Monitoring Rail Bed Infrastructure Using Wireless Passive Sensing

Final Report
October 2025

Principal Investigator: Ehsan Ghazanfari

Department of Civil and Environmental Engineering
The University of Vermont

Authors
Malla, B., Ghazanafari, E., Frolik, J.

Sponsored By
Transportation Infrastructure Durability Center

TIDC

Transportation Infrastructure Durability Center
AT THE UNIVERSITY OF MAINE

A report from
The University of Vermont
Department of Civil and Environmental Engineering
33 Colchester Ave.
Burlington, VT
Phone: 802-656-1770
Website: https://www.uvm.edu/cems/cee

1865 THE UNIVERSITY OF MAINE | UMASS LOWELL | WESTERN NEW ENGLAND UNIVERSITY WNE | UCONN | THE UNIVERSITY OF RHODE ISLAND | The UNIVERSITY of VERMONT

About the Transportation Infrastructure Durability Center

The Transportation Infrastructure Durability Center (TIDC) is the 2018 US DOT Region 1 (New England) University Transportation Center (UTC) located at the University of Maine Advanced Structures and Composites Center. TIDC's research focuses on efforts to improve the durability and extend the life of transportation infrastructure in New England and beyond through an integrated collaboration of universities, state DOTs, and industry. The TIDC is comprised of six New England universities, the University of Maine (lead), the University of Connecticut, the University of Massachusetts Lowell, the University of Rhode Island, the University of Vermont, and Western New England University.

U.S. Department of Transportation (US DOT) Disclaimer

Acknowledgements

Funding for this research is provided by the Transportation Infrastructure Durability Center at the University of Maine under grant 69A3551847101 from the U.S. Department of Transportation's University Transportation Centers Program. The authors would like to thank the Vermont Agency of Transportation for supporting this project and providing access to the data used in this study. The administrative support provided by the University of Vermont Transportation Research Center (UVM TRC) is appreciated.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient Catalog No.**
4 Title and Subtitle Monitoring Rail Bed Infrastructure Using Wireless Passive Sensing		**5 Report Date** 10/31/2025 **6 Performing Organization Code**
7. Author(s) Birasa Malla https://orcid.org/0009-0000-0375-5335 Ehsan Ghazanfari https://orcid.org/0000-0002-8501-3294 Jeff Frolik https://orcid.org/0000-0002-4006-9163		**8 Performing Organization Report No.**
9 Performing Organization Name and Address The University of Vermont, Civil & Environmental Engineering Dept. 33 Colchester Avenue, Burlington, VT 05405		**10 Work Unit No. (TRAIS)** **11 Contract or Grant No.**
12 Sponsoring Agency Name and Address		**13 Type of Report and Period Covered** **14 Sponsoring Agency Code**
15 Supplementary Notes		

16 Abstract

Railroad ballast plays a critical role in distributing train loads, maintaining track stability, and ensuring proper drainage. Over time, intrusion of fines and moisture leads to ballast fouling, which can compromise track structural integrity and service life. Early detection of ballast fouling is therefore essential for effective maintenance and extending the operational life of rail infrastructure. This study investigated the use of passive harmonic transponders as a low-cost, sustainable, and long-lasting sensing solution for monitoring ballast conditions. Laboratory experiments were conducted using clean and fouled ballast under varying moisture levels and transponder embedment depths. The harmonic transponder is unique in that it returns a signal at twice the frequency of that which interrogates it, allowing clear separation of the transponder response from background reflections and noise. Two types of harmonic transponders, one is commercially available sensing device (RECCO, operated at fundamental frequency 890 MHz) and another university developed sensing device (developed by Czech Technical University, operated at 1.17 GHz), were tested to evaluate signal responses under different conditions. The results indicate that moisture content and embedment depth are the primary factors influencing signal attenuation, while fouling level plays a secondary role. The transponders operated at lower frequency demonstrated more stable performance, whereas the device operated at higher frequency was more sensitive to ballast heterogeneity and moisture fluctuations.

The findings suggest that embedding passive harmonic transponders during new rail-bed construction can provide a built-in monitoring system capable of early fouling detection. Interrogation of the embedded transponders can be performed using portable units, moving trains, or drones, offering a flexible and non-destructive approach. Their low-cost and passive design eliminates the need for batteries or continuous power supply, reducing both maintenance requirements and environmental impact. This energy-efficient operation enables long-term field deployment with minimal resource consumption. As a result, harmonic transponders represent a practical and sustainable solution for continuous monitoring of fouling in railway ballast.

17 Key Words Passive sensor, harmonic transponder, ballast fouling, wireless sensing, rail bed monitoring		**18 Distribution Statement** No restrictions. This document is available to the public through	
19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages**	**22 Price**

Form DOT F 1700.7 (8-72)

Contents

List of Figures

List of Key Terms

Passive sensor, harmonic transponder, ballast fouling, wireless sensing, rail bed monitoring

Abstract

Railroad ballast plays a critical role in distributing train loads, maintaining track stability, and ensuring proper drainage. Over time, intrusion of fines and moisture leads to ballast fouling, which can compromise track structural integrity and service life. Early detection of ballast fouling is therefore essential for effective maintenance and extending the operational life of rail infrastructure. This study investigated the use of passive harmonic transponders as a low-cost, sustainable, and long-lasting sensing solution for monitoring ballast conditions. Laboratory experiments were conducted using clean and fouled ballast under varying moisture levels and transponder embedment depths. The harmonic transponder is unique in that it returns a signal at twice the frequency of that which interrogates it, allowing clear separation of the transponder response from background reflections and noise. Two types of harmonic transponders, one is commercially available sensing device (RECCO, operated at fundamental frequency 890 MHz) and another university developed sensing device (developed by Czech Technical University, operated at 1.17 GHz), were tested to evaluate signal responses under different conditions. The results indicate that moisture content and embedment depth are the primary factors influencing signal attenuation, while fouling level plays a secondary role. The transponders operated at lower frequency demonstrated more stable performance, whereas the device operated at higher frequency was more sensitive to ballast heterogeneity and moisture fluctuations.

The findings suggest that embedding passive harmonic transponders during new rail-bed construction can provide a built-in monitoring system capable of early fouling detection. Interrogation of the embedded transponders can be performed using portable units, moving trains, or drones, offering a flexible and non-destructive approach. Their low-cost and passive design eliminates the need for batteries or continuous power supply, reducing both maintenance requirements and environmental impact. This energy-efficient operation enables long-term field deployment with minimal resource consumption. As a result, harmonic transponders represent a practical and sustainable solution for continuous monitoring of fouling in railway ballast.

Chapter 1: Introduction and Background

1.1 Project Motivation

Continuous assessment and monitoring the performance and condition of railbed structures are critical for prioritizing the repairs and replacements, as well as for extending the operational life of transportation infrastructure. A key component of the rail system is the railroad ballast, which serves a critical function in distributing train loads to the subgrade, providing both lateral and vertical stability, and enabling proper drainage. The effectiveness of this ballast layer is essential for maintaining track geometry and ensuring overall structural performance. However, over time, the intrusion of fine particles from the subgrade or the surface can lead to ballast fouling, which impairs track drainage and adversely affects the serviceability of the track. Addressing this issue requires development and implementation of advanced strategies for assessing and monitoring railbed health, particularly by detecting fouling in its early stages, which in turn can significantly extend the service life of the track-bed infrastructure.

Several fouling assessment/detection techniques, such as Ground Penetrating Radar (GPR) and thermal imaging, have been explored for this purpose (Guo et al., 2023; Koohmishi et al., 2024; Leng & Al-Qadi, 2010; Liang et al., 2023). However, these methods come with notable limitations, including high equipment costs, complex data interpretation, and reduced reliability under varying environmental and loading conditions. As a result, there is a clear need for innovative, cost-effective, and reliable sensing solutions that can detect fouling at an early stage and perform effectively under real-world railway environments. In response to this need, this project explores the effectiveness of using an embedded passive wireless sensing techniques, based on a harmonic transponder design. These compact, low-cost sensors can be embedded within the ballast for the new railbed construction projects. When interrogated wirelessly, they produce measurable signals at twice the interrogation frequency that can be tracked over time to detect changes associated with fouling. At scale, these sensors can be produced at very low cost and thus liberally embedded within the ballast, operating without the need for onboard power. Consequently, they present a practical, and continuous monitoring solution that enhances safety, reduces maintenance costs, and extends the operational life of railway infrastructure.

1.2 Research, Objectives

The main aim of this project is to develop and test an advanced passive wireless sensing approach for early detection of ballast fouling in railway tracks, ultimately helping to extend the service life of rail infrastructure.

The specific objectives of are:

(i) Develop a robust interrogation method for harmonic transponders that can operate effectively in multipath-rich environments like railway ballast,

(ii) Conduct a series of controlled experiments, by preparing the ballast samples with known and specific level of fouling conditions (i.e., fouling levels and moisture percentage), and apply the newly developed interrogation method to measure the response of an embedded harmonic transponder.

1.3 Report Overview

This report is organized into the following chapters, which collectively present the research methodology, experimental findings, and conclusions of the study.

Chapter 2 details the research methodology, including a description of the materials and equipment used. The chapter outlines the design and setup of the experimental testbeds developed to evaluate the effectiveness of the passive wireless sensing techniques for ballast fouling detection.

Chapter 3 presents the research tasks undertaken, and provides a detailed analysis of the key data and results obtained from the experiments.

Chapter 4 concludes the report by summarizing the main findings and offering recommendations for the practical implementation of the proposed sensing techniques in real-world railway applications.

Chapter 2: Methodology

2.1 Materials

The experimental methodology was designed to progress in complexity through a series of scaled laboratory setups, involving both engineering materials and electrical/electronic instrumentation.

Engineering Materials

In the initial phase, coarse aggregates with particle sizes ranging from 10 to 25 mm were mixed with coal dust to simulate fouling conditions. These materials were used to conduct preliminary experiments aimed at calibrating the response of the harmonic transponder on a smaller scale.

In the final phase, tests were performed using real railway ballast mixed with silty sand as the fouling material. The clean ballast was collected from Frank W. Whitcomb Construction Corp., located in Colchester, VT, and exhibited a gradation similar to AREMA #4 ballast specifications.

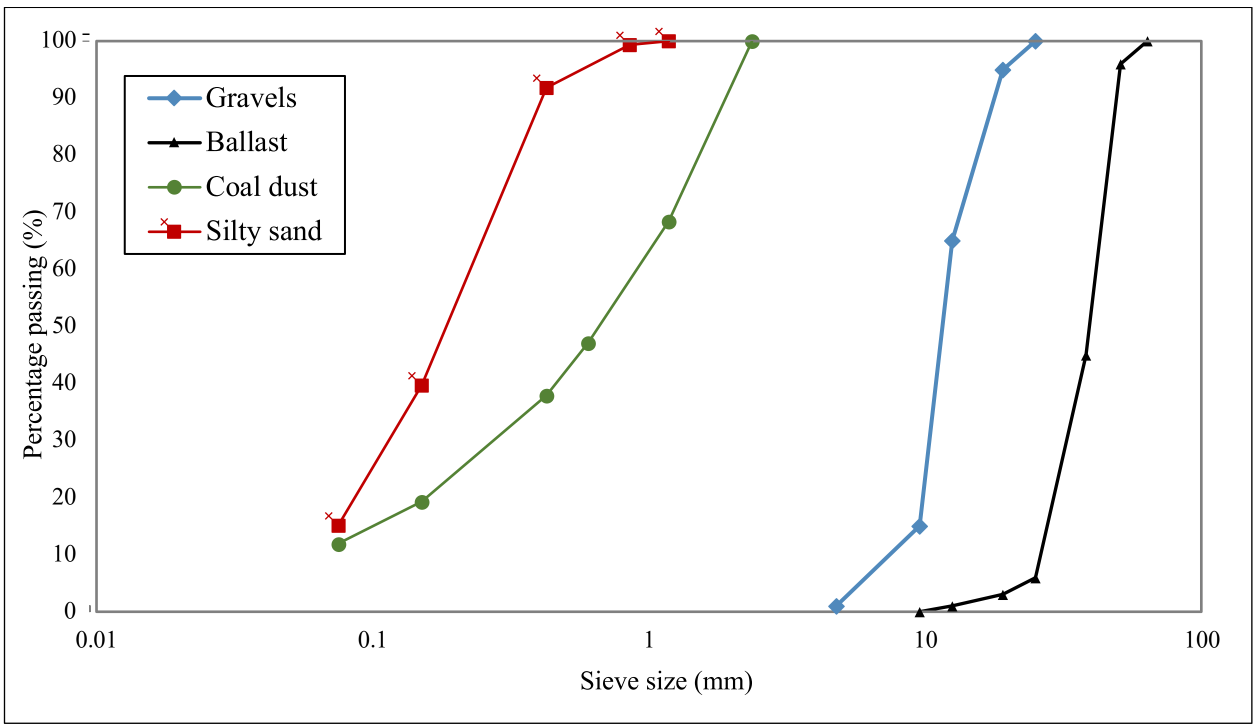


Figure 1: Particle size distributions of fouling materials, gravels, and ballast used in the study

Figure 2: Gravels and coal dust materials used in preliminary experiment

Figure 3: Ballast aggregates and fine silty sand (fouling) materials used in experiments

Electrical/Electronic Instrumentation

The electrical measurement system consisted of the following components:

Harmonic Transponders: Two types of harmonic transponders were used for signal reflection and harmonic generation during testing. First one, the commercial type (left) manufactured by (RECCO, n.d.) and the other one, devices developed by the Czech Technological University in Prague (right) based on the design presented in (Polivka et al., 2022) (see Figure 4).

Antennas: A log-periodic antenna was employed for transmitting and receiving RF signals over a wide frequency range.

Software-Defined Radio (SDR): Served as the primary transceiver for generating and capturing the transmitted and received signals.

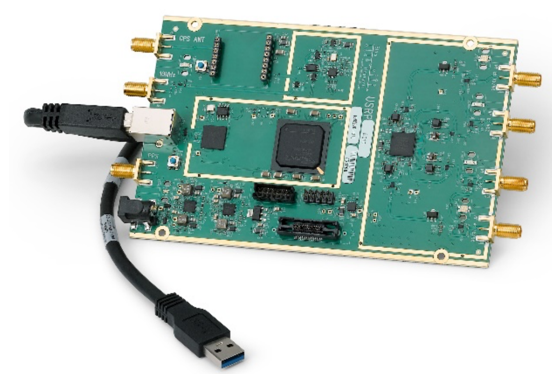
Amplifier: Used to boost the transmitted signal strength before it reached the antenna.

Filters: A combination of low-pass and high-pass filters was used to isolate desired harmonic frequencies and suppress unwanted signals.

Cables and Connectors: High-quality RF coaxial cables and connectors ensured minimal signal loss between components.

Harmonic transponders


Antenna


SDR


Amplifier


Filters


Cable

Figure 4: Components of the electrical measurement system

2.2 Test Setup & Testing Procedures

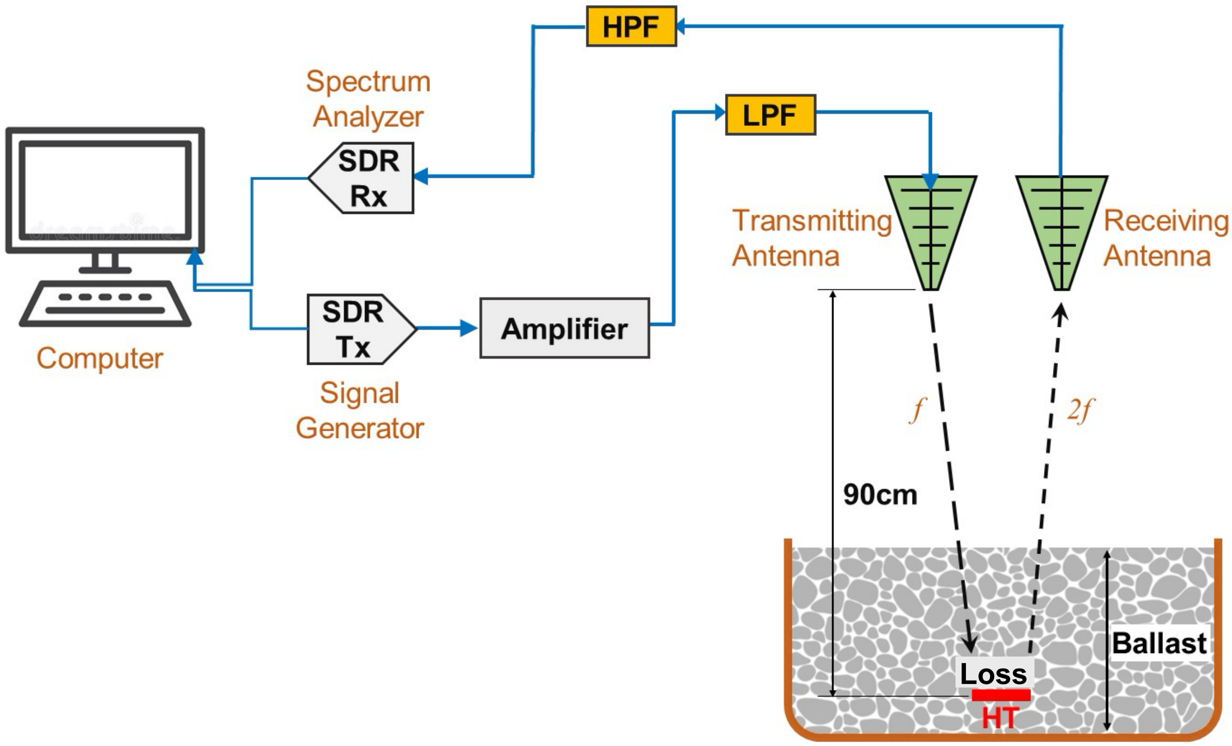


Figure 5: Experimental setup consisting all components

The experimental setup for data collection consisted of several key components configured as shown in Figure 5. A harmonic transponder was used for frequency doubling from the fundamental frequency (f) to its second harmonic ($2f$). The transmission system utilized a software-defined radio (SDR)-based signal generator to produce an amplitude-modulated signal at the fundamental frequency. This signal was first amplified using a low-noise amplifier, passed into the low-pass filters and then fed into the transmitting antenna positioned at a height of 90 cm above the harmonic transponder. The reception system included a receiving antenna mounted at the same height, which collected reflected signal at the second harmonic frequency. The high-pass filters are employed to suppress the fundamental frequency in the received signal, thereby isolating the second harmonic component and then fed into the SDR receiver. The receiver transmitted the processed signal to a computer interface, where the power at $2f$ was recorded and analyzed.

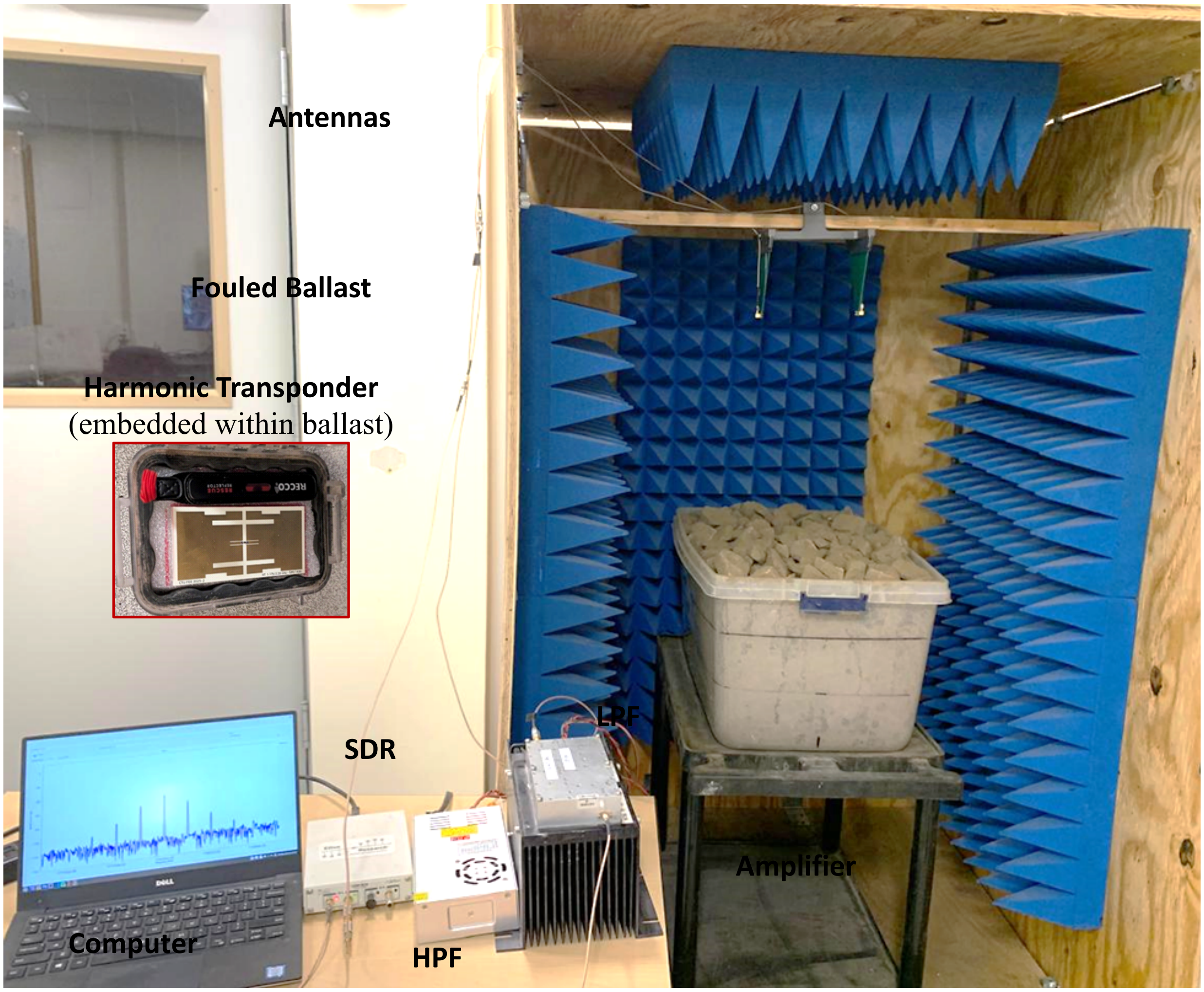


Figure 6: Test setup for silty sand fouled ballast materials

Chapter 3: Results and Discussion

3.1 Test Results

This section presents the results obtained from the experimental investigations conducted during the study. It begins with the preliminary laboratory tests performed using the small size gravels, and they were used to establish baseline observations and understand the influence of fouling on material behavior. Subsequently, the section discusses the outcomes from experiments using real-size ballast under varying fouling and moisture conditions.

3.1.1 Clean and fouled gravels

The laboratory experiments were conducted to assess the harmonic transponder's response under varying fouling and moisture conditions in coarse aggregates. Gravel samples were prepared in a plastic box measuring 39 × 29 × 11 cm, containing 18.2 kg of material. Coal dust was introduced as the fouling agent in two concentrations of 0.55 kg (Fouling Index, FI = 3%) and 1.1 kg (FI = 6%), and water was added to achieve saturation degrees (S) of 25% and 50%. In the first phase, the harmonic transponder was placed beneath the box, with transmitting and receiving antennas positioned 90 cm above it. Tests were carried out for clean gravels under dry and moist conditions, as well as for coal-fouled gravels at different moisture levels, using a fundamental frequency of 1.2 GHz and recording received power at the second harmonic (2.4 GHz). The results (see Figure 7) showed that higher fouling content and higher moisture levels increased the input power required to achieve the same Carrier-to-Sideband (C/SB) ratio, while the reverse signal at 2.4 GHz decreased in strength under these conditions.

In the second phase, the harmonic transponder was embedded within the gravel, positioned at the center of the box with an embedment depth of 15 cm. The same fouling and moisture conditions were tested, and the relationship between input power, received power, and C/SB ratio was recorded. The results confirmed that increasing moisture content in the fouled gravel consistently reduced the received power at the reverse frequency of 2.4 GHz. This attenuation effect was more pronounced in embedded configurations compared to the setup where the transponder was placed beneath the gravel, indicating greater signal loss when electromagnetic waves passed through more material volume containing moisture and fines.

The test was repeated to examine the effect of antenna height on signal response. The harmonic transponder remained embedded at the same depth, but measurements were taken with antennas placed at 45cm and 90cm above it. Tests were performed in 6% coal-fouled gravel under dry conditions at two fundamental frequencies of 890 MHz and 1.2 GHz. The results, revealed a clear presence of path loss in the reverse signal, with reduced received power at the greater antenna height.

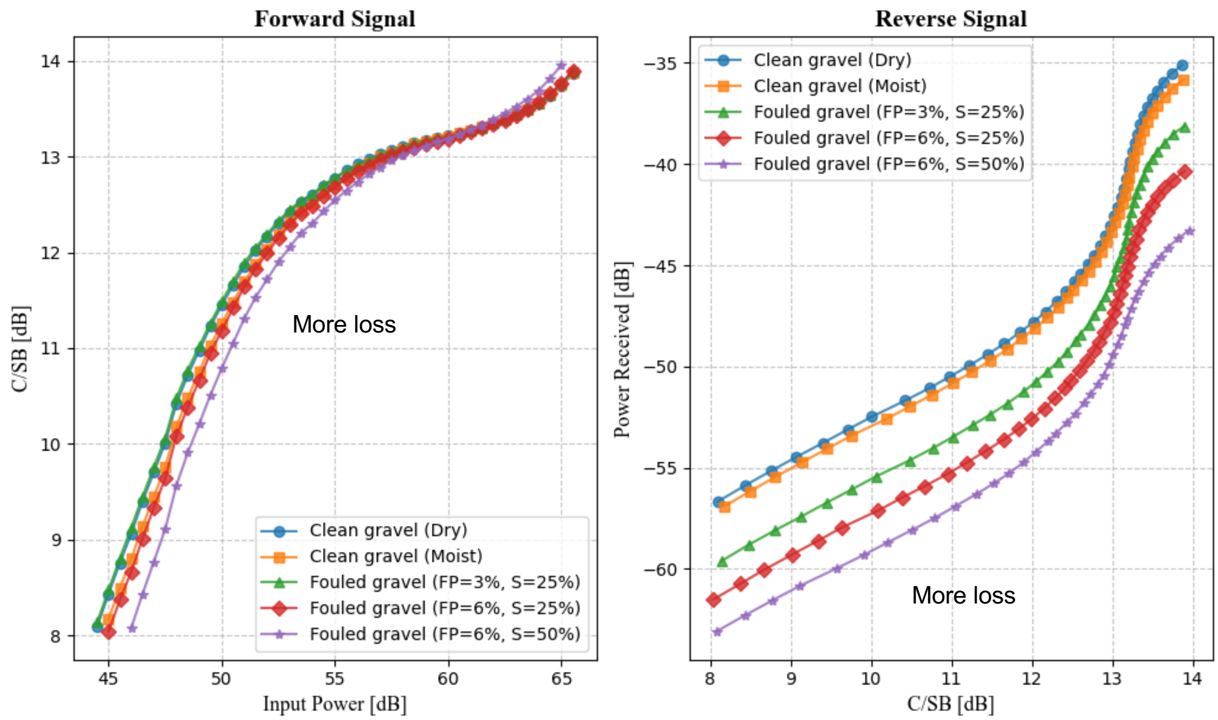


Figure 7: CSB vs input power from forward signal at 1.2 GHz (left) and power received vs CSB from reverse signal at 2.4 GHz (right) for clean and fouled gravels

3.1.2 Fouled ballast at various moisture levels

In this phase, moisture content in ballast with 10% fouling by weight was varied to 15%, 25%, 40%, and 55% (by weight relative to the mass of fouling). Thus, the fouling content remained constant while only moisture levels were altered. Interrogations were performed at two fundamental frequencies of 890 MHz (using commercial RECCO) and 1.17 GHz (using experimental), with both transponders placed in the same test box. Measurements were taken at embedment depths of 10 cm and 20 cm. Results are shown in Figures 8-11, showing increased signal attenuation with higher moisture content in the fouled ballast. Comparisons between the two frequencies revealed that the low frequency (890 MHz) exhibited better performance, while the higher frequency showed greater fluctuations and inconsistent results, suggesting that higher frequencies are more sensitive to ballast particle arrangements.

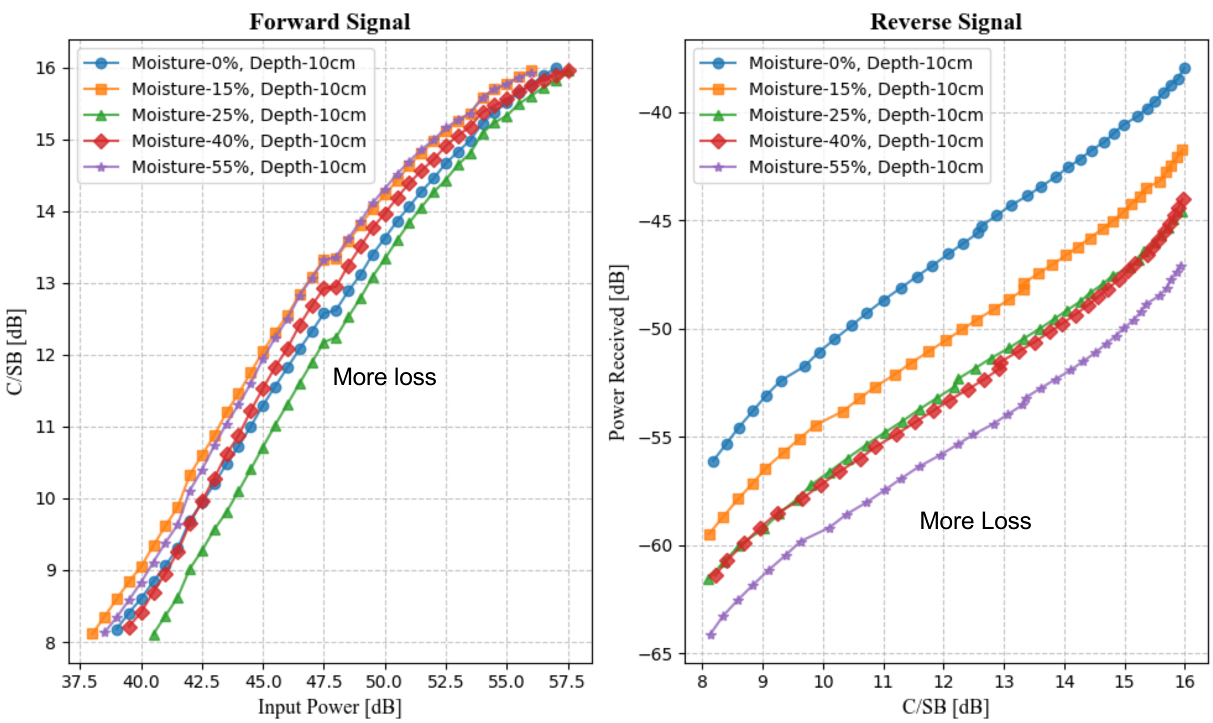


Figure 8: Forward and reverse signal at various moisture levels for embedment depth of 10cm, interrogated at frequency of 890 MHz

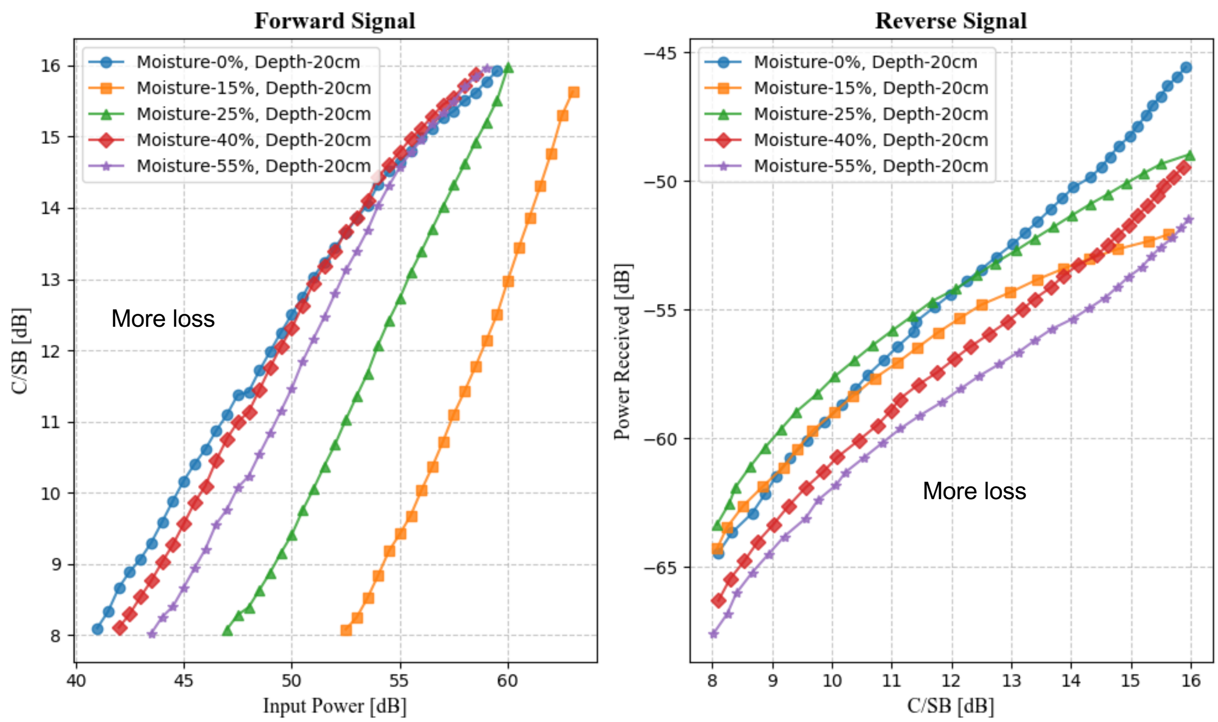


Figure 9: Forward and reverse signal at various moisture levels for embedment depth of 20cm, interrogated at frequency of 890 MHz

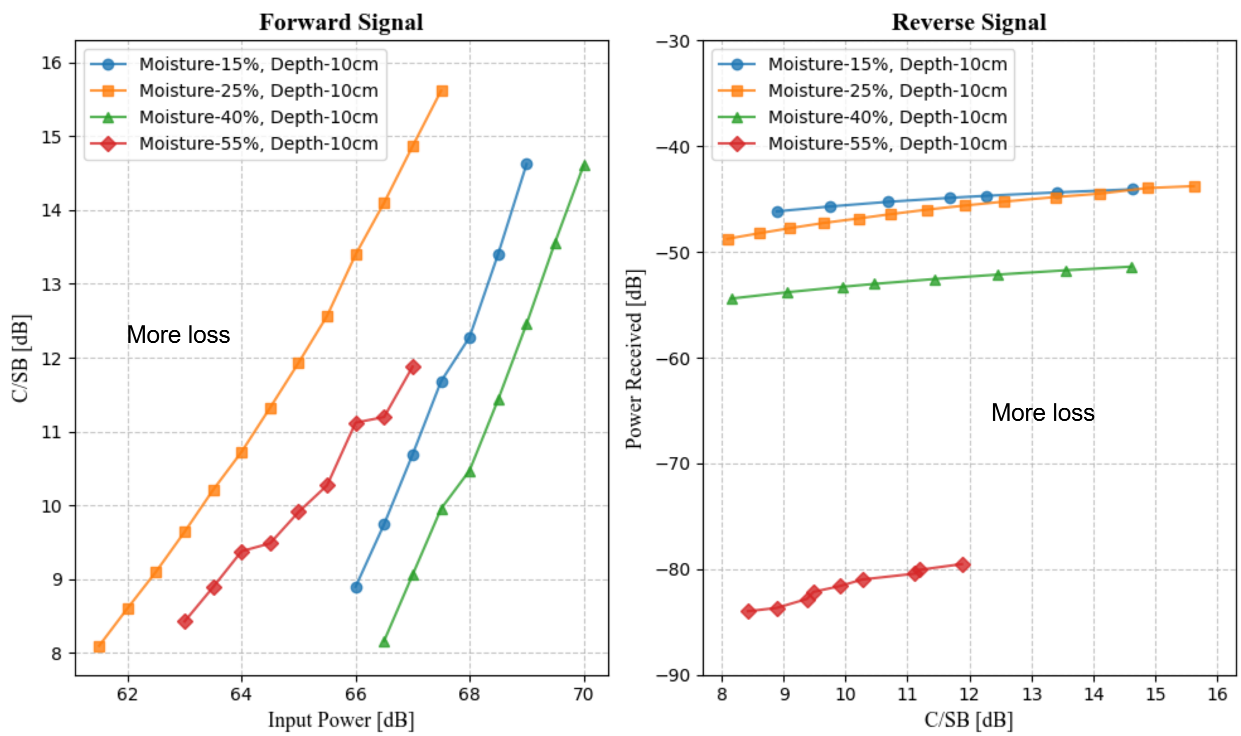


Figure 10: Forward and reverse signal at various moisture levels for embedment depth of 10cm, interrogated at frequency of 1.17 GHz

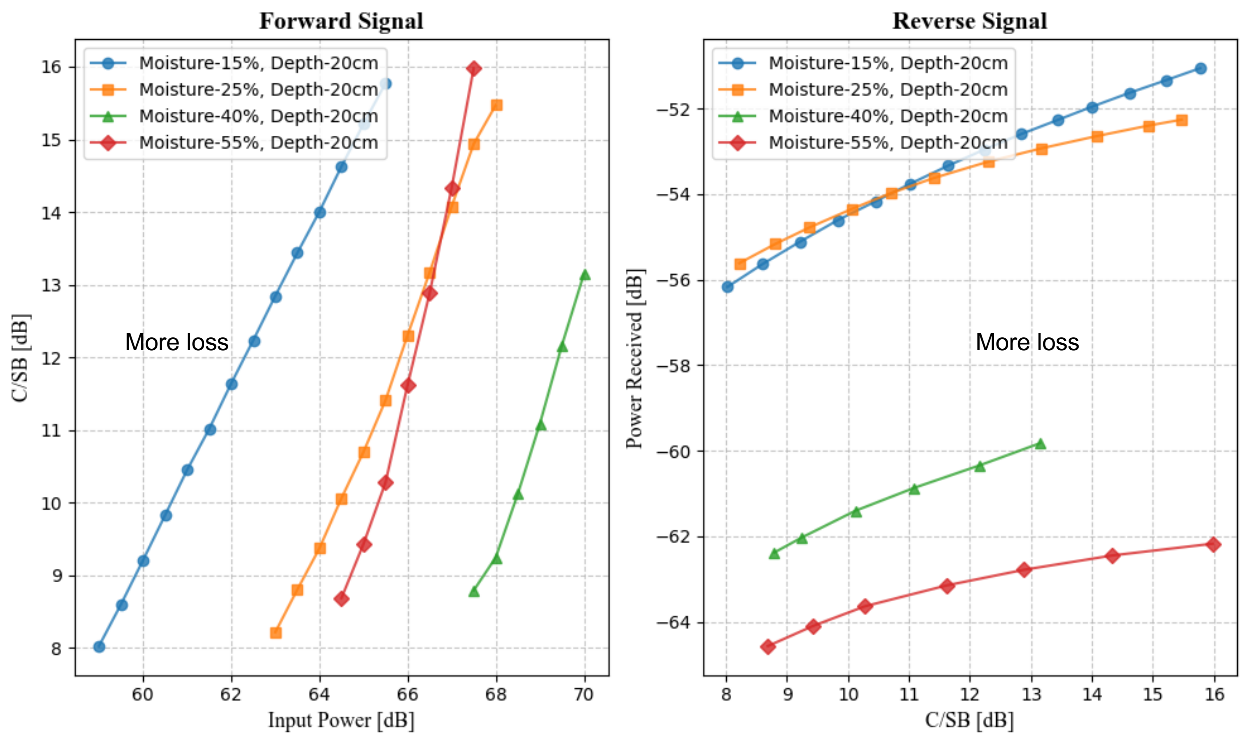


Figure 11: Forward and reverse signal at various moisture levels for embedment depth of 20cm, interrogated at frequency of 1.17 GHz

The power received from the reverse signal was used to calculate the reverse path loss. Since the transponder was interrogated using an amplitude-modulated (AM) signal with a 50% modulation index, corresponding to a carrier-to-sideband (C/SB) ratio of 12 dB, this condition was used as a reference point for comparing received power across different test scenarios. A C/SB of 12 dB indicates that the power of the carrier is 12 dB higher than that of each sideband, ensuring consistent interrogation strength and facilitating direct comparison between tests conducted under different moisture conditions.

For ballast with a 10% fouling level, the clean (unfouled) ballast condition was taken as the baseline. All received powers were normalized to the corresponding power measured in the clean ballast at each embedment depth. The following histograms (see Figure 12) illustrate the variation of normalized power loss with increasing moisture content (0%–55%) for ballast containing 10% fouling.

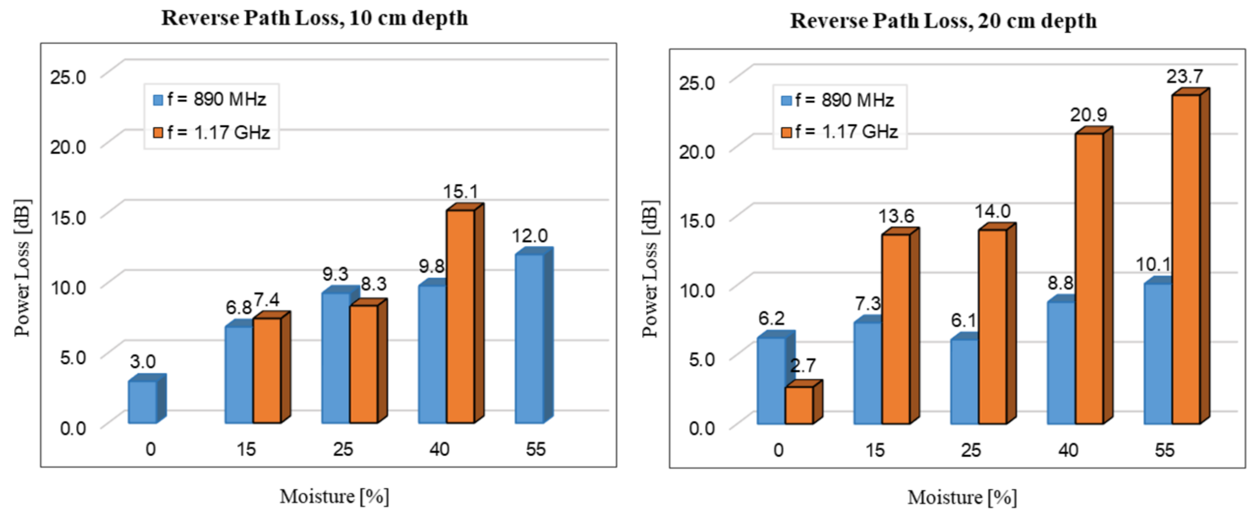


Figure 12: Normalized reverse path loss at varying moisture contents

The results show a clear trend of increasing power loss with increasing moisture content at both 10 cm and 20 cm embedment depths. When comparing the two operating frequencies, the higher-frequency transponder (1.17/2.34 GHz) exhibited greater attenuation than the lower-frequency device (890/1780 MHz), indicating stronger susceptibility to moisture-induced dielectric losses. At certain moisture levels (0% and 55%) for the 10 cm depth, the reverse signal was not sufficiently strong to achieve the target C/SB ratio of 12 dB, indicating signal saturation and therefore, data for those cases are not presented here.

3.2 Discussion

The laboratory experiments demonstrated that both embedment depth and moisture content are key factors influencing the performance of passive harmonic transponders in railway ballast. Signal strength consistently decreased with increasing embedment depth, indicating that greater burial reduces the ability of the interrogator to excite and detect the harmonic response. Similarly, elevated moisture levels led to higher power attenuation, particularly in fouled ballast, due to the increased dielectric loss and signal absorption by the retained water.

At constant moisture, varying the degree of fouling did not show a clear or consistent trend in the received power. This is likely attributed to the heterogeneous packing of ballast particles, differences in particle contact, and air void distribution, all of which can cause local variations in the propagation path and signal scattering. Among the two transponders tested, the lower-frequency (890 MHz) exhibited more stable and reliable performance under different conditions, whereas the higher-frequency (1.17 GHz) showed greater sensitivity to ballast arrangement and moisture fluctuations, resulting in higher variability in response. These observations suggest that lower-frequency transponders may be more suitable for subsurface applications where moisture and fouling conditions vary significantly.

However, certain limitations should be acknowledged. The laboratory setup simplified field conditions and may not fully capture the effects of compaction, stress distribution, and large-scale variability present in real railway tracks. The limited number of transponder types and test repetitions may also restrict the generalization of the results. Additionally, electromagnetic coupling between the interrogator and transponder could vary in outdoor environments, especially under fluctuating temperature and humidity.

Future studies should focus on validating these findings under field-scale conditions, including long-term monitoring of ballast sections with varying fouling and moisture contents. Expanding the range of transponder frequencies and designs could also help identify optimal configurations for different track environments. In addition, combining harmonic transponder measurements with other sensing techniques, such as ground-penetrating radar or moisture probes, could provide complementary information on the physical and dielectric properties of ballast. Such combined approaches would improve data reliability, and enhance the accuracy of fouling detection in practical field applications.

3.3 Potential field application

This study demonstrates the potential of passive harmonic transponders as a practical and scalable solution for monitoring ballast fouling in railway infrastructure. By embedding these devices during new railroad construction, a built-in, long-term monitoring system can be established to track ballast condition without the need for intrusive inspections. Because transponders are passive devices, they require no direct power source; only the interrogator requires power, and that is minimal compared to conventional active sensing systems.

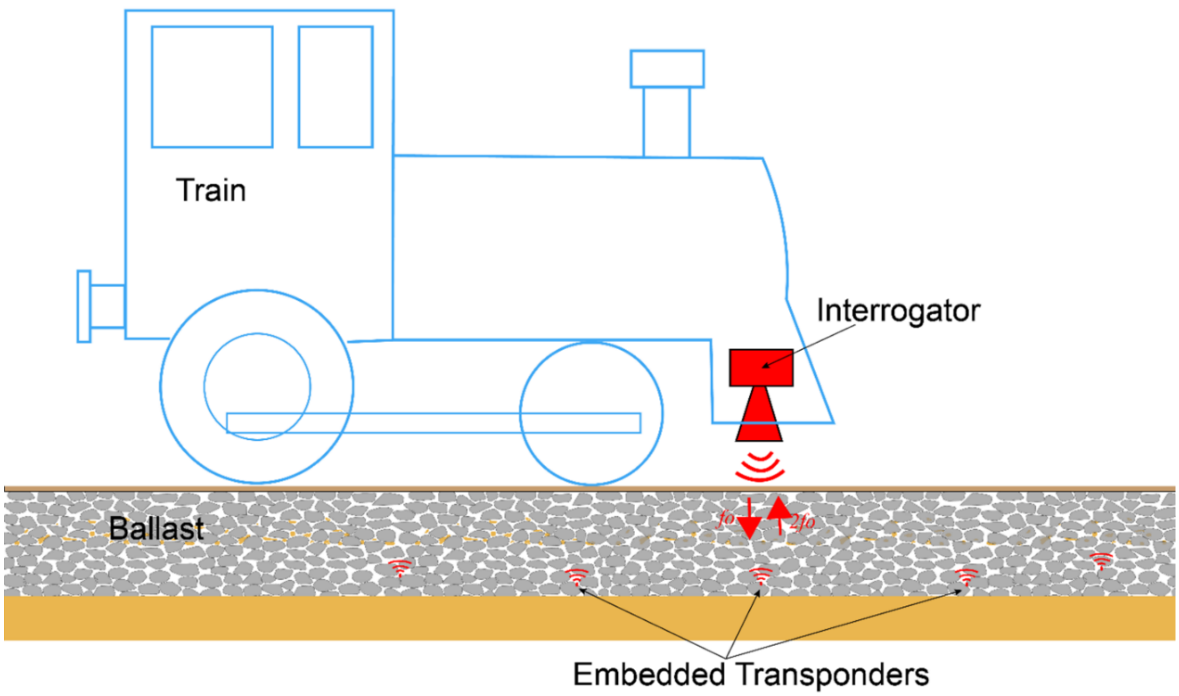


Figure 13: Conceptual field deployment of the passive wireless tag for railbed monitoring

An additional advantage is that harmonic transponders respond instantaneously to the interrogation signal, meaning that data can be collected even when the interrogator is in motion. This feature makes it feasible to mount the interrogation system on a moving train at the normal speeds, enabling real-time assessment of ballast conditions (see Figure 13). Alternatively, the system could be installed on a drone or a track inspection vehicle for targeted surveys, offering exceptional flexibility in deployment. This approach allows railway operators to remotely detect changes in ballast conditions and identify localized fouling or moisture-related issues before they escalate into costly maintenance interventions or service disruptions.

The technology's working principle is directly based on moisture-related signal attenuation, making it especially suitable for detecting changes in highly conductive media such as wet, fouled ballast. The harmonic transponders are low-cost, environmentally sustainable, and, if properly sealed, can last for decades underground. The study also found that lower interrogation frequencies, such as the 890 MHz, perform more reliably under varied moisture and embedment conditions, strengthening the case for real-world adoption.

However, there are some limitations associated with this technology. The system's performance can be influenced by ballast heterogeneity, particle arrangement, transponder-interrogator orientation, and inconsistent contact between the transponder and surrounding material. Higher frequencies were found to be more sensitive to particle arrangement and exhibited greater signal fluctuations. In addition, while the method is effective for moisture-related fouling, it may be less sensitive to purely mechanical degradation without moisture presence.

Chapter 4: Conclusions and Recommendations

This study investigated the performance of passive harmonic transponders for detecting ballast fouling under controlled laboratory conditions. Experiments were conducted in progressive stages, beginning with clean ballast under dry and moist conditions, followed by varying levels of fouling, and finally, different moisture contents in fouled ballast. Two types of harmonic transponders were evaluated: the commercial RECCO tag (operating at 890 MHz) and an experimental transponder designed for high frequency (operating at 1.17 GHz), embedded at depths of 10 cm and 20 cm.

The results consistently indicated that both moisture and embedment depth significantly attenuate the reverse signal power. Increased depth reduced signal strength in all cases, and higher moisture levels caused greater power loss, especially in fouled ballast. While the degree of fouling alone (at constant moisture) did not consistently affect the signal amplitude, this may be due to the heterogeneous packing of ballast particles and the resulting variability in particle contact. Comparisons between the two frequencies showed that the lower-frequency provided more stable and reliable readings, particularly in moist conditions, whereas the higher-frequency exhibited greater sensitivity to ballast arrangement and moisture fluctuations.

These findings suggest that passive harmonic transponders have considerable potential for ballast condition monitoring, but their performance is influenced by several interacting factors, with moisture being the dominant attenuating factor.

Based on the findings of this study, the following recommendations are proposed for future research and field applications:

- Conduct additional laboratory experiments with a wider range of ballast fouling levels, moisture conditions, and transponder frequencies to better characterize performance under variable environments.
- Implement pilot-scale field testing under real railway operating conditions to evaluate long-term stability, signal reliability, and the effects of temperature, and vibration.
- Compare harmonic transponder performance with established methods such as ground-penetrating radar (GPR), time-domain reflectometry, or moisture probes to assess relative accuracy and reliability.

- Study optimal antenna configurations, interrogation angles, and signal processing methods to maximize detection range and minimize attenuation effects.
- Develop and test systems capable of real-time interrogation from moving trains or drones to demonstrate feasibility for large-scale, non-intrusive monitoring.
- Formulate a practical deployment and maintenance plan for embedding transponders during new track construction or scheduled maintenance activities to enable long-term monitoring networks.

References

Charoenwong, C., Connolly, D. P., Costa, P. A., Galvín, P., & Romero, A. (2024). Transportation Geotechnics The effect of ballast moisture content and fouling index on railway track settlement. *Transportation Geotechnics*, *45*(January), 101193. https://doi.org/10.1016/j.trgeo.2024.101193

Clark, M. R., Gillespie, R., Kemp, T., Mccann, D. M., & Forde, M. C. (2001). *Electromagnetic properties of railway ballast*. *34*, 305–311.

Feldman, F., & Nissen, D. (2002). Alternative testing method for the measurement of ballast fouling: percentage void contamination. *Conference on Railway Engineering (2002: Wollongong, NSW)*, 101–111.

Frolik, J. (2023). AM Interrogation of Harmonic Transponders for Measuring Channel Loss. *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, *2023-July*(3), 1805–1806. https://doi.org/10.1109/USNC-URSI52151.2023.10237917

Frolik, J., Lens, J. E., Dewoolkar, M. M., & Weller, T. M. (2018). Effects of Soil Characteristics on Passive Wireless Sensor Interrogation. *IEEE Sensors Journal*, *18*(8), 3454–3460. https://doi.org/10.1109/JSEN.2018.2810132

Guo, Y., Liu, G., Jing, G., Qu, J., & Wang, S. (2023). Ballast fouling inspection and quantification with ground penetrating radar (GPR). *International Journal of Rail Transportation*, *11*(2), 151–168. https://doi.org/10.1080/23248378.2022.2064346

Huang, H., Tutumluer, E., & Dombrow, W. (2009). Laboratory Characterization of Fouled Railroad Ballast Behavior. *Transportation Research Record*, *2117*, 93–101. https://doi.org/10.3141/2117-12

Indraratna, B., Ngo, N. T., Rujikiatkamjorn, C., & Vinod, J. S. (2014). Behavior of Fresh and Fouled Railway Ballast Subjected to Direct Shear Testing : Discrete Element Simulation. *International Journal of Geo-Mechanics*, *14*(February), 34–44. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000264.

Koohmishi, M., Kaewunruen, S., Jing, G., & Guo, Y. (2024). Thermal imaging analysis of ballast fouling: Investigating the effects of parent rock and fouling materials through IRT passive camera. *Transportation Geotechnics*, *48*, 101313. https://doi.org/https://doi.org/10.1016/j.trgeo.2024.101313

Leng, Z., & Al-Qadi, I. L. (2010). Railroad ballast evaluation using ground-penetrating radar. *Transportation Research Record*, *2159*, 110–117. https://doi.org/10.3141/2159-14

Liang, X., Niu, X., Liu, P., Lan, C., Yang, R., & Zhou, Z. (2023). Test on fouling detection of ballast based on infrared thermography. *NDT & E International*, *140*, 102956. https://doi.org/https://doi.org/10.1016/j.ndteint.2023.102956

Narayanat, R. M., Kumkea, C. J., & Lii, D. (1999). *Railroad Track Monitoring Using Ground Penetrating Radar: Simulation Study and Field Measurements*. *3752*(July), 243–251.

Ngamkhanong, C., Kaewunruen, S., & Baniotopoulos, C. (2017). A review on modelling and monitoring of railway ballast. *Structural Monitoring and Maintenance*, *4*(3), 195–220. https://doi.org/10.12989/smm.2017.4.3.195

Polivka, M., Hubata-Vacek, V., & Svanda, M. (2022). Harmonic Balance/Full-Wave Analysis of Wearable Harmonic Transponder for IoT Applications. *IEEE Transactions on Antennas and Propagation*, *70*(2), 977–987. https://doi.org/10.1109/TAP.2021.3111226

RECCO. (n.d.). *RECCO Reflector*. Retrieved October 29, 2025, from https://recco.com/attachable-recco-reflector/

Shafique, R., Siddiqui, H. U. R., Rustam, F., Ullah, S., Siddique, M. A., Lee, E., Ashraf, I., & Dudley, S. (2021). A novel approach to railway track faults detection using acoustic analysis. *Sensors*, *21*(18), 1–19. https://doi.org/10.3390/s21186221

Uluer, I. H., Frolik, J., & Weller, T. M. (2022). Battery-free Mechanically-Tunable Wireless Sensors for Railroad Track Ballast Monitoring. *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, AP-S/URSI 2022 - Proceedings*, *1*, 117–118. https://doi.org/10.1109/AP-S/USNC-URSI47032.2022.9886888

Yilmaz, Y., Weller, T., Frolik, J., & Bruzek, R. (2021). *Autonomous Inspection System Based on Passive Sensing and Anomaly Detection* (Issue August).

Appendices

N/A

TIDC

Transportation Infrastructure Durability Center
AT THE UNIVERSITY OF MAINE

35 Flagstaff Road

www.tidc-utc.org