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DEVELOPMENT AND IMPLEMENTATION OF WIRELESS SENSOR NETWORKS (WSN) FOR INFRASTRUCTURE MONITORING, WITH A CASE STUDY OF THE BRIDGE ON THE BOSNIA RIVER IN DOBOJ

Sandi Božičković

Secondary School of Transportation and Electrical Engineering, Cara Dušana 18, Doboj, RS, Bosnia and Herzegovina
Corresponding author: sandi.bozickovic@gmail.com

Abstract
This scientific paper investigates the design, development and implementation of a wireless sensor network (WSN) for continuous monitoring and condition assessment of critical infrastructure, such as bridges, buildings and pipelines. Traditional inspection methods are expensive, controversial and often ineffective in detecting early degradation. The proposed system uses WSN nodes equipped with vibration, temperature and humidity sensors, which enable real-time data collection. The paper describes in detail the system architecture, including the choice of an energy-efficient hardware platform, communication protocols (e.g. LoRaWAN) adapted for long-distance data transmission with low power consumption, and the development of software for signal processing at the node itself. The experimental part of the paper includes the placement of a WSN prototype on a simulated structure, thus demonstrating the system's ability to accurately detect and classify structural changes and anomalies. The results show high reliability in data transmission and efficiency in detecting critical parameters. The conclusion emphasizes that the implementation of WSN technology significantly improves preventive maintenance and reduces the risk of catastrophic failures, providing a basis for the development of smart systems for predictive maintenance of infrastructure.
Keywords: Wireless sensor networks, LoRaWAN, Doboj, vibrations, infrastructure monitoring

1. INTRODUCTION

The city of Doboj, due to its strategic geographical position, is a key traffic hub connecting the north and south, east and west of Bosnia and Herzegovina. However, this position also brings significant challenges to the sustainability of its infrastructure. The bridge on the Bosna River, a key link spanning the river and connecting vital parts of the city, is exposed to intense traffic loads on a daily basis. Historically, Doboj has also been subject to periodic flooding, which further threatens the stability and long-term safety of construction projects, including bridges. Conventional approaches to bridge monitoring, which rely on visual inspections and periodic inspections, have proven to be insufficient and inadequate for the early detection of hidden damage that can occur due to constant vibrations, temperature and humidity changes [1]. The absence of continuous monitoring poses a significant risk to public safety and economic stability. The need for a system that could provide precise, continuous and remote insight into the structural condition of the bridge is obvious. In this paper, the problem of traditional monitoring is placed in the context of the specific challenges faced by Doboj. The proposed wireless sensor network (WSN) represents a modern technological solution that could provide proactive risk management and improve the efficiency of maintenance of key infrastructure, making the city more resilient to future challenges[1]. Bridges are a critical component of transport infrastructure. Weathering, traffic congestion, natural

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disasters (such as floods, which are common in Doboj) and seismic activity threaten their integrity. Regular visual inspections are insufficient to detect early stages of damage. Traditional infrastructure monitoring methods, which have been applied for decades, rely primarily on manual and periodic inspections. While traditional methods of visual inspection and localized manual testing have been the cornerstone of infrastructure maintenance for decades, they are fraught with significant limitations that make them increasingly inadequate for modern infrastructure management needs.

1.1.Problem

Bridges are exposed to extreme weather conditions (rain, snow, high and low temperatures), which can damage sensor equipment. Bridges on the Bosna River are subject to flooding, which can lead to physical damage to sensors and loss of data. Water resistant sensors and equipment are required. Due to the public location, there is a risk of vandalism or theft of the equipment, which requires additional physical protection measures. In some locations, it can be a challenge to provide a stable power supply or cellular network for the main node. Engineers and technicians physically inspect the bridge, looking for visible damage. The focus is on noticing cracks, corrosion, deformations, damage to concrete and steel, and the general condition of the load-bearing structure [2]. Inspection can be done with the ground, from a vehicle, using a ladder or scaffolding, or from a boat if the bridge is over water. In more modern versions, drones can also be used. The results depend on the experience and judgment of the inspector. It is not possible to detect internal stress or damage that is not visible to the naked eye. The measurement process is slow and requires a lot of work. It is possible to measure only a few points, which does notgive a complete picture of the state of the entire bridge. The data is static and

- Continuous monitoring: 24/7 data.
- Early damage detection: Automatic anomaly detection.

represents the state at that moment, and does not follow changes over time.

Objective:

Gain a detailed understanding of the current condition, standard practices, and site-specific conditions

1.2.Disadvantages of classical monitoring methods

Traditional methods of infrastructure monitoring, which have been applied for decades, rely primarily on manual and periodic inspections. Although they were the standard, these methods have serious shortcomings that make them inadequate for modern maintenance needs: high cost and time inefficiency, lack of continuity, subjectivity and imprecision, limited availability and safety risks [2]. Increasing traffic load, the impact of climate change and the aging process of infrastructure further emphasize the need to move to a continuous, objective and efficient monitoring system. Wireless sensor networks (WSN) are emerging as a modern technological solution that can overcome these shortcomings and provide proactive risk management.

1.3.Solution

A WSN is a network of autonomous sensor nodes that collaborate to collect, process, and transmit data about the physical condition of a structure to a central station. WSNs) are distributed systems composed of numerous autonomous, small devices called sensor nodes (or "motes"), which are equipped with sensors, a processor, a wireless communication module, and a power source (usually a battery). These nodes are interconnected by wireless communication and work together to collect, process, and transmit data about the physical environment (such as temperature, humidity, vibration, pressure, light, etc.) to a central location (called a "sink" or gateway node) for further analysis [3]. Key benefits include:

- Reduced costs: Less expensive than periodic inspections by expert teams.

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- **Minimal traffic impact**: Installation is carried out without major disruption.
- **Decision support**: Objective data for maintenance plans.

2. METHODOLOGY

This work will be conducted through an expert, analytical and project methodology, combining theoretical research with practical steps of design and implementation [3]. The methodology is divided into six sequential phases:

- Data analysis
- Phase 0: Preparation and modeling
- Phase 1: System architecture design
- Phase 2: Layout and specification of sensor nodes
- Phase 3: Implementation and calibration plan
- Phase 4: Maintenance and upgrade

2.1. Data analysis

Doboj was severely affected by the floods of 2014, which damaged the foundations and load-bearing capacity of many bridges. The region is also seismically active. The bridges on the Bosna River in Doboj represent a challenging but ideal scenario for the application of WSN. The main risks to the structure are erosion of the foundations during floods and traffic loads. The bridges in Doboj are exposed to a unique combination of risks that directly determine the type of sensors and their placement. This analysis directly determines:

- **Types of sensors**: Accelerometers, tensiometers, erosion and temperature sensors are mandatory.
- **Sensor positions**: The most critical points are the pier foundations in the river and the main load-bearing beams.
- **Choice of technology**: LoRaWAN is the undisputed choice due to its range and resistance to harsh conditions.
- **Node design**: Housings must be waterproof (IP68) and vandalism resistant, and the power supply system must be robust and hybrid (solar + battery).

Table. 1. *Geographical and environmental analysis*

ASPECT	DESCRIPTION AND IMPACT ON WSN
Topography	Doboj is located in a valley, surrounded by hills. The Bosna River flows through the city center. Topography can create obstacles for wireless communication. The gateway should be placed on a high point (e.g. a building in the center or a nearby hill) to ensure direct line-of-sight to the bridges.
Climatic conditions	Direct threat to sensor nodes placed on poles and near water. Complete destruction of equipment by torrential waves and washed-up material is possible. Ice can damage sensors and cover solar panels, preventing charging. Low temperatures reduce battery capacity and efficiency. Increased humidity can lead to condensation inside the case and corrosion of electrical connections.
River Bosnia	Water flow varies throughout the year (minimum in summer, maximum during spring snowmelt and autumn rains). Dynamic conditions that directly load the bridge structure. Sensors must be able to detect changes caused by erosion of the foundation, impact of sediment on the piers and rising water levels.

Bridges in Doboj are exposed to aunique combination of risks that directly determine the type of sensors and their placement.

Table. 2. *Risk analysis for bridge construction*

TYPE OF RISK	PROPOSED SURVEILLANCE METHOD
Hydraulic Risks (Floods)	• Sonar sensors or underwater accelerometers to measure the depth of erosion around the foundation. • Accelerometers on the pillars to detect impacts. • Water level sensors (ultrasonic) on the pillars to alert you of rising water levels.
Seismic Risks	• High-resolution accelerometers along the entire structure for seismic monitoring and post-event modal analysis.
Traffic Load	• Strain gauges at critical sections of main beams to measure stresses. • Accelerometers to measure traffic-induced vibrations and identify changes in dynamic behavior.
Weather Conditions	• Temperature sensors for compensating the readings of other sensors and monitoring thermal voltages. • Corrosion sensors that measure the rate of corrosion in concrete reinforcement.

Risk analysis for the WSN system itself it refers to the survival and performance of the sensor system itself [4].

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Tabl. 3. Risk analysis for the WSN system itself

RISK CATEGORY	MITIGATION
Loss of communication (due to topography, interference)	**Detailed field signal testing** (RF survey). Selection of LoRaWAN technology due to longer range and better penetration. Installation of repeaters if necessary.
Loss of power (due to prolonged cloudiness)	**Hybrid systems:** Solar panels + high capacity batteries. **Aggressive power management:** Nodes sleep 99% of the time.
Flood damage to equipment	**Placement strategy:** Place the sensors on the poles ABOVE the historical maximum water level. **Protection:** HERMETICALLY CLOSED housings (IP68 standard) which are completely waterproof.
Vandalism or theft	**Concealed installation:** Incorporation of sensors into the bridge structure where possible. Steel, locked enclosures for outdoor units. Surveillance markings as psychological deterrent.
Misinterpretation of data	**Calibration:** Initial and periodic calibration with reference instruments. "Baseline" period: Collection of "healthy" data over 6 months before alarm thresholds are set. Staff training.

The conclusion of the analysis is that the bridges on the Bosna River in Doboj represent a challenging but ideal scenario for WSN deployment. The main risks to the structure are foundation erosion during floods and traffic loads [5].This analysis directly determines:

- **Sensor types:** Accelerometers, tensiometers, erosion and temperature sensors are mandatory.
- **Sensor positions:** The most critical points are the foundations of the river piers and the main supporting beams.
- **Technology selection:** LoRaWAN is the undisputed choice due to its range and resistance to harsh conditions.
- **Node design:** The housings MUST be waterproof (IP68) and vandal-resistant, and the power system must be robust and hybrid (solar + battery).

2.2. Phase 0: Preparation and Modeling

Before any installation, it is necessary to [6]

- **Detailed inspection and 3D scanning:** Creation of a digital twin of the bridges to accurately identify each critical point.
- **RF Planning (Radio Frequency Survey):** Field testing to determine the optimal location for the Gateway and confirm signal coverage at all intended sensor positions. This is crucial due to the topography of Doboj.
- **Selection of specific equipment:** Selection of specific sensor models, microcontrollers and communication modules that meet the environmental conditions (temperature range, IP rating).

2.3. Phase 1: System architecture design

The system will use a hierarchical architecture with LoRaWAN communication [7].

- Sensor Nodes (Leaf Nodes):
  Microcontroller: ESP32 (due to low cost, good SDK tools and low consumption in deep-sleep mode).
  - **Communication:** LoRaWAN module (e.g. RA-01S or RN2483) for long range and low consumption.
  - **Power supply:** 10,000 mAh Li-Ion battery with a small 10W solar panel for each node. The panel must be at an angle that reduces snow accumulation.
  - **Housing:** Steel, waterproof housing (IP68) with internal silica-gel inserts against condensation [7].
- Communication Gateway:
  - **Location:** Roof of the Doboj University of Applied Sciences or a similar tall, central building with good visibility towards bridges and power source.

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- **Function:** Collects data from all sensor nodes and sends it to the cloud server via LAN/Ethernet connection (or 4G backup).
- **Power supply:** Directly to city power with UPS.
- **Analysis:** Python scripts (using libraries such as NumPy, SciPy, TensorFlow) for anomaly detection algorithms and modal analysis.
- **Dashboard:** Grafana for real-time data visualization, historical trends, and alarm setting.

- User Interface:
  - **Web Dashboard:** Grafana dashboard accessible via browser to the responsible engineers in the city administration.
  - **Alarms:** Automatic SMS/Email alerts sent to defined numbers/ addresses when a set threshold is exceeded.

2.4. Phase 2: Layout and specification of sensor nodes

It is proposed to install 6 sensor nodes per bridge, each with a specific purpose. The installation scheme is shown in the picture below(*Fig.1*)[8]:

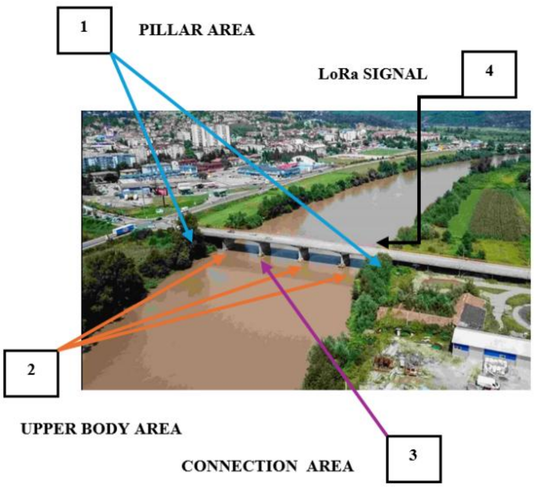

Fig. 1. *Bridge sensor nodes (Bridge in Doboj)*

Pillar area:

- 1,2 nodes (Pillar fondation):
  - ➢ Acceleremeter
  - ➢ Erosion sensor
  - ➢ Humidity sensor

Upper body area:

- 3,4,5 nodes (Beam):
  - ➢ Acceleremeter
  - ➢ Tensio meter

Connection area:

- 6 node (Joint):
  - ➢ Acceleremeter
  - ➢ Tensio meter
  - ➢ High resolution sensor

LoRa signal area:

- LoRa WAN gateway in main building
- Cloud platform AWS
- Database InfuxDB
- User dashboard Grafana
- Automatic alarms SMS

2.5. Phase 3: Implementation and calibration plan

1. **Pilot Phase (Month 1)**: Installation of 2 nodes (1 and 3) on one bridge. Testing of communication[9], power supply and basic data collection.
2. **Full Implementation (Month 2):** After successful testing, installation of the remaining 4 nodes on the first bridge and the entire system on the other bridges.
3. **Baseline Reading Period (Months 3-8):** The most important phase. The system only collects data without alarms being set. This period serves to establish a "fingerprint" of the bridges in a normal, healthy state

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under the influence of traffic, weather and seasons [9].

4. **Algorithm Calibration (Month 9):** Based on the baseline data, intelligent alarm thresholds are set and ML models are trained to detect anomalies.
5. **Full Commissioning (Month 10):** Activation of the automatic alarm system. Continuous maintenance and periodic calibration.

2.6. Phase 4: Maintenance and Upgrade

1. **Regular Maintenance:** Cleaning of solar panels, visual inspection of the housing (every 6 months).
2. **Remote Monitoring:** Monitoring of battery status and signal quality of each node via dashboard.
3. **Upgrade:** Possibility to add new types of sensors (e.g. air quality sensors) to the same network.

Implementation Conclusion

The proposed implementation is specific, robust and feasible. Step by step, it focuses on addressing the biggest risks to bridges in Doboj – erosion during floods and material fatigue from traffic – through careful technology selection (LoRaWAN) [10], strategic sensor placement and implementation of smart data analytics. The pilot phase minimizes project risks, and the baseline period ensures that the alarms will be reliable and useful[11].

CONCLUSION

Implementing wireless sensor networks (WSNs) offers numerous advantages over traditional monitoring methods, but it is important to realistically consider its challenges. Here is a detailed analysis of the pros and cons for the proposed project in Doboj. The proposed implementation is specific, robust, and feasible. Step by step, it focuses on addressing the biggest risks to bridges in Doboj – erosion during floods and material fatigue from traffic – through careful technology selection (LoRaWAN), strategic sensor placement, and implementation of smart data analytics. The pilot phase minimizes project risks, and a baseline period ensures that alarms will be reliable and useful. Here is a detailed analysis of the pros and cons for the proposed project in Doboj:

Advantages (Good Points)

The system provides 24/7 monitoring, collecting data without interruption. Key information is available to engineers instantly, via a web dashboard, enabling rapid response to anomalies. During the flood season, authorities can monitor the impact of rising water levels and erosion on bridge foundations in real time. WSN can detect subtle changes in the behavior of a structure (change in frequency, stresses) that are imperceptible to the human eye, warning of a potential problem months or years in advance. The risk of sudden bridge failure is reduced, which directly increases the safety of citizens. Although it requires an initial investment, the system leads to preventive maintenance. Expensive repairs are planned in advance, and expensive teams of experts are engaged only when and where necessary, which saves money.

The city budget can be planned more efficiently, avoiding unforeseen high costs of emergency interventions. Installation and maintenance of WSN equipment requires minimal work on the bridge itself compared to conventional methods, thus avoiding lane closures and congestion.

Disadvantages (Weaknesses)

The initial investment for acquiring quality, robust equipment, software development and installation services can be high. The system requires maintenance (e.g.

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cleaning solar panels, replacing batteries) and special skills for data interpretation. Sensor nodes are exposed to vandalism, theft or extreme weather conditions (floods, storms). Using steel, locked enclosures, placing sensors in hard-to-reach places and setting alarms for unauthorized access. Prolonged periods without sunlight (eg in winter) can drain batteries and shut down nodes, causing data loss. A huge amount of data is generated that can overwhelm users. There is a risk of "false alarms" if the algorithms are not well tuned. Sensors can "drift" (lose accuracy) over time, requiring periodic calibration.

The advantages of WSN far outweigh its disadvantages. Most of the challenges are technically and managerially solvable through careful design, good equipment selection and clear maintenance procedures. The biggest obstacle is the high initial costs, but they should be seen as a strategic investment in safety, longevity and economic efficiency. For a city like Doboj, with its specific flood risks, implementing WSN is not a luxury, but a rational and modern approach to critical infrastructure management that brings long-term security and significant financial savings.

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