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Safeguarding Forest Ecosystems: Harnessing IoT for Fire Detection

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Abstract

Forest fires represent a significant threat to natural ecosystems and human lives, necessitating early detection and rapid response for effective mitigation. In recent years, the Internet of Things (IoT) has emerged as a promising technology for forest fire detection. IoT-based solutions leverage Wireless Sensor Networks (WSNs), which consist of sensor nodes equipped with various sensors, data processing capabilities, and wireless communication, all powered by batteries. Energy efficiency is a critical consideration for WSNs, as they lack the luxury of periodic recharging. This paper explores the utilization of IoT-enabled WSNs in forest fire detection, with a specific focus on the sensor nodes' ability to monitor environmental parameters such as temperature, pressure, and humidity, as well as chemical indicators including Carbon Monoxide, Carbon Dioxide, and Nitrogen Dioxide. The self-healing and self-organizing characteristics of IoT sensor networks enhance their reliability and robustness in remote forested areas. ZigBee, based on IEEE 802.15.4, is a wireless technology that has gained prominence due to its low-cost, battery-powered applications and suitability for low data rates and short-range communications. This paper highlights the advancements, challenges, and potential applications of IoT-enabled WSNs for forest fire detection, underscoring the expanding possibilities enabled by the rapid development of the IoT. It emphasizes the growing research interest in IoT sensor networks and their potential deployment in various domains. The insights provided aim to contribute to ongoing efforts in developing efficient forest fire detection systems, ultimately enhancing the safety and preservation of our natural environment.

Keywords: Fire IoT, Wireless Sensor Network, Forest sensors, Environmental monitoring, WSN applications.

1 | Introduction

Forests play an indispensable and multifaceted role in the global ecosystem, exerting a profound influence on various interconnected systems, including the environment, biodiversity, and human societies. These sprawling green expanses have far-reaching implications, significantly impacting phenomena such as greenhouse gas emissions, atmospheric carbon absorption, and soil erosion reduction [1]. However, one of the most devastating and persistent challenges faced by forests worldwide is the occurrence of forest fires, which rank among the most perilous natural disasters afflicting virtually all countries [2]. Forest fires represent a pervasive, disruptive force with profound consequences for forested areas across the globe. They pose not only physical threats but also environmental and socio-cultural risks, capable of causing extensive damage and leaving a lasting imprint on affected regions [3]. To address this pressing issue, the integration of Wireless Sensor Network (WSN) technologies and the Internet of Things (IoT) has emerged as a promising and innovative approach. By leveraging the power of WSNs and IoT devices, we can enhance our capacity to monitor, detect, and respond to forest fire incidents in real-time, thereby mitigating the adverse

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ecological, environmental, and societal impacts that arise from such events. WSNs consist of a multitude of small, affordable sensors strategically deployed throughout forested areas, capable of collecting physical data such as temperature, humidity, and smoke levels. These sensors are interconnected, forming a network that relays the collected data to a central location for analysis and interpretation [4]. Simultaneously, IoT devices, including smart cameras, weather stations, and drones, can be integrated into the network to provide additional real-time data on fire behavior and environmental conditions [5].

The seamless connectivity and communication enabled by IoT devices allow for the transmission of data to centralized command centers, where sophisticated algorithms and Artificial Intelligence (AI) can process and analyze the information. This facilitates early detection and identification of fire hotspots, prediction of fire spread patterns, and the generation of timely warnings and alerts to relevant stakeholders, including firefighters, emergency services, and local communities [6]. Furthermore, IoT devices can be integrated with existing infrastructures, such as fire alarm systems and automated sprinkler systems, to enable rapid response and containment of fire incidents. The combination of WSNs and IoT devices also offers opportunities for proactive forest management practices. Continuous monitoring of environmental conditions, such as soil moisture levels and vegetation health, can inform forest planning and resource allocation, enabling sustainable land management practices and reducing the risk of fire ignition [7]. However, the implementation of WSNs and IoT in forest fire management is not without challenges. Ensuring reliable connectivity in remote areas, managing large volumes of data generated by IoT devices, and addressing privacy and security concerns are among the key considerations [8]. Overcoming these challenges requires collaborative efforts from researchers, policymakers, and technology developers to design robust and scalable solutions.

Despite the obstacles, the integration of WSNs and IoT into forest fire management holds great promise in revolutionizing our approach to fire prevention, detection, and response. By harnessing the power of these technologies, we can significantly improve our ability to safeguard our precious forests, protect lives and property, and preserve the invaluable ecosystem services provided by these vital natural resources.

2 | Research Objectives

This research objective is to construct an organization through conveyed remote sensors arbitrarily spread in the forest. The research objective is to develop an organization using distributed wireless sensors deployed throughout a forested area to create a self-coordinated and robust network. This network aims to cover large regions of the forest that may be susceptible to or at risk of fire damage [8]. The primary function of this sensor network is to detect fires in the covered area at regular intervals, such as every 10-15 minutes, and transmit an early warning message to a central server for further dissemination to emergency services immediately upon fire detection [9]. Once a fire is detected, all sensors within the vicinity of the fire area will become active and initiate the necessary initialization and routing tasks [10]. Since the sensors are equipped with short-range wireless transmitters, the data will be transmitted from one sensor to another until it reaches the sink (central server) [11]. Upon receiving the data, the sink will initiate a processing routine and assess whether the fire poses a clear danger by analyzing the rate of fire spread [12]. If the processing result indicates a genuine and imminent threat, the sink will determine the location of the fire [13]. Subsequently, the sink will transmit an alert message to the local fire department, providing information about the precise location of the fire, temperature readings, and the rate of fire spread to understand the fire behavior. Based on this information, the fire department will be able to assess the extent and severity of the situation and make an informed decision [14]. In the case of an actual threat, appropriate preventive measures can be implemented to mitigate the situation before the fire escalates out of control.

3 | Problem Description and Previous Work

Forest fires arise in remote and unmanaged areas filled with highly flammable materials such as trees, dry wood, and leaves [15]. These elements create an ideal environment for fire ignition and fuel for its progression [16]. Fires can be caused by human activities like smoking or barbecues or natural factors like high temperatures or concentrated sunlight [16]. Once a fire starts, it can rapidly spread and transition from a surface fire to a crown fire, causing extensive damage to the landscape [17], [18]. Forest fires destroy millions of hectares of wood annually and emit a significant amount of carbon monoxide, surpassing that produced by car traffic [19]. Detecting high-risk areas and detecting fires early can significantly reduce response time, minimize damage, and lower firefighting costs [20]. The key is to identify fires as quickly as possible, accurately determine their boundaries, and provide early warnings to fire units.

One promising technology for early forest fire detection is WSNs, which consist of interconnected devices or nodes that can monitor the environment and transmit collected data wirelessly [21]. These nodes can be stationary or mobile, aware or unaware of their location, and homogeneous or heterogeneous [22]. Various methods have been explored for forest fire monitoring, starting with observation towers, which proved inefficient. Camera surveillance systems and satellite imaging technologies were also attempted but had limitations in effectively capturing the initial stages of surface fires. Satellite images, although more efficient than cameras, had a long time interval between captures and were subject to weather conditions [2]. In recent years, WSN technology has revolutionized forest fire detection by enabling early detection. These sensors need to be self-organized, efficient in their algorithms, and capable of interacting with other technologies and networks. Several studies have investigated the integration of WSNs into forest fire systems. For instance, Doolin and Sitar [23] experimented with 10 sensors equipped with GPS devices to measure temperature and humidity, transmitting the data back to a central sink. However, the large distance between sensors (approximately 1km) could result in coverage gaps if a node fails. Lloret et al. [24] proposed a mesh network of sensors with IP cameras. The sensors detected fires and sent alerts to the sink, which activated nearby cameras to provide real-time images of the fire. Hartung et al. [25] utilized WSN and web cameras to analyze fire behavior in forests. Son et al. [26] proposed a hybrid WSN and camera surveillance system for fire detection in South Korea. They employed a clustered topology where each cluster had a head node responsible for measurements such as temperature and moisture. However, their approach increased power consumption and did not address power balancing, which could result in some sensors deactivating before others, leading to coverage gaps. Researchers [7] developed an intelligent system based on the Fire Weather Index (FWI), which predicts the probability of fire occurrence and spread rate. The FWI incorporates moisture content and fuel code to describe the forest ground's soil content.

To summarize previous methods, early methods relied on observation towers but proved inefficient. Camera surveillance systems required manual positioning and had limitations in capturing images under various conditions. Satellite images from AVHRR and MODIS satellites had a long delay between captures and were influenced by weather patterns. Finally, WSN technology started to be considered as a partial solution, often integrated with IP cameras, weather databases, and fuel databases.

3.1 | Background on Forest Fire

The Fire Factors Triangle is a visual representation that illustrates the three essential components required for a fire to occur and sustain itself: heat, fuel, and oxygen. Heat acts as the ignition source, fuel refers to any substance that can undergo combustion, and oxygen supports the chemical reaction between the heat and fuel. Understanding the interactions between these three elements is crucial for fire prevention, control, and extinguishment. By effectively managing heat sources, handling and storing fuels safely, and controlling oxygen supply, we can mitigate fire risks and promote fire safety in various environments. *Fig. 1* visually represents the three essential components required for a fire to occur and sustain itself. Before delving into a discussion about forest fires and their behavior, let's first define a forest fire [6]. Ignition is a complex process in which fuel is heated, ignited, and rapidly oxidized, releasing heat in the process. Fire is a specific type of ignition that is self-sustaining, characterized by the emission of heat, and accompanied by flames and smoke. In order to sustain a fire, three essential elements must be present. If any one of these elements is absent, the fire will be extinguished. These elements include a source of combustible fuel, a source of heat to initiate and sustain the reaction (the fire itself), and an adequate concentration of oxygen to support the reaction [8].

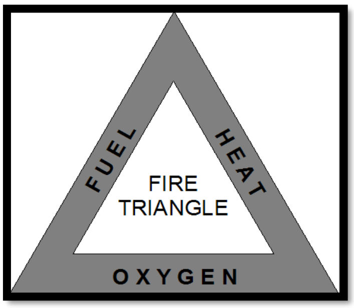

Fig. 1. Fire factors triangle.

A forest fire is a dynamic phenomenon that exhibits different properties and behaviors as it moves from one location to another and evolves. Due to the finite availability of fuel in a given area, for a fire to continue burning, it must spread to adjacent fuel sources. This propagation is facilitated by complex heat transfer and thermochemical processes that govern fire behavior [27]. Understanding the morphology of a forest fire by identifying its different components is highly beneficial during firefighting operations, as it can significantly impact firefighter safety. Predicting forest fire behavior is both an art and a science, heavily reliant on deciphering weather patterns that influence the rapid spread of fires. Even experienced firefighters often struggle to interpret fire behavior accurately and predict the potential threat a forest fire poses to property and lives [7].

A wildfire burning in a uniform environment assumes an oval shape (*Fig. 2*). However, the fire environment can vary over time as the fire expands beyond its ignition area. Different parts of the fire may burn under different conditions, such as wind direction, slope, moisture levels, wind speed, and more. This heterogeneity in fire conditions can result in a highly complex shape, even if each part of the fire spreads in a circular pattern [8], [9].

Fig. 2. Simple ellipse shape for fire under a constant fire environment.

A forest fire is a dynamic and ever-changing phenomenon characterized by various components. Fingers, which are long, thin extensions of the main fire body, can reach outwards. Pockets are unburned spaces within the fire perimeter, enclosed on three sides by the fire. Islands are unburned areas entirely surrounded by the burning region, forming distinct patches within the fire [16]. Spot fires are separate fires ignited outside the primary fire by embers or other sources. These components contribute to the complex shape

Atighi and Zhou | Big. Data. Comp. Vis. 3(4) (2023) 146-153

and behavior of a forest fire, and recognizing and understanding them is essential for effective firefighting operations.

3.2 | Fire Detection and Decision Making

The use of sensors for fire detection and monitoring has revolutionized the application of new technologies in the field of firefighting. Sensors can analyze various dynamic and static factors such as humidity, fuel type, slope of the land, wind direction and speed, smoke, and more. They enable us to determine the direction and potential movement of the firefront [10]. Sensor-based systems are extremely valuable in detecting fires and making informed decisions to combat them. *Fig. 3* illustrates a sensor network for a fire detection scheme..

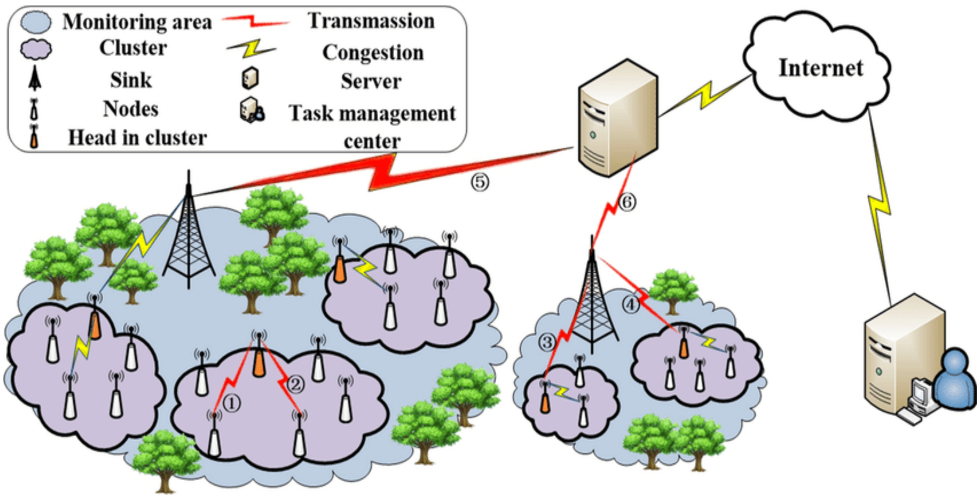

Fig. 3. Sensor network for fire detection.

Previous research has relied on images or databases, such as weather condition indices, fuel index models, gas charts, and intelligent sensors, to inform decision-making. In this study, all nodes have known locations and use temperature sensors programmed with a specific threshold temperature. When the temperature exceeds this threshold, the node sends an alert message to the central processing unit (sink). The focus is on the nodes' behavior in response to the probability of an emergency, providing detection and information about whether it is a controlled fire or the start of a wildfire. This approach relies on tracking fire spread and analyzing the underlying logic rather than utilizing complex datasets or imaging technologies. The most practical method is to monitor the forest using a Graphical User Interface (GUI) to visualize events and receive alert messages on the monitoring screen, using logical assessment to make decisions. The study tested 50 nodes in NS2 under different scenarios [21].

The provided figures illustrate different types of fire propagation. In *Fig. 4*, the fire spreads over a large distance but is narrow and has low fire density. This type is easily detectable as it raises temperatures in the vicinity and crosses multiple sensor ranges. *Fig. 5* depicts a slow propagation fire, which may extinguish on its own or pose a potential threat. In the latter case, the nodes continue to monitor the fire's growth until it exceeds a predefined threshold. The relationship between the sensor deployment scheme and early detection is highlighted, with traditional and moderate-density deployment plans being more efficient for early detection. The distance between the fire start location and the nearest sensor node decreases with increasing density, resulting in faster detection [5]. The distance between sensor nodes affects the time it takes for heat waves to reach the nodes. Keeping the distance between sensor nodes under 20 meters is crucial for an effective early detection system. The performance of the weather-aware design is significantly better in this regard. During non-fire seasons, more extended periods of rest time are feasible due to the low fire danger level. However, during the fire season, the weather-aware model's fire detection time is significantly shorter due to the elevated fire risk. The sensing results can provide simple information to firefighters regarding fire behavior, such as the ignition point, fire spread speed, and direction of maximum spread. This information can guide their actions, such as deploying more firefighters to areas threatened by the fire or directing them to the rear of the fire to control its advance, reduce its intensity, limit its spread, minimize risks, and facilitate extinguishment. Early fire detection plays a vital role in minimizing the damage caused by wildfires. Sensor-based systems can provide real-time data on fire behavior, allowing for quick response and decision-making. By analyzing the data from the sensor network, algorithms can identify patterns and anomalies associated with fire development. This enables early detection and alerts, giving firefighters a head start in containing the fire and protecting lives and property [27]. The integration of sensor data with advanced technologies such as machine learning and AI further enhances the accuracy and efficiency of fire detection systems.

Fig. 4. Medium propagation fire.

Fig. 5. Slow propagation fire.

In addition to fire detection, sensor-based systems also aid in decision-making during firefighting operations. The data collected by the sensors, including temperature, wind speed, and fuel moisture, can be analyzed to assess the fire's behavior and predict its potential spread. This information is crucial for determining the appropriate firefighting strategies and resource allocation. For example, if the sensors detect a rapid spread of the fire in a specific direction, firefighters can deploy resources strategically to contain the fire and protect vulnerable areas. Moreover, sensor-based systems can provide real-time updates on the effectiveness of firefighting efforts, allowing for adjustments and optimization of tactics as the situation evolves. Overall, the use of sensors in fire detection and decision-making significantly enhances the efficiency and effectiveness of firefighting operations.

4 | Conclusion

In conclusion, the background information provided in this paper highlights the significance of forest fires and the challenges associated with detecting and predicting their behavior. Forest fires are dynamic and can spread to adjacent fuel sources, making it crucial to understand their morphology and behavior. The use of sensor networks offers a promising solution for fire detection and decision-making. By monitoring dynamic and static variables such as humidity, fuel type, wind speed, and smoke, sensors can provide valuable information about the direction and potential movement of the firefront. The research emphasizes the importance of early detection and decision-making based on real-time data from sensors, rather than relying on complex databases or imaging technologies. The findings suggest that sensor deployment strategies, including the distance between sensor nodes, can significantly impact the effectiveness of early detection systems. The results of this research can contribute to improving forest fire management and the safety of firefighters by providing crucial information about the behavior and progression of fires.

In addition, the research highlights different types of forest fire propagation, such as medium propagation and slow propagation fires. Each type requires specific monitoring and response strategies. Medium propagation fires spread over a large distance with low fire density, making them relatively easy to detect due to the increased local temperature. On the other hand, slow-propagation fires may initially appear less threatening. Still, they require continuous monitoring as they can either extinguish on their own or grow into a significant threat. The research emphasizes the importance of the sensor deployment plan in relation to early detection. A denser network of sensors reduces the time required for a sensor node to detect a temperature increase caused by a fire. Maintaining a distance of less than 20 meters between sensor nodes is recommended to ensure an efficient early detection system. The research also highlights the importance of weather-aware design in fire detection systems. By considering the fire danger level during different seasons, the system can adapt its detection capabilities and response times accordingly. The simulation results provide valuable information to firefighters, including the fire's starting point, spread speed, and direction, enabling them to make informed decisions and prioritize their firefighting efforts. Overall, the research presented contributes to the development of effective forest fire detection and decision-making systems, enhancing the safety and efficiency of fire management operations.

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