TEEN Protocol Adaptation for Energy Optimization in Railway Track Monitoring

Ljubomir Vračar[1], Dragan Marinković[2], Milan Stojanović[1], Miloš Milovančević[3]

[1]Department of Microelectronics, Faculty of Electronics Engineering, Aleksandra Medvedeva 4, 18000 Niš, Serbia
{ljubomir.vracar, milan.stojanovic}@elfak.ni.ac.rs

[2]Mechanical Science Institute, Vilnius Gediminas Technical University – VILNIUS TECH, Plytinės st. 25, LT-10105 Vilnius, Lithuania,
dragan.marinkovic@vilniustech.lt

[3]Faculty of Mechanical Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia,
milos.milovancevic@masfak.ni.ac.rs

Abstract: Railway systems rely heavily on sensor networks to ensure the safety, reliability, and efficiency of operations. These networks monitor parameters such as track vibrations, structural integrity, and environmental conditions. However, sensor nodes deployed along tracks or on train components often operate in remote environments with limited power supplies. This study adapts the Threshold-sensitive Energy Efficient Sensor Network (TEEN) protocol to railway applications to optimize energy consumption and enhance data accuracy. Two methods for defining the Soft Threshold (ST) value are proposed: (1) using the difference between consecutive measured values and (2) using the rate of change over time. Experiments simulate railway scenarios, analyzing energy savings and data accuracy under various ST values. Results show that the second method significantly improves energy efficiency and data integrity, ensuring reliable monitoring with minimal energy expenditure. The proposed method achieved energy savings of up to 95% while maintaining data accuracy with an RMSE < 1 and Pearson's correlation coefficient > 0.95. These findings have implications for extending sensor lifetimes and enhancing the robustness of railway monitoring systems. Future research will explore scalability in large railway networks and integration with IoT platforms.

Keywords: Wireless Sensor Network; Sensor Node; Energy Consumption; TEEN protocol; Soft Threshold

1 Introduction

Railway networks are critical infrastructures that demand constant monitoring to ensure safety and operational efficiency [1]. From detecting structural anomalies to monitoring track vibrations and environmental conditions, sensor networks play a pivotal role. However, these sensor nodes are often battery-powered and deployed in remote or harsh environments, where recharging or replacing batteries is challenging. Current railway monitoring systems face challenges such as limited battery life, inconsistent data accuracy, and difficulties in predictive maintenance due to energy constraints.

This paper examines how the TEEN protocol, originally designed for general wireless sensor networks, can be tailored to the unique requirements of railway systems. Specifically, we explore optimizing energy consumption through effective thresholding strategies, ensuring accurate data collection for track monitoring and predictive maintenance.

A WSN is a self-configuring network composed of hundreds or even thousands of autonomous devices called sensor nodes. The sensor nodes, or just nodes, are equipped with one or more sensors, a processor module, a communication module, and usually a battery, such as a power supply. They have the ability to monitor physical or environmental conditions, such as vibration, sound, pressure, air quality, radiation, humidity, moisture, and so on. The gathered data from sensor nodes are transmitted wirelessly between nodes or to the base station. Because of the small size, cost-effective, long life cycle of the devices [2, 3, 4] and their easy deployment, WSN has been effectively implemented in home automation, industrial sensing [5, 6, 7], intelligent transportation systems, monitoring of environmental conditions [8, 9, 10], remote patient monitoring, infrastructure security, event detection, etc.

Based on the structure WSNs can be divided into two groups. The homogeneous WSNs in which all sensor nodes have the same hardware and software conditions, and the heterogeneous WSNs whose sensor nodes have two or more different computing power, communication range, energy, and others. On the other side, based on the way of operation, WSNs are divided into proactive and reactive networks. A reactive network responds immediately to changes in the relevant parameters, while proactive networks collect data and periodically transmit them.

Sensor nodes are generally deployed in harsh and inaccessible environments and are supposed to operate over long periods without human intervention. In most cases, the sensor nodes are battery-powered because it is impossible to supply them with a continuous power supply. Considering that batteries are limited and irreplaceable power sources, and the WSN needs to work for a long time, it is necessary to minimize the energy consumption of individual sensor nodes to maximize their lifetime and the lifetime of the entire network.

Two ways to extend the lifetime of sensor nodes are implementing the additional energy source or reducing the consumption on the nodes. Energy harvesting technologies based on solar, wind, thermal, mechanical, or electromagnetic energy can recharge batteries. An RF signal is composed of information and energy, and the transmitted energy can be recycled at the receiver side using wireless energy harvesting technology [11, 12, 13]. However, changes in battery performance during alternating charge and discharge cycles are not negligible [14, 15]. The highest amount of energy is consumed during the data transmission. Reducing energy consumption is possible by using low-power transceiver modules or by implementing routing protocols that regulate the amount of transmitted data. One of the most effective ways to transmit data is using LoRa modules. A LoRa module represents a physical layer of the LoRaWAN wireless communication protocol developed by LoRa Alliance. The operation of LoRa modules is based on the Chirp Spread Spectrum modulation technique, and it is associated with low power consumption and long-range communication, which makes it an attractive solution for the WSN, Internet of Things, and Machine-to-Machine communication. One proposed routing protocol is the Threshold-Sensitive Energy Efficient Sensor Network Protocol (TEEN). In this protocol, a network is divided into clusters, so every cluster has a cluster head and cluster members. The cluster head collects data from members and transmits them to the base station. The member will transmit data to the base station only if one of the two conditions is met. The measured values are higher than the Hard Threshold (HT) value, or the change in the measured value is greater than the predefined value named Soft Threshold (ST).

Implementation of this protocol will reduce energy consumption because less data is sent to the base station. However, less data on the receiver side tends to reduce the accuracy of measured parameters. This paper aims to describe a method for determining the ST value for the TEEN protocol that provides high data accuracy on the receiver side. Another goal is to investigate how much energy can be saved in a sensor node equipped with a LoRa module by applying the calculated ST algorithm. The rest of the paper is divided as follows. Section 2 presents a literature review that describes different approaches for reducing the energy consumption of sensor nodes. Section 3 presents two ways for the determination of ST value. Section 4 contains results that explain the accuracy of the measured parameter on the receiver side and energy consumption at the sensor node depending on the selected ST value. Finally, Section 5 contains the conclusion and plans for future research.

2 Related Work

Wireless sensor networks have been increasingly adopted for railway monitoring, addressing issues such as track deformation, vibration analysis, and environmental stressors. However, these systems face energy constraints that limit their long-term operation. Studies on energy optimization in general sensor networks have proposed various protocols, but their application to railway-specific scenarios remains underexplored. This paper seeks to bridge this gap by tailoring the TEEN protocol for railway monitoring applications. Energy management represents managing various supply mechanisms and efficient consumption of available energy in a sensor node. There are different approaches, algorithms, and protocols to achieve maximum energy efficiency.

The first way to reduce energy consumption is to select a radio module of appropriate performance. Long transmission range and low power consumption make LoRa well-suited for application in large and harsh environments. The power consumption of the sensor node equipped with a LoRa transceiver depends on many parameters, such as acknowledged transmission, spreading factor, coding rate, payload size, and communication range [16, 17]. The analytical models that characterize device current consumption, device lifetime, and energy cost of data delivery with LoRaWAN were analyzed in [8] based on measurements performed on a currently prevalent LoRaWAN platform. The stability and periodic behavior of micro-electromechanical systems (MEMS), as examined by [18, 19], can provide valuable insights into optimizing vibration sensors for railway monitoring systems. Incorporating such advancements into TEEN protocol implementations could ensure more stable and efficient data acquisition in harsh railway environments. Energy consumption does not have a significant variation with the payload size at lower SF, but these variations become notable for the higher values of SF. The transmission current is constant up to a certain level of RF output power, but after that, the current consumption increases nonlinearly at higher RF output power [10]. The other research [20, 21], made on SX1276 and SX1272 LoRa transceivers, shows that power consumption can be minimized by reducing the transmitter output power and the power supply voltage. Increasing RF output power should be used for higher transmission ranges before raising the spreading factor, and the transceiver should be switched off during sleep mode. The main limitation in wireless transmission is the duty cycle, which represents the maximal number of transmissions in a defined time interval. A mathematical model to overcome this limitation and improve the node's transmission and power efficiency is proposed in [20, 21]. The radio module is a major contributor to energy consumption of each node. The operation of a radio module includes transmitting, receiving, listening and sleeping processes. Minimization of the energy consumption can be achieved by putting the radio module in sleep mode, which consumed the smallest amount of energy, when there is no needs for transmitting or receiving data. As energy consumption is always of great interest in railways, [22, 23], the model should consider, among mentioned operation, energy consumption of switching components that put the radio module in active or sleep mode [24, 25].

The required information is usually gathered by a fixed schedule and transmitted to the base station, which is connected to the server. The merged data-collecting method in time-division multiple access can provide uniform energy consumption across all nodes [26, 27]. Reducing the number of generated data packets contributes to lower energy consumption. The implementation of the system with a control component that can manage a WSN and determine whether the sensors should transmit data is presented in [28, 29]. The proposed system is focused on reducing the energy consumption of a WSN by removing duplicated traffic by combining concepts such as learning (on the controller), content awareness (on the sensor nodes), and caching.

In most cases, the same amount of energy is consumed to transmit data whenever to the distance between the sensor node and the base station. It is necessary to reduce the distance between sensor nodes and the base station and reduce the output power level of nodes closer to the base station to optimize energy consumption. Paper [30] proposes an energy optimization model based on data transmission at a lower energy level.

The data transmission in the WSN is classified into direct and indirect methods. The network with the direct data transmission method includes sensor nodes and base station. The sensor nodes collect and transmit data directly to the base station. The problems of this method occur if the sensor node is far from the base station. The battery power can drain quickly due to the long distance needed to cover the data transmission, and the data may not be sent to the base station if the sensor node is too far away. The indirect transmission method that can solve the mentioned problems contains the sensor nodes with additional functionality. These sensor nodes, called cluster heads, collect data from other sensor nodes and send them to the base station. A node is selected as the cluster head from each cluster using computational and probabilistic operations based on the higher residual energy. However, the problem in both methods is a different amount of energy consumption because of the unequal distance between sensor nodes to the base station or cluster heads. Hierarchical routing protocols are prominent among various strategies for using network energy effectively [31, 32]. Two levels of threshold-based hybrid clustering and routing algorithms with threshold-based data collection for heterogeneous wireless sensor networks are proposed in paper [33, 34]. Threshold-based protocols prevent unnecessary transmission when minor or no change is observed to reduce unnecessary data transmission.

The TEEN Protocol is proposed for reactive networks, and it is a data-driven technique that uses HT and ST characteristics. HT value defines a predefined threshold value that the node must transmit to the Cluster Head (CH). ST value is a little distinction in the detected value that initiates the sensor node to transmit data to the (CH). A potential problem can arise if the detected properties never reach the Hard/Soft Threshold value. Then, there is no communication between the sensor node and the base station, which leads to the unknown status of the sensor node. Paper [35, 36] analyses the impact of the number of sensor nodes on the network life. The network life is extended when the energy threshold equation of the TEEN protocol is tuned along with dynamically changing the cluster heads after some rounds. Paper [37, 38] proposes a time-critical threshold-based protocol in which data are transmitted when the sensed threshold value meets the time-critical based. The first condition for data transmission is related to HT or ST values, and the second threshold level is time-critical. If a sensed value equals the time-critical value, it starts data transmission as a high priority. The isolated node occurs in TEEN protocol because of the random selection of cluster head and not equally distributed energy on every node. The modified TEEN protocol that can accommodate the isolated node, named protocol threshold sensitive energy efficient sensor network with isolated nodes (TEEN-IN), is proposed in the paper [39]. The cluster head is based not only on probability but also on the energy ratio in nodes. Selection of the appropriate cluster heads and localization of the cluster's membership, based on fuzzy logic, consumes less energy than periodic clustering. Research [40] proposes a hybrid algorithm for energy consumption optimization based on neural network and Fuzzy logic, named the Neuro-Fuzzy algorithm. The optimization process considers available energy, proximity to the base station, and mobility factors to increase the network lifetime and decrease the death of the node.

3 Methodology for Determining Soft Threshold Value

To simulate railway conditions, vibration sensors were placed on a test railway track segment. The TEEN protocol was implemented with two ST determination methods: (1) the difference between the current and previously transmitted values and (2) the rate of change of vibrations over time. Energy consumption and accuracy were measured under varying ST values, reflecting conditions such as heavy axle loads and high-speed train operation. Although the application of the TEEN protocol is well described, the scientific literature does not contain papers that describe the process of selecting the ST value depending on a sensor node application. With the implementation of the TEEN protocol and ST algorithm, the amount of data transmitted from a sensor node is reduced. It contributes to the reduction of power consumption in a sensor node, but less data on the receiver side decreases the accuracy of the measured parameter. The receiver reconstructs the original data using received values with an unavoidable error, which depends on the number of received data. Therefore, the error value is higher if the reconstruction is made using the less received value or if the value of ST is higher. On the other hand, a smaller value of ST increases the accuracy of the receiver side, but the sensor node consumes more energy. Two approaches to finding the appropriate value of ST, which contribute to reduced energy consumption in a sensor node while the accuracy on the receiver side is still high, are described in this paper.

The power consumption analysis was conducted for the sensor node, presented in Figure 1. The sensor node is composed of microcontroller PIC18F45K22, vibration sensor, and LoRa module RN2483.

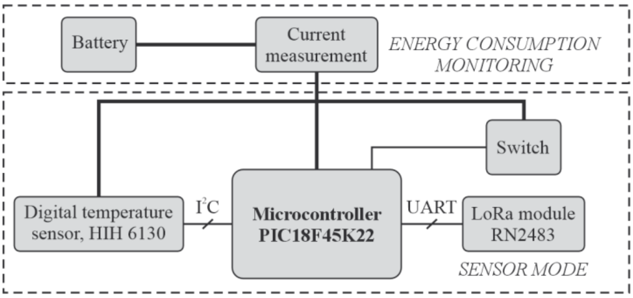

Figure 1
The block schematic of the sensor node

A single measurement was performed approximately every 5 min, so the number of total transmitted packets is 2427. One packet is composed of NodeID, which describes which node sends data, TempID, which indicates the meaning of the following value, and the measured value of vibration. The LoRa module adds a preamble at the beginning of every packet. The transmission time of a single packet is 1392 ms, while the consumed energy is 70.16 mJ. The subject of this test is a diesel engine train – DMV manufactured in "Metrovagonmaš" for Serbian Railways. presented in Figure 2.

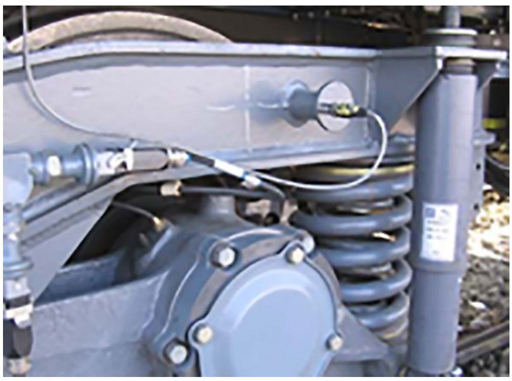

Figure 2
The vibration sensor experimental setup

The TEEN protocol with the ST algorithm is implemented in the sensor node to reduce the number of transmitted packets and energy consumption. The ST values were determined in two ways, as the difference between the measured and last sent value and as the change rate between the last two measured values. In both cases, the sensor node measures the vibration and determines if it transmits the packet. If the transmission is needed, the LoRa module is turned on and sends data. After that, the sensor node goes to sleep mode until the following measurement. When transmission is not necessary, the sensor node goes to sleep.

3.1 Soft Threshold based on Difference

The first approach for determining the ST value is based on the difference between the measured and the value that was sent last. A need for packet transmission is described as

$$transmit\ packet = \begin{cases} yes,\ x_m - x_0 \geq ST,\ x_0 = x_m \\ no,\ x_m - x_0 < ST,\ x_0 = x_0 \end{cases} \quad (1)$$

x_m is the last measured value, and x_0 is the last transmitted value.

A packet is transmitted if the calculated difference is equal to or greater than the defined ST value. Figure 3 shows the vibration changes over time on the receiver side for different ST values.

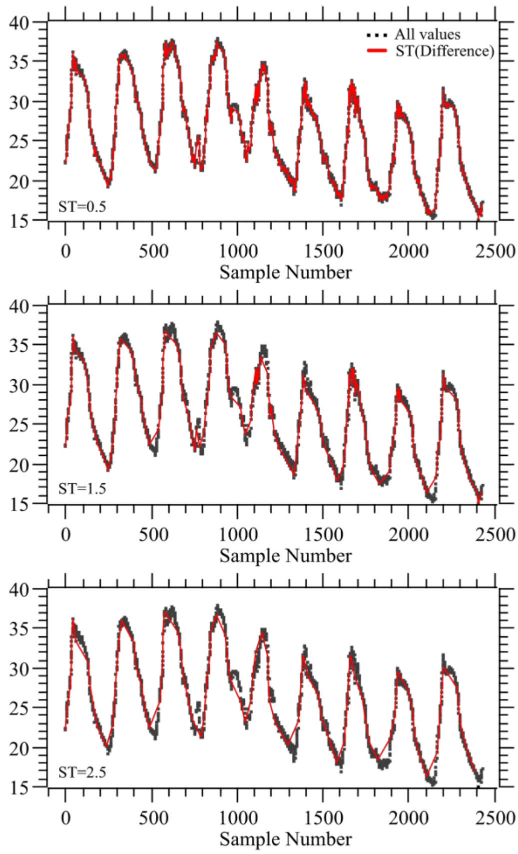

Figure 3
The measured values of vibration – receiver side
The number of packets for transmittion is determined by ST based on the difference

3.2 Soft Threshold based on Change Rate

The second approach for determining ST values, based on the rate of change, proved particularly effective for railway applications. It allowed for significant energy savings of up to 95% while maintaining the accuracy required for detecting track anomalies. This approach is well suited for scenarios requiring both high energy efficiency and reliable anomaly detection, such as monitoring high-speed railway segments. The change rate is calculated as the difference between the last two measured values divided by the time between these measurements. In this case, a packet transmission operation depends on

$$transmit\ packet = \begin{cases} yes, & \dfrac{x_m - x_{m-1}}{\Delta t} \geq ST \\ no, & \dfrac{x_m - x_{m-1}}{\Delta t} < ST \end{cases} \tag{2}$$

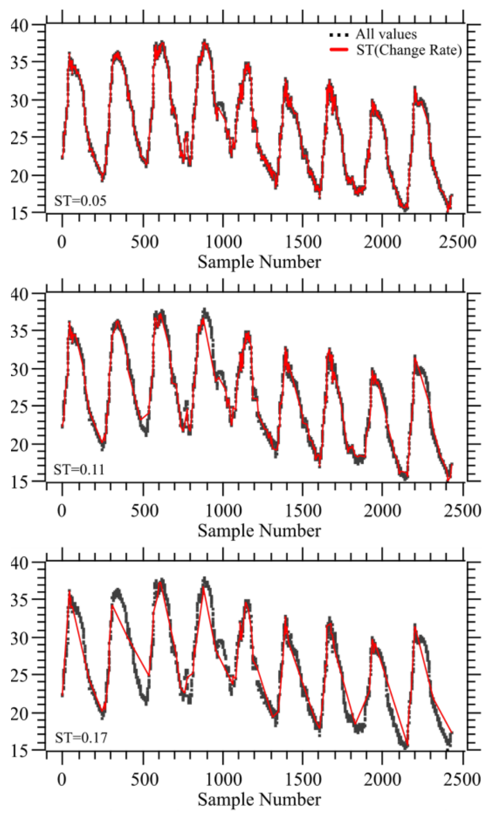

Figure 4
The measured values of vibration – receiver side
The number of packets for transmittion is determined by ST based on the difference

The measured value is denoted by xm, and xm-1 is the value measured previously, while Δt represents the time between measurements. A sensor node sends data if the change rate is equal to or greater than the ST value. In this way, the detection of high-intensity changes and sudden low-intensity changes is ensured. The vibration changes on the receiver side for ST calculated using the change rate are presented in Figure 4.

Depending on the selected ST value, a different number of measured values will be sent to the receiver. As can be seen, the higher value of ST contributes to less accurate data on the receiver side in both cases. The reconstruction process on the receiver side includes interpolation to initial 2427 values to provide missing data and improve accuracy. The reconstructed curves are compared with the original by Root Mean Square Error (RMSE) and Pearson's Correlation Coefficient to determine the optimal ST value.

4 Results and Discussion

Regarding the receiver side, the maximal number of received values during the noted measurement period is 2427. With the increasing ST value this number is reduced. Figure 5 shows the number of received packets if the ST value is calculated using the first described method.

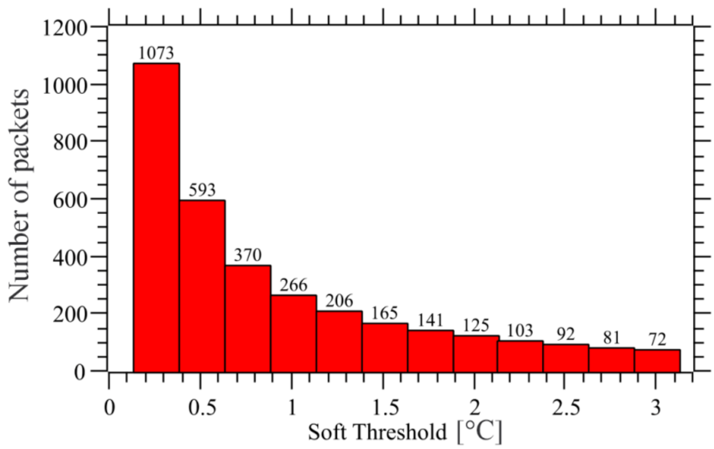

Figure 5
The number of the received packet for different value of ST determined as the difference

Implementation of this method contributes to reducing the number of packets the sensor node should transmit to the receiver. Because of that, less amount of energy is needed for the transmitting operations. Reduction of energy consumption depending on the ST value is shown in Figure 6.

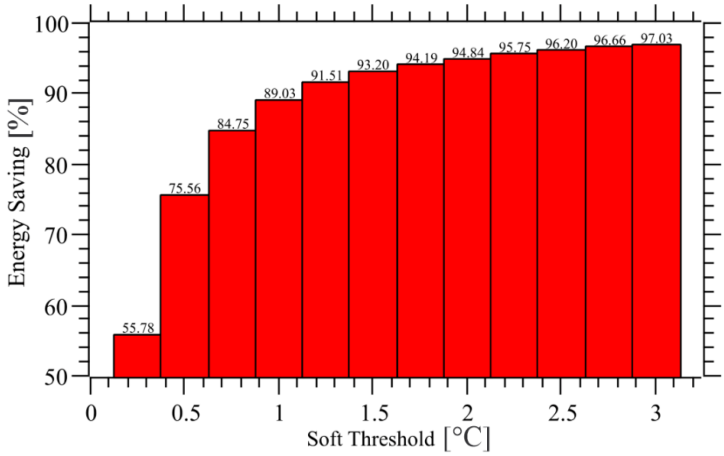

Figure 6
The amount of saved energy in sensor node for different value of ST determined as the difference

The higher value of ST contributes to the higher reduction of energy consumption, and it provides the extended lifetime of the sensor node. However, increasing ST reduces the accuracy on the receiver side because the receiver gets fewer packets. The receiver can reconstruct the original data using the received packets. The reconstructed data are compared with the original using RMSE and Pearson's Correlation Coefficient to determine that the value of ST can be used in the sensor node. RMSE shows the mismatching between data, and Pearson's Correlation Coefficient shows linearity between them. The values of RMSE and Pearson's Correlation Coefficient depending on the ST value are shown in Figure 7.

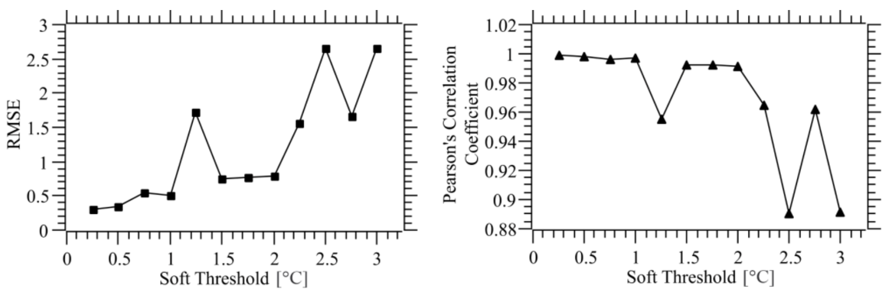

Figure 7
The RMSE and Pearson's Correlation Coefficient between measured and reconstructed received data for different value of ST determined as the difference

As can be seen, it is impossible to determine the steady dependence of RMSE and Pearson's Correlation Coefficient from ST. We assumed that the acceptable value of RMSE is equal to or smaller than one, and Pearson's Correlation Coefficient is equal to or greater than 0.95 (95% linearity). Due to the inconsistent dependence, only the four smallest values of ST can be considered. Therefore, higher energy saving can be achieved when ST equals one or when the sensor node transmits a packet when the vibration is changed minimum of one Celsius degree. In this case, the sensor node would have about 89% energy savings.

The energy absorption capabilities of hierarchical structures, such as the fractal buffer inspired by gecko's pads [41], offer a novel perspective for enhancing sensor node durability. Adopting similar designs in railway sensor nodes could improve their resilience to vibrations and environmental stress, further complementing the energy efficiency achieved through the TEEN protocol.

Another approach for determining ST is applied to provide the possibility of detecting sudden vibration changes of lower intensity. Also, it is expected to obtain a consistent dependence on RMSE and Pearson's Correlation Coefficient, which would ensure additional Energy Savings. As mentioned previously, the ST value in this method is calculated as the quotient of the difference between two consecutive measurements and the interval between them. The number of received packets in this case is shown in Figure 8.

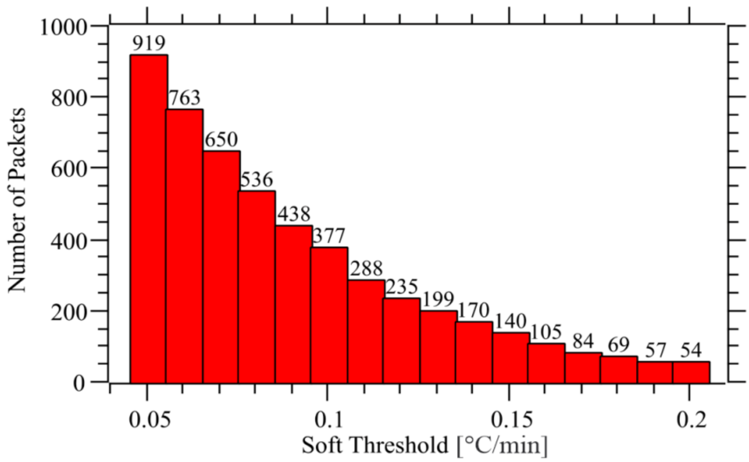

Figure 8
The number of the received packet for different value of
ST determined based on the change rate

With the increase of ST value, the number of transmitted packets decreases, as in the first presented approach case. Energy consumption is also reduced proportionally to the number of packets. Figure 9 shows the Energy Saving depending on the ST value.

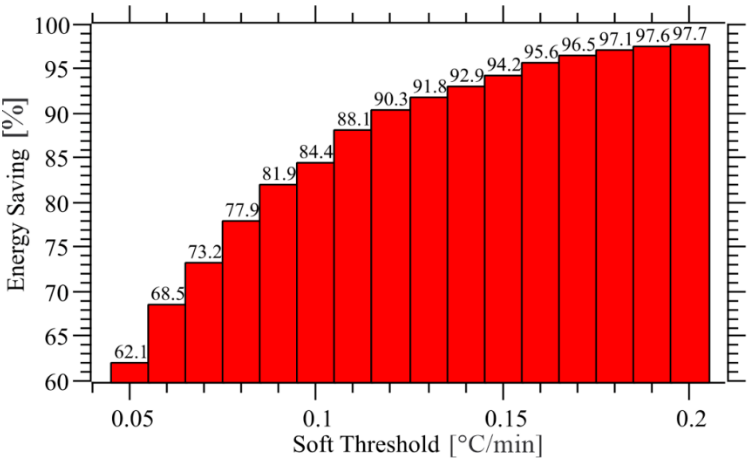

Figure 9
The amount of saved energy in sensor node for different value of
ST determined based on the change rate

As it is expected, a higher ST value contributes to less transmission packet and lower energy consumption of the sensor node. The values of maximal energy saving are similar in approaches for the observed range of ST. The same principle, as in the first approach, is conducted to compare data accuracy at the receiver side. Figure 10 presents the dependence on RMSE and Pearson's Correlation Coefficient of ST value, which is calculated based on the change rate of measured vibration.

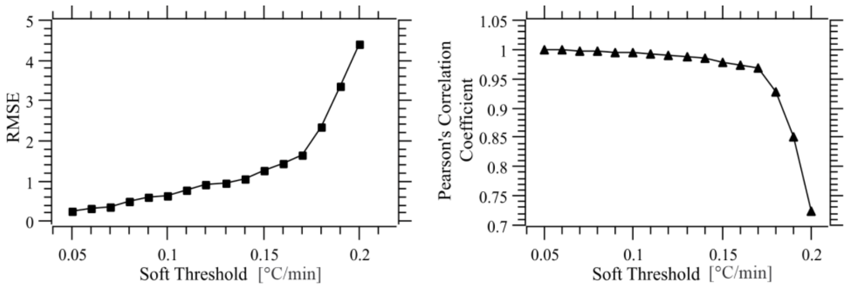

Figure 10
The RMSE and Pearson's Correlation Coefficient between measured and reconstructed received data
for different value of ST determined based on the change rate

The obtained values of parameters presented in Figure 10 show that RMSE increases slightly up to ST value 0.17 °C/min, while for higher ST values, the increase is more intense. It can be seen that the decrease of the Pearson correlation coefficient is less pronounced up to 0.17 °C/min, after which it decreases rapidly. Using the same threshold values of RMSE and Pearson's Correlation Coefficient, as in the first approach, the Saving Energy with the ST values determined based on the change rate is about 95%. This approach also allows ST values to be determined for applications where both higher and lower accuracy are required.

Conclusions

Adaptability of TEEN Protocol to Railway Sensor Networks

- Demonstrates significant energy savings while maintaining data accuracy.
- Tailoring the Soft Threshold (ST) value to railway-specific parameters (e.g., track vibrations, environmental conditions) enhances efficiency and reliability.
- Future work will integrate these methods into large-scale railway operations, focusing on predictive maintenance and real-time safety monitoring.

Energy Conservation in Wireless Sensor Networks (WSN)

- Various hardware and software methods are employed to reduce power consumption and extend the lifetime of sensor nodes.
- Because data transmission demands a major amount of energy, different protocols at varying transmission levels are introduced to mitigate energy usage.

TEEN Protocol with Soft Threshold Method

- Significantly reduces sensor node energy consumption by lowering the number of transmitted packets.
- The ST value represents the minimum change in measured parameters that triggers data transmission.

Two Approaches to Determine the ST Value

- Difference from the Last Sent Value: ST is the gap between the newly measured value and the last sent value.
- Change Rate: ST is based on the difference between the two latest measurements divided by the time between them.

Accuracy vs. Energy Consumption

- Fewer transmitted packets reduce energy consumption but may decrease data accuracy.
- The sensor node used in testing (vibration sensor, microcontroller, and LoRa module) measures performance against the original data (transmission without TEEN) using RMSE <1 and Pearson's Correlation Coefficient > 95% as benchmarks.

Results of the Second ST Method

- Achieves up to 95% energy savings while maintaining acceptable data accuracy.

- Provides more accurate data on the receiver side with fewer transmitted packets.
- The energy used to determine whether to send data is negligible compared to transmission energy, offering significant overall savings.

Future Research Directions

- Explore the scalability of the TEEN protocol in large railway networks, including data aggregation from multiple sensor nodes and integration with centralized IoT platforms.
- Investigate the protocol's application in high-speed rail environments and its ability to simultaneously monitor multiple parameters.

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List of Abbreviations

WSN – Wireless Sensor Network
TEEN – Threshold-sensitive Energy Efficient Sensor Network
ST – Soft Threshold
HT – Hard Threshold
LoRa – Long Range Communication
RMSE – Root Mean Square Error
IoT – Internet of Things

List of Symbols

x_m – Last measured value
x_0 – Last transmitted value
Δt – Time interval between measurements

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