ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

FIBER OPTIC NETWORK-BASED REMOTE SENSING OF RAIL SYSTEMS VEHICLES

Ph.D. THESIS

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Department of Communcation Systems

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

RAYLI SİSTEM ARAÇLARININ FİBER OPTİK AĞLAR KULLANILARAK UZAKTAN ALGILANMASI

DOKTORA TEZİ

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Serhat BOYNUKALIN, a Ph.D. student of ITU Graduate School student ID 705172004 successfully defended the thesis entitled "FIBER OPTIC NETWORK-BASED REMOTE SENSING OF RAIL SYSTEMS VEHICLES", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Dear all,

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FOREWORD

Technological advancement has brought a growing demand for high-precision positioning of moving vehicles in urban metros. However, the existing positioning technologies, such as FBG and DAS, have limitations in obtaining accurate positioning information, especially in urban environments. To address this issue, a newly developed hybrid system with a unique signal encoding method has been proposed to achieve high-precision positioning of moving vehicles in urban metros. The hybrid system eliminates the need to examine multiple signals while achieving high precision in speed, position, and direction determination by correlating two systems and protecting against erroneous data. This thesis comprehensively investigates the feasibility of utilizing a hybrid system to achieve high-precision positioning of moving vehicles in urban metros, aiming to contribute to the growing body of knowledge on high-precision positioning systems for moving vehicles. This thesis mainly compares and contrasts the two sensing methodologies, FBG and DAS, and determines which is more suitable. Additionally, it aims to investigate the technical requirements for implementing a hybrid system that combines both methods. The study also evaluates the hybrid system's accuracy, speed, and direction-determination capabilities. Finally, it explores the potential applications of the hybrid system in urban environments and how it can enhance the efficiency and safety of urban transportation systems. The literature review in this thesis extensively discusses the FBG and DAS systems, which are widely researched for positioning capabilities in various applications, such as railway systems. The review also highlights the limitations of these systems in providing accurate positioning information in urban environments. This thesis aims to contribute to developing and testing a novel hybrid system using advanced simulation software to identify optimal configurations and parameters for the proposed system. The hybrid system's performance will be rigorously evaluated and compared to existing systems, and its potential applications in various transportation contexts will be explored. Overall, this thesis sheds light on the hybrid system's feasibility and potential to revolutionize the urban transportation sector by providing high-precision positioning capabilities. The findings of this research will be valuable for researchers, engineers, and policymakers in the transportation sector.

February 2024

Serhat BOYNUKALIN
(Yüksek Mühendis)

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ABBREVIATIONS

FOS	**:** Fiber Optic Sensing
FBG	**:** Fiber Bragg Gratings
DAS	**:** Distributed Acoustic Sensing
YHT	**:** High-Speed Train
ITU	**:** Istanbul Technical University
PN-Code	**:** Pseudo-Noise code
ϕ-OTDR	**:** Phase-Sensitive Optical Time Domain Reflectometry

SYMBOLS

n1, n2	**:** Refractive Index of the Medium
l	**:** Phase load
$\lambda_{\mathbf{B}}$,	**:** Center Wavelength of the Reflected Signal (Bragg Wavelength)
$\mathbf{n_{eff}}$, ,	**:** Effective Refractive Index
Δ_{ε}	**:** Strain Variable in the Horizontal Axis
Δ**T**	**:** Temperature Increase
$\rho_{\mathbf{e}}$	**:** The Elastic-Optical Coefficient of the Fiber
$\alpha_{\mathbf{f}}$,ζ**F**	**:** Thermo-Optic Coefficient and the Coefficient of Thermal Expansion of the Fiber Opt
$\mathbf{n_e}$	**:** Effective Index
K(λ)	**:** Connection Power
Δ**n**	**:** Index Modulation
L	**:** Grating Length
$\Delta\beta$	**:** The Phase Difference
r(λ)	**:** Reflected Wavelengths of the FBG
t(λ)	**:** Transmitted Wavelengths of the FBG
$\alpha_{\mathbf{TE}}$	**:** The Thermal Expansion Coefficient
$\alpha_{\mathbf{TO}}$	**:** The Thermo-Optic Coefficient
g	**:** The Gauge Factor
$\sigma_{\mathbf{ZZ}}$, $\sigma_{\mathbf{XX}}$ $\sigma_{\mathbf{YY}}$	**:** The Longitudinal Strain and Transverse Strain Components
E	**:** The Young modulus
υ	**:** The Poisson Ratio
$\mathbf{F_R}$	**:** Train Resistance Force [N]
$\mathbf{K_{rr}}$	**:** Rolling Resistance [N/kg]
$\mathbf{M_r}$	**:** Total Weight of the Train [kg]
M	**:** Empty Weight of the Train [kg]
$\mathbf{M_{load}}$	**:** Total Load Weight of the Train [kg]
$\mathbf{F_{coeff}}$	**:** Falanj Constant [N/(kg km/h)]
V	**:** Speed [kmph]
$\mathbf{A_{coeff}}$	**:** Front Drag Air Resistance Constant [N/m$^2 kmph^2$]
$\mathbf{S_{coeff}}$	**:** Coefficient Of Air Drag on the Train Surface [N/m$^2 kmph^2$]
n	**:** Number Of Vehicles in the Train
A	**:** Area Of The Front of the Train [m^2]
$\mathbf{A_R}$	**:** Acceleration of the Train Due to Resistance Forces (negative)
kTunnel	**:** The Tunnel Coefficient

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FIBER OPTIC NETWORK-BASED REMOTE SENSING OF RAIL SYSTEMS VEHICLES

SUMMARY

In recent years, the need for precise positioning of moving vehicles has become increasingly important, especially in smart cities. Accurate positioning is critical for an efficient and safe transportation system. However, the existing positioning systems are often limited because they are point-based, and the error margin for non-point-based systems is usually more than one meter, sometimes even exceeding ten meters. This limitation significantly reduces the potential use of these positioning technologies, particularly in urban metro systems.

To address the accuracy problem in fast positioning, a new hybrid system utilizing Fiber Bragg Gratings (FBG) technology is proposed within the scope of this thesis. One unique feature of this designed model is the ability to encode the transmitted signal. Another essential feature is the correlation between the reference and reflected signals. This allows for precise positioning, even at high noise levels.

With the help of the coding of transmitter signal 1, 2, 4, 8, 16, 32, 64, 128, 256-bit pulse sequences have been created for the transmission side, and the localization errors were 118.4, 68.1, 4.8, 0.4, 0.3, 0.3, 0.2, and 0.1 m respectively for 50 km track line under high Gaussian noise.

Additionally, the hybrid system can determine the speed and direction of a moving object by interpreting two consecutive or just a single transmitted signal. Speed and direction estimation can also be achieved by examining the frequency shift of the signal. This approach contributes to speed, position, and direction determination without analyzing multiple signals, providing higher accuracy and protection against erroneous data.

The research aims to address four main questions:

1. Which should be chosen between FBG and Distributed Acoustic Sensing (DAS) methodologies for sensor applications?

2. What technical specifications are essential for implementing the hybrid FBG and DAS system to position mobile vehicles in railway applications precisely?

3. How do the hybrid system's performance, speed, and direction determination capabilities compare to existing systems, and what are the optimal configurations and parameters of the proposed system?

4. What are the hybrid system's potential uses, advantages, and limitations in various transportation types, and how can it enhance the efficiency and safety of urban transportation systems?

The literature review has indicated the positioning capabilities, technical specifications, and limitations of FBG and DAS systems. Using fiber optic sensors, these systems expose external stimuli to measure stress and temperature changes in optical fibers. These changes cause a shift in the Bragg wavelength of FBG, which can be detected by measuring the reflected signal from the fiber. Furthermore, DAS, another sensing system, is used to detect the position and movement of an object by utilizing acoustic waves originating from external stimuli. However, the random nature of the backscattered signal limits the mathematical modeling to randomness. Development studies are ongoing in this scope.

An advanced simulation software, using Optiwave's OptiSystem, was conducted for a newly developed and tested design to evaluate the hybrid system's performance. The software can simulate FBG sensors based on a mathematical model with a limited randomness of the reflected and transmitted signals. The effect of train on FBG expressed related to IEEE 1698 std. which defines air resistance force at the surface of the train which is directly effects the FBG sensor. This model was developed and verified with field tests to provide the highest accuracy and reliability during simulation. The behavior of FBG sensors calibrated and optimized related to field results. Also, the proper FBG working frequencies selected related to the FS Community channels guide. The performance of the proposed hybrid system was carefully evaluated and compared to existing systems. The most suitable configurations and parameters for the designed model were determined. The design and implementation of the system were evaluated considering the provided accuracy, speed, direction determination, and potential applications in various transportation contexts.

To showcase the system's capabilities, a cleaning train cleaning operation in clearing the track was modeled and demonstrated using the hybrid system. Various measures against foreign objects on the track could also be provided. The proposed hybrid sensing system fills a gap in the literature by analyzing potential applications in the railway transportation sector. It could contribute significantly to the knowledge of high-precision positioning for detecting moving vehicles.

This thesis extensively researches the implementation of a hybrid system for high-precision positioning in urban transportation. Addressing the research questions above demonstrates this model's feasibility and potential to revolutionize the urban transportation sector. The published articles from this thesis have significantly contributed to the knowledge of high-precision positioning systems and their applications in the transportation sector.

The proposed hybrid system has several potential uses, advantages, and limitations in various transportation types. For instance, the system can be used in railway transportation to track trains and ensure their safe and efficient operation. The system can also be used in road transportation to track vehicles and optimize traffic flow. Additionally, the system can be used in air transportation to track airplanes and ensure their safe and efficient operation.

One of the significant advantages of the hybrid system is its high accuracy in positioning, speed, and direction determination. The system can provide accurate positioning even at high noise levels, making it suitable for use in busy urban

environments. The system is also robust and can withstand harsh environmental conditions, making it suitable for use in various transportation contexts.

However, the hybrid system has certain limitations that need to be considered. For instance, the system requires a network of sensors to provide accurate positioning, which can be costly to implement.

In conclusion, the proposed hybrid system utilizing Fiber Bragg Gratings (FBG) technology is a promising solution to the accuracy problem in real-time positioning. The system can provide high-precision positioning, speed, and direction determination, making it suitable for use in various transportation contexts. The system has several potential uses, advantages, and limitations that need to be considered when implementing it. Overall, the system has the potential to revolutionize the urban transportation sector by ensuring safe and efficient operation.

RAYLI SİSTEM ARAÇLARININ FİBER OPTİK AĞLAR KULLANILARAK UZAKTAN ALGILANMASI

ÖZET

Son yıllarda, özellikle akıllı şehirlerde, hareket halindeki araçların hassas bir şekilde konumlarının tespit edilmesi ihtiyacı giderek daha fazla önem kazanmıştır. Doğru konumlandırma, etkin ve güvenli bir ulaşım sistemi için kritik önem taşır. Ancak, mevcut konumlandırma sistemleri genellikle noktasal bazlı oldukları için sınırlıdır. Noktasal olmayan hattın sürekli izlenmesine imkân veren fiber optik sensörlerin ise hata payı genellikle bir metreden fazladır, bazen on metreyi bile aşabilmektedir. Bu sınırlama, özellikle şehir içi yeraltı trenni (metro) sistemlerinde araç konumlandırma teknolojilerinin potansiyel kullanımını önemli ölçüde azaltmaktadır.

Hızlı konumlandırmadaki doğruluk problemine bir çözüm olarak, bu tez kapsamında Fiber Bragg Izgara (FBG) teknolojisini kullanan yeni bir hibrit sistem önerilmektedir. Tasarlanan bu modelin benzersiz özelliklerinden biri, gönderilen sinyalin kodlanabilme yeteneğidir. Bir diğer önemli özellik ise referans ve yansıyan sinyaller arasındaki ilgileşim (korelasyonu) sayesinde yüksek gürültü seviyelerinde bile kesin konumlandırmaya olanak tanır.

Simülasyon ortamında yapılan testlerde, referans işareti için 1, 2, 4, 8, 16, 32, 64, 128, 256-bitlik darbe dizileri oluşturulmuştur. Yüksek Gauss gürültüsü altında 50 km'lik hat için sırasıyla 118.4, 68.1, 4.8, 0.4, 0.3, 0.3, 0.2 ve 0.1 m konumlandırma hata miktarları ile konumlandırma elde edilebilmiştir.

Ayrıca, hibrit sistem, iki ardışık veya tek bir gönderilen sinyali yorumlayarak hareketli bir nesnenin hızını ve yönünü belirleyebilir. Hız ve yön tahmini, sinyalin frekans kaymasını inceleyerek de gerçekleştirebilmek mümkün olmaktadır. Bu yaklaşım, çoklu sinyalleri analiz etmeden hız, konum ve yön belirlemesine katkı sağlar, daha yüksek doğruluk sunar ve hatalı verilere karşı koruma sağlar. Araştırma dört ana soruyu ele almayı hedeflemektedir:

1. Sensör uygulamaları için FBG ve Dağıtılmış Akustik Algılama (DAS) metodolojileri arasından hangisi seçilmelidir? 2. Demiryolu uygulamalarında hareketli araçları hassas bir şekilde den pozisyonlandırmak için hibrit FBG ve DAS sisteminin uygulanması için hangi teknik özellikler esastır? 3. Hibrit sistemin performansı, hız ve yön belirleme kapasiteleri mevcut sistemlerle nasıl karşılaştırılır ve önerilen sistemin optimal konfigürasyonları ve parametreleri nelerdir? 4. Hibrit sistemin çeşitli ulaşım türlerindeki potansiyel kullanımları, avantajları ve sınırlamaları nelerdir ve bu sistem şehiriçi ulaşım sistemlerinin etkinliğini ve güvenliğini nasıl artırabilir?

Literatür taraması, FBG ve DAS sistemlerinin konumlandırma yeteneklerini, teknik özelliklerini ve sınırlamalarını belirtmiştir. Fiber optik sensörler kullanarak, bu

sistemler optik fiberlerdeki stres ve sıcaklık değişikliklerini ölçmek için dış uyaranlara maruz kalırlar. Bu değişiklikler, FBG'nin Bragg dalga boyunda bir kaymaya sebep olur ve bu fiberden yansıyan sinyalin ölçülmesiyle tespit edilebilir. Ayrıca, başka bir algılama sistemi olan DAS, dış uyaranlardan kaynaklanan akustik dalgaları kullanarak bir nesnenin konumunu ve hareketini tespit etmek için kullanılır. Ancak, geri saçılan sinyalin rastgelelik doğası matematiksel modellemeyi rastlantısallığa sınırlar. Bu kapsamda geliştirme çalışmaları devam etmektedir ama henüz trenin oluşturacağı etkinin matematiksel bir denklemle ifade edilip saçılan işaretin modellenmesini sağlayan kararlı bir formülasyon ortaya konamamıştır. Genellikle rasgelelik kabulleri üzerine yaklaşımlar ile devam etmektedir.

Yeni geliştirilen ve test edilen tasarımın hibrit sisteminin performansını değerlendirmek için Optiwave'in OptiSystem adlı gelişmiş bir simülasyon yazılımı kullanılmıştır. Yazılım, yansıyan ve iletilen sinyallerin sınırlı rastlantısallığına dayalı matematiksel bir model bazında FBG sensörlerini simüle edebilmektedir.

Trenin FBG üzerindeki etkisi, IEEE 1698 std.ile ilişkilendirilmiştir ve bu standart trenin yüzeyindeki hava direnci kuvvetinin matametiksel denklemlerini tanımlar. Bu doğrudan FBG sensörü üzerinde oluşan basınç miktarının hesaplanması için kullanılabilmektedir.

FBG sensörlerin davranışları, saha sonuçlarına göre kalibre edilmiş ve optimize edilmiştir. Ayrıca, FS Community kanallar rehberine göre uygun FBG çalışma frekansları seçilmiştir. Önerilen hibrit sistemin performansı dikkatlice değerlendirilmiş ve mevcut sistemlerle kıyaslanmıştır. Tasarlanan model için en uygun konfigürasyonlar ve parametreler belirlenmiştir. Sistemin tasarımı ve uygulanması, sağlanan doğruluk, hız, yön belirleme ve çeşitli ulaşım bağlamlarındaki potansiyel uygulamalar göz önünde bulundurularak değerlendirilmiştir.

Sistemin yeteneklerini sergilemek amacıyla, hibrit sistem kullanılarak temizleme treninin rayları temizleme operasyonu modellenmiş ve gösterilmiştir. Raylar üzerindeki yabancı nesnelere karşı çeşitli önlemler de sağlanabilir. Önerilen hibrit algılama sistemi, demiryolu taşımacılığı sektöründeki potansiyel uygulamaları analiz ederek literatürde bir boşluğu doldurur. Hareket halindeki araçların tespiti için yüksek hassasiyetli konumlandırma bilgisine önemli katkılar sağlayabilir.

Bu tez, şehiriçi ulaşımda yüksek hassasiyetli konumlandırma için bir hibrit sistemin uygulanmasını geniş çapta araştırmaktadır. Yukarıdaki araştırma sorularını ele almak, bu modelin uygulanabilirliğini ve şehiriçi ulaşım sektörünü dönüştürme potansiyelini göstermektedir. Bu tezden yayımlanan makaleler, ulaşım sektöründeki yüksek hassasiyetli konumlandırma sistemleri ve uygulamaları hakkındaki bilgiye önemli katkılarda bulunmuştur. Ayrıca örnek olabilecek bir çalışma modelini de sunarak endüstriye direk katkı yapma hedefi de içermektedir.

Önerilen hibrit sistemin çeşitli ulaşım türlerinde birçok potansiyel kullanımı, avantajları ve sınırlamaları vardır. Örneğin, sistem demiryolu taşımacılığında trenleri takip etmek ve onların güvenli ve etkin çalışmasını sağlamak için kullanılabilir. Sistem ayrıca karayolu taşımacılığında araçların takibinde ve trafik akışının optimize edilmesinde kullanılabilir. Ayrıca, sistem hava taşımacılığında uçakları takip etmek ve onların güvenli ve etkin çalışmasını sağlamak için de kullanılabilir.

Hibrit sistemin önemli avantajlarından bir diğeri ise konumlandırma, hız ve yön belirlemedeki yüksek doğruluk oranıdır. Sistem, yüksek gürültü seviyelerinde bile doğru konumlandırma sağlayabilir. Fiber optik doğası gereği elektromanyetik girişimlere karşı doğal olarak direnci bulunmaktadır ve sert çevre koşullarına dayanabilir, bu da onu çeşitli ulaşım bağlamlarında kullanım için uygun kılar.

Ancak, hibrit sistemin dikkate alınması gereken belli sınırlamaları vardır. Örneğin, sistem, doğru konumlandırma sağlamak için sensörlerin bir ağına ihtiyaç duyar, bu da uygulamasının belli bir maliyeti olacağını aynı zamanda kalifiye insan ihtiyacı olacağı anlamına gelir. Bu sistemlerin kurulması ciddi bir teknik bilgi gerektirmektedir. Sensörlerin ve yazılımların kalibrasyonu hayati önem arz etmektedir.

Sonuç olarak, Fiber Bragg Izgara (FBG) teknolojisini baz alan hibrit sistem, hızlı bir şekilde konumlandırmadaki doğruluk problemi için umut verici bir çözüm sunmaktadır. Sistem, çeşitli ulaşım ağlarında kullanıma uygun olmak ile birlikte özellikle demiryolu sektörüne yüksek oranda hizmet verebilme kapasitesine sahiptir. Yüksek hassasiyetli konumlandırma, hız ve yön belirleme kabiliyetleri ciddi birer özelliktir. Sistemin birçok potansiyel kullanımı, avantajları olmasına rağmen uygulanırken dikkate alınması gereken sınırlamaları vardır. Genel olarak, sistem, güvenli ve etkin çalışmayı sağlayarak şehir içi raylı ulaşım sektörüne önemli katkı sağlayabilme potansiyeline sahiptir.

1. INTRODUCTION

In recent years, there has been a growing demand for high-precision positioning of moving vehicles in urban metros. Fiber Bragg Grating (FBG) and Distributed Acoustic Sensing (DAS) are two technologies that have been explored for this purpose [1]. However, in the literature, the localization error of moving vehicles in these applications is often above one meter and occasionally exceeds ten meters or more [2]–[5]. Furthermore, the positioning error in this case varies with the distance from the source of the vehicle. Therefore, the potential usage of these technologies is lower in urban metros due to the need for high-precision positioning capabilities.

A newly developed hybrid system with a unique signal encoding method has been proposed to address accurate positioning within one to two centimeters regardless of the distance, even under high noise levels [6]. Moreover, by interpreting two consecutive signals, it is possible to determine the speed and direction of a moving object, and by analyzing the frequency shift of the reflected signals, it is possible to estimate the speed and direction using just a single signal [6]. Consequently, the hybrid system eliminates the need to examine multiple signals while achieving high precision in speed, position, and direction determination by correlating two systems and protecting against erroneous data. With the help of the coding of transmitter signal 1, 2, 4, 8, 16, 32, 64, 128, 256-bit pulse sequences have been created for the transmission side, and the localization errors were 118.4, 68.1, 4.8, 0.4, 0.3, 0.3, 0.2, and 0.1 m respectively for 50 km track line under high gaussian noise.

This thesis explores the feasibility of utilizing a hybrid system to achieve high-precision positioning of moving vehicles in urban metros. The main research problems that this thesis try to address are as follows:

1. In the context of sensing applications, it is pertinent to determine the superior choice between FBG and DAS sensing methodologies. 2. For the precise positioning of mobile vehicles in urban environments, it is essential to identify the technical

specifications required to implement a hybrid FBG and DAS system. 3. It is crucial to evaluate the hybrid system's accuracy, speed, and direction determination to determine how it compares to existing systems. 4. The hybrid system's potential applications in urban environments merit exploration to identify how it can enhance the efficiency and safety of urban transportation systems.

This research study's primary objective is to review the literature surrounding Fiber Bragg Grating (FBG) and Distributed Acoustic Sensing (DAS) systems for high-precision positioning of moving vehicles in urban metros. Through a systematic inquiry, the research aims to shed light on the feasibility of the system and its potential to revolutionize the urban transportation sector. The research will primarily focus on identifying and analyzing the technical requirements for implementing a hybrid system (FBG and/or DAS). It will develop and test a novel design using advanced simulation software, Optiwave's OptiSystem. It will thoroughly assess the effectiveness of the hybrid system and compare it to current systems. Our main focus will be determining the best possible setups and parameters for the proposed system. Furthermore, the study will explore the potential applications of the hybrid system, highlighting its benefits and limitations in various transportation contexts. Overall, this research aims to contribute to the growing body of knowledge on high-precision positioning systems for moving vehicles and to provide valuable insights into the design, implementation, and performance of a novel hybrid system that has the potential to revolutionize the urban transportation sector.

1.1 Literature Review

Fiber Bragg Grating (FBG) and Distributed Acoustic Sensing (DAS) systems are extensively researched for positioning capabilities in various applications, such as railway systems, aerospace, medical and underwater vehicles [1]–[8]. When subjected to external stimuli, these systems utilize fiber-optic sensors to measure strain and temperature changes in the optical fiber. The strain and temperature changes cause a shift in the Bragg wavelength of the FBG, which can be detected by processing the reflected signal from the fiber. Additionally, the DAS system utilizes acoustic waves generated by external stimuli to detect the position and movement of the

object. The FBG and DAS systems have proven reliable and efficient in providing accurate positioning information, making them popular for positioning or detecting applications.

The precise positioning of moving vehicles in urban metros is a challenging task due to the noise over the fiber line, signal The limitations of traditional sensing systems have led to the development of a hybrid FBG system [6], which offers several advantages over its predecessors. The system employs a unique encoding technique to eliminate the noise effect present in the signal, allowing for accurate positioning within a range of one to two centimeters, irrespective of the distance. Furthermore, by analyzing two consecutive signals, the system can calculate the velocity and direction of a moving object. In contrast, the frequency shift of the reflected signals can be used to estimate the velocity and direction using just a single signal. The hybrid system eliminates the need to examine multiple signals while achieving high precision in speed, position, and direction determination by correlating two systems and protecting against erroneous data.

The hybrid FBG system is a promising solution for various applications, including structural health monitoring, aerospace, and civil engineering. Its high precision and reliability have been demonstrated in this thesis. The hybrid system's unique encoding technique and accurate positioning capabilities make it a suitable candidate for applications where precise location tracking is crucial. Its ability to determine the speed and direction of a moving object using a single signal makes it a ideal choice for applications requiring real-time monitoring of moving objects.

The hybrid system offers a new and exciting novel approach with its innovative encoding technique and precise positioning capabilities. Its ability to extract speed, direction, and other vital data without relying on multiple signals makes it a reliable and promising solution for various applications, such as structural health monitoring and aerospace. Unlike any traditional system, this system offers high precision and exceptional performance.

1.2 Technical Requirements

Several technical requirements must be considered when implementing the hybrid system for high-precision positioning of moving vehicles in urban metros. The first requirement is the selection of appropriate FBG and/or DAS sensors that can resist the harsh environmental conditions in urban metros, such as temperature changes and vibrations [9]–[11]. The sensors should also have a fast response time and a high sensitivity to external stimuli.

The second requirement is the development of a unique encoding technique that can eliminate the noise that is present in the signal. This requires advanced signal processing techniques, such as wavelet or Fourier transform and filter banks, to remove the noise and extract the relevant information from the signal.

The third essential requirement for successfully implementing a navigation system is integrating multiple systems to determine speed, position, and direction accurately. This involves using correlation techniques to align the various systems' signals and eliminate discrepancies effectively. Furthermore, the system should possess the capability to detect and rectify any erroneous data that may be present in the signal. This integration process is crucial to developing a reliable and accurate navigation system and must be executed with the highest care and precision . [6].

1.3 Simulation and Testing

Simulation and testing are required to evaluate the performance of the hybrid system. The system will be designed and tested using simulation software OptiSystem and MATLAB to identify potential issues that may happen during the execution phase. The simulation results are matched to the theoretical predictions to validate the system's accuracy.

The system's core elements have undergone thorough performance testing in the field, as demonstrated in the thesis. Furthermore, with the aid of simulations, the system is scheduled to be tested in real-world conditions. This is challenging, as gaining permission to conduct field tests under controlled circumstances is difficult.

The assessment of the system's performance will concentrate on its accuracy in positioning, speed determination, and direction determination. The outcomes will then be compared to those of current systems, allowing for a determination of the sensing system's effectiveness. This novel solution aims to enhance the system's performance, and this comparison will help assess its potential.

1.4 Potential Applications

The positioning system exhibits significant potential for urban metro applications, particularly in railway, autonomous vehicles, and traffic management systems. In the railway industry, high-precision positioning of trains can be achieved through this system, improving system efficiency and safety. The system can also be leveraged for accurate positioning and movement control in autonomous vehicles, thereby enhancing the safety and reliability of the system. Moreover, in traffic management systems, the localization system can facilitate real-time monitoring and control of traffic, resulting in improved system efficiency and reduced congestion.

1.5 Aims and Scope

This study investigates the potential use of fiber optic cables for detecting object movements with a focus on accuracy and sensitivity. The goal is to transform the detailed aspects of objects' presence, direction, speed, and time-dependent movement within the vicinity of fiber optic cable systems. A new hybrid technique is proposed to repurpose fiber optic cables into high-precision sensors capable of meticulous monitoring. The research demonstrates the feasibility of detecting object movements with a resolution sensitivity ranging from 1 to 2 centimeters over a substantial span of 50 kilometers, unaffected by the distance to the source. This has significant implications for transportation, security, and infrastructure management. The proposed hybrid system offers a novel approach to revolutionizing the high-precision positioning of moving vehicles in urban metros, with potential applications in railway systems, autonomous vehicles, and traffic management systems. This contribution can enhance safety and security in diverse contexts like transportation systems and border control. However, further research is necessary to optimize the system and evaluate its

performance under real-world conditions before implementation. This study aims to demonstrate the feasibility of repurposing fiber optic cable systems into high-precision sensors capable of detecting object movements with high accuracy and sensitivity, with potential applications in transportation, security, and infrastructure management.

2. COMMON RAILWAY OPERATION TYPES

Rail transportation systems are complex networks that require meticulous consideration of various factors to ensure optimal efficiency. Among these factors, capacity is particularly critical as it determines the cargo or passengers a rail network can transport over a specific period. It influences the density of trains and stations, the frequency of services, and the passenger-carrying capacity, all of which are critical aspects of a well-functioning rail system.

Three different railway systems widely used in Turkey were examined based on the positions of fiber optic cable, and possibilities of conditions for fiber optic sensor applications in railway applications were discussed.

2.1 High-Speed Intercity Train (YHT)

Figure 2.1 shows an intercity track and the position of fiber optic cables relative to the vehicle and the track. The vibration generated by the movement of the vehicle wheels and its effect on the cables is demonstrated. As seen, fiber cables are concealed in a special chamber right next to the ballast. Although this application may vary according to the project, the fundamental structure remains as depicted in the visual.

Figure 2.1 : YHT trackline and the position of the fiber.

2.2 Urban Light Rail Systems (Tramway)

As seen in Figure 2.2, mixed traffic can be applied where tram systems are present, and there is occasional movement with road traffic. Many points also have pedestrian crossings. Since there is no need for fiber optic cable-supported communication in sensor applications, especially when not demanded, no fiber communication infrastructure can be used.

Figure 2.2 : Urban tramway interaction with external vehicles and pedestrians.

2.3 Urban Metro Systems

Figure 2.3 shows the trays of an under-construction metro. Fiber trays are installed, and in the lower part, trays carrying signalization equipment cables can be seen. In some cases, fiber cables are used in areas where signal cables are present, but they are generally not preferred in designs used in Türkiye.

Figure 2.3 : Fiber optic cable location at the Metro construction.

Figure 2.4 shows the detailed design of the metro construction. The height of the trays where fiber cables are placed is 3.38 and 3.18 meters relative to the rails. The distance of the trays to the train gauge is approximately 1 meter, and the distance from the trays to the rails is around 4 meters.

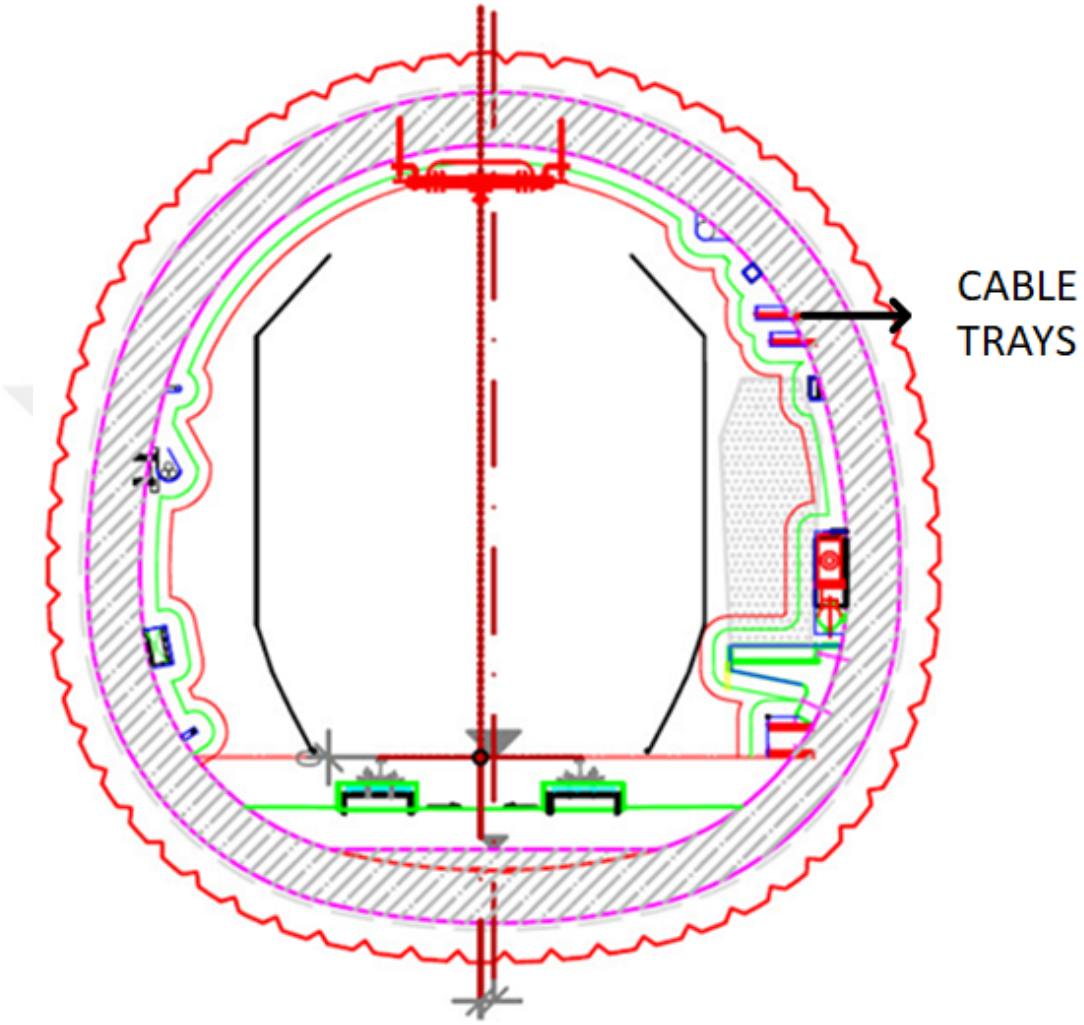


Figure 2.4 : Metro construction detailed design for a tunnel.

3. ENHANCING SAFETY AND SECURITY WITH FOS

In economically enhanced societies, public transportation relies on rail systems, which offer critical mobility means in urban and intercity contexts. Ensuring these systems' optimal and safe functioning demands continuous tracking of trains and vigilant monitoring of their positions. In this regard, advanced technology like fiber optic systems presents a paradigm shift and a more efficient means of addressing rail systems' monitoring and positioning requirements. This article delves into the role of fiber optic applications in modern rail systems, focusing on their transformative potential in enhancing safety, efficiency, and maintenance facets. Additionally, the article examines the importance of vehicle tracking in railway systems and the integration of technological advancements in optimizing their performance.

3.1 Literature Review of the Tracking and the Role of Fiber Optic Applications in Rail Systems

In order to maintain the optimal and secure functioning of rail systems, it is imperative to continuously track trains and continuously monitor their positions [12,13]. This is a procedural requirement and a critical factor contributing to the rail system's overall safety, operational efficiency, and maintenance. By ensuring that trains are tracked and monitored closely, potential issues can be detected and addressed in a timely manner, ultimately improving the reliability and safety of the rail network.

In the pursuit of operational efficiency in rail systems, financial constraints and the limited capacity of existing equipment often pose significant challenges [13]. However, the advent of fiber optic systems presents a paradigm shift and a more efficient means of addressing rail systems' monitoring and positioning requirements. The distinct advantage of fiber optic technology lies in its ability to comprehensively track the entire rail line in real-time during each operational cycle [6].

Fiber optic systems are cutting-edge technology and represent the next generation of advancements aimed at fortifying the safety of rail systems [14]. The underlying mechanism involves the strategic deployment of fiber optic cables along the rail track, facilitating continuous monitoring of trains. This real-time surveillance affords precise determination of critical parameters such as speed and position, thus significantly enhancing the safety standards of rail systems [6].

Beyond safety enhancements, the transformative impact of fiber optic systems extends to maintenance efficiency within railway systems [15]. In contrast to conventional maintenance practices, which operate on predefined intervals or in response to equipment malfunctions, the continuous monitoring facilitated by fiber optic systems enables a proactive approach to predicting maintenance requirements. This predictive capability, in turn, translates to reduced maintenance costs and an overall decrease in operating expenses for rail systems [16].

The positive influence of fiber optic systems on rail systems' safety, efficiency, and maintenance sides is highly effective [16,17]. This technological innovation elevates safety standards through the continuous monitoring and precise positioning of trains, thereby mitigating potential risks due to the nature of new systems. Furthermore, the augmented efficiency in maintenance processes translates to distinguishable economic benefits, fostering reduced operating costs for rail systems [17].

Fiber optic systems play a significant role in the evolution of public transportation networks. They make rail systems safer, more cost-effective, and sustainable in the long run. This highlights the transformative potential of adopting fiber optic systems to enhance the multifaceted dimensions of rail system operations, representing a vital area of future research and development.

3.2 Vehicle Tracking

Railway systems are a critical component of modern transportation, and their safe and efficient operation is of utmost importance. Vehicle tracking, which involves real-time monitoring and control of train positions, is a critical component of ensuring the safe

operation of railway systems. This process is essential to guarantee that trains operate safely and effectively, and it can be achieved using various technologies and methods.

The technological revolution in wireless communication, such as GPS and GSM-R, has played a significant role in revolutionizing the field of vehicle tracking in railway systems [18,19]. With these systems, trains' locations can be tracked in real-time, allowing instant monitoring and control of their positions, speeds, and routes. This information enables operators to take the necessary precautions to ensure the safe travel of trains.

Furthermore, automatic vehicle tracking is feasible in railway systems, where sensors and intelligent software can continuously detect and monitor trains' positions. A central system can then manage this data, allowing for optimal control and management of train traffic.

It is crucial to note that integrating these technological advancements has significant implications for optimizing railway systems. Incorporating these technologies can provide a more efficient and safe transportation experience for passengers while reducing operational costs and increasing the overall capacity of railway systems.

Vehicle tracking is a critical aspect of railway system operation, and technological advancements have significantly improved its implementation. As academics, it is our responsibility to continue researching and exploring new methods to optimize the performance of railway systems further.

There are three distinct approaches to vehicle tracking in railway systems. First, Global Positioning System (GPS) technology is extensively employed for tracking train locations within rail systems. In tandem with wireless communication technologies like GSM-R or LTE-R, engineered explicitly for rail systems such as ERTMS, GPS receivers determine train positions with an error margin of approximately 1-10 meters. This real-time data is seamlessly transmitted to a central control room or operators, facilitating regular updates on train positions. Such precision, inherent in GPS, enables operators to meticulously oversee and ensure the safe progression of trains [20].

Second, Fiber Optic Detection Systems have emerged as a critical player in vehicle tracking within railway systems. These systems exhibit prowess in discerning

subtle changes occurring on the tracks, including precise detection of distances between tracks, positions of train wheels, track conditions, and even temperature differentials. The continuous monitoring of these data points not only safeguards the unhindered progression of trains but also serves as a proactive means to identify and address maintenance needs for the tracks. Remarkably, modern fiber optic systems have evolved to allow vehicle tracking with a remarkable centimeter-level accuracy, underscoring their pivotal role in optimizing railway system operations [6].

Third, Signaling Systems are integral to the paradigm of vehicle tracking in railway systems. Signaling devices strategically positioned along the tracks, utilizing technologies such as track circuits and balises, vigilantly monitor the positions of trains. This real-time information is transmitted to a central control room, delivering a synchronized effort to allow trains to travel safely. The incorporation of these signaling-interlocking technologies significantly enhances safety and operational efficiency in rail transportation [21].

3.3 Role of Fiber Optic Applications

Recent studies have shown that fiber optic sensors hold great potential in revolutionizing the field of vehicle tracking, especially in rail systems. Despite being a comparatively new technology, fiber optic sensors have demonstrated remarkable sensitivity and accuracy in detecting changes in rail conditions, providing critical data for optimizing rail operations [6]. This data includes parameters such as rail conditions, train wheel position, rail distance, and rail temperature, which, when collected and effectively utilized, can considerably improve the safety and efficiency of rail networks.

Using fiber optic sensors in rail systems has become an indispensable tool for proactive maintenance. These sensors enable monitoring rail wear and tear, detecting cracks, and identifying other potential issues, providing real-time insights for timely maintenance interventions. By leveraging this data, rail operators can take timely maintenance actions, substantially enhancing the overall safety of rail systems.

This academic perspective highlights the evolving role of fiber optic sensors in rail systems, emphasizing their demonstrated functionalities in enhancing the precision of vehicle tracking and contributing to a proactive approach to guaranteeing the integrity and safety of rail structures. As technology advances, the integration of fiber optic sensors in rail systems exemplifies a promising trajectory in optimizing safety and efficiency within transportation.

3.4 Resistant Force Calculations for Trains

The above section illustrates the trains' distances to fiber optic cables. As seen, the distances of trains to fiber cables are very close (below 1m, as shown in Figure 2.4). Assuming the pressure on these cables and the train surface have similar air pressure at the optimum speeds of the trains. It is possible to calculate the tensions on the cables and, hence, the reflection amounts of FBG from the mathematical model according to the IEEE 1698 standard.

Train resistance forces are derived from the Davis equations of IEEE 1698 standard as formulated below [22]:

$$F_R = \underbrace{K_{rr}(M+M_{\text{load}})}_{\text{Static Resistance Force}} + \underbrace{(F_{\text{coeff}}(M+M_{\text{load}})V)}_{\text{Kinetic Resistance Force}} + \underbrace{(A_{\text{coeff}}+S_{\text{coeff}}(n-1))AV^2}_{\text{Air Resistance Force}} \tag{3.1}$$

F_R : Train Resistance Force [N]
K_{rr} : Rolling Resistance [N/kg]
$M + M_{load}$: Total Load Weight of the Train [kg]
F_{coeff} : Falanj Constant [N/(kg km/h)]
V : Speed [kmph]
A_{coeff} : Front Drag Air Resistance Constant [$[\mathrm{N}/\mathbf{m}^2\mathbf{kmphh}^2]$]
S_{coeff} : Coefficient Of Air Drag on the Train Surface [$[\mathrm{N}/\mathbf{m}^2\mathbf{kmphh}^2]$]
n : Number Of Vehicles in the Train
A : Area Of The Front of the Train [m^2]

Figure 3.1 illustrates the variation of resistance forces of a real train with respect to its speed. As seen, as the speed increases, the resistance force increases due to kinetic and air friction.

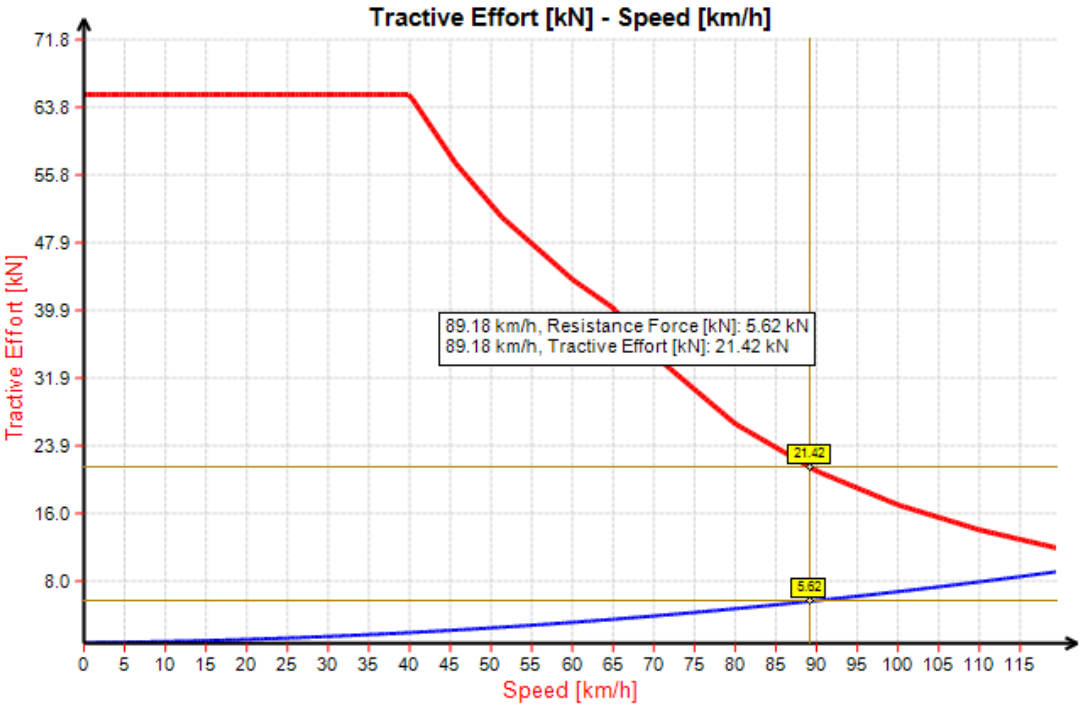


Figure 3.1 : Variation of tractive effort and resistance forces of a sample train with speed.

Acceleration of the train due to resistance forces (negative):

$$a_R = \frac{F_R}{M_r} = \frac{K_{rr}\,(M + M_{\text{load}}) + F_{\text{coeff}}\,(M + M_{\text{load}})\,V + (A_{\text{coeff}} + S_{\text{coeff}}\,(n-1))\,AV^2}{\left(1 + \frac{\rho}{100}\right)M + M_{\text{load}}} \tag{3.2}$$

It should be noted that when the train enters the tunnel, the last part of the equation, i.e., the air resistance force

$$\left[(A_{\text{coeff}} + S_{\text{coeff}}\,(n-1))\,AV^2\right] \tag{3.3}$$

should be multiplied by the tunnel coefficient (usually kTunnel=1.5 or 2). Thus, the tunnel effect is considered.

4. SELECTING THE PROPER WAVELENGTH AND SENSING MODEL FOR LONG-DISTANCE FOS APPLICATIONS

In addressing one of the formidable challenges in fiber optic communication, signal losses present multifaceted aspects. These losses encompass absorption losses, where a notable 20 percent of the signal is absorbed even in optimal fiber conditions over a 5 km expanse [23]. Additionally, scattering losses, influenced by environmental factors, temperature variations, and the wavelength of the waveguide, contribute to the overall signal attenuation. Furthermore, external factors such as splice and connector losses further contribute to the intricacies of signal degradation in fiber optic communication. This multifaceted perspective underscores the complexities inherent in signal integrity maintenance and the imperative need for comprehensive solutions within the fiber optic communication landscape [23].

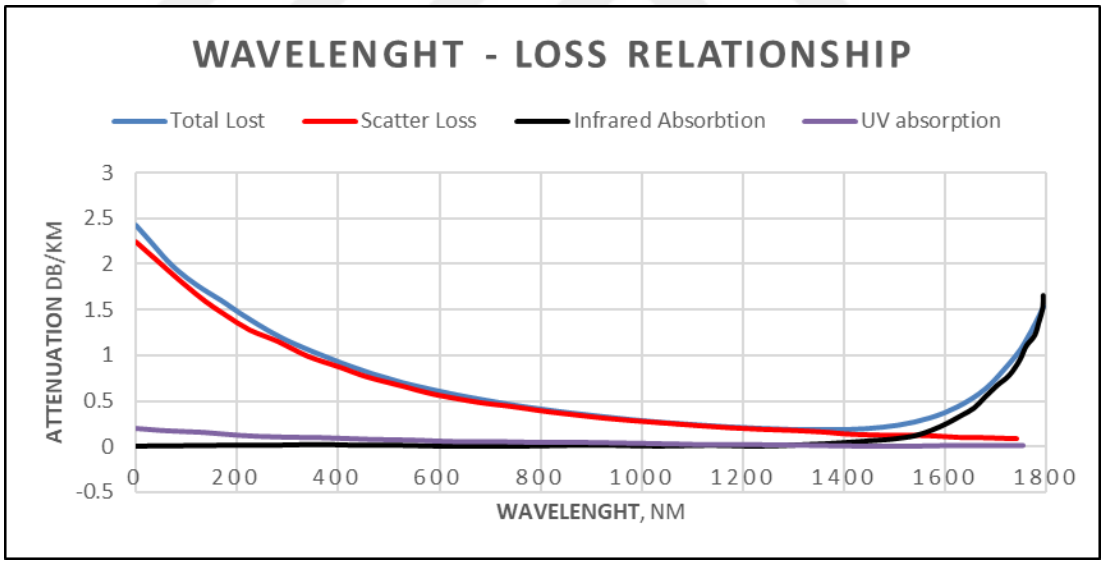


Figure 4.1 : Loss-Wavelength Relationship.

Figure 4.1 shows that the strategic utilization of the 1550 nm band emerges as highly advantageous, especially in long-distance sensing applications. This preference is rooted in meticulously considering losses and absorptions across various wavelengths [23]. The rationale behind this choice is grounded in the overarching

objective for long-distance transmissions, which inherently demands a concerted effort to minimize losses and absorptions within the waveguide to the greatest extent feasible. This deliberate wavelength selection at 1550 nm underscores a conscientious approach toward optimizing signal integrity and mitigating attenuation over extended transmission distances, substantiating its appropriateness for applications requiring robust and efficient long-distance sensing [23].

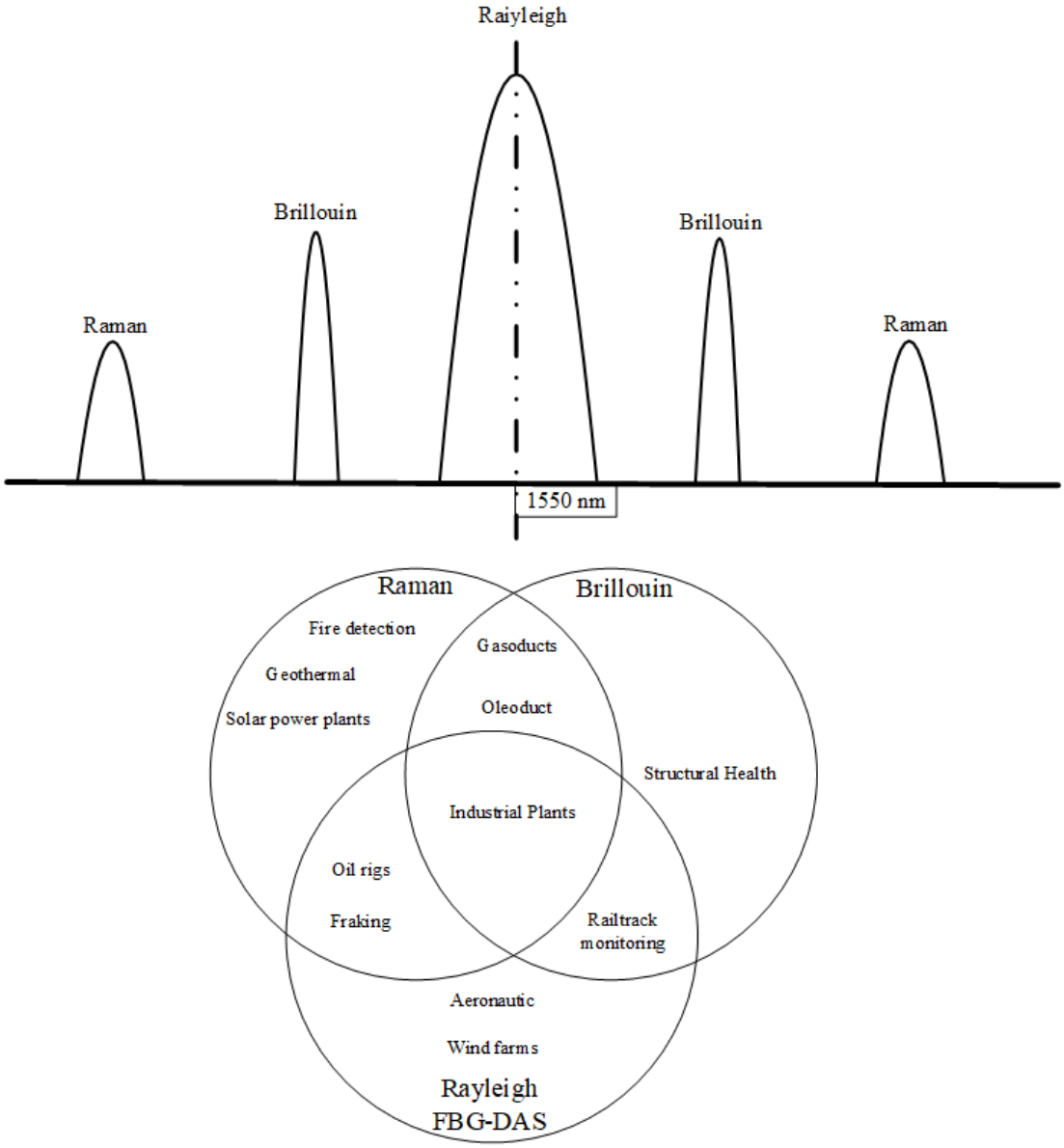


Figure 4.2 : Rayleigh, Raman, and Brillouin usage areas.

In Figure 4.2, the graphical representation delineates the detection sensitivities associated with Rayleigh, Raman, and Brillouin phenomena, elucidating their specific

application domains. The insights from Figure 4.1 and Figure 4.2 highlight the particular consideration required in cable selection. Opting to operate within the Rayleigh range at 1550 nm is the most reasonable decision, particularly for applications demanding precision in long-range sensor functionalities.

The critical factor influencing this choice is the region characterized by elastic scattering, which stands out as the domain with the most negligible absorption losses. This distinctive attribute positions the Rayleigh wavelength as the optimal choice for applications emphasizing vibration-based position sensing. Utilizing a single-mode cable at a wavelength of 1550 nm is deemed sufficient for sensor applications, attesting to the robustness of this configuration in meeting sensing requirements.

4.1 Fiber Optic Sensors (FOS)

FOS has emerged as a promising alternative to traditional electrical sensors for precise measurements in demanding conditions. FOS are known for their compact structures, passive sensing capabilities, and inherent resistance to electromagnetic interference. The core principle of fiber optics detection relies on harnessing the physical effects induced by stress and vibrations on the fiber cable, enabling swift and precise determination of where these effects occur. The distinct advantage of FOS lies in their ability to navigate challenging environmental conditions, offering a reliable solution for applications where accuracy, compactness, and resilience to electromagnetic interference are paramount [23].

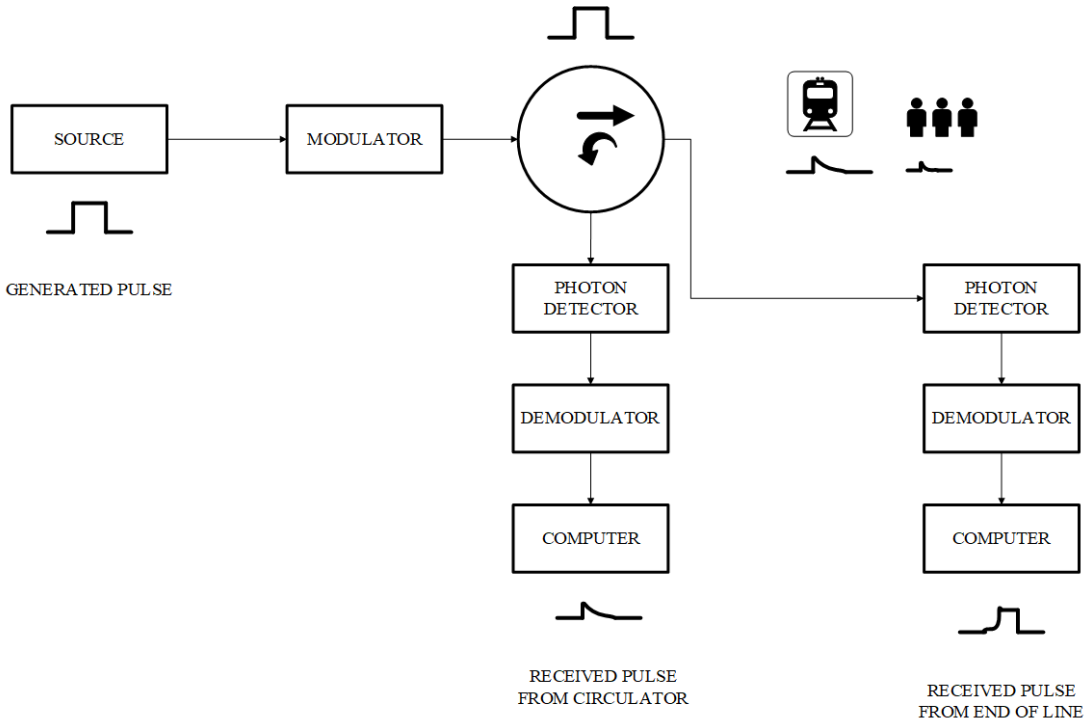


Figure 4.3 : Basic diagram of fiber optic sensor applications.

The diagram depicted in Figure 4.3 outlines all conceivable components constituting a fundamental communication system. Critical elements such as the source, modulator, fiber link, demodulator, and sensor require refinement to improve efficiency and performance in vibration detection.

The remote detection of moving objects involves scrutinizing the transmitted or generated signal or signal sequence compared to the transmitted or reflected portion of the reference signal. This analysis facilitates the inference of information regarding the scattering position and events triggering scattering. Depending on the chosen fiber optic cable, two foundational methods come into play: DAS and FBG. The primary distinction between these methods lies in the cable structure through which the signal traverses [23].

In addition to the higher scattering rate, DAS may face challenges in detecting resolution changes related to the sensing point information. This is because DAS relies on analyzing the signal segment that is transmitted or backscattered using a conventional bit channel, which may need to provide more detail about the sensing point. As a result, FBG is sometimes preferred as it can provide more accurate and

detailed information about the sensing point. FBG sensors are the optical sensors commonly used to detect and measure environmental changes. Among the various types of FBG sensors, uniform FBG sensors are the most fundamental and widely used type. These sensors feature a regular reflective grating structure embedded in an optical fiber. They are highly sensitive to environmental dynamics such as temperature, pressure, strain, and vibration, making them suitable for various applications. Moreover, uniform FBG sensors are relatively cost-effective and readily available.

Nonlinear FBG sensors, on the other hand, employ a grating structure with nonlinear optical properties to alter the behavior of optical signals by utilizing nonlinear effects within the optical medium. These sensors are utilized in applications involving high-power optical signals, such as optical fiber communications, laser systems, and optical signal processing. However, the cost and availability of nonlinear FBG sensors may be higher than uniform FBG sensors.

Wavelength-Division Multiplexing FBG (WDM FBG) sensors combine FBG sensors with Wavelength-Division Multiplexing technology, which allows multiple FBG sensors to be placed on the same fiber at different wavelengths. As a result, multiple parameters can be measured using a single fiber. The cost and availability of WDM FBG sensors may be slightly higher than other FBG sensors.

Tilted fiber Bragg grating (TFBG) sensors are another type of FBG sensor increasingly gaining attention due to their unique characteristics. Unlike uniform FBG sensors, TFBG sensors have a tilted grating structure that allows for measuring more complex environmental parameters, such as refractive index, bending, and twist. TFBG sensors are highly sensitive to the surrounding refractive index, making them useful for biosensing applications. In addition, they can detect various environmental parameters simultaneously, which is not possible with uniform FBG sensors. However, TFBG sensors are more challenging to fabricate and often require specialized equipment and techniques. Therefore, the cost of TFBG sensors may be higher than uniform FBG sensors.

It is important to note that selecting the appropriate sensor type is essential based on specific application requirements and measurement needs. While uniform FBG sensors are often preferred due to their cost-efficiency and wide range of applications, TFBG sensors, nonlinear FBG sensors, and WDM FBG sensors may be more suitable for specific applications. Therefore, considering each sensor type's advantages and disadvantages before planning is crucial. In the scope of this thesis, Uniform FBG sensors are preferred for use in simulations and applications, but it is always good to evaluate other options.

Another important section is the correlation; with the help of a coded signal, it is much easier to recover the reflected signal, and it enhances sensitivity. During vibrations, the high reflectivity of the grating in the cable facilitates efficient detection of low-vibration events, surpassing DAS in this aspect. However, the heightened backscattering rate in FBG poses challenges in detecting events occurring at a considerable distance.

Addressing this challenge, focusing on increasing line sensitivity emerges as a potential solution. Alterations to the line can significantly impact its performance, considering its physical structure and placement. This aspect becomes pivotal given the system's emphasis on monitoring elastic movements.

The presented thesis modeled a high-sensitivity detection system for FBG-based systems with experimental validation. The ensuing system and algorithm development aimed at controlling sensitivity over extended distances. Software enhancements in the source and detection components, combined with backscattering integration and the correlation technique, created a distinctive reference sequence in rail systems. This innovative approach enabled precise position detection and, for the first time, determining vehicle speed and direction. Further details on these advancements will be expounded upon in subsequent sections. Several considerations merit attention for enhancing the designed system's performance, a topic that will be elaborated on in the following sections.

The assessment of FOS applications encompasses evaluation across four primary categories [23]: Measurable resolution, spatial resolution, range, and resolution of

sampling. Measurable resolution refers to the slightest discernible change that sensors can detect, while spatial resolution signifies the minimum spatial distance changes that sensors can reliably detect. Range denotes the maximum distance the sensor retains its detection capability, and sampling resolution encompasses the distance between sampled analog signals and the time necessary for accurate measurements. This involves the time required to precisely read points along the line to achieve the necessary spatial resolution.

The four criteria mentioned above are intricately connected to the signal-to-noise ratio (SNR), wherein changes in SNR have direct implications for spatial resolution and range. Temperature variations introduce delays, lengthening the line and impacting performance. When examining reflected signals after sending a single pulse, it becomes imperative to dispatch very narrow pulses for enhanced resolution, leading to lower energy requirements. However, this approach results in a substantial reduction in backscattering amplitude. Conversely, broader bandwidth pulses are necessary to optimize spatial resolution efficiency, intensifying susceptibility to noise interference. Consequently, strategic trade-offs between pulse width and amplitude may improve spatial resolution and range, considering the system's unique requirements.

4.1.1 FBG

FBG sensors have gained significant attention due to their ability to detect changes in resistance and unintended or undesirable fiber bending losses. One critical factor influencing numerous engineering applications is vibration, and detecting, mitigating, minimizing its impact, or eliminating it is a phenomenon many advanced systems attempt to achieve. Fiber optic vibration sensors (FOVS), based on demodulation principles, can be broadly classified into density-based, interferometric-based, and wavelength-based.

A low cost and broad bandwidth characterize density-based demodulation sensors. However, such sensors contend with challenges related to unstable measurements and susceptibility to power fluctuations. Interferometric-based demodulation sensors offer high connection efficiency and stability but grapple with limitations in terms of bandwidth and elevated system costs. Wavelength-based modulation sensors operate

based on wavelength variations, but the current study needs to provide specific details regarding their features and challenges.

The selection of the appropriate demodulation method primarily depends on the explicit requirements and limitations of the application. Each demodulation method possesses distinct advantages and challenges, and understanding these factors is crucial in selecting the most proper method for a particular application. As such, researchers and engineers must carefully evaluate the available options based on the particular parameters of their application, such as cost, bandwidth, stability, and measurement accuracy, among others.

The coupled-mode theorem is a theoretical framework that helps analyze the properties of FBGs in sensing applications. Per this theorem, the reflected light from an FBG can be defined in terms of its center wavelength, related to the effective refractive index and the periodic distance between each grating (spatial). According to the Coupled-mode theorem, the reflected light can be defined as the center wavelength:

$$\lambda_B = 2n_{eff}\Lambda \tag{4.1}$$

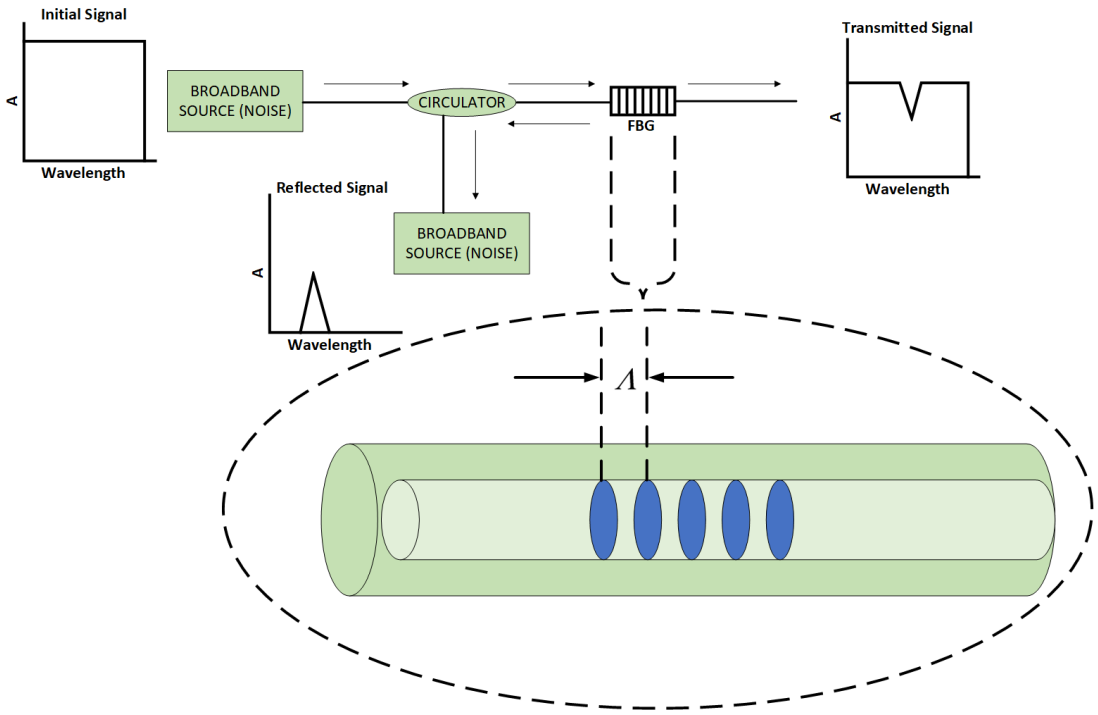


Figure 4.4 : FBG Design in sensing application.

where λ_B is the center wavelength of the reflected signal, n_{eff} is the effective refractive index, and Λ is the periodic distance between each grating (spatial).

Figure 4.4 shows details of FBG design, which is brag gratings are uniformly distributed.

Equation 4.2 shows that n_{eff} and Λ are linearly connected. Both n_{eff} and Λ are sensitive to stress and heat. If gratings are exposed to external stress and temperature, the wavelength of the reflected wave can be obtained through the following equation (shift):

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)(\Delta_\varepsilon) + \left(\alpha_f + \xi f\right)\Delta T \tag{4.2}$$

Where Δ_ε is the strain variable in the horizontal axis, ΔT is the temperature increase, ρ_e is the electrooptical coefficient of the fiber, α_f and ξf are the thermo-optic constant and the constant of thermal spreading out of the fiber optic line, respectively.

The Coupled-mode theorem provides a powerful analytical tool for understanding the behavior of FBG in sensing applications. By considering the relationships between the various parameters involved, researchers can develop more accurate models and optimize the performance of these devices for a wide range of applications.

4.1.1.1 Uniform FBG sensor

The FBG sensor is a crucial component for characterizing events that modify the optical properties of the sensor due to temperature and/or stress/strain events. The smooth FBG model is sensitive to temperature and strain changes, which alters the Bragg wavelength, thereby changing the reflection and transmission spectrum. Uniform FBG sensor selected parameters:

• Original Bragg wavelength: 1550 nm

• Original effective index: 1.45

• Index modulation: 0.0001

• Original length: 10mm

• Bandwidth: 5 GHz

• Reflectivity: 0.99 or a specific value arranged by the user

• Temperature effects: No

• Strain effects: depends on selected parameters (x, y, and z-axis)

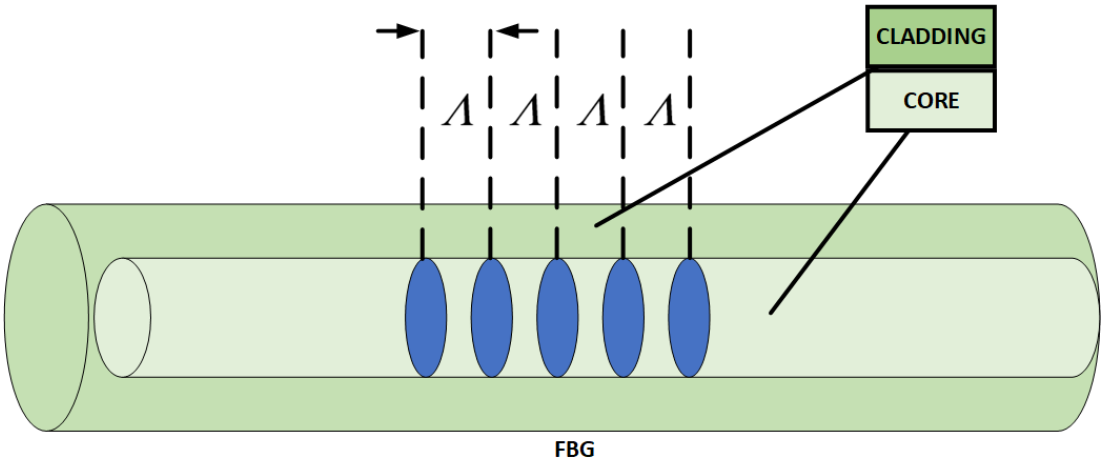


Figure 4.5 : Details of Uniform Fiber Bragg Gratings.

Figure 4.5 presents the structure of uniformly distributed FBG. This structure reflects a weakened form of the incoming signal by multiplying the received signal with a sinc function, making it possible to generate more accurate coded signals. This feature is advantageous for coding and decoding digital signals with high precision in various applications, including telecommunications, sensing, and metrology. The FBG sensor is a reliable and sensitive device for detecting changes in optical properties due to external factors, making it a promising technology for future research and development.

4.1.1.2 Reflection and transmission of the FBG signal

The Bragg wavelength, denoted by λ_B, is a critical parameter in FBG sensors. It is defined as the wavelength at which the refractive index of the fiber core and cladding match the periodicity of the grating structure. Due to the core, cladding, and grating repetition, the effective index determines the Bragg wavelength.

The Bragg wavelength is given as:

$$\lambda_B = 2n_e\wedge \tag{4.3}$$

where λ_B is the Bragg wavelength, n_e is the effective index (due to the core and cladding), and Λ is the grating repetition (periodic)

The parameters that determine how much of the signal will pass through the FBG sensor and how much will be reflected can be calculated from the following equations [1]

$$r(\lambda) = \frac{iK\sinh(QL)}{Q\cosh(QL) - i\Delta\beta\sinh(QL)} \tag{4.4}$$

$$t(\lambda) = \frac{Q}{Q\cosh(QL) - i\Delta\beta\sinh(QL)} \tag{4.5}$$

$$Q(\lambda) = \sqrt{|K|^2 - |\Delta\beta|^2} \tag{4.6}$$

$$\Delta\beta = 2\pi n_e\left(\lambda^{-1} - \lambda_B^{-1}\right) \tag{4.7}$$

where $K(\lambda) = \Delta n\pi/\lambda$ is the connection power, Δn is the index modulation, L is the grating length, and $\Delta\beta$ is the phase difference. These parameters are essential in determining the proportion of the signal received by the FBG sensor that will pass through and the amount that will be reflected.

The Bragg wavelength, signal transmission, and reflection proportions calculation are critical aspects of FBG sensors. The equations are used to determine these parameters to improve the accuracy and reliability of FBG sensors.

4.1.1.3 Detecting with the FBG

The detection sensitivity is primarily due to changes in the Bragg wavelength on the FBG caused by external effects. λ_B, the change in wavelength, will directly affect the maximum transmitted and reflected wavelengths. However, it will also alter the reflection and transmission spectra. Changes will occur in the magnitudes of $r(\lambda)$ and $t(\lambda)$, but these can be neglected. Assuming that the external effects on the grating are longitudinal strain and temperature, the total difference can be defined as the effect of the longitudinal strain and temperature working on the FBG. By

generalizing the equation, we can express the total difference in terms of longitudinal strain, temperature change, photo elastic coefficient, thermal expansion coefficient, and thermo-optic coefficient. These coefficients are given as input parameters:

$$\Delta\lambda_\beta = 2\left(\frac{\partial n_e}{\partial T}\cdot\wedge\Delta T + n_e\frac{\partial\Lambda}{\partial T}\cdot\Delta T + \frac{\partial n_e}{\partial l}\cdot\wedge\Delta l + n_e\frac{\partial\Lambda}{\partial l}\cdot\Delta l\right) \tag{4.8}$$

Generalized the equation:

$$\Delta\lambda_\beta = (1-p_e)\varepsilon + (\alpha_{TE}+\alpha_{TO})\Delta T \tag{4.9}$$

Here, ε is longitudinal strain, ΔT is temperature change, pepe is the photo-elastic coefficient, α_{TE} is the thermal expansion coefficient, and α_{TO} is the thermo-optic coefficient. These coefficients are given as input parameters by the user.

Note: Instead of defining p_e it is possible to define the gauge factor (g), given by the formula $g = (1-p_e)*\lambda_B/1\mathrm{e}6$, where λ_B is expressed in nm.

Alternatively, for an isotropic material (without cutting), it is possible to use the relationship between longitudinal strain and stress components.

$$\varepsilon = \frac{1}{E}(\sigma_{zz} - v\sigma_{xx} - v\sigma_{yy}) \tag{4.10}$$

Here, σ_{zza} is the longitudinal strain, σ_{xx}, and σ_{yy} are the transverse strain components. E is the Young modulus, and v is the Poisson ratio. Mechanically, these are the mean values acting on the core-core compound.

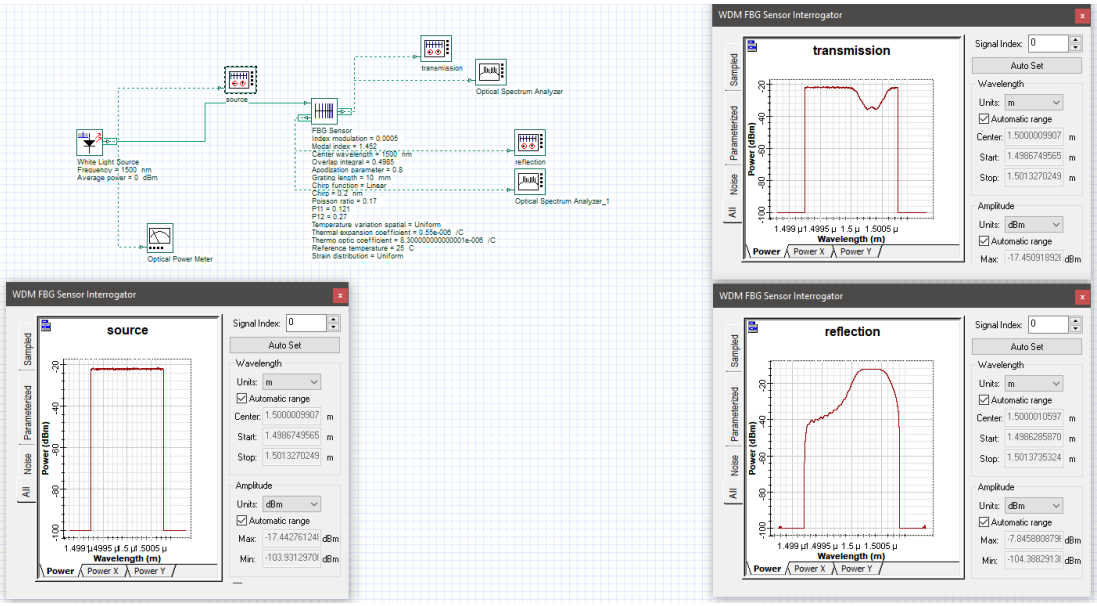


Figure 4.6 : Example of FBG reflection visualization.

Figure 4.6 shows a simulation displaying the reflected and transmitted signals of an FBG application. As depicted in the Figure 4.7, the simulation models a portion of both the transmitted and reflected signals. With the ability to model all interactions within the FBG sensor structure, including pressure and temperature, simulations can provide a more accurate representation of these interactions in an environment conducive to modeling. These findings demonstrate the potential of FBG sensors for a wide range of applications. By accurately modeling the effect of external factors on the grating, we can improve the sensitivity and reliability of FBG sensors, paving the way for their use in various fields.

4.1.2 DAS

FOS has emerged as a promising technique for detecting and measuring physical parameters such as temperature, strain, pressure, and acoustic waves. Among the various FOS techniques, DAS has gained widespread attention in applications that require long-range monitoring. DAS employs fiber-optic cables to detect acoustic vibrations along their length. The technique measures the changes in the backscattered light caused by the acoustic waves.

DAS applications can be developed by focusing on Raman, Brillouin, and Rayleigh scatterings. Raman scattering is used to detect temperature changes, while Brillouin scattering is used to detect strain and acoustic waves. Rayleigh scattering is used to detect vibrations in the fiber itself. Figure 4.7 shows that DAS is especially preferred for long-range sensor applications.

Phase-sensitive optical time-domain reflectometry (ϕ-OTDR) is a crucial application in this field. It is a technique that uses a laser to generate a pulse of light and then measures the changes in the backscattered light caused by acoustic waves. This application enables real-time monitoring over long distances.

Despite significant progress in DAS technology, research is ongoing to improve its sensitivity and resolution. Scientists are exploring ways to mitigate the impact of environmental dynamics, such as temperature changes and vibrations. Additionally,

new applications of DAS are being explored, such as geophysical monitoring and pipeline security.

In Figure 4.7 from [2]–[5], the authors demonstrate the potential of DAS in long-distance monitoring applications.

Movements with a resolution of around 10 meters were observed on an approximately 100-125 km track line. This highlights the capability of DAS to detect and locate events with low accuracy over long distances.

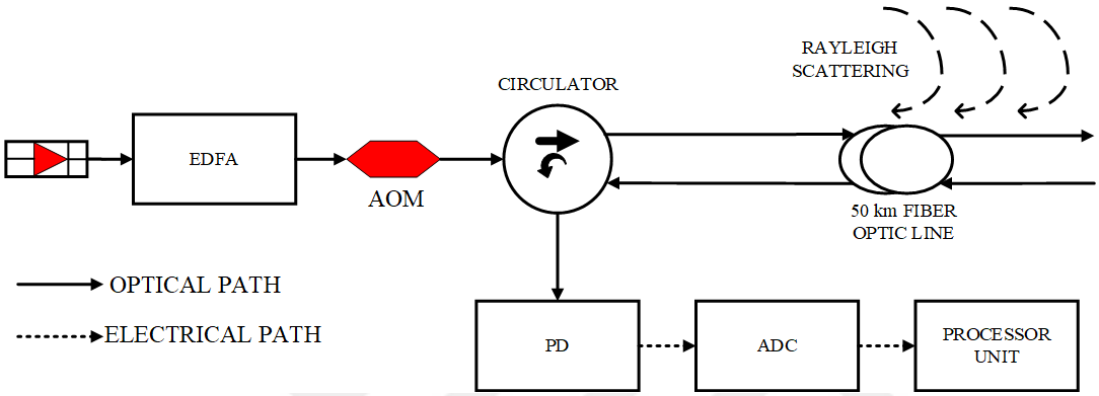


Figure 4.7 : Example of DAS application diagram.

Another example shows motion detection with a resolution of 2.1 meters was achieved [24]. However, it is essential to note that these resolution values are generally given based on the best-case scenario. The use of these applications is limited, especially in urban transportation lines, as the expected resolution is often below 1 meter.

Distributed Acoustic Sensing (DAS) is a promising technology for long-distance monitoring applications. It uses fiber-optic cables as distributed sensors to monitor backscattered light caused by acoustic waves. These waves can be generated by natural events such as earthquakes or artificial events such as traffic or industrial processes. By analyzing the backscattered signal, it is possible to extract information about the source of the acoustic wave.

Three main scattering mechanisms can be used for DAS applications: Raman, Brillouin, and Rayleigh scattering. Raman scattering is used to detect temperature changes, while Brillouin scattering is used to detect strain. Rayleigh scattering is used to detect acoustic waves. Each scattering mechanism has its advantages

and disadvantages, and the choice of scattering mechanism depends on the specific application.

One essential application of DAS is ϕ-OTDR, which enables real-time monitoring of long distances. It works by measuring the phase shift of the backscattered signal caused by acoustic waves, which is proportional to the acoustic wave amplitude and can be used to determine the location of the acoustic source. DAS has numerous applications in various industries. In the oil and gas industry, DAS can be used to monitor the production of oil wells and detect leaks in pipelines. In civil engineering, DAS can monitor the structural health of buildings, bridges, and tunnels. DAS can also be used in transportation to monitor railway lines and detect rail defects.

However, there are some limitations to DAS that must be considered when designing monitoring systems. One limitation is the system's spatial resolution, which depends on the length of the fiber-optic cable and the type of scattering mechanism used. Another limitation is the system's sensitivity to environmental factors such as temperature and humidity. These environmental dynamics can cause changes in the fiber-optic cable, leading to faulty readings. Heat and moisture sensors can be integrated into the monitoring system to mitigate this issue.

DAS technology has great potential for monitoring acoustic signals across long distances. However, when designing monitoring systems, it is essential to consider certain potential limitations. While DAS has several advantages over conventional sensors, further research is needed to improve its performance and expand its applications in various industries.

4.2 Comparison of FOS applications (FBG and DAS)

The basic working principles of the two sensor models are similar. Figure 4.8 illustrates the most basic diagram of these two detection methods. Calculating the event's point, speed, and direction by examining the backscattering generated by the moving object from the source is common to both methods. The main difference lies in the mathematical calculations used for detection. In FBG calculations, the backscattered signal is multiplied by a Dirac function. In DAS applications, this is mainly done with

randomness. Therefore, in FBG structures, it is possible to model the effect of the interaction point more realistically with mathematical models. In DAS applications, one would have to operate based on randomness.

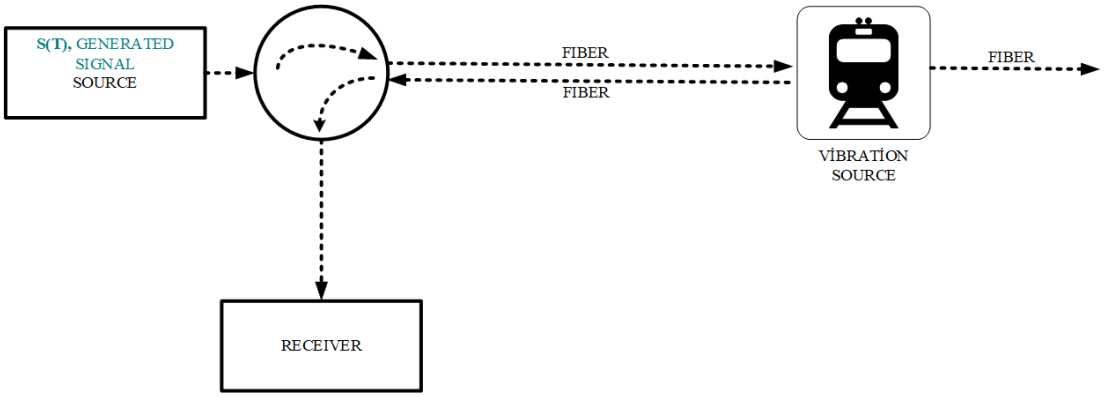


Figure 4.8 : Basic fiber optic detection structure.

This thesis will present improvements using the FBG concept for high-precision position, speed, and direction determination. The proof of the system and an example application are detailed in the following sections.

5. HYBRID FOS SYSTEM FOR RAILWAYS

Fiber optic sensing (FOS) technology has become increasingly popular among railway transportation systems in recent years. Despite the availability of various electronic sensing systems in the market, FOS technology offers an efficient and versatile all-in-one solution. A recent paper has presented a hybrid fiber optic sensing system to enhance our understanding of FOS capabilities [6]. This hybrid sensing scheme is designed for long-distance applications and incorporates two different sensing systems to provide accurate data on the train's location, speed, and direction. By utilizing a coding technique and a wavelength drift examination of the reflected signal, this system can predict the train's location with a precision of up to one cm. The hybrid fiber optic sensing system is designed to ensure sustainability and security for railway transportation applications, making it an ideal solution for primary or secondary security interfaces. In this context, the present study aims to provide a comprehensive overview of the hybrid fiber optic sensing system and its capabilities in railway transportation.

5.1 Introduction to the Investigated System

Implementing traditional detection approaches, such as track circuits or balises, has been plagued with many challenges. These systems' reliability to accurately reflect real-time conditions is hindered by disturbances such as external factors or electromagnetic interference, leading to catastrophic consequences. Conventional localized sensor networks require an extensive array of sensors and wiring for broad coverage, increasing the overall cost of such projects.

In contrast, FOS technology presents a versatile solution, offering consistent monitoring and preemptive accident avoidance by identifying objects' position, velocity, and dimensions across extended ranges. The FOS systems strongly resist electromagnetic disruptions, enhancing their dependability. The fiber optic cables,

already laid down for redundancy in all current subway networks, serve as an excellent infrastructure for deploying FOS technology.

The applications of FOS technology are diverse and include use in railway systems, roadways, structural monitoring of bridges, security in military applications, building surveillance, and patrols at international boundaries. A critical component of the FOS framework is the Optical Time-Domain Reflectometer (OTDR), initially designed to identify flaws or inconsistencies in fiber optics and evaluate signal delays [25]–[33]. Over time, the cost of OTDR technologies has decreased considerably, thanks to advancements and reduced prices in photonic components.

Remote fiber optic sensing systems are widely used across various industries, and specific parameters need to be fulfilled to ensure their proficiency. These parameters include the precision of sensors, operational distance, detail resolution, data sampling interval, and time to detect.

The operational distance capability of a fiber within an FOS setup is directly proportional to the pulse repetition frequency of the light pulses in transmission. However, there is a potential for location uncertainty if a second pulse is dispatched before the backscatter detection of an initial pulse.

The sensor's ability to resolve fine details - spatial resolution - is contingent upon its reaction to the pulse width and the span required to produce a relevant response. Spatial detail may not be fully represented, as illustrated in Figure 5.1. The sampling resolution interval, indicated by the time span between capturing two sequential samples from the received pulse, should be less than half the time compared to the necessary spatial resolution [23]. The powers behind the transmitted pulses and the discernment ability of the receiver influences the system's performance.

Techniques such as coherent detection and photon counting can be used to enhance receiver sensitivity. The system's range can be extended through optical frequency domain reflectometry (OFDR) or pulse compression coding technology [23,34]–[36].

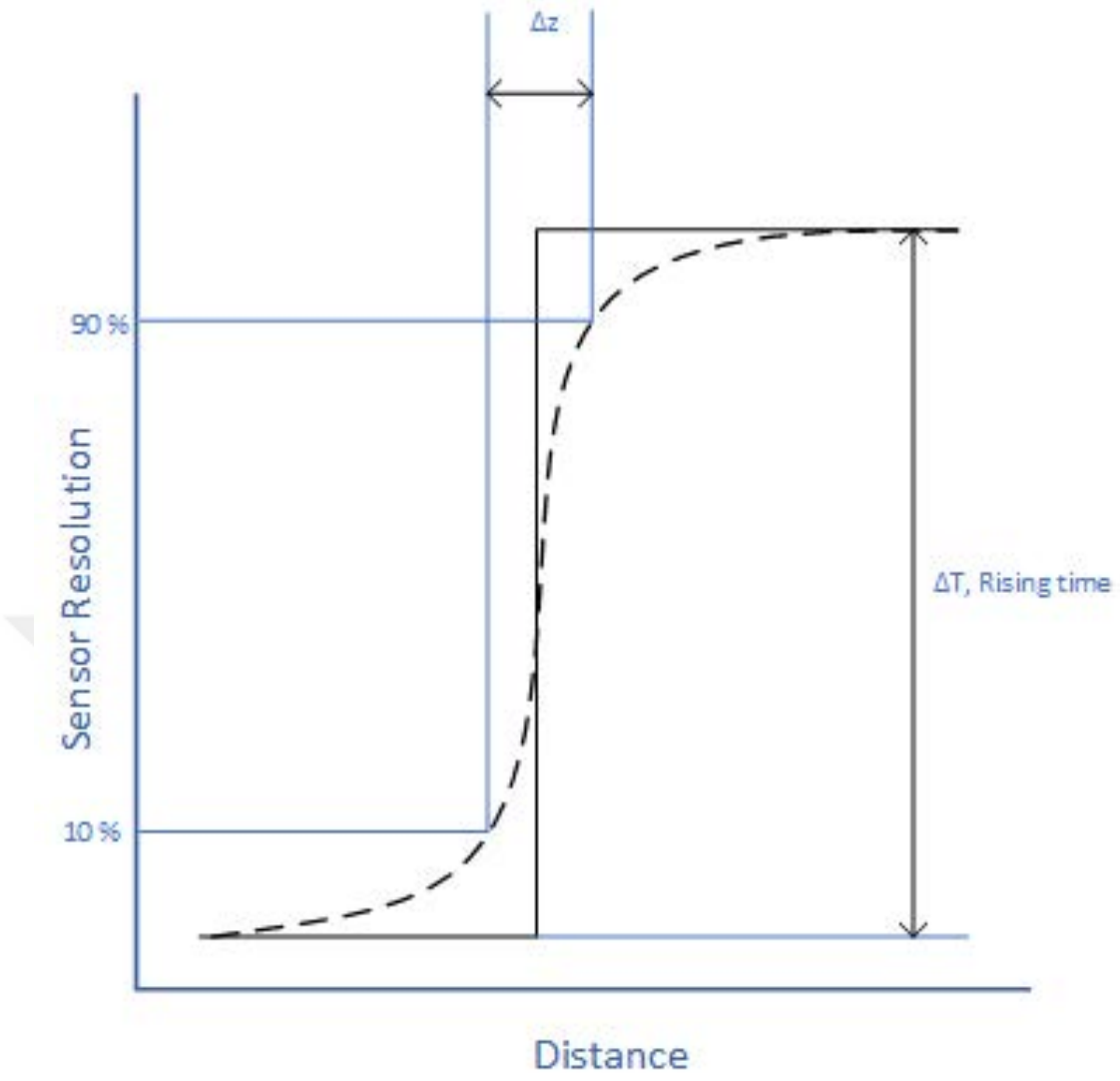


Figure 5.1 : Sensor resolution—distance, pulse generation progress.

Railway sensing is a vital aspect of ensuring the safety and efficiency of train travel. In this regard, two primary sensing applications are used in railway sensing: FBG-based and DAS-based systems. While DAS systems are recommended for long-reach sensing, they suffer from localization accuracy issues that permit errors of up to 2.1 to 10 meters or more for the spatial resolution of DAS systems in long distances. [2]–[5,24,36]–[38]. In contrast, the proposed hybrid system shows that FBG sensors could be used for long-range railway lines with a much lower localization error of just 1 cm. This accuracy is expected to be slightly higher in practice, depending on the electronics used in data processing.

This work proposes and investigates a hybrid fiber optic sensing system using commercial software. The system ensures localization calculation with two different outputs to increase accuracy and provide redundancy for safety assurance. Although a single system is used to localize moving objects to cut costs, dual systems are considered better for sustainability and safety.

This study explores the possibility of utilizing coding and FBG shift detection techniques to achieve highly accurate localization of moving objects with exceptional resolution. The study takes into account the air pressure created by the movement of a train and applies a mathematical model to calculate the strain on the FBG sensors. The hybrid FOS system uses uniform FBG sensors distributed along the fiber, enabling it to detect moving objects with a resolution of approximately 1 cm over a distance of 50 km. The analytical models used in the simulation tool account for temperature, stress, and strain effects, which cause a change in the grating optical reflection and transmission spectra, resulting in a drift in the Bragg center frequency.

It is considered that the strain effect caused by the air pressure generated when a train passes by the FBG sensor. To enhance the sustainability and security of the system, we also use modulated encoded pulses transmitted via the same optical fiber. By cross-correlating the reflected pulses with the reference pulses, we can determine the localization of FBGs. The shift of the FBG center wavelength is then monitored to determine the train's location, speed, and movement direction. To achieve this, a tunable optical filter and pin photodetector are utilized to determine the wavelength shift. The goal of this research is to develop a reliable, secure, and sustainable sensing system that can accurately and efficiently detect the movement of objects on railway lines, with the speed of the train being determined by the strain applied to the FBG.

5.2 Investigation of Possible Sensing System

The FOS system, illustrated in Figure 5.2, comprises several key components that work in unison to achieve its objectives. The first component is the transmitter subsystem, composed of a laser, modulator, encoder, and an electrical pulse source. These components work together to generate an optical pulse sequence, which is then transmitted into the fiber. The second component is the circulator, which governs the

launch of optical pulses into the fiber and receives the backreflected signal from the FBG sensors for analysis. FBG sensors are placed at different center wavelengths along a 50 km fiber, generating signals as the train passes through them. The displacement on the FBG sensor is caused by the air pressure at the sensor location, which is created by the moving train. Finally, the receiver subsystem comprises several components, including the photodiode, clock recovery, tunable optical filter, and data analysis components. The receiver subsystem is responsible for processing the received signals and extracting relevant information for further analysis. Here is calculation of the train air resistant force:

The Train Air Resistant Force $[N]$ / Cable Area $[\mathrm{m}^2]$:

$$\frac{5646}{12.5 \times 0.164} = 2754 \text{ Pa} \tag{5.1}$$

The subsystem responsible for receiving signals can effectively ascertain the speed, location, and direction of a train from the back-reflected signal that is influenced by the air force generated by the train.

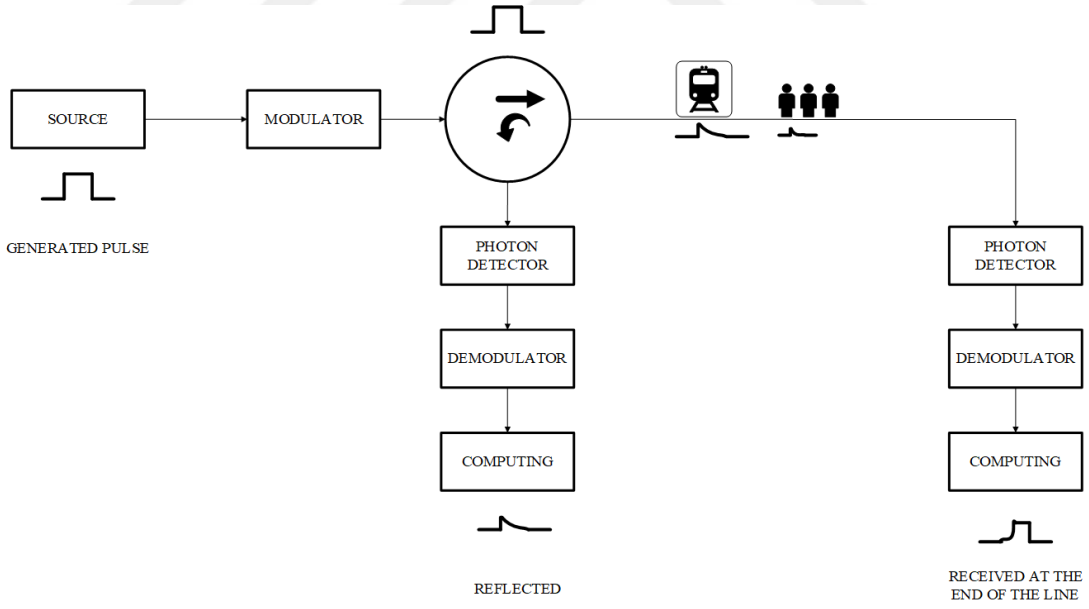


Figure 5.2 : General block diagram of the FOS system.

5.3 Train-Resistant Forces for FOS Application

Calculating the force of resistance that a train encounters is a critical aspect of railway engineering. A widely-accepted method for this calculation is the Davis equation, which is recommended by the IEEE 1698 standard. This equation takes into account several factors, such as static, kinetic, and air resistance forces, and is crucial for predicting the efficiency and performance of trains under varying operating conditions [22]:

$$\begin{aligned} F(R) = (\text{Krr} \times (M + \text{Mload})) + (\text{Fcoeff} \times (M + \text{Mload})V) \\ + ((\text{Acoeff} + \text{Scoeff} \times (n-1))A \times V^2) \end{aligned} \tag{5.2}$$

where $F(R)$ is the train resistance force $(N), K_{rr}$ is the rolling resistance $(N/kg), M+$ Mload is total train total mass (kg), Ecoeff is the flange coefficient $(\text{N}/(\text{kgkm}/\text{h})), \text{V}$ is the train velocity (kmph), Acoeff is the frontal air drag coefficient (N/m2 kmph2), Scoeff is the skin effect air drag coefficient $(\text{N}/\text{m2kmph2}), \text{n}$ is the number of cars in 36 the train set, and A is the frontal area of the train (m2). It should be noted that when a tunnel section is located along the train line, the last term of the equation is to be multiplied by the tunnel coefficient (kTunnel = 1.5 to 2), as typically used in metro applications. The last term represents the air-resistant force. The maximum air pressure is usually applied at the front side of the train. Air-resistant force calculation when a train passes through a tunnel at different train speeds is summarized in Table 5.1, where the force is given by

$$F\,(R\_\text{Air}) = (\text{Acoeff} + \text{Scoeff}(n-1))A \times V^2 \times k\ \text{Tunnel} \tag{5.3}$$

Assuming Acoeff = 0.444829644, Scoeff = 0.12392, $\text{A} = 8, \text{n} = 4$ (total train length 125 m), and kTunnel = 1.75, the air pressure created by the train on the fiber cable with the FBG sensors with a diameter of 0.164 m (with a cover of the fiber cores) and train speed of 80 km/h is given as pressure will cause a pull effect on the FBG sensor and strain it. The strain effect will cause a shift in the center wavelength of the FBG sensor.

Table 5.1 : Train speed vs. air-resistant force values.

Tain Speed (km/h)	Air Resistant Force (F(R Air)(N))
20	353
50	2205
80	5646

The diagram presented in Figure 5.3 showcases the air pressure that is generated in the tunnel as the train moves forward. The front of the train experiences compressive air pressure, while the back of the train experiences an expansion of air pressure. The air pressure reaches its maximum point in the front of the train.

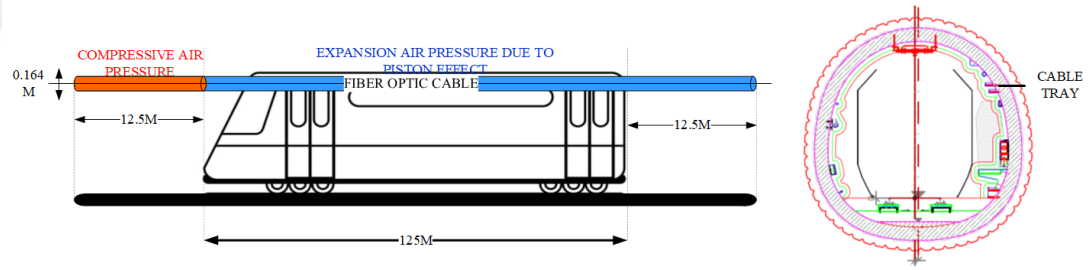


Figure 5.3 : An air-resistant force approximation model is applied to a fiber cable. Side (left) and front view (right).

The primary objective of this research is to determine the position of maximum strain in fiber Bragg gratings (FBGs) by analyzing the areas that undergo the highest air pressure. The study focuses on the anterior and posterior ends of the train that experience significant pressure, covering a distance of approximately 10 to 15 meters, corresponding to a train speed and acceleration of 80 km/h [38]. Based on our estimations, the average distance is around 12.5 meters, and it is crucial to investigate only the FBGs located in these specific regions. Although it should be noted that air pressure is present and gradually declines with an increase in margin length, its impact on our calculations is minimal. However, it may be crucial in future analyses when considering the train's presence. Therefore, to obtain more accurate results, we must consider the effect of air pressure on FBGs.

5.4 General Setup and Base Design

Within the context of this thesis, the simulation software models used for independent work are verified experimentally. A research project funded by the government, namely NSERC/Card1 538408-18, was exclusively dedicated to this purpose in 2019 [39]. The comparison between the temperature and strain sensing data obtained by the software simulation and the experimental data, as listed in Table 5.2, was conducted over five different FBG sensor samples.

Table 5.2 : Comparison summary of experimental and simulated temperature and strain sensing data.

Parameter	Set	Bragg Wavelength Value
Experimental Temperature (Transmission)	23	1548.036
Simulated Temperature (Transmission)	20	1548.11494
Simulated Proposed System Temperature (Transmission)	23	1548.33
Experimental Temperature (Reflection)	22	1548.055
Simulated Temperature (Transmission)	20	1548.000028
Simulated Temperature Proposed System (Reflection)	22	1548.21
Experimental Strain (Reflection)	0.001176	1548.62
Simulated Strain (Reflection)	0.002	1550.5169
Simulated Strain Proposed System (Reflection)	0.001176	1548.41

Table 5.2 (Continued) : Comparison summary of experimental and simulated temperature and strain sensing data.

Parameter	Set Value	Wavelength (nm)
Experimental Temperature (Transmission)	93	1548.74
Simulated Temperature (Transmission)	100	1549.07486
Simulated Proposed System Temperature (Transmission)	93	1549.32
Experimental Temperature (Reflection)	92	1548.723
Simulated Temperature (Transmission)	100	1549.154909
Simulated Temperature Proposed System (Reflection)	92	1549.131549
Experimental Strain (Reflection)	0.011765	1560.262
Simulated Strain (Reflection)	0.012	1563.291
Simulated Strain Proposed System (Reflection)	0.011765	1562.19

The sensing temperature varied between 10 °C and 100 °C while the strain varied from 0 to 0.012. The comparison of the results is shown in Figure 5.4 and Figure 5.5. The root means square error (RMSE) is calculated for the measured data and summarized in Error! Reference source not found.. The error can be attributed to deviations from the actual central wavelength of the practical laser, the thermo-optic coefficient, and the photo-elastic coefficient from the ones used in the simulation. Figure 5.4 illustrates the Bragg wavelength shift for the transmission and reflection ports of the FBG sensor measured experimentally and simulated for different temperatures. On the other hand, Table 5.3 shows the Bragg shift of the FBG sensor for different strain values measured and simulated using the OptiSystem software tool. The simulation results are very close to the experimentally measured data, which provides credibility to the models used in the commercial software and assures that the simulations of the FOS systems are trustworthy.

Table 5.3 : FBG sensor accuracy for temperature and strain sensing.

Measurand	Accuracy (RMSE)%
Temperature (Transmission)	0.429
Temperature (Reflection)	0.28
Strain (Reflection)	1.39

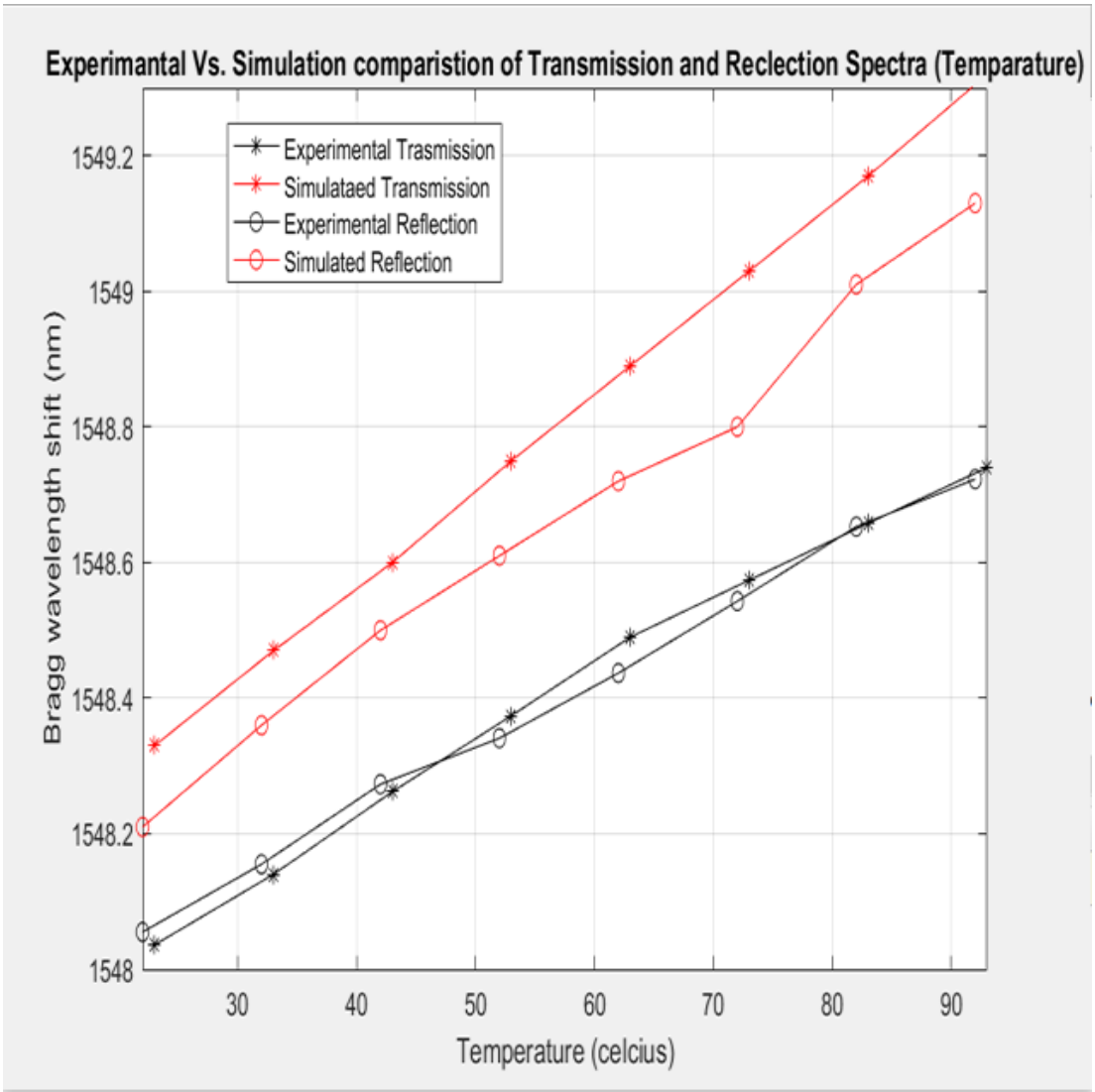


Figure 5.4 : Experimental and simulated comparison for temperature sensing in FBG sensor.

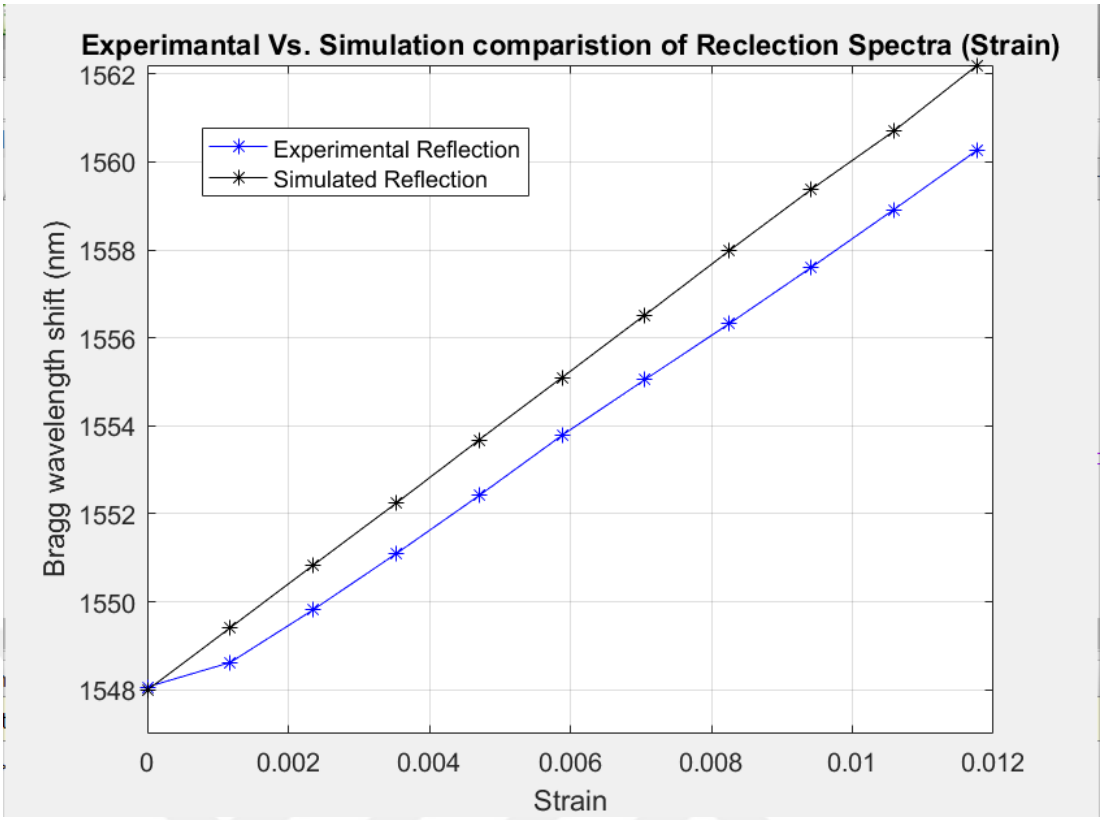


Figure 5.5 : Experimental and simulated comparison for strain sensing in FBG sensor.

Fiber Optic Sensing (FOS) technology is crucial for ensuring safety and efficiency in train services. By continuously monitoring train locations in real-time, FOS technology allows for tracking various train parameters such as position, velocity, and trajectory, which are essential to maintaining secure and efficient train dynamics. Unlike conventional sensing techniques that rely on discrete sensors at intervals along the track, FOS technology allows for expansive, ceaseless, and agile assessments of rail operations by installing optic sensors along the entirety of the railway [23]. This enhanced surveillance can detect extraneous elements, such as the presence of vehicles, environmental calamities, fauna, or individuals on the track, which might cause severe collisions. Figure 5.6 shows is a schematic of a dynamic object detection apparatus incorporating a fiber optic sensor, which leverages an encoded pulse sequence mechanism and an array of Fiber Bragg Grating (FBG) sensors situated sequentially. The system uses encoded signals dispatched and reflected by FBGs to determine the train's location, speed, and direction. OptiSystem is used to simulate this

advanced hybrid sensing configuration. Selecting the proper simulation parameters, including the pulse sampling and temporal resolution, is crucial to ensure accurate results. A referential bitrate one-tenth of the pulsation frequency transmitted is used to maintain precision within the resultant findings, as listed in Table 5.4.

Table 5.4 : OptiSystem simulation environment global parameters.

Name	Value	Units
Bit rate	1.00×10^4	bit/s
Time window	0.0008	s
Sample rate	1.31×10^9	Hz
Sequence length	8	bits
Samples per bit	131,072	
Guard Bits	0	
Symbol rate	2000	symbols/s
Number of samples	1,048,576	
Refractive Index	1.467	
Speed of Light in Space	299,792	m/μs
Fiber length	50	km
Laser Power	10	dBm
Laser wavelength	1550	nm

Figure 5.6 illustrates the proposed system's transmitter (TX) section. It includes the laser, electrical pulse source, and modulator. The pulses are coded first using the 11101001 code and then modulated using a Mach–Zehnder modulator (MZM). The code indicates that 62.5 percent of the pulses consist of ones. A 10 dBm laser source is used to carry the modulated pulses.

A three-port circulator is used to direct the launched pulses into the fiber and the backreflected signal from the FBG sensor that represents the moving object to the receiver, as shown in Figure 5.6. The moving object creates a strain action on the uniform FBG sensors, generating backreflected pulses propagating through the same fiber link. It is worth mentioning here that it is possible to use other types of FBG sensors, like apodized FBG sensors; however, a typical sensor has been chosen to be used in this paper because it has been experimentally validated. A MATLAB component is used in the setup for cross-correlation calculation.

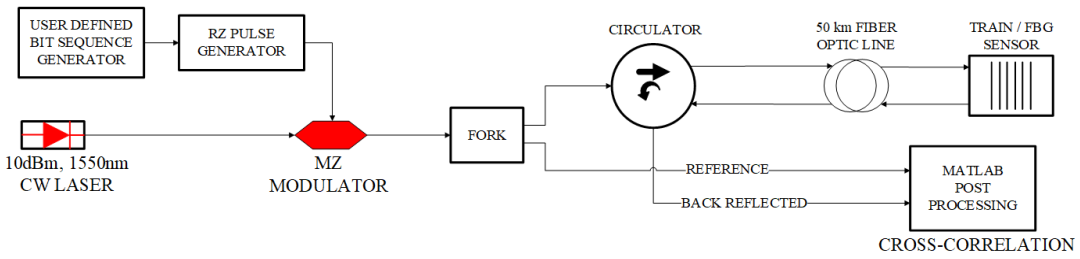


Figure 5.6 : The simulated sensor system in OptiSystem software.

5.5 Transmitted Pulse Coding

Using pseudorandom noise (PN) coding in satellite navigation systems such as GPS has been widely recognized for enhancing positional determination through cross-correlation techniques. The inherent resilience of PN codes allows for signal detection in environments with significant noise interference, making them an indispensable tool in the sensing framework. PN coding employs a diverse set of coding lengths in this framework, ranging incrementally from 2 to 256 bits. The sequences emitted are subject to a cross-correlation process with signals reflected back, enabling the ascertainment of Fiber Bragg Grating (FBG) locales. Figure 5.7 represents a 16-bit PN-coded sequence, where the encoding for each bit (value '1' or '0') is plotted along the x-axis, and the corresponding magnitude of the signal is denoted on the y-axis. However, due to computational constraints, especially the limited random-access memory (RAM) capacity inherent in the computational resources employed, exploratory tests of the PN code's effectiveness were not extended beyond the 256-bit threshold in the current analysis. Nonetheless, the effectiveness of pseudorandom noise codes, similar to the characteristics of Golay codes, has been adopted here, with an expectation of boosted signal-to-noise ratio (SNR) as the bit sequence is lengthened [26]. As such, expanding the coding length from a singular bit to 1024 bits or even beyond is posited to refine the preciseness of locational detection further. This assertion is supported by later sections of this study, which will demonstrate the efficacy of PN codes in improving the accuracy of positional determination. Thus, using PN coding in satellite navigation systems is expected to continue playing a crucial role in enhancing location-based services.

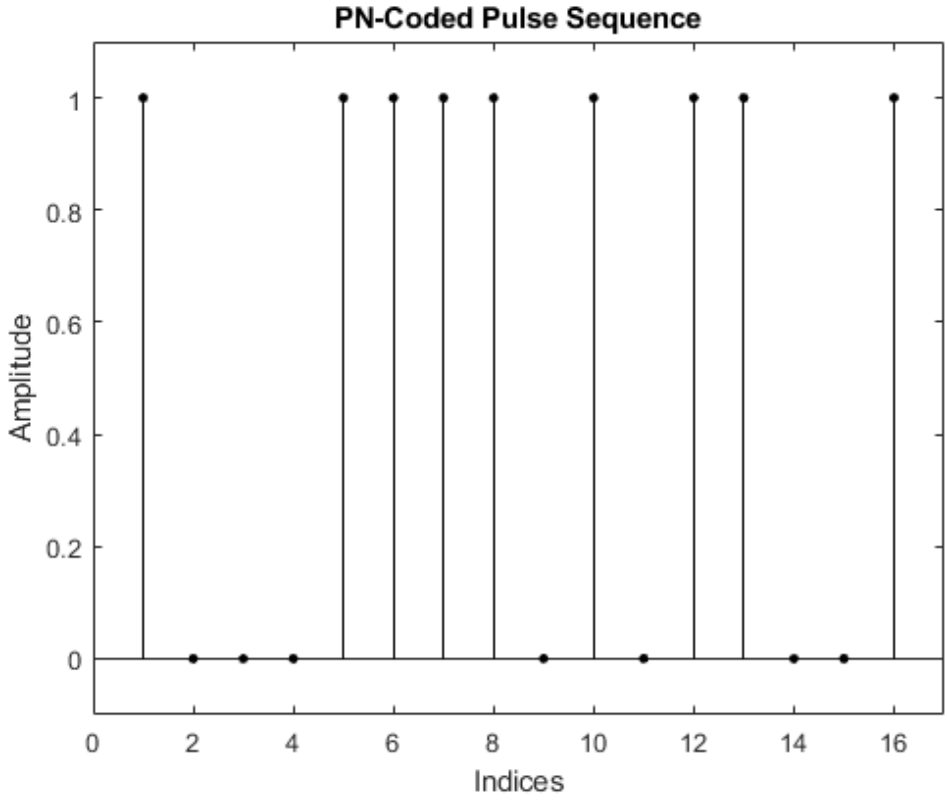


Figure 5.7 : A 16-bit PN-Coding of pulse series, 56.2 percent of ones

One of the FBG sensors is placed 50 km from the transmitter block. The transmitted pulses are initially coded and launched into the optical fiber. They reflect from the FBG sensor, propagate through the same fiber to the circulator, and arrive at the MATLAB component. The system's performance has been evaluated both with and without noise. The extremum points of the cross-correlation function for different datasets between 1 and 256 bits long are monitored. Gaussian noise is added to the backreflected signals using snr= -15,and kernel = awgn(kernel,snr,'measured') to make the system more realistic. The added Gaussian noise to the system has an amplitude of around ten times more than the backreflected signal level. Figure 5.8 shows the cross-correlation results with and without noise in the system. The results for a single-bit sequence pulse achieve around 118 m localization error resolution when the vibration event is 50 km away, as shown in Figure 5.8(a.2). If there is no noise in the system, the localization error is around 2.7 cm, as shown in Figure 5.8(a.1). However, a 256-bit pulse sequence offers a 1 cm localization error for an event 50 km away, which is not affected by the

noise, as lower-bit-sequenced coding alternatives are shown in Figure 5.8(B.1, B.2). Using 256-bit coding helps avoid noise effects in the system. Hence, it helps in creating a more straightforward system with simple hardware. Figure 5.8(B.2) shows that the noise reduces the system lobe to around 0 dB, so the localization is much harder to achieve without coding. However, the calculated system lobe is around 25 dB without noise, as shown in Figure 5.8(B.1).

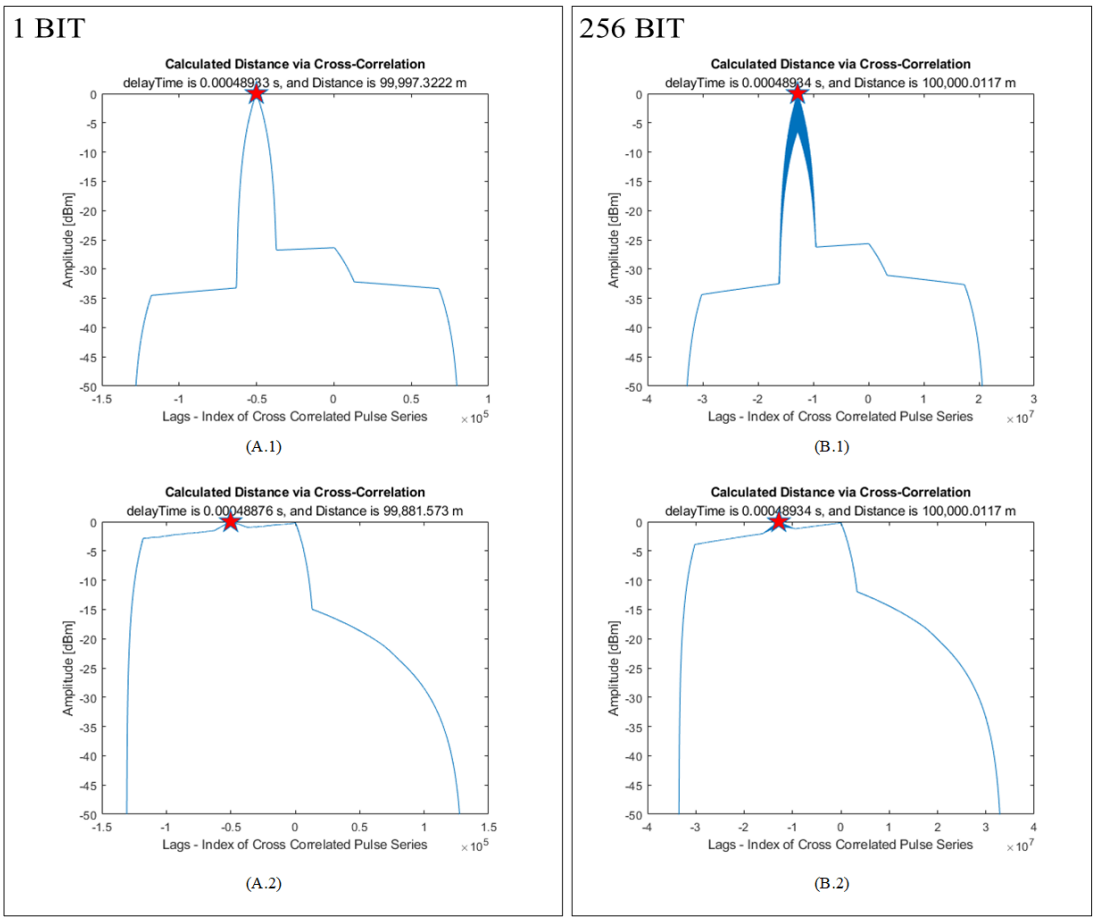


Figure 5.8 : Cross-correlation for single-bit pulse ((A.1): no noise, (A.2): Gaussian noise added) and 256-bit ((B.1): no noise, (B.2): Gaussian noise added) pulse sequence.

Figure 5.9 shows the data relating to the originally transmitted signal (Tx), the pristine back-reflected signal (Rx) without noise, and the back-reflected signal tainted with Gaussian noise (Rx). There is an observable attenuation in the strength of the received signal, which is diminished by a factor of 1/100,000 (-20 dB) with respect to the initial transmitted signal. The Gaussian noise imposed on the system is notably intense,

possessing an amplitude that is tenfold (10 dB) the magnitude of the backreflected signal, to such an extent that differentiating the signal from the noise becomes problematic. Under these particular circumstances, conventional methodologies, such as the mean power method, prove ineffectual. Nevertheless, applying the PN-Coding strategy before executing cross-correlation on the noise-laden backreflected signal can deliver a refined outcome, as evidenced by the ultimate pattern illustrated in Figure 5.9. With this technique, the setup is able to achieve an estimated localization precision within 1 centimeter for an FBG sensor that is 50 kilometers distant in conditions where the signal's power is considerably overshowed by the level of noise. Further, Figure 5.10 examines the efficacy of cross-correlation for diverse PN-coded pulse sequences, ranging from 1 to 256 bits, while keeping the timing frame constant across all sequences. The variation is solely in the length of the coding sequence. Each progressive increment in the bit length of these sequences is plotted to manifest its relative performance within the system.

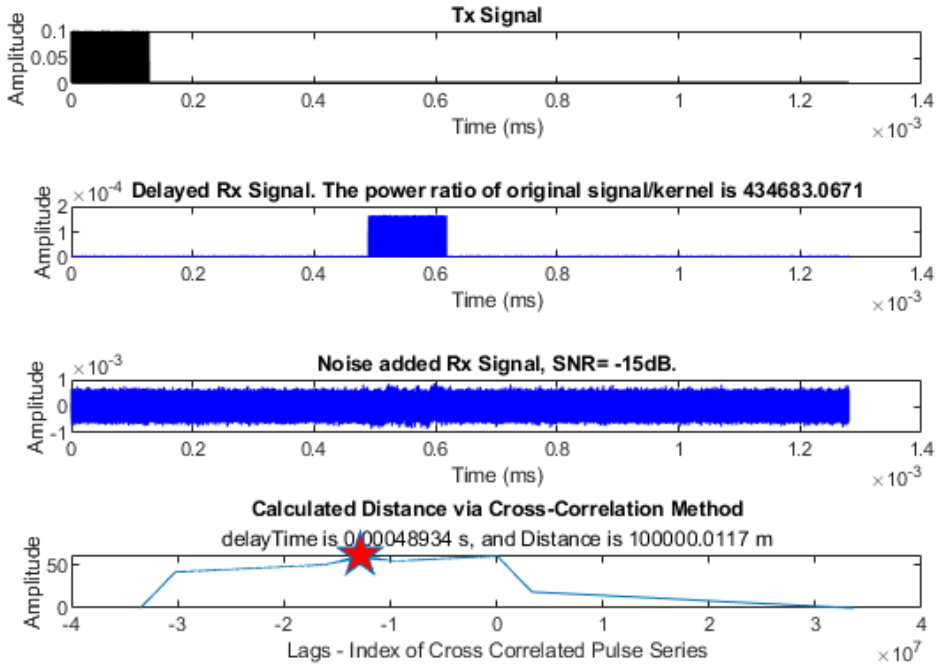


Figure 5.9 : Detailed, transmitted, backreflected 256-bit pulse sequence and calculated localization, with and without noise.

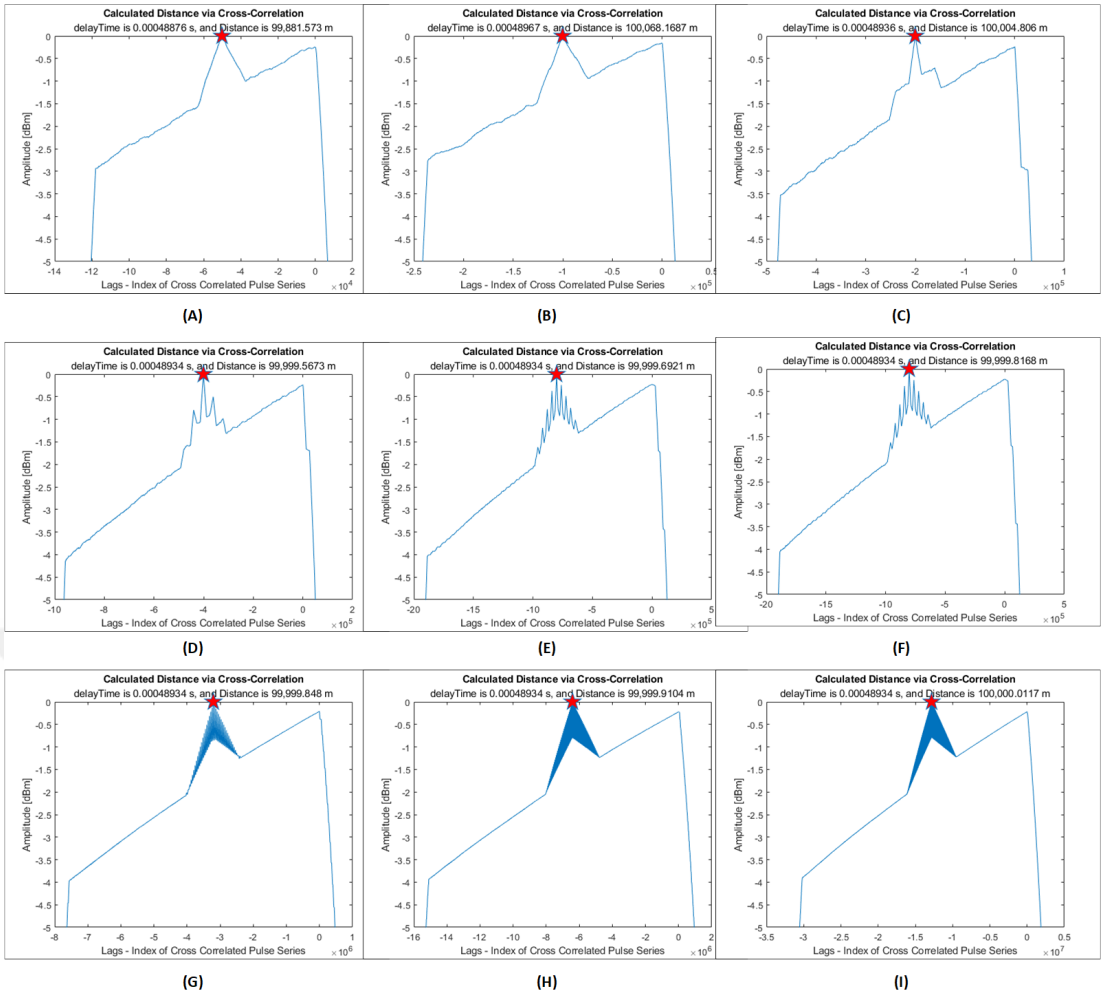


Figure 5.10 : Cross-correlation performance under Gaussian Noise for 100 km (50 km forward, 50 km backward). (a) 1-, (b) 2-, (c) 4-, (d) 8-, (e) 16-, (f) 32-, (g) 64-, (h) 128-, (i) 256-bit pulse sequence length

As depicted in Figure 5.11 the implementation of a pseudorandom noise (PN) coding technique in conjunction with cross-correlation under noisy conditions reveals varying degrees of positional discrepancies. Specifically, the localization inaccuracies are observed to be around 118.4 meters for a single-bit pulse sequence, 68.1 meters for a two-bit sequence, 4.8 meters for four bits, 0.4 meters for eight bits, followed closely by 0.3 meters for both sixteen and thirty-two-bit sequences. The error further diminishes to 0.2 meters for a sixty-four-bit sequence and narrows down to merely 0.1 meters for sequences spanning 128 and 256 bits, respectively. These measurements pertain to an FBG sensor that is located 50 kilometers from the source.

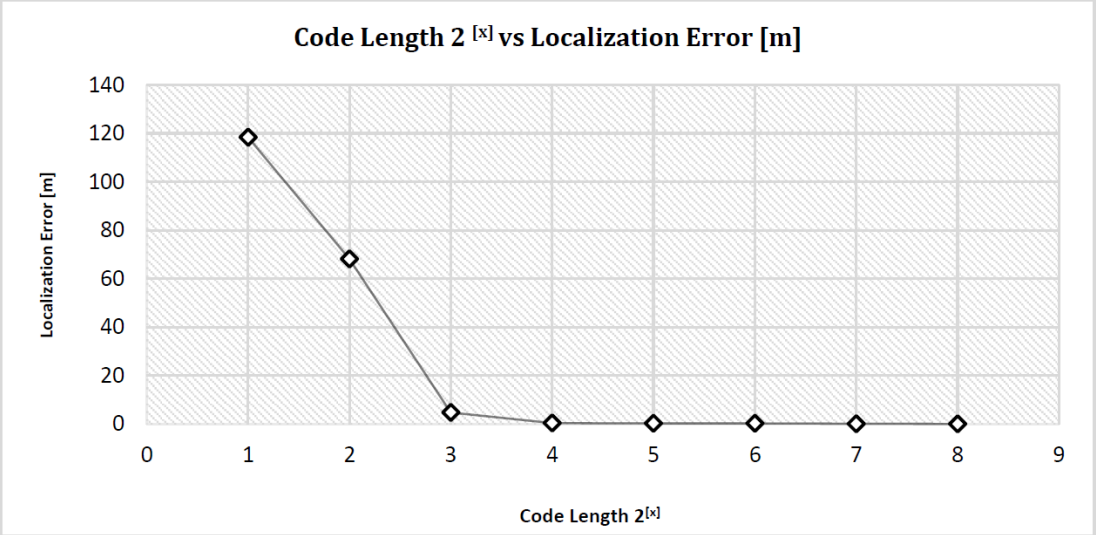


Figure 5.11 : Localization error under high noise for different code lengths for an event 50 km away.

Within a noise-free environment, the sensor system, utilizing an 8-bit coded sequence, is capable of discerning the location of an event at a remarkable accuracy, with a mean error margin of just 0.12 meters for a distance extending up to 50 kilometers. However, applying a PN-Code pattern to a system disturbed by noise results in a more significant average localization error, approximately 4.5 meters, as indicated in Figure 5.11. It's observed that as the coding sequence length escalates, the precision in localizing events improves correspondingly, albeit at the cost of increased requirements for computational processing power.

Train Speed Detection Mechanism Using Bragg Shifting Regarding the technology employed to ascertain the velocity of a train through Bragg shift analysis, the underlying operational principle is founded on monitoring the alterations in the Bragg wavelength stemming from the FBG sensor due to external physical factors. The intrinsic wavelength at the core of the FBG, known as the Bragg wavelength, is influenced by ambient temperature modifications and the levels of stress and strain exerted upon it. These perturbations in the Bragg wavelength (λ_B) can be mathematically encapsulated as follows [40].

$$(\Delta\lambda_B)/\lambda_B = (1-p_e)\,\varepsilon + (\alpha_{TE}+\alpha_{TO})\,\Delta T \tag{5.4}$$

In the given formula, ε denotes the longitudinal strain experienced by the fiber, ΔT represents temperature variations, p_e is indicative of the photo-elastic coefficient within the fiber material, α_{TE} designates the coefficient of thermal expansion, and α_{TO} refers to the thermo-optic coefficient. According to Figure 5.12 the approach deployed to measure the train's motion, as outlined in Figure 5.12. involves detecting differences in air pressure gradients caused by the train. It is noted that the train generates a compressive air disturbance near the leading front, approximately at 10 percent of its length, imparting varied strain phenomena upon the FBG sensor. Figure 5.13 presents the data related to both the transmitted and back-reflected light spectra for various train velocities. It is observable that as the speed of the train augments, so does the strain applied to the FBG sensor, which in turn leads to a more pronounced shift in the central Bragg wavelength. The degree to which this Bragg wavelength is displaced is directly proportional to the train's velocity. Furthermore, the direction in which this central Bragg wavelength is shifted reveals the direction the train travels.

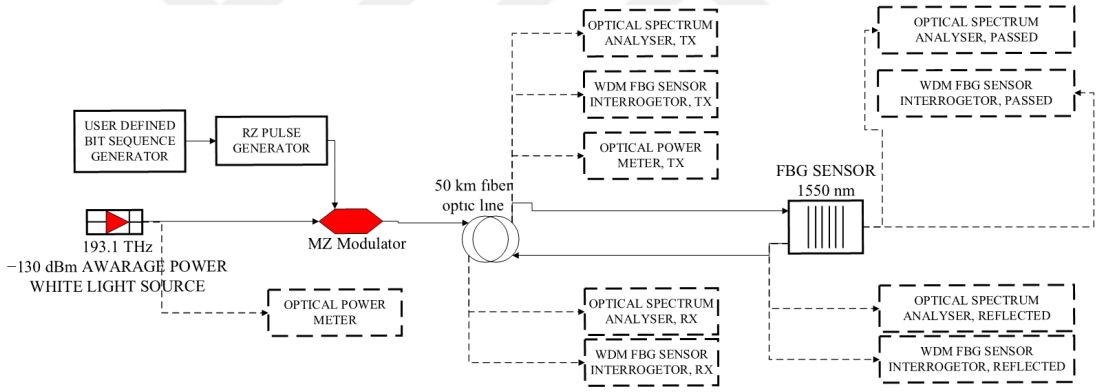


Figure 5.12 : FBG Sensor setup in OptiSystem software

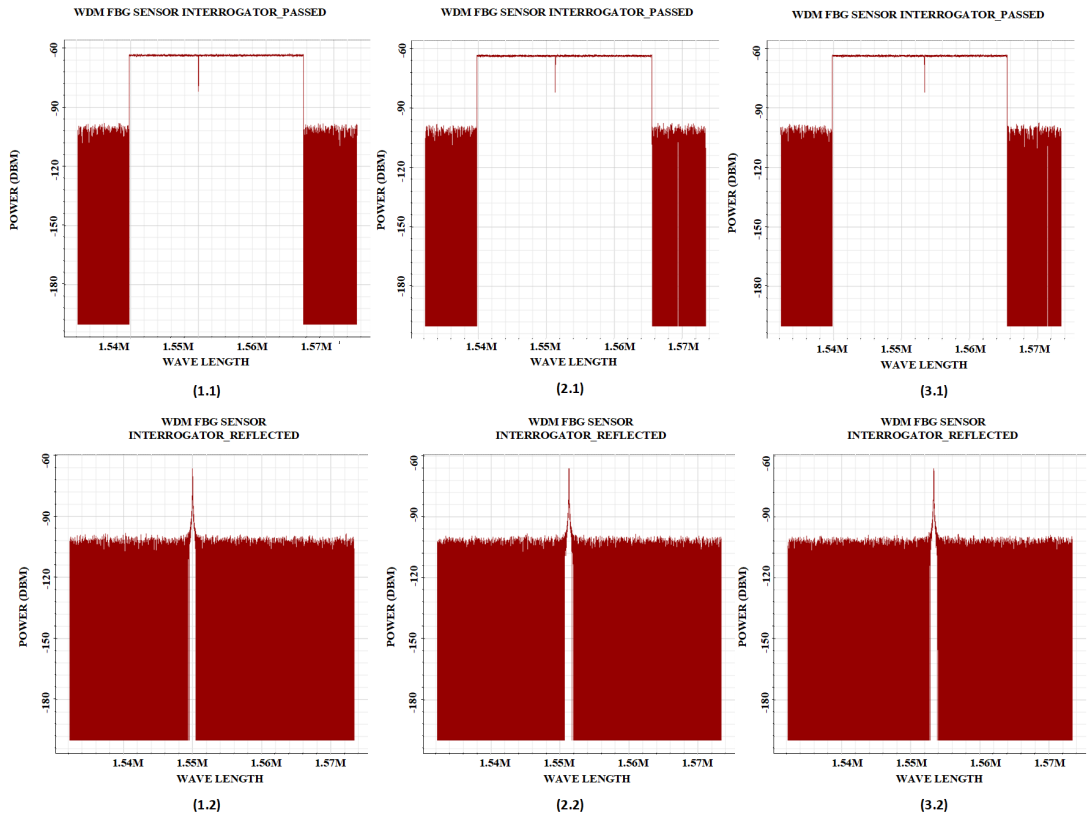


Figure 5.13 : FBG sensor transmitted (*.1) and reflected spectra (*.2) for different train velocities: (a) velocity of train 0 km/h (no strain), (b) 50 km/h, (c) 80 km/h.

In Table 5.5, the reflected signal parameters are presented. It encapsulates a range of data about the performance of an FBG-based sensing mechanism at varying train velocities, with the FBG situated at a substantial distance of 50 kilometers from the transmission source. The table delineates several key variables, including the time required for the train to traverse a 125-meter distance, the magnitude of aerodynamic forces exerted, the degree of FBG-induced strain along the cable at the point of detection, variations in the FBG's central wavelength, and the intensity of the signal that is reflected back. The standard central wavelength for the FBG under consideration is set at 1550 nanometers. It is noted that a train moving at a speed of 80 km/hour has a distinctive wavelength shift of the reflected signal's center, amounting to approximately 3.33 nanometers.

It does not considered the impact of external atmospheric conditions, such as sudden squalls of wind. Nevertheless, the combined or hybrid monitoring system is adept

at recognizing transient stresses that impact the optical fiber cable that may stem from such environmental conditions, enabling the system to distinguish these events. Upon identification of such anomalies, the system can activate an alert. This feature underscores an additional benefit of the hybrid sensing system being proposed.

Table 5.5 : Reflected signal parameters.

Train Velocity (km/h)	Duration to Pass 12.5 m(s)	Air Force (N)	Strain Over Cable (Pa)
80	0.56	5646	2754
70	0.64	4322	2108
60	0.75	3176	1549
50	0.90	2205	1076
40	1.13	1411	688
30	1.50	794	387
20	2.25	353	172
10	4.50	88	43
0	NA	0	0

Table 5.5 (Continued) : Reflected signal parameters.

Train Velocity (km/h)	Shifted Center Wavelength(nm)	Reflected Power (dBm)
80	3.33	-66.2
70	2.56	-66.2
60	1.88	-66.37
50	1.3	-66.21
40	0.84	-66.38
30	0.46	-66.35
20	0.21	-66.38
10	0.05	-66.16
0	0	-66.44

5.6 FBG Sensing Design

In the proposed hybrid sensing paradigm, five FBG sensors are employed to facilitate temporal and spectral detection capabilities. This sensor array is systematically duplicated at judicious intervals along the rail network infrastructure to achieve extensive coverage and ensure fidelity in monitoring. The implementation's efficacy has been corroborated through a series of empirical validations, wherein a prototype assemblage of these sensors operated collaboratively with the previously delineated encoding-based sensing apparatus, verifying the robustness and utility of the integrated approach.

5.7 General Layout of the FBG Design

Illustrated in Figure 5.14 is the architecture of the Fiber Bragg Grating (FBG) sensor array, which is constructed using off-the-shelf components. This assembly has a broadband white light source, emitting a central noise spectrum of 193.1 terahertz. The array consists of five uniform FBG sensors, each tuned to distinct wavelengths: 1525.66 nm, 1538.19 nm, 1550.92 nm, 1563.86 nm, and 1577.03 nm, as referenced in [6]. he FBG sensor positioned nearest to the transmission module resonates at 1525.66 nm. A circulator within the system effectively channels incoming light towards the FBG sensors and reroutes reflected signals to the receiving section. The detection suite's monitoring mechanism is initially calibrated to capture the reflected signatures from all FBG sensors. This is achieved through monitoring devices that register variations in peak power for each FBG as the train circumnavigates the vicinity of the sensor. After identifying the FBG sensor with the highest power fluctuation, a tunable filter is employed to detect any changes in wavelength. This indicates the impact of train-induced strain on the FBG, caused by the aerodynamic pressure changes as the train passes by the sensor.

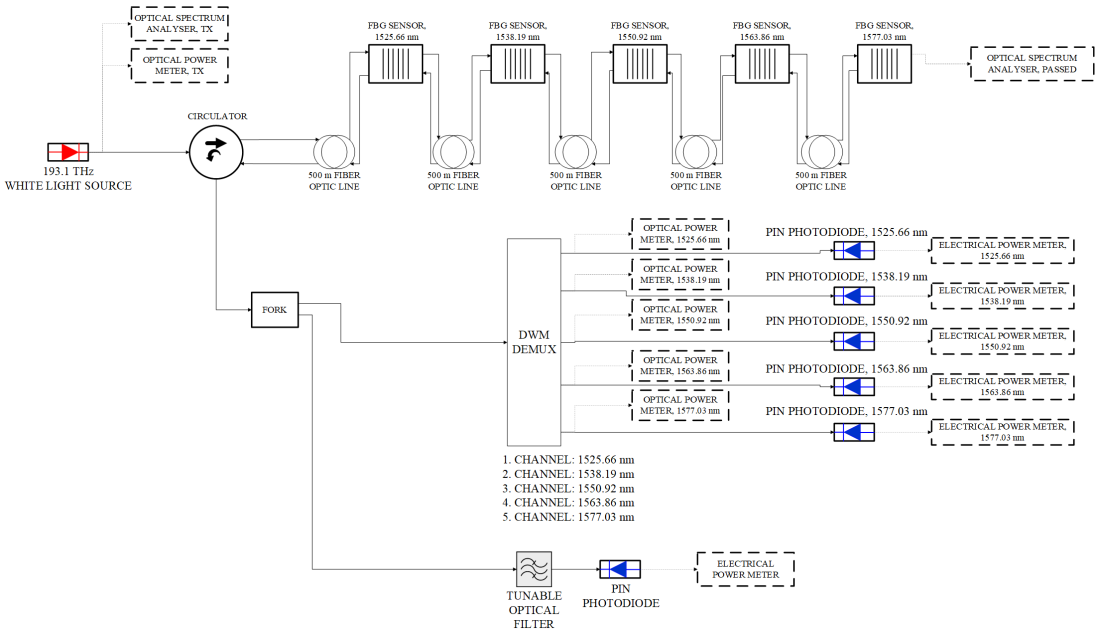


Figure 5.14 : The general design of the FBG sensor system.

A differential atmospheric pressure pattern is established in the vicinity of a moving train, characterized by compressive air pressure at the train's forefront and tensional pressure in the wake of the train. These pressure differentials exert variable strains on FBG sensors deployed along the rail line. As the strain is applied to these sensors, an adjustment occurs in their intrinsic Bragg wavelength, subsequently altering the behavior of both transmitted and reflected optical signals. The peak compressive pressure at the front of the train is approximately 2754 Pascal, with an equivalent but opposite pressure trailing the locomotive. These strain-induced wavelength shifts in the FBG sensors manifest as a redshift or blue shift from the core wavelength, as delineated in Figure 5.15. In an effort to prevent the overlap of backscattered signals, the system is configured to choose sensor wavelengths that are sufficiently spaced. This facilitates the system's operation even at train velocities reaching 80 kilometers per hour and ensures the safe separation of readings. The FBG sensors are positioned with a gap of 500 meters, accommodating trains up to a length of 125 meters. Detailed statistics on the frequencies and wavelengths pertinent to the FBG sensors in question are compiled in Table 5.6.

In Table 5.6, the FBG working frequency/wavelength is presented.

Table 5.6 : FBG working frequency/wavelength.

FrequencyGHz >GHz	Wavelengthnm >nm
190.1	1577.03
191.7	1563.86
193.3	1550.92
194.9	1538.19
196.5	1525.66

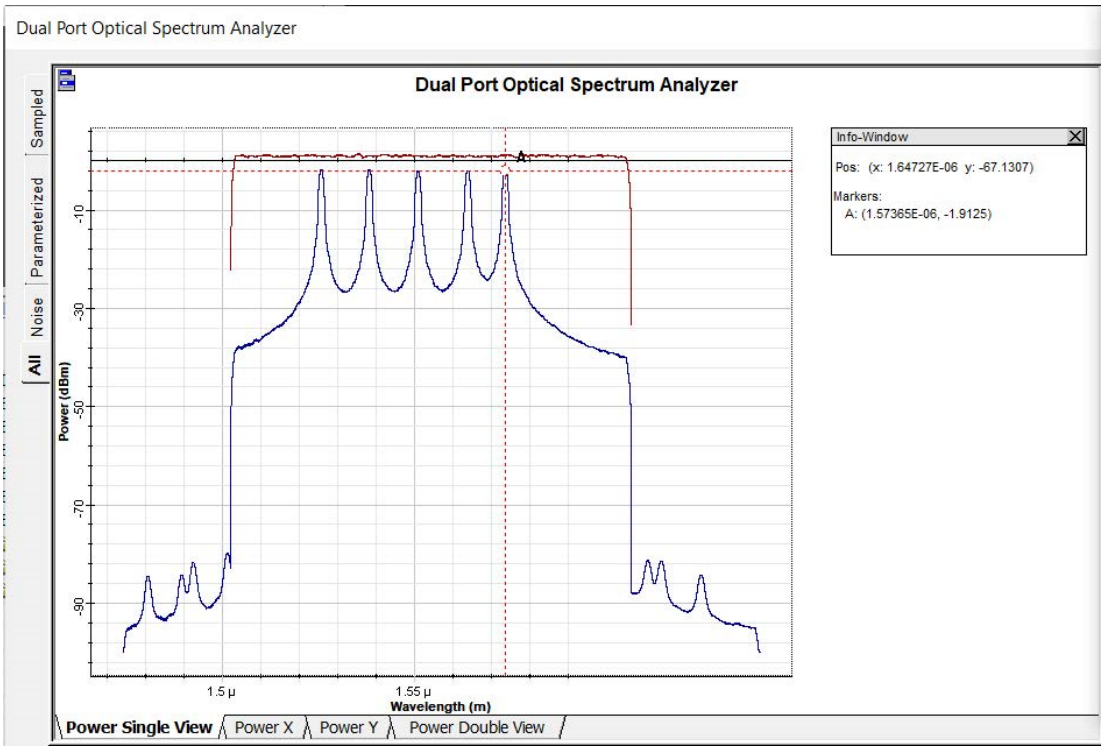


Figure 5.15 : Transmitted and received spectra for the FBG sensors system.

Demonstrated in Figure 5.15 are the spectral profiles for Fiber Optic Sensor (FOS) arrays, where the emission (depicted in red) and corresponding reflection (portrayed in blue) are annotated for a scenario where the fifth sensor is subject to strain. Subsequently, Figure 5.16 captures the dynamic response of all FBG sensors integrated within the FOS system to the deformation induced by the train in motion. The first (1) and the eighth (8) visual representations establish the baseline conditions without mechanical strain. At the same time, the intervening frames articulate the spectral variations concurrent with the train's passage. From these observations, one can discern that the peak strain exerts a pressure of 2754 Pascals, positivized at the train's

leading edge and negativized at the train's rear, with the locomotive operating at a velocity of 80 kilometers per hour. The system is designed so that a maximum of two adjacent FBGs can simultaneously detect strain. The directional red arrows symbolize the impact of compressive air pressure on the Bragg wavelength shifts, whereas the blue arrows reveal the influence of the active air pressure. The spectral data convey no discernible pressure-induced deformation during the initial and terminal stages.

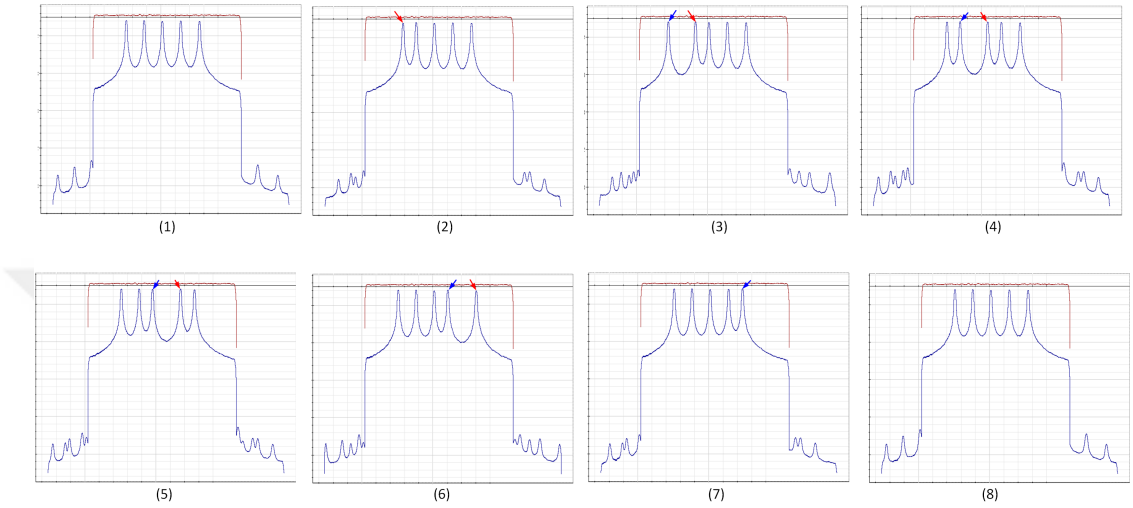


Figure 5.16 : The effect of moving the train on FBG spectra (initial states one through eight).

he integrated sensing system has been designed to efficiently identify, monitor, and locate trains traversing through a tunnel. The system's ability to register the movement of trains and the consequent air pressure fluctuations on various Fiber Bragg Gratings (FBGs) within the array have been meticulously recorded and analyzed in Table 5.7 and Table 5.8. The leading FBG in the sequence has been observed to incur maximal compressive air pressure, as indicated by a red arrow, within the confines of the system's design parameters. On the other hand, the terminal sensor in the array suffers from maximal tensile air pressure, as noted by a blue arrow. It is to be noted that this scenario has been contrived within simulations to evaluate the system's response to extreme frequency shifts that may occur and may not align perfectly with practical, in-situ conditions. The air pressure values affecting the discrete FBGs have been computed while presuming that the train attains top velocity, and the sensor spacing extends to 500 meters, with the train's length being fixed at 125 meters.

Table 5.7 : The first to sixth steps simulate the train movement over the FBGs.

Iteration	Air Pressure (Mpa), 1525.66 nm	Air Pressure (Mpa), 1538.19 nm	Air Pressure (Mpa), 1550.92 nm	Air Pressure (Mpa), 1563.86 nm	Air Pressure (Mpa), 1577.03 nm
1	0.002754	0	0	0	0
2	-0.002754	0.002754	0	0	0
3	0	-0.002754	0.002754	0	0
4	0	0	-0.002754	0.002754	0
5	0	0	0	-0.002754	0.002754

Table 5.8 simulates the train movement operations.

Table 5.8 : Train movement effect on the PIN photodiode detection system for white light source output.

	Total Power of Photodiodes				
Iteration	PIN 1525.66 nm	PIN 1538.19 nm	PIN 1550.92 nm	PIN 1563.86 nm	PIN 1577.03 nm
1	-2.2272	-2.2345	-2.2039	-2.1348	-2.1332
2	**−24.963**	-2.2364	-2.2054	-2.1359	-2.1316
3	**−24.953**	**−24.653**	-2.2046	-2.1341	-2.1335
4	-2.2256	**−24.811**	**−24.436**	-2.1267	-2.1323
5	-2.2276	-2.2343	**−24.442**	**−24.005**	-2.127
6	-2.2288	-2.2342	-2.2024	**−24.528**	**−24.391**
7	-2.2275	-2.2347	-2.2043	-2.1364	**−24.417**
8	-2.2272	-2.2345	-2.2039	-2.1348	-2.1332

Table 5.8 shows the optical power levels at the photodiodes after demultiplexing for wavelengths 1525.66 nm, 1538.19 nm, 1550.92 nm, 1563.86 nm, and 1577.03 nm. The air pressure applied has a negligible effect when no train is near the FBG sensor, and the recorded power remains stable at around -2.2 dBm. However, when a train passes near an FBG sensor, there is a noticeable decrease in detected power levels, with measurements reaching approximately -24 dBm. When the train passes over two FBG sensors at the same time, each photodetector records similar power reductions, estimated to be around -24 dBm. These sensors have Bragg wavelengths that change with air pressure. One grating's Bragg wavelength shifts to a higher value while the other shifts to a lower value, resulting in divergent responses. An optical tunable filter is utilized to pinpoint the shifted Bragg wavelength of the impacted

sensors. By first detecting which sensor's power has been altered after the DEMUX, the tunable filter is then finely adjusted around the presumed Bragg center wavelength to discern the peak power output, as demonstrated in Figure 5.17. The optical tunable filter applied in this simulation has a bandwidth specification of 10 GHz. Enlarging the filter's bandwidth would result in an uptick in detected power, but this does not undermine the system's detection performance, predicated on monitoring power variations across different wavelengths. In Figure 5.17, the showcased FBG sensor is designated as FBG 1 with a center Bragg wavelength of 1525.66 nm. The data point labeled as B denotes the recorded power without any air pressure on the sensor, thereby maintaining its center at 1525.66 nm. Data point C reflects the condition under compressive air pressure, resulting in a Bragg reflection centered at 1522.66 nm. Meanwhile, point A signifies the effect of tensile air pressure, yielding a Bragg reflection centered at 1527.66 nm. To circumvent overlap of the spectral responses due to wavelength shifting when a high-speed train passes, the center wavelengths of the FBG sensors should be judiciously selected, factoring in the maximal shifts induced by the train's velocity. The system is calibrated to reliably capture speeds up to 80 km/h, incorporating sufficient margins to ensure operational safety. If train velocities exceed this threshold, such as reaching speeds of 120 km/h, the selection of center wavelengths for the FBGs, as shown in Table 5.6 , and their spatial arrangement would require reassessment to stave off interference between backscattered signals. This refined arrangement would maintain the integrity of the system's functionality.

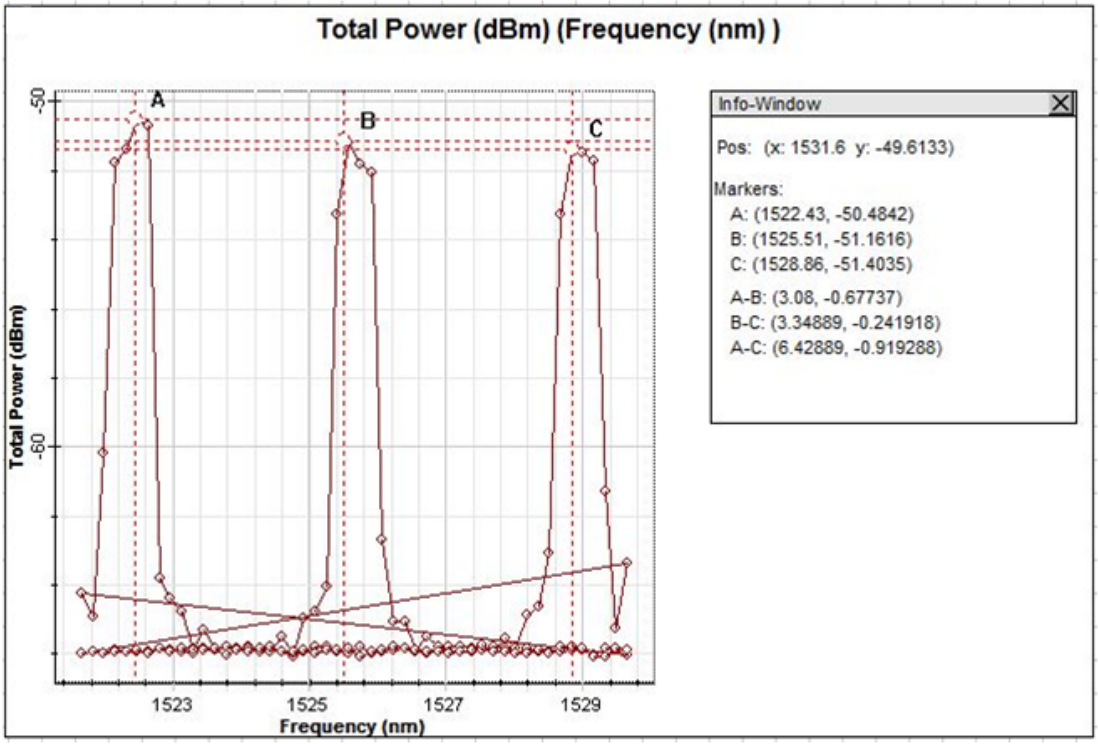


Figure 5.17 : Center frequency shifting for different air pressures for the FBG 1 backreflected signal (A: expansion air pressure, B: no air pressure, and C: compressive air pressure).

The operational protocol for the composite sensing system unfolds in the following stages. Initially, a wide-spectrum light source is injected into five Fiber Bragg Grating (FBG) sensors, all tuned to identical wavelengths. Concurrently, the reflection coefficient of each FBG collection is tailored so that the light echoed back from the furthest FBG cluster is approximately equal in power to that of the initial one. Specifically, the foremost FBG array exhibits a modest reflectance of 1% . In contrast, the final array demonstrates a high reflectance of 99%, accounting for the total of twenty FBG arrays dispersed along the 50-kilometer track. Without a train presence, the optical power detected by the photodetectors, as indicated in Figure 5.16 (1), remains consistent. Upon the introduction of a train at any point along the line, alterations to the center wavelength of the corresponding FBG arise due to strain effects, provoking detectable variance in received power levels. These wavelength modifications are pinpointed by the methodology displayed in Figure 5.17. This data informs the system of the train's velocity and trajectory. A swift alternation at the

emission end, toggling between the broadband source and a slender-band Continuous Wave (CW) laser pulsing with encoded sequences, is indispensable for pinpointing the train's precise locale. After detecting the shifted wavelength, the CW laser is tuned accordingly, and the returning pulsed signals are cross-correlated with standardized transmitted pulses, as detailed in Section 5.5 of the document, to ascertain the train's position.

The rapidity of switching the light input within the system is imperative to preempt the train's progression past an FBG sensor. Given a speed of 22.22 meters per second, or 80 kilometers per hour, a train would take approximately 5.6 seconds to clear the vicinity of an FBG sensor. This window allows ample time to orchestrate the light source changes and to process the data for each independent source. The optical switches and photodetectors employed in this system can operate in microseconds or even fractions, indicating suitably high switching speeds for the task..

5.8 The Results of the Investigation of Hybrid System Purpose.

In the investigation, an advanced hybrid fiber optic sensing configuration was developed, utilizing Fiber Brag Grating (FBG) sensors dispersed at intervals along a railway infrastructure. The pioneering approach in this system leverages a pulse coding strategy to attain high-resolution measurements, achieving an approximate granularity of 1-centimeter resolution, even in the middle of environments characterized by marked Gaussian noise. This is accomplished by applying cross-correlation techniques, which place alongside the returning pulse patterns from the FBG sensors with a predetermined coded pulse sequence transmitted from the source. Such precise methodologies better the locational accuracy of conventional sensing practices and maintain their efficacy in high-noise scenarios. Further expanding the system's capabilities is the capability to detect the locomotive's speed and the vector of its trajectory by monitoring the center wavelength fluctuations within the FBG sensors. This secondary feature is critical for ascertaining the train's relative position concerning a stationary FBG sensor. When a train transits along the track, the applied aerodynamic pressure on the fiber cable induces mechanical strain. This phenomenon results in a corresponding shift in the center wavelength of the impacted

FBG—either compressive or vacuum shift—indicative of the direction of the train's motion. By synthesizing observations from both the high-resolution pulse coding system and the wavelength shift detection mechanism, this hybrid sensor network provides a robust means of data triangulation, thereby fortifying the system against confounding environmental variables such as gustatory wind forces or other stochastic perturbations. The dual-faceted nature of this sensing system significantly reinforces the monitoring instrument, supporting the railway system with an elevated level of operational security and contributing to the overarching safety of the railway transportation network.

6. HYBRID SYSTEM IMPLEMENTATION: MONITORING TRAIN MOVEMENT AND RAIL CONDITION

In railway transportation, various electronic sensors such as track circuits, axle counters, and active beacons are commonly used for tracking trains. However, these systems can be influenced by electromagnetic fields and environmental factors. Conversely, FOS can provide multiple functions through a single system and exhibit good resistance to electromagnetic interference. Moreover, their responses to environmental influences can be categorized and detected. Standard methods may not detect every possible event (such as debris falling onto the tracks). However, FOS has the potential to detect the position of moving objects over long distances with a single system, grouping these events based on their speed and size to generate general or specific alerts. A detection system designed using OptiSystem software focusing on rail systems demonstrates the ease of implementing train tracking and sweeping train tasks. The proposed structure involves selecting an FBG design optimized according to the modulator for the rail.

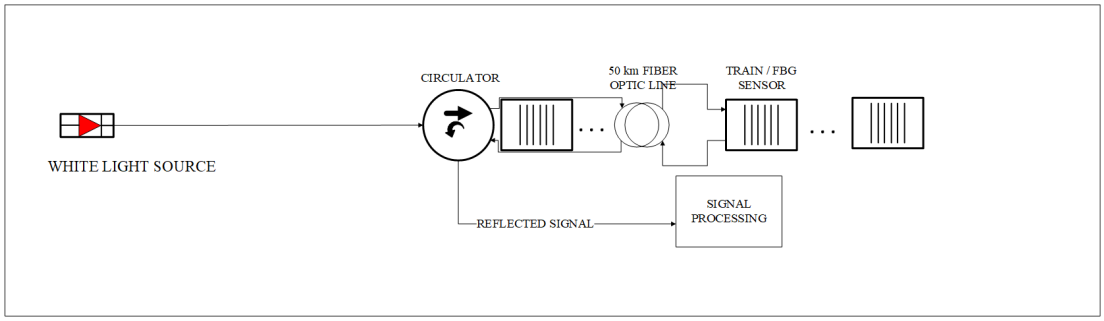
6.1 Introduction to Clearance Train System Proposal

Controlling and managing intercity railway lines is challenging. Even after maintenance, the line must be checked to ensure safe operation if there are no faults in the system. Following the line check, the operation can commence safely if there are no issues. The line occupancy is usually determined by moving an empty vehicle on the track or visually inspecting the track, after which an employee confirms that there is no problem. Actively used track circuits, axle counters, or active beacon systems in rail systems can be passive in detecting problems not specific to rail systems, such as those caused by natural disasters. An example could be the train accident in Çorlu. Monitoring and managing track disruptions with conventional systems are dangerous and prone to errors.

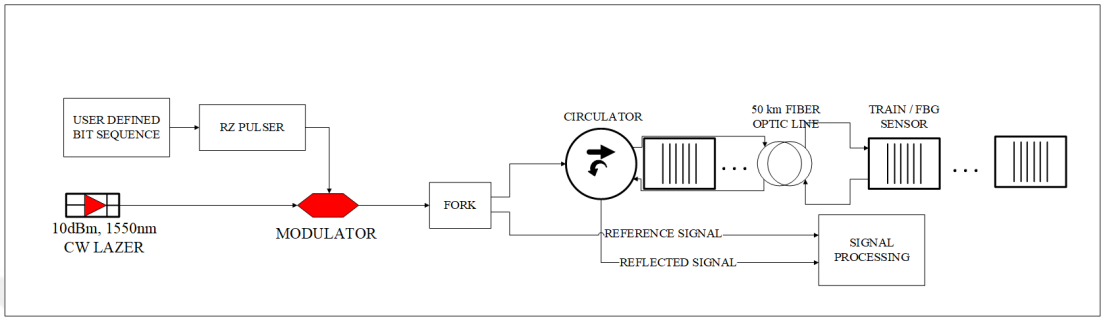
In FOS systems, an appropriate FBG design and advanced coding techniques enable real-time tracking of moving objects and the track and the operation of a sweeping train. Another significant advantage of fiber optic systems is their resistance to electromagnetic fields.

FBG is a sensor placed inside or on the fiber during production, allowing adjustable reflection of a frequency range it passes through. Changes in the reflection coefficient due to physical movement resulting from pressure exerted by moving objects cause changes in the received signal. They are usually integrated into single-mode fibers. The reflected signal due to physical movement is sensitive to environmental effects (temperature, stress, pressure, etc.) and allows their categorization. They find applications in various fields, such as medicine, transportation, aviation, and oil.

The first section of the article discusses how the source is chosen, followed by an example system design and a new perspective integrated into this design. Then, the advantages and disadvantages of the developed method are discussed, and conclusions are provided. Figure 6.1(A) presents a general design template for tracking using the coding technique.



(A)



(B)

Figure 6.1 : Modulated FOS design for the application (A), General FOS Design with White Light source (B), (B) is a general design template analyzing the reflected portion of the signal with the same amplitude in fixed frequency regions sent to the track in the coding technique.

6.2 Source Selection

When designing an FBG-based system, the choice of the source is crucial. The aim is to propose a real system that can cater to the industry, so the most accurate parts with reasonable costs have been preferred. For example, a simple 10-dBm laser source easily available in the market was chosen for a modulated and coded system. Relevant improvements were mainly made on the software side to increase the system's efficiency. Figure 6.1 shows the general parameters of the OptiSystem program used.

Table 6.1 : General parameters of the OptiSystem program.

Parameter Name	Value	Unit
Reference bit rate	1.00×10^4	
Bit rate	1.00×10^4	bit/s
Time window	0.0008	s
Sample rate	1.31×10^9	Hz
Sequence length	8	bits
Samples per bit	131072	
Guard Bits	0	
Symbol rate	2000	symbols/s
Number of samples	1048576	
Reference wavelength	1550	nm
Refractive Index	1.467	
Speed of Light in Space	299.792	m/μs
Fiber length	50	km
Laser Power	10	dBm
Laser Frequency	1550	nm

6.3 Modulator Selection

According to Figure 6.1 and the parameters in Table 6.1, the simulation results of the modulator selection are given in Table 6.2. The most preferable modulator is the "Dual-drive MZM" by considering performance and costs. The "Direct Modulator" shows the worst performance related to Table 6.2.

Table 6.2 : Table examining the signal quality according to the selected modulator type.

No	Modulator Selection	Tx Max. Q Effect
1	MZ Modulator	546.52
2	Single Drive MZ Modulator Absorption-Phase	554.24
3	Dual Drive MZ Modulator-Phase	556.84
4	Amplitude Modulation	544.81
5	EA Modulator Measured	568.43
6	Dual Port MZ Modulator Measured	602.50
7	Dual Port Dual Drive MZ Modulator Absorption-Phase	551.92
8	Dual Drive MZ Modulator-Phase with QAM	3.27
9	Direct Modulator	544.82

A carefully crafted Table **??** (continued) that assesses various modulator types' signal quality and costs can significantly aid performance analysis. By discerning the pros

and cons of each modulator type, one can make informed decisions on which is best suited for specific use cases for various parameters.

Table 6.2 (Continued) : Table examining the signal quality according to the selected modulator type.

No	Tx Signal Power [dBm]	Rx Max. Q Effect	Rx Signal Power [dBm]	Error Amount [m], for 50 km
1	-22.85	2.98	-126.09	0.12
2	-12.84	2.43	-116.20	0.12
3	-12.27	2.78	-115.77	0.12
4	-22.86	3.11	-126.11	0.12
5	-22.86	3.45	-125.90	0.12
6	-20.21	0.00	-121.44	0.12
7	-15.72	1.00	-118.36	0.12
8	-17.40	0.00	-119.70	4.71
9	-24.94	0.00	-126.65	NA

6.4 Signal Level and Frequency Shift Tracking

According to the design in Figure 6.2, a shift occurs in the standard reflection region when FBG sensors are subjected to any external influence. As shown in Figure 6.2 (A), the reflection of a signal designed at 1550nm normally occurs at 1550nm. Still, when positive (shifted to the right side of 1550nm) or negative (shifted to the left side of 1550nm) pressure is applied to the FBG sensor, a shift in energy and frequency of the reflected signal occurs. A decrease in energy is observed in the reflected part at 1550nm [6].

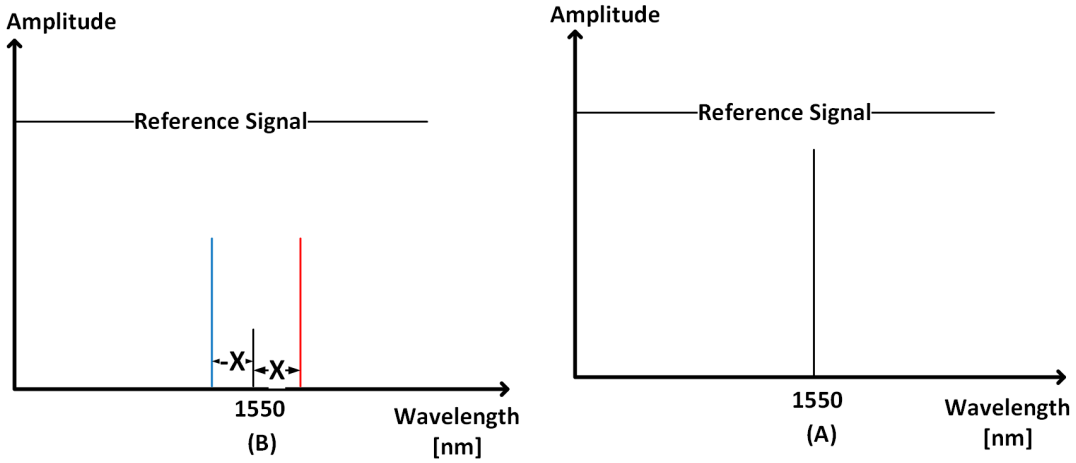


Figure 6.2 : FBG signal shifting detecting.

6.5 Detection with Coding (PN-Code) Method

This method aims to integrate the coding technique that provides the highest correlation with itself, thanks to the unique coding technique used in GPS systems, into FOS applications for location determination. With this technique, under the condition of 1, 2, 4, 8, 16, 16, 32, 64, 128, and 256 bits of code levels under high noise in the movement of an object at a range of 50 km, the error amount in position detection is 124, 86, 16, 4.5, 3.7, 0.35, 0.17, 0.05, and 0.01 m, respectively as mentioned in section 5.5. Using more coding bits significantly improves resolution but should be considered due to the increased processor power required for longer codes. As the number of bits in the coded signal increases, the system is less affected by noise. Although noise power is much higher in a 256-bit code, precise location detection is possible thanks to cross-correlation.

6.6 Sweeping Train Feature

Before opening a line for operation, an empty sweeping train is sent to test the robustness and suitability of the track. The goal is to ensure that the track is in the correct physical condition and that the signaling system, if present, is working as expected (by passing an empty train over the track) before human or freight transportation begins. The sweeping/guide train is also at risk from a safety perspective. An example of this risk is shown in Figure 6.3. The guide locomotive derails due to the emptying of the track underneath.

Figure 6.3 : High-Speed Train (YHT) derailment of the guide locomotive on the Ankara-Sivas line, June 2023.

FOS applications can play a significant role, especially in detecting rapidly occurring problems in the physical structure of the track. FBG sensors, placed at critical points or at regular intervals along the entire track, can monitor the track's condition by continuously tracking signal levels. Figure 6.4 shows a design example of signal tracking. Figure 6.5 (A) illustrates the general signal level of a calibrated track. In the event of a problem in a region, as shown in Figure 6.5(B), there will be a change in the reflected signal of the FBG sensor in that region [6,23,28,40]–[42]. This change will be triggered by detecting less power at the expected frequency during the scanning of fixed frequency points, and the intensity and direction of the event can be determined by detecting the shift and shift frequency width through moving frequency detection.

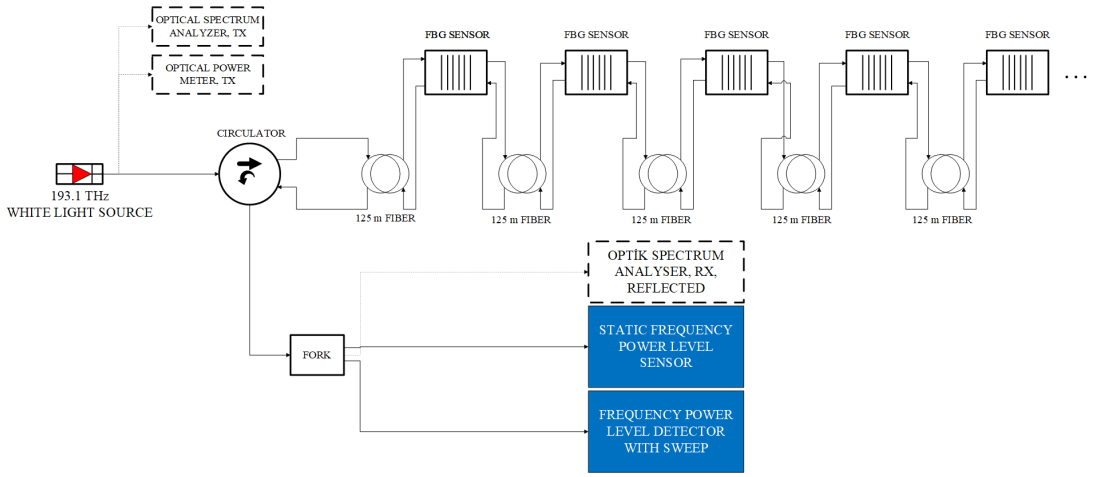


Figure 6.4 : Example signal tracking design.

Figure 6.5 (A) shows the state of a calibrated track's signal level. If a problem occurs in the track, as in Figure 6.3, there will be a change in the reflected signal of the FBG sensor in that region [6,23,28,40]–[42]. This change will be triggered by detecting less power at the expected frequency during the scanning of fixed frequency points, and the intensity and direction of the event can be determined by detecting the shift and shift frequency width through moving frequency detection.

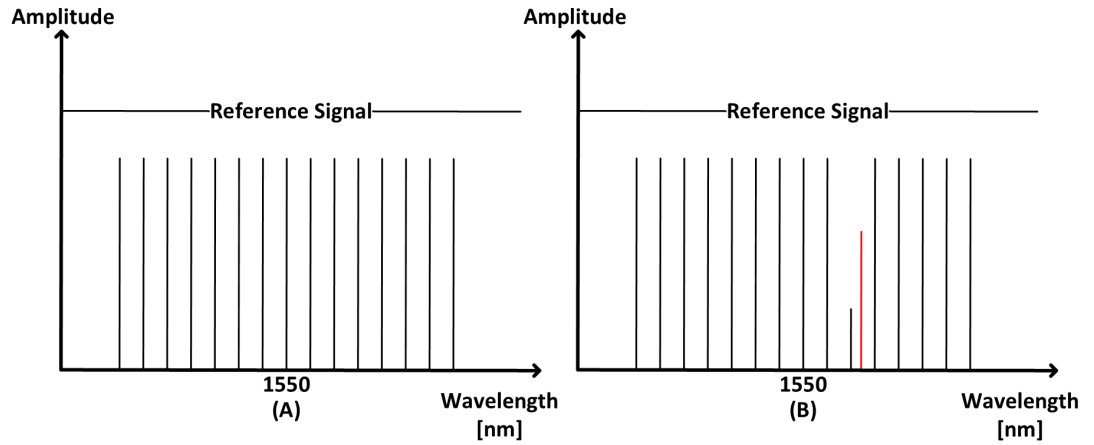


Figure 6.5 : FBG design of the general signal level (A) and the reflected signal (B) examination.

As Figure 6.5 demonstrates, track disturbances can be detected, and at the same time, the movements of sweeping or other trains can be detected through shifts in these frequencies. Figure 6.6 shows the structure of a moving, sweeping train affecting the

track. The reflection of the signal due to the train's movement on a solid track provides information about the speed and direction of the train. The effect of a guide train moving on an empty track can be examined in this way, and the detection of possible future problems can be confirmed by monitoring changes in reflection levels beyond normal.

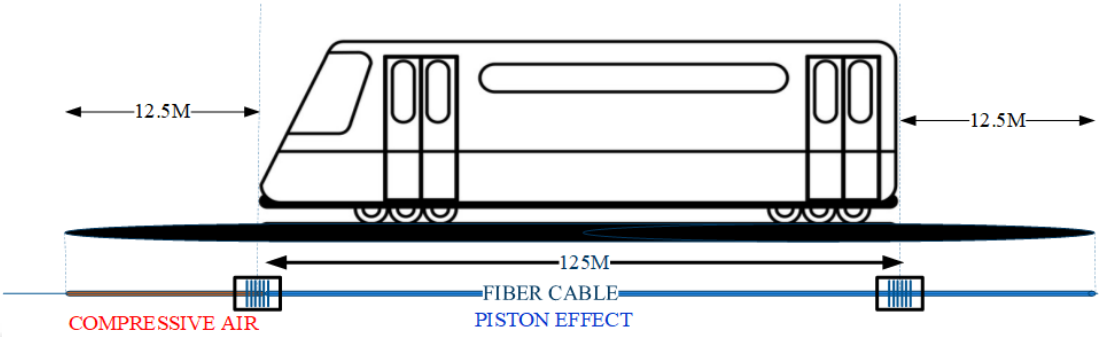


Figure 6.6 : Clearance train.

6.7 Conclusion of Proposal of Real-Life System

Tracking the track is a vital and critical operation in rail systems. Therefore, minimizing or eliminating human errors in track status monitoring will significantly enhance the system's safety. By integrating the coding technique of signal processing with the coding of the source signal, the proposed system allows for the high-precision positioning of moving objects. Additionally, continuous monitoring of track continuity using a specially designed FBG sensor allows for detecting shifts in selected frequencies, enabling the estimation of the intensity and direction of events occurring at the relevant point. Thus, the suggested system significantly contributes to rapidly tracking moving objects' positions and movement directions and quickly detecting disturbances on the track. Moreover, compared to currently used systems for monitoring vehicles and tracks on long lines, the cost per kilometer for the proposed system is much lower. However, it should be noted that existing systems cannot protect against natural disasters. In contrast, FOS systems have the potential to contribute significantly to accident prevention and high resilience against natural disasters by continuously monitoring both the track and moving objects.

7. CONCLUSION

In conclusion, this thesis has significantly contributed to the fiber optic sensing (FOS) systems field, especially regarding the railway and urban transportation industries. FOS systems are increasingly being recognized as a promising technology for monitoring structural health, and this research study underscores their potential to revolutionize the way railways are monitored and maintained. Through a judicious blend of theoretical analysis, numerical simulations, and experimental measurements, the practicality and efficacy of a new FOS system for railway monitoring have been convincingly demonstrated. The research has yielded valuable insights into the system's performance under diverse conditions, leading to optimization. The strong correlation between the outcomes of the experiments and simulations provides additional evidence for the validity of theoretical models and the efficiency of the suggested system, indicating that the models have been accurately developed and the system is functioning well. The high congruence between experimental and simulated results further verifies the proposed models' strength and the suggested system's usefulness. One of the key findings of this research is the remarkable improvement in localization resolution made possible by the FOS system. By measuring strain and temperature along the rail, the system can accurately identify potential defects or anomalies far more effectively than traditional methods. Increased precision in the railway system is of utmost importance as it helps identify problems early. Doing so can prevent major issues, reduce the risk of accidents, and promote overall railway safety. The significance of precision in the railway system cannot be overstated, as it directly impacts the safety of both passengers and employees. The transmission of data across a track line spanning 50 km in high Gaussian noise conditions required the development of transmitter signal coding with pulse sequences ranging from 1 to 256 bits. As a result, the localization errors for these sequences were calculated to be 118.4, 68.1, 4.8, 0.4, 0.3, 0.3, 0.2, and 0.1 meters, respectively. The hybrid FOS system is a remarkable achievement that enhances the efficiency and safety

of railway operations. It is cost-effective, versatile, and equipped with advanced cross-correlation and reflected signal power level detection features. These features facilitate accurate localization with two systems, enabling the system to determine the direction and speed of the train in a single processing cycle. The system is highly efficient, catering to multiple monitoring tasks and comprehensively analyzing the railway track and surrounding environment by combining distributed and discrete sensors. Reviewers have highly regarded this research for its ingenuity and technical level. It can potentially revolutionize FOS systems for railway and urban transportation monitoring. In summary, this thesis represents a significant breakthrough in FOS systems, offering enhanced localization resolution, a cutting-edge hybrid system, and precise direction and speed extraction. These findings substantially contribute to the field and inspire further advancements in FOS systems for railway and transportation applications. Furthermore, FOS systems offer increased flexibility and continuous sensing capability with a single fiber optic line compared to traditional sensing methods. This makes them a cost-effective and efficient solution for achieving sustainability and security in transportation applications. The thesis explores explicitly the feasibility of utilizing a hybrid Fiber Bragg Grating (FBG) system for high-precision positioning of moving vehicles in urban metros. By addressing key research questions related to sensing methodologies, technical specifications, accuracy, and potential applications, the research demonstrates that the hybrid FBG system can achieve high-precision positioning, speed, and direction determination within one to two centimeters, regardless of distance and under high noise levels. This represents significant progress compared to existing systems that often have localization errors exceeding two meters. The hybrid system eliminates the need to examine multiple signals for different determinations, streamlining the process. Furthermore, the study delineates the technical requirements for deploying the hybrid system, encompassing signal encoding, sensor setup, and data processing methodologies. The research investigates the prospective uses of the hybrid system in urban transportation systems, with a specific emphasis on its ability to augment operational efficiency and safety. This study facilitated the integration of the Dual Port OTDV component into the OptiSystem commercial software, enabling international users to utilize it. This thesis

contributes to expanding knowledge of high-precision positioning systems for moving vehicles. The hybrid FBG system's potential to revolutionize urban transportation is significant, with the potential to increase efficiency and safety. The system has already directly impacted the industry, and as a result, it holds transformative potential for railway transportation sensing. This development will lead to a safer and more efficient experience for passengers and operators.

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