transmitter, $L_{T\text{-}R}$ (dB) is propagation loss on the path between the transmitter and the receiver.

According to [2], the strength of the interference signal from each wind turbine at the receiver location can be calculated as

$$P_{WT\text{-}R} = EIRP - L_{T\text{-}WT} + 20\log(\rho)$$

where $L_{T\text{-}WT}$ (dB) is propagation loss on the path between the transmitter and the wind turbine and ρ is a scattering coefficient. The scattering coefficient ρ, which includes the free-space path loss for the path from the wind turbine to the receiving location, could be defined as

$$\rho = \frac{A}{\lambda r}\mathrm{sinc}^2\left[\frac{S}{\lambda}(\cos\theta - \cos\theta_0)\right]\sin\theta$$

where $\mathrm{sinc}(x) = \sin(\pi x)/(\pi x)$, A ($m^2$) is the total area of the turbine blades, S (m) is the mean width of the blade, λ (m) is the signal wavelength, *r* (m) is the distance between the wind turbine and the receiver, θ (˚) is angle of the scattering signal from the blade, and θ_0 (˚) is angle of the incident signal at the blade.

4.4 Measurement Methodology

Figure 16 depicts the field measurement methodology to determine the impact of wind farm interference on ITC communication system. The measurement equipment includes:

- Vehicle mounted ITC CGR base radio (see Figure 17(a))
- Backpack transportable or vehicle mounted ITC CGR wayside radio wayside radio (see Figure 17(b))

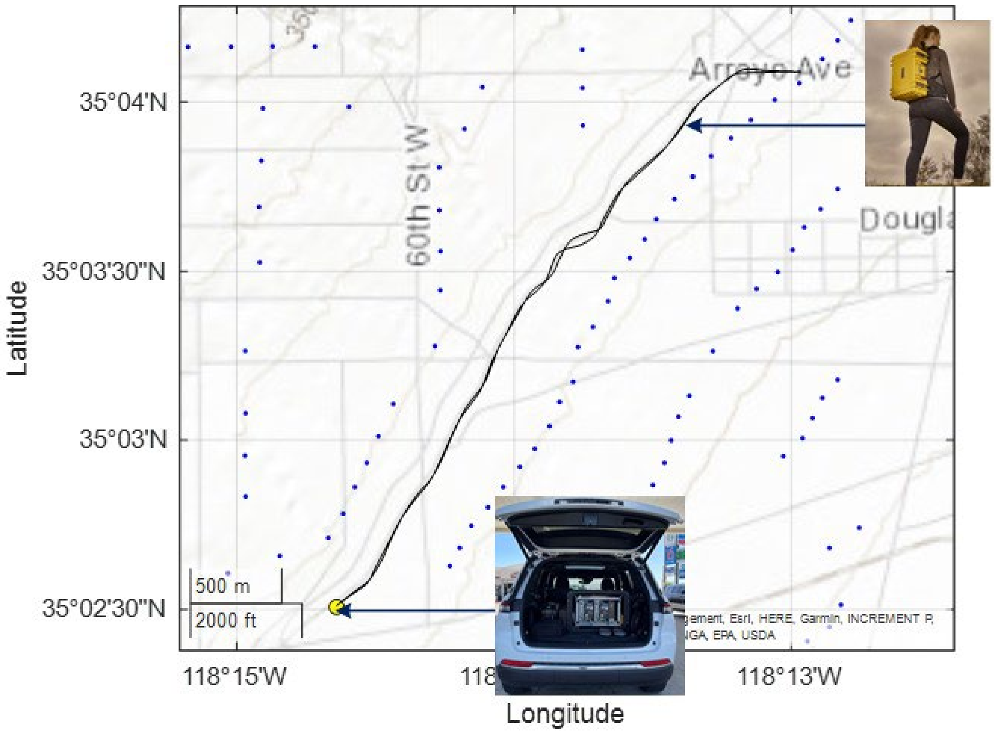


Figure 16: Field measurement methodology of wind farm interference impact on ITC communications system

(a) Transmitter

(b) Receiver

Figure 17: Measurement equipment (a) Transmitter (b) Receiver

Measurement approach is as follows:

- The ITC base radio was used as the transmitter. The vehicle mounted base radio was parked at a fixed location, marked by yellow dot in Figure 16.
- The ITC wayside radio was used as the receiver. The wayside radio was carried in a backpack along the selected route which is about 2.4 miles from the base radio location and back. The wayside radio locations are marked by black dots in Figure 16.
- At each receiving location, base radio sent multiple ITC test packets. Wayside radio was set to operate in BER RX mode. In this mode, the wayside radio demodulates the received test packets and calculates the BER and PER. The radio reports the estimated RSSI, BER, and PER as well as the GPS location. Figure 18 below shows a sample of measurement data that was collected at each receiving location.

```
RSSI(Pri)dBm: -114.0    (RX 2)
Noise(Pri)dBm: -125.9    (RX 2)
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, HR, T1 RES
Packets =         61, BER = 4.269126E-05, PER = 1.639344E-02, FR, T1 RES
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, HR, T2 RES
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, FR, T2 RES
 05/30/24 22:02:42 Scheduled Command:
L1_TEST,DISPLAY,TIMED,2,3
Disabling DSP Log, BER, and PER displays during timed test
OK
 05/30/24 22:02:42 Scheduled Command:
POS 05/30/24 22:02:42
 GPS Interval = 30, Tx format = TEXT, Input format = UBX
 22:02:41 47:28.3855N 122:14.0047W S000 H000 A00012 V1
 Position entered from GPS fix
 Precision = HIGH, NSAT = 10, HDOP = OFF (0.86)
 COPY Port = OFF
 Timing mode: Requested = OFF, Actual = OFF
 Surveyed ECEF position: x = -230366156 cm, y = -365342374 cm, z = 467746969 cm
 Survey parameters: fixed err = 4984 mm, req err = 5000 mm, req time = 60 sec
 Antenna State = OK, Antenna Power = ON
 GPS Dynamic Platform Model: Requested = STATIONARY, Actual = STATIONARY
 GPS software version = 7.03 (45969)
 GPS hardware version = 00040007
RSSI(Pri)dBm: -114.1    (RX 2)
Noise(Pri)dBm: -126.0    (RX 2)
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, HR, T1 RES
Packets =         60, BER = 1.736111E-04, PER = 1.666667E-02, FR, T1 RES
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, HR, T2 RES
Packets =          0, BER = 0.000000E+00, PER = 0.000000E+00, FR, T2 RES
```

Figure 18: Example of measurement data collected at each receiving location

- The measurement data was collected in multiple trips along the same route. Different combinations of modulation rate and FEC coding scheme were used for each trip.

  - Modulation rate includes DQPSK 16 kbps (half rate) and DQPSK 32 kbps (full rate).
  - FEC coding schemes includes RS(16,12) and convolution coding with different coding rates
- Measurement period was optimized for peak season and maximum wind turbine rotor speed. Peak seasons for maximum wind turbine speed varies by Wind Resource Area. Peak Season for the Tehachapi Pass Wind Resource Area is late June through mid-August. The field measurements were carried out in the second week of August 2024.

5. Results and Assessment

This section documents the impact of wind farm interference on the performance of ITC communication system in the 220 MHz band.

The assessment is based on data from Tehachapi Pass Wind Farm area where the wind farm has high density of wind turbines, and the wind farm is closely located to the radio communication path.

5.1 Measurement and Modeling Results

Figure 19 - Figure 22 below shows the measurement and modeling results for each combination of data rate and FEC coding as follows.

- Figure 19: DQPSK 16 kbps (Half Rate) with RS(16,12)
- Figure 20: DQPSK 16 kbps (Half Rate) with convolutional coding 3/4
- Figure 21: DQPSK 32 kbps (Full Rate) with RS(16,12)
- Figure 22: DQPSK 32 kbps (Full Rate) with convolutional coding 3/4

Each figure includes three plots as follows.

- The first plot shows the distance between transmitter and receiver at each receiving location.
- The second plot shows the measured RSSI at the corresponding receiving location.
- The third plot shows PER results at each receiving location. This includes:

- Measured PER - reported by the receive wayside radio by comparing demodulated receive data with the test data.
- Modeled PER - obtained from the model with wind farm interference, as described in Section 4.3. The received signal, comprising desired signal and wind farm interference, is determined based on the locations of transmitter, receiver, and wind farm and the RSSI.
- No Interference PER - obtained from the model in case of no wind farm interference. The PER in case of no interference is included here as a reference.

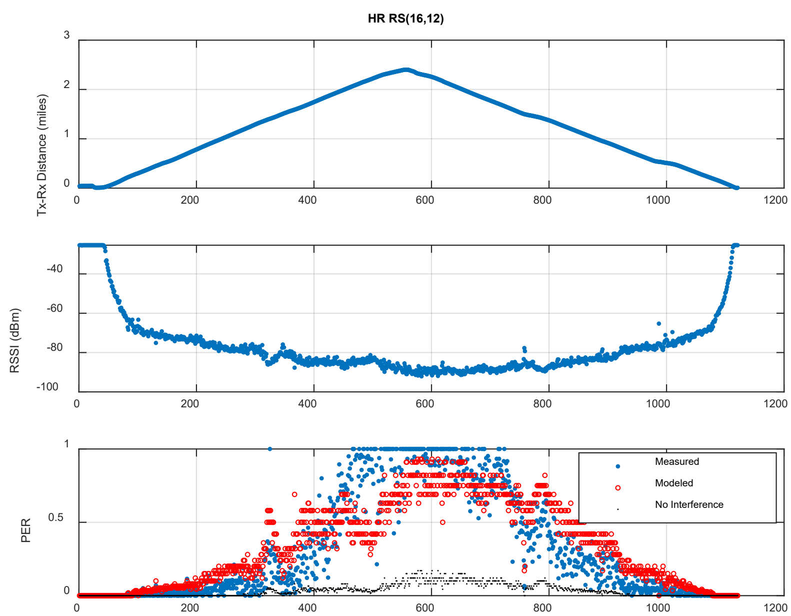


Figure 19: Performance in case of half rate with RS(16,12) coding

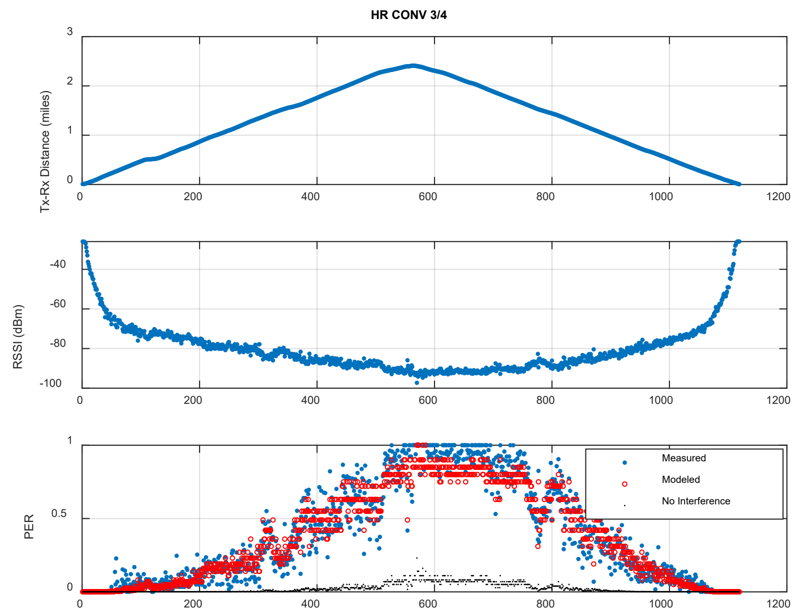


Figure 20: Performance in case of half rate with convolutional 3/4 coding

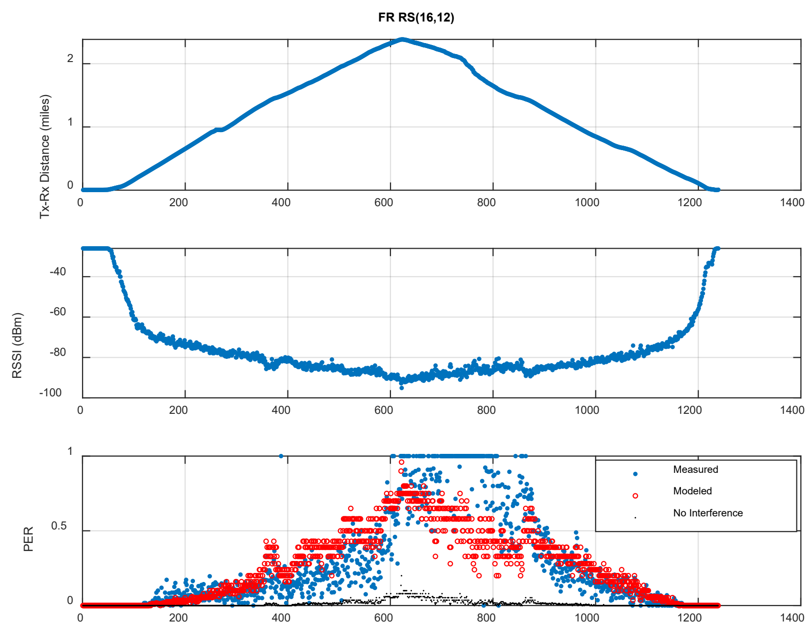


Figure 21: Performance in case of full rate with RS(16,12) coding

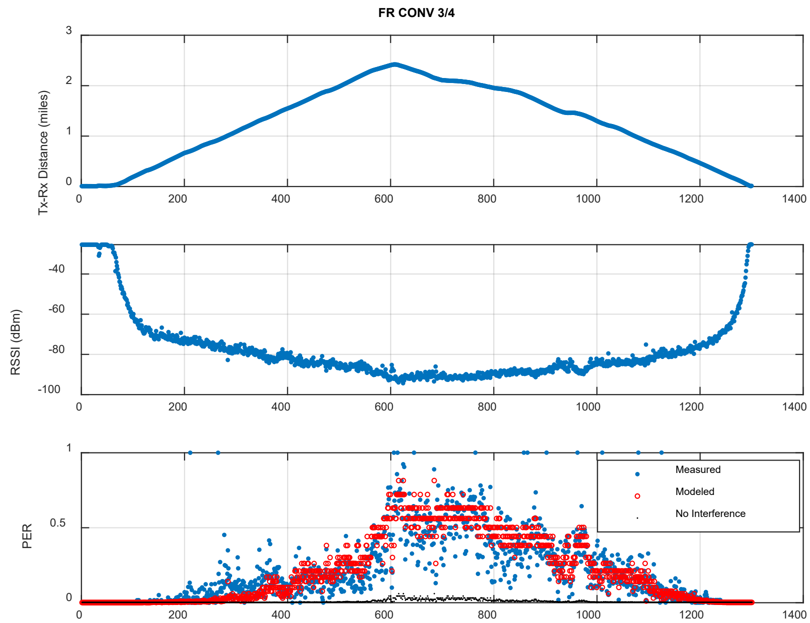


Figure 22: Performance in case of half rate with convolutional 3/4 coding

We can see from Figure 19 to Figure 22 that the received signal has strong RSSI along the selected route. The RSSI was about -80 dBm at a 1 mile distance from the transmitter and about -90 dBm at the end of the selected route which is about 2.4 miles from the transmitter.

With the noise floor for ITC system around -110 dBm, the SNR of the received signal would be about 30 dB at 1 mile and 20 dB at 2.4 miles distance. According to ITC radio performance, this means that if there is no interference, there should be almost no packet loss, i.e. close to 0% PER, at a 1 mile distance and about 10% PER at a 2.4 miles distance.

The third plot in Figure 19 to Figure 22, however, shows that the measured and modeled PER in this study is much higher compared with what is expected from no wind farm interference. We can see from Figure 19 to Figure 22 that the PER is about 10-20% at a 1 mile distance, and the PER is close to 100% at a 2.4 miles distance. The modeled PER is based on multipath Rayleigh fading and interference with an average power of 15 dB. The modeled PER closely matches the measured PER. This confirms that the wind farm interference does exist.

Comparing among different modulation rate and coding schemes, we can see from Figure 19 to Figure 22 that the full rate has lower PER than the half rate. Nevertheless, the wind farm interference increases PER of all considered modulation and coding schemes.

5.2 Exclusion Zone Determination

This section estimates the recommended separation between wind farm and a railroad track that allows an ITC radio communications to be safely operated.

In the previous section, we verified the model and confirmed that wind farm interference does impacts the ITC communication system when the wind farm is close to the railroad track. In this section, we use the model to predict how wind farm interference impacts PTC communications at different distances between wind farm and the railroad track. Based on the impact levels, we then quantify exclusion zones based on distance from the railroad tracks.

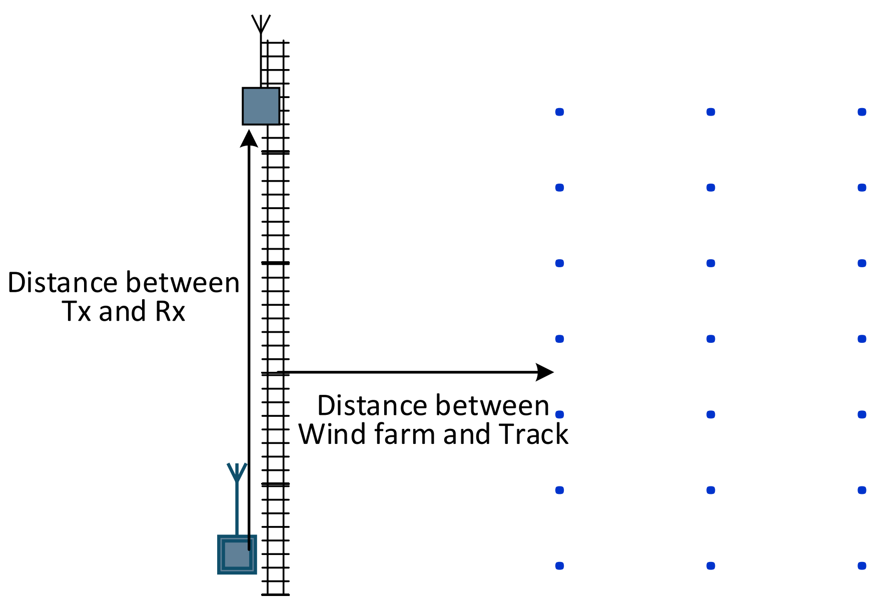


Figure 23: Model of wind farm and radio communications

Figure 23 above illustrates the model of wind farm and radio communications that we considered in this section. In this section, we vary communication range (i.e. distance between transmitter and receiver) as well as distance between the wind farm and the railroad track.

As shown in Figure 23, the model includes two key variables, (1) distance between transmitter and receiver, and (2) distance between wind farm and railroad track. For each specific distance between transmitter and receiver and distance between wind farm and track, the corresponding PER performance is determined to assess the impact of the wind farm interference on the ITC communications.

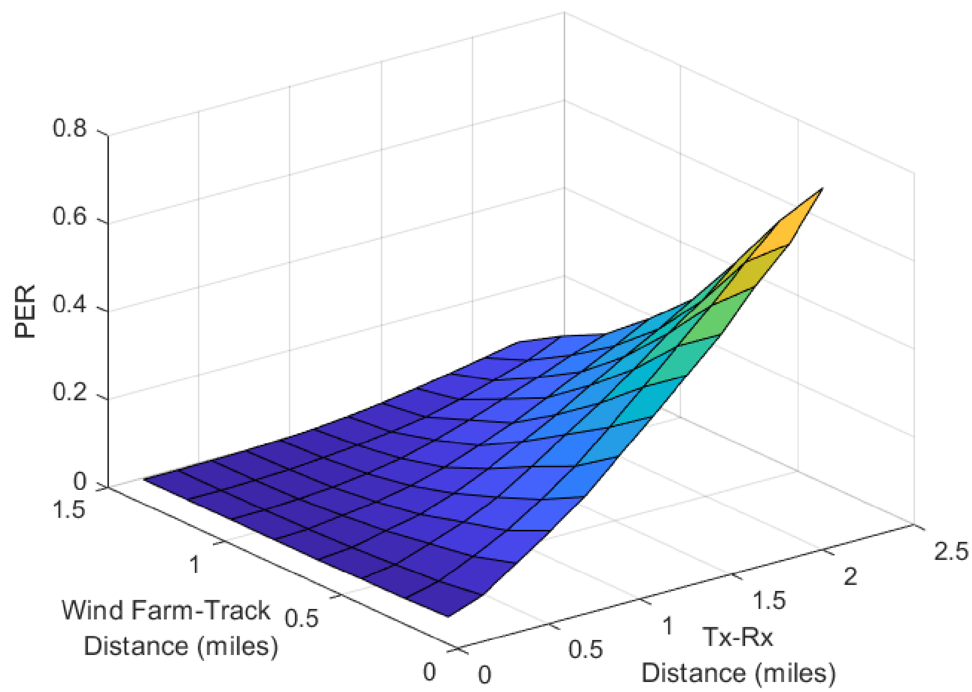


Figure 24: Packet error rate performance at various communication ranges and separations between wind farm and track

Figure 24 shows the PER performance at various communication ranges and distances between the wind farm and the railroad track. We can see from Figure 24 that when the wind farm is closer to the track, the increase in wind farm interference results in higher PER, especially when the receiver is further away from the transmitter.

For example, when the wind farm is 0.2 miles from the railroad track, the PER increases dramatically to more than 50% when the receiver moves 2 miles away from the transmitter, as also confirmed by the results in Section 5.1. On the other hand, when the wind farm is 1.5 miles away from the railroad track, the PER is not more than 10% at the 2-mile communication range, which is close to the system performance when there is no wind farm interference.

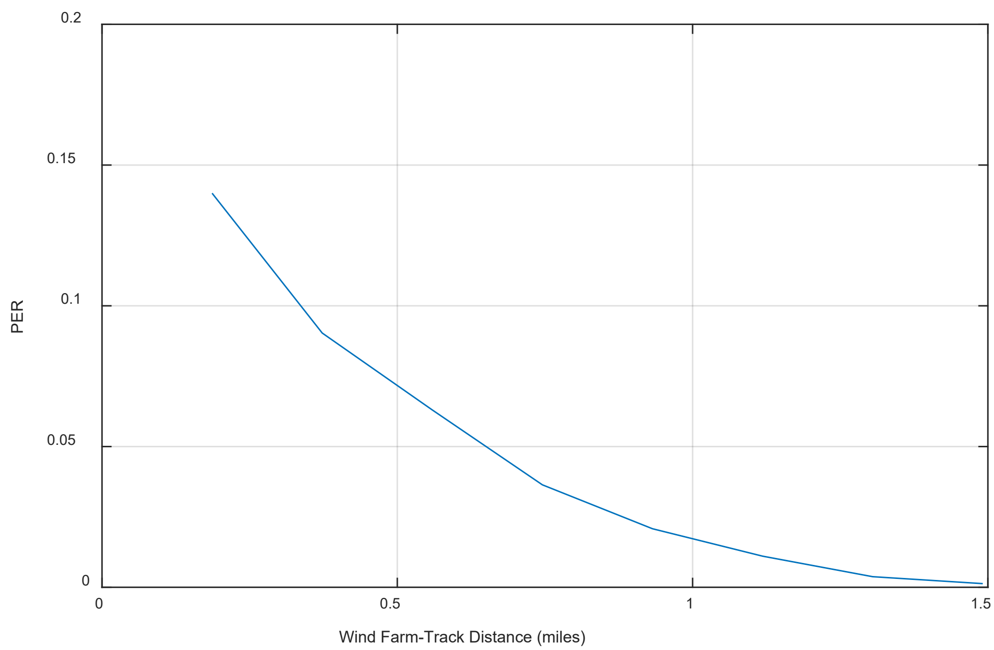


Figure 25: Packet error rate performance versus separations between wind farm and track

Figure 25 above plots PER performance versus separation distances between a wind farm and a railroad track when the receiver is 1 mile away from the transmitter. We can clearly see from the figure that increasing separation distance between wind farm and track would lower the wind farm interference and hence reduce the PER.

Results in this section confirm that the separation distance between a wind farm and a railroad track strongly impacts the ITC communication system's performance. Results also provide an estimated level of wind farm interference impact on the ITC communication system at different separation distances between a wind farm and a railroad track. Based on the results, exclusion zones to avoid wind farm interference are recommended in the subsequent section.

6. Summary and Recommendations

6.1 Key Findings

- Results from field testing and modeling show that the wind farm interference does exist. When the wind farm is co-located or deployed in very close vicinity to PTC railroad tracks (and the associated PTC RF coverage for train control) wind farm interference signal level is high enough to impact PTC RF signal integrity and could potentially cause degradation in PTC operation.

- Results also show that the separation between a wind farm and a PTC railroad track strongly impacts the ITC communication system performance. Increasing distance between wind farm and track would lower the interference and increase the reliability of PTC radio communications.

- Wind farm interference impact strongly depends on wind farm layout and radio locations, so mitigation plan will be unique for each area.

6.2 Recommended Exclusion Zones to Avoid Wind Farm Interference

To avoid wind farm interference to PTC radios operating along railroad tracks, a multiple exclusion zone concept is recommended based on levels of a radio received signal and wind farm interference. An assessment requirement in each exclusion zone depends on severity level of wind farm interference.

Based on the assessment results in Section 5, the exclusion zones can be defined for this scenario. Starting from railroad tracks as a center line, each exclusion zone is defined as follows.

- Zone 1 is an area in the range between 0 and 0.3 miles (0-500 meters) from the railroad tracks.

  Since wind farm interference level in this zone is very strong, it is recommended that wind farms are not permitted in this zone (Safeguarding zone).

- Zone 2 is an area in the range between 0.3 and 0.6 miles (501-1,000 meters) from the railroad tracks.

  In this Zone 2, wind farm interference level highly likely causes signal degradation at the radio, it is recommended that a detailed interference assessment be performed in this zone for each wind farm deployment.

- Zone 3 is an area in the range between 0.6 and 1.2 miles (1,001-2,000 meters) from the railroad tracks.

  In this Zone 3, wind farm interference level is less likely to cause signal degradation at the radio. However, a wind farm interference source is still within the maximum effective radio operating range. It is recommended that a simple interference assessment be performed in this zone for each wind farm deployment.

- Zone 4 is an area in the range of more than 1.2 miles (>2,000 meters) from the railroad tracks.

  In this Zone 4, chance of wind farm interference sufficient to cause signal degradation at the radio is very low. Also, such wind farm interference source is beyond the maximum effective radio operating range. There is no need of interference assessment in this zone.

Recommended exclusion zones and their parameters are summarized in Table 2 below.

Table 2: Recommended exclusion zones, zone parameters, and assessment requirements

Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0 - 0.3 miles (0 - 500 meters) from railroad tracks	0.3 miles – 0.6 miles (501 - 1,000 meters) from railroad tracks	0.6 – 1.2 miles (1,001-2,000 meters) from railroad tracks (Within maximum effective radio range)	> 1.2 miles (>2,000 meters) from railroad tracks (Beyond effective radio range)
Assessment Requirements	Safeguarding	Detailed Assessment	Simple Assessment	No Assessment

The recommended exclusion zones defined above are based on the results in this study where wind farm density is about 10 wind turbines per mile with transmit and receive radios located on the same side of the wind farm. Different wind farm layout and radio locations can result in different exclusion zones than recommended here.

6.3 Mitigation Measures for Wind Farm Interference Impact on Terrestrial Radios

To increase the resilience of existing radios to wind turbines, wind farm interference mitigation measures, as shown in Figure 26 below are recommended.

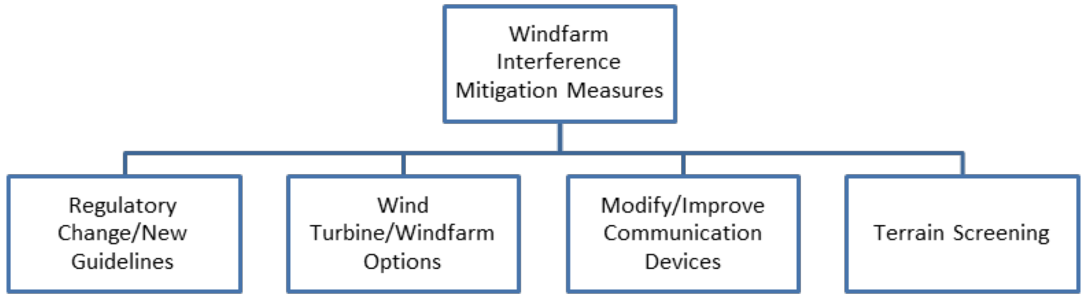


Figure 26: Wind farm interference mitigation measures

6.3.1 Regulatory Change/New Guidelines

6.3.1.1 Provide guideline for wind turbines design to minimize EMI. Wind turbine manufacturers are required to comply with electromagnetic interference standards to ensure their emissions stay within acceptable limits.

6.3.1.2 Employ mitigation strategies to avoid potential interference issues during windfarm site planning and construction.

6.3.1.3 Ensure all relevant parties are notified so that a proper plan, study, and deployment can be agreed to by relevant parties.

6.3.2 Wind Turbine/Wind Farm Options

6.3.2.1 Stealth technology or Radar Absorbent Material: a technology that is designed to cause destructive interference in the reflected signal.

6.3.2.2 Blade design: Using materials with low cross-section to reduce reflections.

6.3.2.3 Electrical system design: Implementing proper shielding and filtering within the turbine to limit electromagnetic emissions.

6.3.2.4 Turbine geometry modified to reflect signals away from the radio or to turn slowly enough to lower or eliminate doppler impact.

6.3.2.5 Install and align turbines in radial pattern in a similar way to spokes of a wheel. This way multiple turbines are placed in a circular pattern, and with each turbine positioned at a similar radius from a central point. essentially radiating outwards from a central location

6.3.3 Wind Turbine/Wind Farm Options

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6.3.4 Modify/Improve Communication Devices or Links

6.3.4.1 Encourage the development of next-generation radio technologies and signal processing techniques that are more robust to wind turbine interference, improve C/I, etc.

6.3.4.2 Optimize antenna design and antenna pattern by using directional antennas that are aimed away from wind farms to help reduce interference.

6.3.4.3 Use a radio repeater or signal booster where appropriate.

6.3.5 Terrain Screening

6.3.5.1 Siting considerations: Carefully selecting turbine locations to minimize line-of-sight with sensitive communication equipment.

6.3.5.2 Conducting radio frequency surveys to assess potential interference before deploying a wind farm.

6.3.5.3 Signal strength optimization by increasing the power of the radio transmitter.

6.3.5.4 Regularly update database and maps.

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- Federal Railway Administration (FRA) for addressing concerns and needs and providing constructive comments.
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