Towards an Efficient Fog-Based Forest Fire Management Architecture

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ABSTRACT

Forest fires cause significant human losses and natural damage and threaten the biodiversity on our planet. Several researchers have studied the potential of wireless sensor networks (WSNs) to manage a forested area and have proven the real potential of this paradigm. Such systems generate a large amount of heterogeneous data in a short time, which may lead to network congestion and delay in data transmission. Processing such data in a short time frame is challenging for a traditional WSN. This article presents a multi-layered architecture for wildfire prevention, detection, and intervention based on WSN, IoT, cloud, and fog computing technologies. The proposed architecture is validated using the iFogSim simulation tool. Two models are compared, cloud-only and fog-cloud-based scenarios. The experimental results show that the cloud-fog model minimizes latency and significantly reduces bandwidth consumption compared to the cloud-only model. To bring fast fire extinguishing ability to the system, the authors recommend the employment of drones equipped with fire extinguishing balls.

KEYWORDS

Cloud Computing, Data Processing, Drones, Fog Computing, Forest Fire Detection, iFogSim, IoT, WSN

INTRODUCTION

Forest fires, wildfires, or even firestorms are all terms that describe the existence of a fire in a forested area. Every year forest fires cause significant losses of environmental systems, infrastructures, biodiversity, and even human lives around the world. According to the 2020 Global Forest Resources

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Assessment report (FAO, 2020), an estimated 7.20 billion hectares of land were burned between 2001 and 2018, with an average of about 29% of the area covered by trees.

In Algeria, the year 2021 has seen many devastating wildfires. The most important ones, which caused the most natural damage and especially human losses, were during August. The newspaper “le monde” (A, 2021), reports that August’s wildfires in Algeria caused at least 90 deaths. The Algerian minister of agriculture and rural development revealed that August’s fires destroyed 89,000 hectares of forest in 35 Wilayas (municipalities) (Le Monde & AFP, 2021).

Forests occupy a large part of the northern part of Algeria. That makes these places very susceptible to fires. Additionally, the lack of modern fire detection systems and methods and reliance on purely traditional methods had a significant impact on the fight against fires and their spread. Therefore, the constant development and implementation of forest fire detection and prevention systems are crucial.

There are two types of forest fire detection systems (FFDS), traditional and modern. Traditional systems encompass old detection methods where human presence in all detection, localization, and extinction operations is indispensable. The full dependence on the human factor may lead to the unreliability of forest fire monitoring due to climatic conditions that hinder the surveillance operation like clouds, mists, etc. Moreover, human characteristics like fatigue, omissions, and negligence may lead to system disruption (Barmpoutis et al., 2020). Throughout the world’s forested areas, implemented fire detection approaches still use traditional methods. Besides, many modern FFDS based on technological and information systems have been developed. Satellite-based image processing systems are one of these methods. Characterized by their wide geographic coverage, NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) (Barnes et al., 1998) and Visible Infrared Imaging Radiometer Suite (VIIRS) (Murphy et al., 2006) satellites have been widely used to monitor large forest areas. However, their interval time between detecting fire and alarming the concerned departments is relatively high (Grover et al., 2019). In addition, climatic conditions such as the presence of clouds and mists and other obstacles to satellite vision proved the limit of this type of system. An emerging trend in forest fire detection is camera-based image processing systems deployed on unmanned aerial vehicles (UAVs). This type of system is relatively inexpensive and can cover multiple types of terrain (Kalatzis et al., 2018). However, limited resources and processing capabilities, UAV’s limited battery life, and privacy preservation are some issues that need to be addressed to achieve better results in such processing systems.

Wireless Sensor Networks (WSNs) have been widely employed for environment perception and monitoring. WSN based systems are suitable for forest fire detection and have proven their efficiency in terms of detecting, localizing, and tracking forest fires in many applications (Grover et al., 2019; Bouabdellah et al., 2013; Saoudi et al., 2016). The vast geo-distribution of environmental sensor nodes (such as temperature, humidity, precipitation, and wind sensors) in a forest area allows better monitoring and an effective detection of forest fires in an early stage. However, WSN based systems present some limitations. A WSN environmental perception system deploys many sensor types, which generate a vast amount of heterogeneous data in a short lap of time (Smys, 2019). Processing such data very quickly is challenging in traditional WSNs. Sensor node limited battery life is another limitation that every WSN system has to overcome.

The paradigm of connected objects or the Internet of Things (IoT) is a trend that is very appropriate to the field of forest fire detection, prevention, and management. In combination with the cloud computing paradigm, for efficient and fast data processing purposes, several researchers have proposed “real-time” FFDS such as (Tomar et al., 2019) and (Sungheetha & Sharma R, 2020). Data processing and transmission of results in real-time are crucial requirements in such systems. Nevertheless, cloud-based forest fire detection implementations have high network usage and latency rate in data acquisition, data processing, and results transmission due to the distance between the source and the data processing center, which is not suitable for time-sensitive applications.

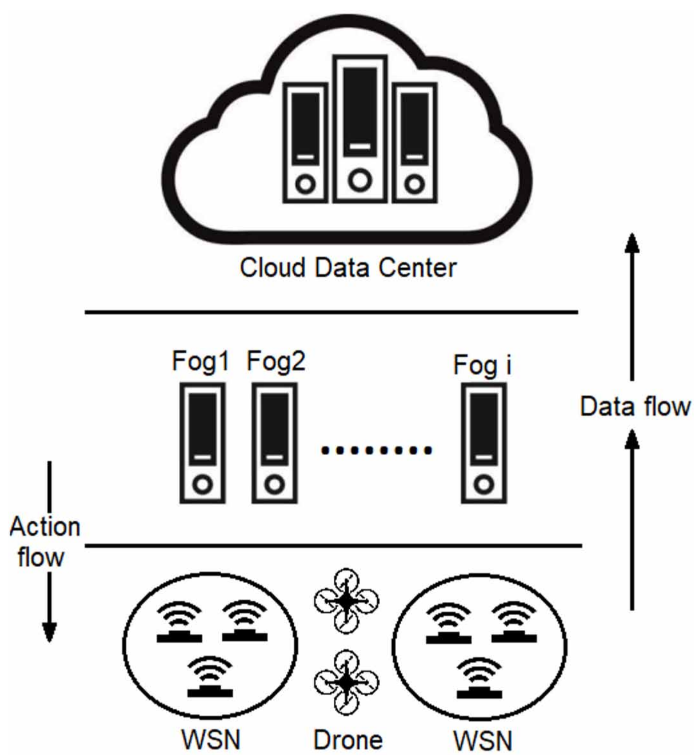
Existing works in the application of forest fire detection and management have proven their effectiveness by employing technologies such as WSN, IoT, and cloud computing. However, such a system requires the deployment of a pervasive number of sensors in extravagantly large forest areas, which will generate an excessive amount of data in a short time frame. To address this situation, the authors suggest implementing an intermediate layer between the data source and the cloud data centers that will be in charge of fast processing of the collected data and minimizing data traffic on the network. This data management mechanism is often called fog computing. The main objective of implementing the fog computing paradigm in the FFDS is to provide fast data processing capability and bandwidth reduction for the network due to the huge number of data-generating devices in such a system.

To overcome the shortcomings of the solutions presented above, this article proposes a multi-layered architecture for wildfire prevention, detection, management, and intervention based on WSN, IoT, Cloud, and Fog computing technologies. The architecture is shown in Figure 1. The proposed approach has been evaluated by performing simulations in iFogSim (Gupta et al., 2017). Two models have been implemented, cloud-only and fog-cloud models. The experimental results demonstrate that the fog-cloud model minimizes latency in the system and has a considerable reduction of the bandwidth consumption compared to the cloud-only model.

The contribution of this paper to the field of forest fire detection is as follows:

1. **Processing performance:** To overcome the processing challenges, fast scalability, and high interoperability of the WSN application, a multi-layer architecture (object, fog computing, cloud computing layer) is presented as a solution. The object layer is composed of a large number of environmental parameters' sensing objects and others for rapid intervention in case of high fire

Figure 1. Wildfire prevention, detection, and intervention architecture



risk. The fog computing layer brings a good processing ability to the edge of the FFDS. The separation of sensing and processing tasks between layers in the proposed architecture also reduces the power consumption of sensors and other devices in the object layer.

2. **Fast intervention and false alarm cost reduction:** A fast fire extinction at its outbreak is crucial in a forest environment that favors rapid-fire spread. Therefore, the use of drones equipped with fire extinguishing balls may be an effective approach for rapid fire extinction. Figure 2 shows an example of a drone equipped with fire extinguishing balls. According to (Aydin et al., 2019), a small extinguishing ball of 0.5 kg can deal with a circle of one meter of a short grass fire. Deploying this type of drone will bring a rapid intervention ability to the presented forest fire fighting system, which is a high requirement to avoid a catastrophic situation.

In case of fire risk detection, before deploying human and material resources to control the fire, firstly, an extinguishing drone equipped with a camera is employed to verify the real presence of the fire and to bring a clearer view of the situation to better plan the intervention of the fire-fighting human and material resources if required. The use of such an approach will reduce the cost of false alarms and provide a better perception of the area at risk of fire.

3. **Wildfire prediction:** When dealing with a critical situation such as a forest fire, having the ability to predict fires and define a degree or index of fire vulnerability for a forested area is an important capability.

Cloud computing infrastructure provides powerful and advanced analytical tools. Processing environmental data using advanced data analytics algorithms and methods will provide crucial information to the decision-makers.

In addition to the fog computing fast data processing ability, using cloud computing as a long-term analysis tool for the decision and planning makers is an interesting approach to provide a fire prediction characteristic to the fire detection system.

Figure 2. Drone equipped with extinguishing balls

The rest of this paper is organized as follows: Section 2 presents some theoretical background about forest fires, fog, edge, and cloud computing. Section 3 discusses recent work on FFDS and other types of systems implementing fog computing. Section 4 provides the proposed approach based on WSN, IoT, fog, and cloud computing. In Section 5, the experimental simulation results are exposed. A comparison of the proposed approach with other similar approaches is discussed in Section 6. Section 7 concludes the paper and highlights possible future research.

THEORETICAL BACKGROUND

For the reader's convenience, let us start by presenting some theoretical background about forest fires, fog, and cloud computing.

Forest and Forest Fires

There are many definitions of the term "forest" depending on latitude and usage. According to the Food and Agriculture Organization of the United Nations FAO, a forest is a land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.

We speak about a forest fire when a fire has threatened a massif of more than one hectare. Generally, the most favorable period for forest fires is summer because the combined effects of drought, the increase in temperatures, and the low water content of the soil, are added to the work in the forest.

A fire can take different forms depending on the characteristics of the vegetation in which it develops:

- **Soil fires** burn organic matter in the soil as fuel. They are light, slow-moving, and hard to extinguish completely.
- **Surface fires** are the low trails of vegetation that serve as fuel. Wind in the relief favors their rapid spread.
- **Crown fires** are located on the upper part of trees. They release large amounts of energy and spread very quickly. Favored by wind and drought, they are difficult to control.

Fog, Edge, and Cloud Computing

(Bonomi et al., 2012) defines fog computing as "*Fog Computing is a highly virtualized platform that provides compute, storage, and networking services between end devices and traditional Cloud Computing Data Centers, typically, but not exclusively located at the edge of network*".

Fog computing refers to a decentralized computing structure where resources, including data and applications, are placed in logical locations between the data source and the cloud. Thus, fog computing can be defined as a distributed computing paradigm which fundamentally extends the services provided by the cloud to the edge of the network. It makes it easy to manage and schedule computation, networking, and storage services between data centers and endpoints. Fog computing supports mobility, computing resources, communication protocols, interface heterogeneity, cloud integration, and distributed data analytics to meet the demands of applications that require low latency with geographic distribution broad and dense (Dastjerdi et al., 2016). The goal is to bring core analytical services to the edge of the network, placing computing resources closer to where they are needed, reducing the distance that data must travel across the network, and improving thus the overall efficiency and performance of the latter. Fog computing can also be deployed for security reasons, as it has the ability to segment bandwidth traffic and introduce additional firewalls to a network.

The fog computing is often erroneously called edge computing and vice versa. Although fog computing and edge computing both move the processing power of the cloud to the network edge, these two paradigms have some differences. While edge computing generally tends to be limited to computing at the periphery, fog computing provides a more advanced and involved source of processing, analysis, data storage, and control in an IoT ecosystem (Yousefpour et al., 2019). Furthermore, compared to edge computing, fog computing offers a continuous processing service from the cloud to the objects rather than treating the network edges as isolated computing units (Chiang et al., 2017).

RELATED WORK

By exploring the research works related to the fire detection field, we notice two categories of FFDS. The first one is based on data collected from WSN composed of environmental perception sensors like temperature, humidity, wind, and other similar sensor types. In the second category, researchers have leaned towards using UAVs equipped with cameras as a means of data collection. Image processing techniques were applied to analyze the collected data and retrieve significant information on the state of the forest.

The authors in (Varela et al., 2020) propose a FFDS using WSN for environment perception combined with information fusion techniques. They introduced a low complexity algorithm to detect fire based on only two environmental parameters (Temperature and humidity). Using regression analysis, they created what is called “base function”. This function is used to define a base model that is employed as a comparative model when the system detects temperature and humidity that potentially represent a fire. The proposed system showed a 100% fire detection rate when sensor nodes are not exposed to sun’s rays. Authors of this FFDS pointed out an important issue in the proposed system, which is an incorrect fire detection information when nodes are exposed to sun’s rays. This kind of issue can be verified using other types of sensors like flame sensor or by employing drones equipped with cameras to check the real existence of fire. Moreover, the proposed FFDS allows only fire detection, managing the fire after its outbreak is as important as the fire detection. Employing sensors such as the wind sensor helps to determine the fire propagation direction.

The employment of UAVs in intelligent environmental perception applications is becoming more and more pervasive. Applying such technology in the forest fire fighting field has been widely studied in several research works. UAVs are relatively inexpensive and can cover a large area in different weather conditions with minimal human implication (Kalatzis et al., 2018). Equipping UAVs with cameras for image collection as well as data communication facilities allows good visualization of the area under surveillance. In (Kalatzis et al., 2018), the authors proposed a hierarchical architecture for early forest fire detection by exploiting the benefits of UAVs’ sensing abilities and the rich and powerful resources of cloud and fog computing technologies. Several scenarios have been evaluated to demonstrate the usefulness of fog-computing involvement. First, an edge-only scenario is evaluated. In this scenario, the image processing classification tasks are performed at the edge nodes. The results show that edge nodes have difficulty executing such computationally intensive tasks. Moreover, the energy consumption of UAVs is twice that of other scenarios. In another scenario, the authors evaluated the data processing at the cloud level only. All data collected by the UAVs is transmitted to the cloud for data processing purposes, which resulted in a very high data flow between the data source and the cloud. However, this scenario achieves the lowest response time compared to the other scenarios. The last scenario involves the deployment of fog computing as an intermediate layer between the data source and the cloud layer. The fog nodes are deployed close to the data source, which reduces network traffic. Besides, they are in charge of the data processing phase, thus reducing the volume of data transmitted to the cloud and only sending the processing results in case of an unusual situation. The test results show that the last scenario of the proposed FFDS is the most balanced among the three proposed scenarios.

By examining UAV-based solutions, we deduce some relevant challenges that need to be addressed. One of the most critical issues is that the deployment of UAVs in a public environment must be well supervised to avoid privacy-related incidents. In addition, the UAVs’ limited battery is a real limitation that must be considered for a more attractive solution.

Prediction and management of natural disasters is another research topic where researchers have exploited the utility of computing services. Researchers in (Sood et al., 2018), to predict and supervise floods, have proposed a four-layer architecture intending to effectively model, manage, and monitor the flood. The authors explored the involvement of several technologies, such as IoT, big data, fog computing, and cloud computing, to design a long-term as well as a real-time forecasting system. IoT is responsible for collecting real-time data in a socially collaborative manner, big data is an efficient approach to data analysis, fog computing brings fast processing capability to the system and reduces latency in the network when predicting floods in real-time, and cloud computing provides the powerful infrastructure for system management and long-term data storage and analysis. In (Kaur et al., 2021), researchers provided an energy-efficient IoT-based cloud framework for early flood prediction. The IoT framework uses a comprehensive historical dataset of environmental factors such as temperature, humidity, precipitation, and hydrological parameters like ñow and water level to predict flooding and related activities. A three-layer model is proposed consisting of a data acquisition layer composed of several environmental sensor types, a fog computing layer in charge of data analysis to adapt the sampling frequency of the sensor nodes for better energy management at the peripheral layer, and a cloud computing layer serving as a data repository and powerful data analysis tool to gather a maximum of valuable information from the collected data.

A property of great importance in time-sensitive systems, particularly in disaster management systems, is the rapid reaction. The IoT universe offers a multitude of devices capable of providing the early intervention aspect before the involvement of more expensive means and human resources. Research on environmental perception and monitoring systems must take into consideration the intervention aspect in the study and design of such systems.

During the last decade, several researchers studied the implementation of fog computing in time sensitive IoT systems. Fog computing brings the autonomy, computational power, efficiency, and rich resources of cloud computing close to the data sources, which makes it very effective in IoT systems. In (Awaisi et al., 2019), researchers study the efficiency of fog computing implementation compared to cloud computing in a smart car parking system. They proposed a three-layer model, where fog computing is applied at the intermediate level between the object layer consisting of cameras and smart LED displays and the cloud layer. The fog nodes are responsible for acquiring and processing the parking slots' images from the cameras and transmitting the analysis results to the LEDs. To evaluate the latency and bandwidth utilization of the proposed system in several scenarios, the authors used the iFogSim simulator. The experimental results show that the scenario based on the fog computing implementation results in low latency and low network usage compared to the cloud computing scenario.

Table 1 summarizes some related work, highlighting the technologies used, strengths, and weaknesses of each cited study.

PROPOSED SYSTEM ARCHITECTURE

In this section, an architecture based on WSN, IoT, fog, and cloud computing for the wildfires early detection and rapid intervention is presented. The proposed system is a three layers architecture consists of object, fog computing, and cloud computing layers, see Figure 1. Each layer has a specific, predefined, and essential functionality.

System Architecture

Object (Peripheral) Layer

The first layer is a data perception layer, composed of IoT devices equipped with several environmental sensor types like temperature, humidity, precipitation, and wind sensors for fire risk monitoring widely dispersed in a forested area. This kind of sensor has proven: a- their efficiency in terms of

Table 1. Related work

Application	Reference	Technologies used	System strengths	System weaknesses
Forest fire detection system	(Varela et al., 2020)	WSN	- Low complexity algorithm for fire detection based on two environmental parameters (temperature and humidity) - Very high fire detection efficiency rate	- Incorrect fire detection results when sensors are exposed to the sun - Lack of ability to monitor fire activity
	(Kalatzis et al., 2018)	- UAVs equipped with cameras - Fog computing - Cloud computing	- Relatively inexpensive implementation - Fog computing deployment reduces network traffic - Fast data processing - Can cover multiple types of terrain	- The use of cameras may give rise to the privacy issues - UAV's limited battery life
	(MODIS) (Barnes et al., 1998); (VIIRS) (Murphy et al., 2006)	Satellite-based image processing	- Wide geographic coverage	- A relatively high delay between the detection of the fire and the alarm of the concerned services. - The climatic conditions often prevent satellite vision.
	(Grover et al., 2019; Bouabdellah et al., 2013; Saoudi et al., 2016)	WSN	- Effective monitoring of the forest area. - An effective detection of forest fires.	- The use of many sensor types generates a vast amount of heterogeneous data. - Processing generated data very quickly is challenging in traditional WSNs. - Sensor nodes limited battery life.
	(Tomar et al., 2019; Sungheetha & Sharma R, 2020)	- IoT - Cloud computing	- Efficient and fast data processing	- High network usage - High latency rate
Smart car parking	(Awaisi et al., 2019)	- IoT - Cloud computing - Fog computing	- Fog computing deployment reduces network traffic - Fast data processing	The use of cameras for parking space detection may give rise to privacy issues.

sensing fire's causing parameters, b- their reduced fault-tolerance and good sensing abilities, c- their endurance in difficult wild environments. The IoT sensing nodes are also equipped with Wi-Fi module to allow the wireless communication of the sensed values. In addition, the Gps service can be easily implemented to provide geo-location capability to every sensing node in the WSN.

This layer is also composed of drones equipped with distinguishing balls. Their function is to intervene as early as possible in case of fire high risk. These drones receive the exact geo-location provided by the IoT sensing nodes of the area at risk and move in an attempt to extinguish the fire or at least prevent its spread by the time firefighters arrive. After receiving the exact geo-location of the area at risk of fire, the drone in the first phase will move automatically to the forest area without any human interaction. When arriving at the exact location, human interaction may be required for effective use of the extinguishing balls and to avoid possible errors and waste of the limited number of extinguishing balls. These drones are also equipped with cameras to provide a real-time image of the forest area to the fire department to provide the ability to analyze the situation and plan the intervention operation.

Fog Computing Layer

For the low-latency, wide-spread distribution, and the scalable large number of the IoT sensing nodes requirements in a FFDS, deploying the fog computing paradigm is the best choice (Smys, 2019). Fog computing provides easy and efficient connectivity to the object layer. Also, the fog computing paradigm has been proposed to bring the processing power of cloud computing to the edge of the network to minimize bandwidth usage and provide powerful processing units close to the end devices.

The principal function of the fog layer is the acquisition, filtering, and processing of the received data from the object layer. The second function of the fog layer is the communication of the data processing results via the internet to any interested institution or service, for example, the fire department. Besides, to intervene as quickly as possible, the fog nodes alert the drones of the object layer with the exact geo-location of the area at risk of fire.

Cloud Computing Layer

Due to the reduced storage volume and limited processing capacity of the fog layer, it is difficult to perform an in-depth analysis of the data to predict wildfires. Therefore, a third layer based on the cloud computing paradigm is used. This layer stores data from fog nodes and uses advanced learning tools to improve the fire detection system. The cloud computing layer brings a long-term analysis tool for the FFDS. This analysis will serve as a basis for decision-makers to decide on mechanisms and protocols for forest fire detection and prevention. In addition, such an analysis will identify the area's most vulnerable to fire throughout the year.

Data Analytics Phases

Fast data analysis is crucial in a FFDS. The data collected by the IoT sensor nodes goes through three processing phases, data collection, data analysis, and decision making regarding the analysis' results.

Data Collection

The peripheral layer is responsible for the data collection phase. It is composed of a network of a wide variety of IoT sensor nodes deployed in the forest canopy. Their function is to collect meteorological data such as temperature, humidity, precipitation, and wind speed and transferring it to the upper layer. The IoT sensing nodes detect, accumulate, and transmit climate data values to the fog nodes at specific time intervals. In addition to this, geographic coordinate parameters also play a vital role in mitigating the adverse effects of forest fires. The data collected by the IoT sensor nodes are classified into two categories:

1. **Weather data set:** It includes many weather factors such as temperature, humidity, wind speed, and precipitation.
2. **Location parameters:** It includes the geographical coordinates of the monitored area.

The sensors send collected data updates to the appropriate fog node via the Wi-Fi network. After processing this data, the fog node either triggers an action or not.

Data Analysis

The large number of IoT sensor nodes deployed in the target geographical area leads to excessive data generation for analysis. Excessive bandwidth use can clog the network and lead to delayed responses. Hence, the network must be sufficiently scalable and robust to handle this high traffic. The application of the fog computing paradigm is the ideal solution in such systems.

The fog layer lies between the peripheral layer and the cloud layer. It is in charge of acquiring and processing raw and unfiltered data (sent by IoT sensing nodes of the peripheral layer) of a predefined area, then sending orders to the appropriate actuators in this area.

In the presented system, the functions of the fog layer are:

- Data processing and decision making
- Connect the system to the internet
- Transmit data to the upper layer (cloud) for further analysis
- Transmit the decisions resulting from the data analysis to the actuators of the lower layer (peripheral)

To maintain a continuous improvement of the detection system, a second processing on the fog layer analysis results is performed for predictive and prescriptive purposes.

This type of data processing is computationally intensive, which makes cloud computing the appropriate solution. The cloud layer stores the data from the fog nodes and uses advanced learning tools to improve the detection system.

The cloud layer is able to:

- Store collected data
- Apply an in-depth analysis on the data
- Determine the optimal detection strategy
- Optimize the analysis methods used by the fog layer
- Analyze the received data in the long-term to predict forest fires.

This paper does not focus on the data analysis method for forest fire detection. The main interest is in the general architecture and mechanisms that allow better management of a forested area.

Decision Making

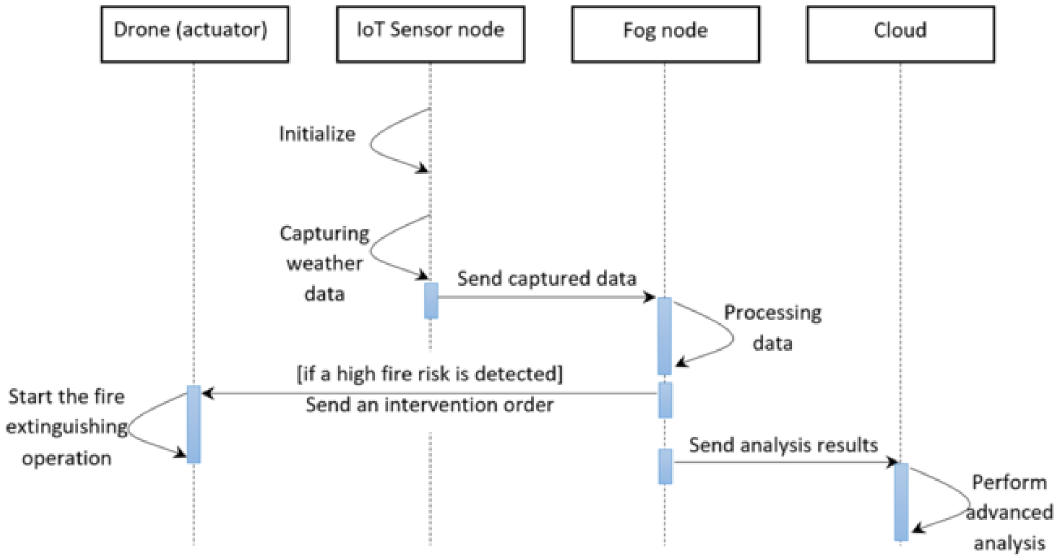
Once the data collected by the sensor networks are analyzed by fog nodes, in case of a high risk of fire outbreak, the fog layer sends orders to the actuators located in the peripheral layer. The actuators are responsible for applying the instructions of the fog layer. In the present proposed system, the authors suggest the combination of two types of actuators (traditional and modern) for optimal, functional, and safe control. The human factor is the main component of the traditional forest fire fighting methods. Human resources based methods are still used in all forest areas worldwide, even in countries that have developed other more advanced mechanisms (classified as "current or modern") such as Australia, Canada, and the United States of America.

In addition to the traditional methods, the use of fire extinguishing drones is recommended. Being able to intervene when a fire is detected at its early stage is the main objective of using such types of drones. Extinguishing the fire in its first stage will prevent its spread, avoid a probable natural disaster, and limit the exorbitant cost when dealing with such type of fire.

Fire Detection Process Cycle

In the proposed forest fire detection model, the components of the different layers collaborate and communicate between them to better manage a forest area. Figure 3 shows the forest fire detection cycle in the presented architecture. The detection process is data-driven. First, the sensors are in charge of acquiring data on the environmental parameters. This information about the weather condition is then transmitted to the corresponding fog node in the monitored forest area. Afterward, the fog node performs data analysis to determine the risk rate of fire outbreaks. According to the analysis result, the fog node trigger or not a fire extinguishing operation. A drone equipped with fire extinguishing balls and a camera to allow the visualization of the situation in real-time performs this operation. The fog nodes periodically transmit the analysis results to the cloud server for further analysis in order to determine the rate of fire vulnerability in each forested area.

Figure 3. Forest fire detection and intervention cycle



EXPERIMENTAL PHASE

Simulation

To evaluate the effectiveness and performance of the system outlined in the previous section, two fire detection scenarios are simulated. The first scenario combines cloud and fog computing technologies, while cloud computing is the main data processing engine of the second scenario. The iFogSim toolkit is used to create the network topologies for both scenarios and to compare the results of each scenario with the other. iFogSim is a simulator that supports the evaluation of resource management policies by focusing on their impact on latency, energy consumption, network congestion, and operating costs (Gupta et al., 2017). It simulates edge devices, cloud data centers, and network links to measure performance metrics. The application model supported by iFogSim is the Sense-Process-Actuate model. In such models, sensors publish data to IoT networks, applications running on fog devices subscribe and process the data from the sensors, and finally, the information obtained is translated into actions transmitted to the actuators.

Components of the simulator are summarized in the subsequent (Mahmud & Buyya, 2019):

- **Physical components**: include fog devices or fog nodes that are orchestrated in a hierarchical order. Fog devices act like data centers in a cloud computing paradigm by providing memory, network, and computing resources.
- **Logical components**: In iFogSim, applications are considered as a collection of interrelated AppModules. The dependency between two modules is defined by the settings of AppEdges. AppModules can be represented with virtual machines and AppEdges are the logical data flows between two virtual machines.
- **Management component**: Consists of the "Controller" and "Module Mapping" objects. The "Module Mapping" object, according to the requirements of the AppModules, identifies the resources available in the fog devices and places them there. The "Controller" object launches the AppModules on their assigned fog devices following the placement information provided by the "Module Mapping" object. After the simulation is complete, the Controller object collects the results of costs, network usage, and energy consumption during the simulation period from the fog devices.

The interaction between iFogSim components is shown in Figure 4.

Figure 5 represents the network topology for two monitored forest areas. The author's approach to simulating the fire detection scenario is to start by creating two forest areas that are each represented by a fog node. Every fog node has the function of monitoring and managing all edge devices in its area. In the lower level, we have a set of several weather parameter sensor types connected to a microcontroller and represented by a sensor node. The detection frequency is the same for all sensor nodes. The fire-extinguishing drone is represented by an actuator and connected to the fog node.

The fire detection process is simulated by creating modules for each detection phase as shown in Figure 6.

1. **Filtering Data Module:** A Filtering_data_module is created and assigned to every IoT sensor node. Its function is to validate raw climatic data collected by sensors and then transmit them to the next module (Detect_fire_module).
2. **Detect fire module:** After receiving the filtered data, the Detect_fire_module applies a fire detection analysis to these data. Regarding the analysis results, the Detect_fire_module communicates decision information to the Intervention_module. The Detect_fire_module also sends analysis results to the Storage_module located at the cloud level.
3. **Intervention Module:** In case of an intervention decision, the Intervention_module trigger a fire extinguishing action that is performed by actuators.
4. **Storage Module:** This module is located at the cloud level. Its function is the storage of analytics results that is performed by the Detect_fire_module for farther deep analysis.

Regarding the simulated fire detection scenario (cloud-only or fog-cloud-based scenario) and the available resources of each network component, the iFogSim manages the placement strategy where every module is assigned to the appropriate network component. In the fog-cloud scenario, the Detect_fire_module and Intervention_module are embedded on the fog nodes. Otherwise, in the cloud-only scenario, these modules are assigned to the cloud server. The Filtering_data_module is at the sensor node level in the two scenarios. Also, the Storage_module is embedded in the cloud server regardless of the simulated scenario.

Table 2 gives the multiple network simulation components characteristics (Cloud server, proxy server and fog nodes). These parameters are assigned to their respective devices at the network topology initiation time. The simulation parameters include CPU processing capability (million instructions

Figure 4. The interaction between the components of iFogSim

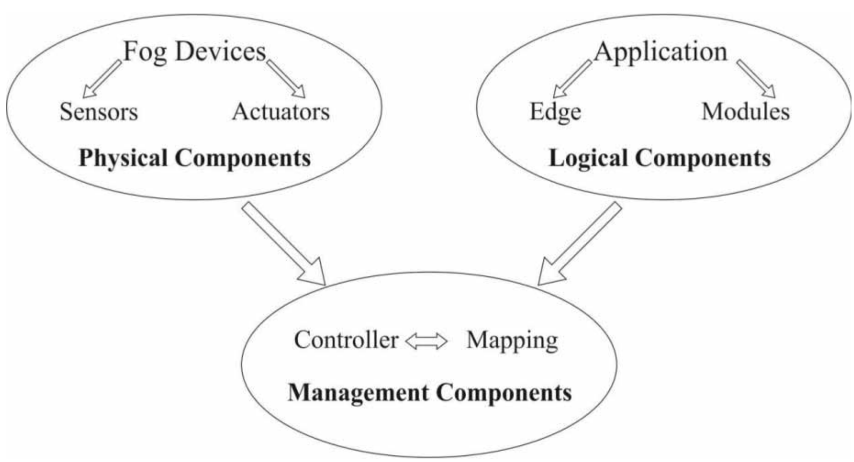


Figure 5. Forest fire detection network topology

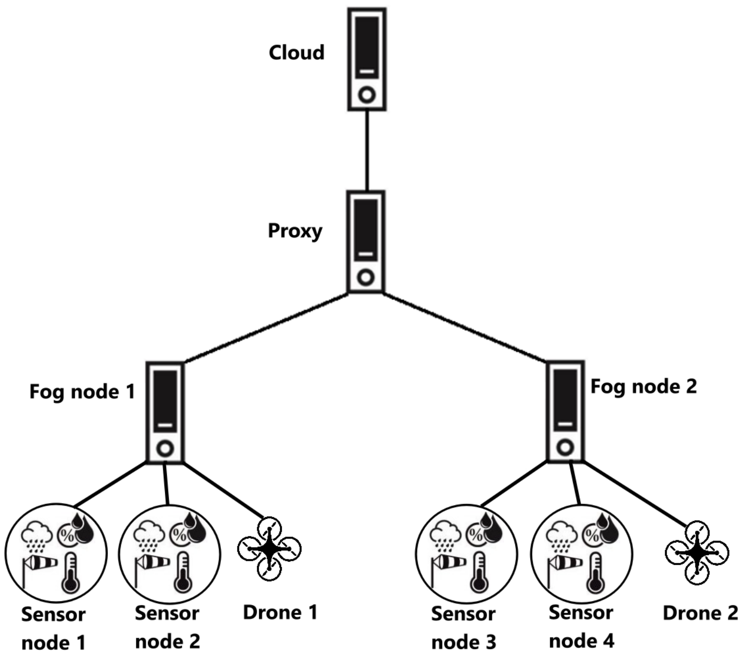
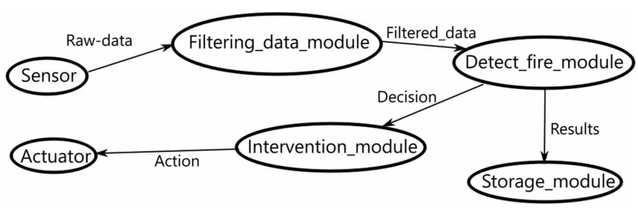


Figure 6. Forest fire detection system application modules



per second), RAM capacity (megabytes), uplink and downlink bandwidth (megabytes), network-level placement of the component, rate per million instructions, and active (busy) and inactive (idle) power.

To properly evaluate the proposed system, in the first phase, four sensor nodes are assigned per fog node. The number of fog nodes is progressively increased to evaluate their impact on latency and network usage. In the second phase, the number of sensor nodes is increased while leaving the number of fog nodes stable. The multiple configurations of the simulated physical topologies are presented in Table 3.

Simulation Results

In this section, the authors discuss the fog computing environment simulation results for the forest fire detection case study. Various metrics reported by iFogSim are collected for the multiple configurations of the physical topology cited in Table 3. The latency between system components and bandwidth usage are the main parameters to be supervised.

Fire Detection Latency

Figures 7 and 8 show the average latency of the fire detection process loop for the cloud-only and fog-cloud strategy placements.

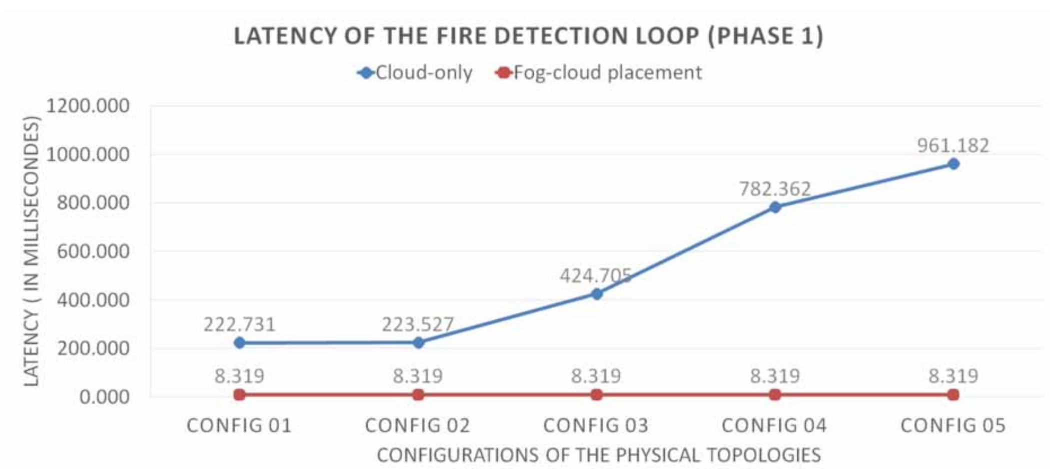
Table 2. iFogSim simulation parameters of cloud, proxy, fog-node and microcontroller sensor-node

Parameters	Cloud	Proxy	Fog-node	Sensor-node
CPU (MIPS)	44800	2800	2800	500
RAM (MB)	40000	4000	4000	1000
Uplink BW (MB)	100	10000	10000	10000
Downlink BW (MB)	10000	10000	10000	10000
Level	0	1	2	3
Rate per MIPS	0.01	0.0	0.0	0.0
Busy power	16*103	107.339	107.339	87.53
Idle power	16*83.25	83.4333	83.4333	82.44

Table 3. Configurations of the simulated physical topologies

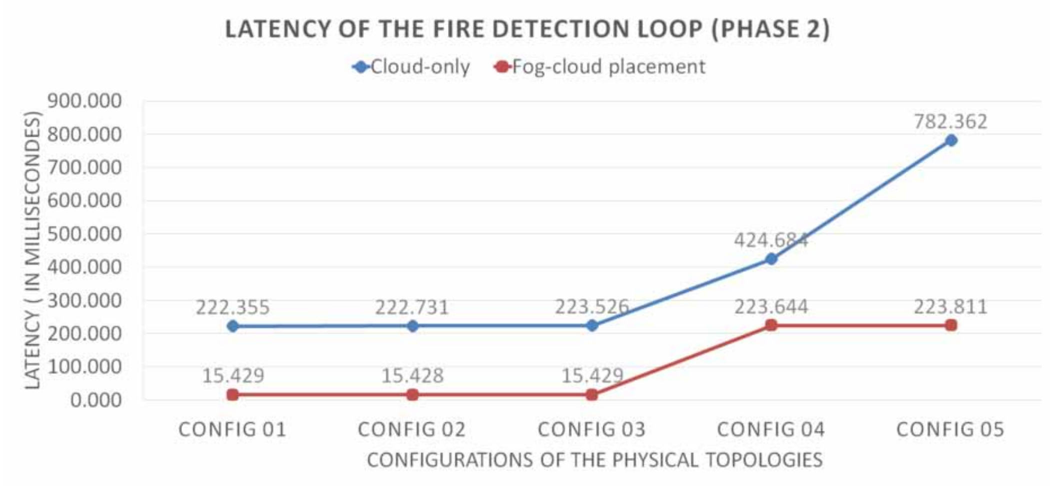
Configurations	Phase 1		Phase 2	
	Number of fog nodes (Areas)	Number of sensor nodes per area	Number of fog nodes (Areas)	Number of sensor nodes per area
Config 1	2	4	2	2
Config 2	4	4	2	4
Config 3	8	4	2	8
Config 4	16	4	2	16
Config 5	32	4	2	32

Figure 7. Comparing the latency in the cloud-only and the fog-cloud placement strategies (Phase 1 configurations)



First, the phase 1 parameters are applied as cited in Table 3. Figure 7 shows the latency simulation results for this phase. We notice that in the case of fog-cloud placement, the latency of the detection loop remains relatively low and stable. The low latency is because, in phase 1, the number of sensor

Figure 8. Comparing the latency in the cloud-only and the fog-cloud placement strategies (Phase 2 configurations)



nodes remains the same for each fog node, and all the detection modules are executed in their regular placement. On the other hand, the cloud-only placement strategy results in a much higher latency than the fog-cloud placement. The latency increases considerably as the number of sensor nodes increases. The simulation result leads to the conclusion that in implementation with a very high number of sensor nodes, the cloud server will have a very high response time to process all the sensor nodes' collected data.

Figure 8 shows the latency of the fire detection loop in phase 2. For the cloud-only strategy placement, we notice almost the same result as phase 1. The latency is considerably increasing with the number of sensor nodes increases. The fog-cloud placement strategy shows some changes regarding the phase 1 results. The latency starts very low for the first three configurations and then starts to climb when dealing with a high number of sensor nodes. The fog nodes have limited resources. By increasing the number of data sources (the sensor nodes), the fog node will not be able to handle all the modules of the detection process. Some modules are then shifted to the cloud server, which explains the increased response time.

Total Network Usage

Figures 9 and 10 represent the total bandwidth utilization by all system components in the different configurations of the two phases of the simulation.

We notice that in the case of the cloud-only placement strategy, as the number of sensor nodes increases, the load on the network increases significantly. Also, in the case of fog-cloud placement, the bandwidth usage grows as the number of sensor nodes increases but remains very low compared to the cloud-only placement strategy. The placement of the processing modules is the main factor for network traffic. Indeed, the Detect_fire_module and Intervention_module modules in the fog-cloud placement strategy are located on the fog nodes at the network edge, which reduces considerably the volume of data sent to the data center. On the other hand, in the case of cloud-only placement strategy, the majority of the processing modules are placed on the cloud server, which causes high traffic on the network.

DISCUSSION

A forest fire detection and management system must be able to provide some key features to be a fully effective system. Different key features can be considered to classify a FFDS. In the present

Figure 9. Comparing the total network usage in the cloud-only and the fog-cloud placement strategies (Phase 1 configurations)

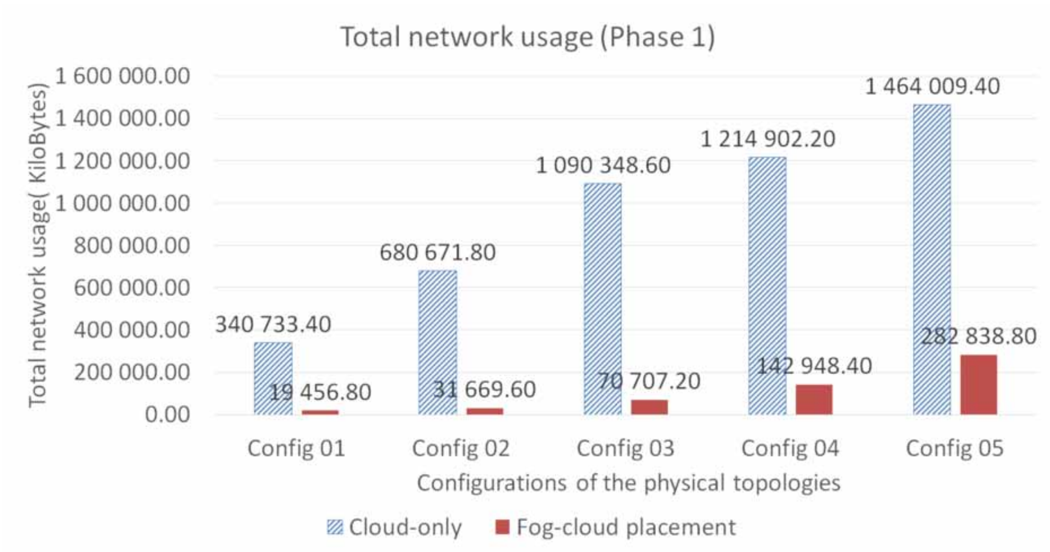
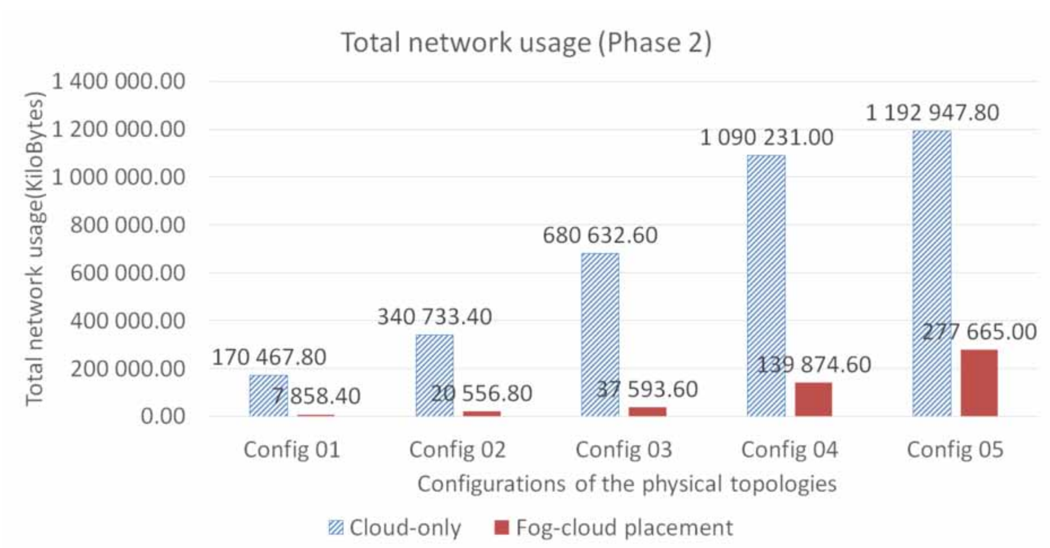


Figure 10. Comparing the total network usage in the cloud-only and the fog-cloud placement strategies (Phase 2 configurations)



research, 7 key features are retained namely: *fast data processing*, *fire spread monitoring*, *long-term data analysis*, *fire extinguishing capability*, *energy efficiency*, *privacy preservation,* and *false alarms rate*. Details of each feature is given in the subsequent. The use of these features as a classification method will permit to situate the proposed approach against other approaches. Table 4 provides a comparison between the proposed system in this paper and a selection of recent FFDSs based on the features mentioned above. The values in the table are given according to the consideration or not of each feature within a particular study.

1. **Fast data processing:** Early fire detection is essential in a FFDS. It allows a rapid intervention to prevent the spread of the fire and thus avoid a possible disaster.
2. **Fire spread monitoring:** Having the ability to monitor the spread of a fire allows for better management. The deployment of a drone equipped with a camera is the ideal solution for this type of mission. In addition, the use of wind direction sensors will help predict the direction of fire spread.
3. **Long-term data analysis:** After an initial data analysis for fire detection, a second and more sophisticated analysis over the long-term is beneficial to designate the most vulnerable zones to fire. The adoption of a cloud-based solution is the best practice for such a process.
4. **Fire extinguishing capability:** It is well known that extinguishing a fire within a short period in a forest area will prevent its widespread. This feature is not addressed in most studies of FFDSs. The employment of drones equipped with a fire extinguishing solution makes it possible to reach the area at risk within a short time and to start the fire extinguishing operation.
5. **Energy efficiency:** In an environmental sensing system, reducing the power consumption of the data sensors allows for a long monitoring time without the need for maintenance. Therefore, separating the data processing task from the data receiver components will result in a considerable reduction in power consumption and a prolonged system lifetime.
6. **Privacy preservation:** UAV-based systems have issues with privacy preservation as they are based on image perception. In contrast, sensor network-based systems have no privacy issues.
7. **False alarms rate:** Sensor network-based systems have a low false alarm rate. In the authors' proposed approach, a second verification of the actual presence of the fire is performed by deploying a drone equipped with a camera. It makes the system more accurate compared to the ordinary sensor network-based systems. In (Kalatzis et al., 2018), when forest fire is detected, new directives are sent to the UAV to focus the surveillance on the area at risk and thus to verify the real presence of fire to avoid the case of a false alarm.

CONCLUSION

IoT applications in time-sensitive areas such as environmental monitoring require sophisticated data processing systems. Cloud computing was a suitable solution to meet this requirement. However, the excessive data generation from environmental perception sensors and the high distance between the data source and the data center leads to network congestion and increases the system response time. The use of fog computing has become a necessity to reduce network traffic in such systems while taking advantage of the processing power of the cloud paradigm.

Table 4. Comparison of authors' proposed approach with other recent FFDSs

	(Grover et al., 2019)	(Kalatzis et al., 2018)	(Varela et al., 2020)	(Benzekri et al., 2020)	Our Approach
Fast data processing	No	Yes	No	Yes	Yes
Fire spread monitoring	No	Yes	No	Yes	Yes
Long term data analysis	No	Yes	No	No	Yes
Fire extinguishing capability	Yes	No	No	No	Yes
Energy efficiency	No	Yes	Yes	Yes	Yes
Privacy preservation	Yes	No	Yes	Yes	Yes
False alarms rate	Medium	Low	Medium	Medium	Low

In this paper, researchers investigated the benefits of using the fog computing paradigm to manage a forested area to detect high fire risks. Experimental results showed that the recourse to a three-layer architecture (object, fog, and cloud layer) significantly reduces bandwidth usage and minimizes system response time compared to a cloud-only model.

In future studies, the authors intend to investigate multiple methods and algorithms for data analysis in fog and cloud levels. The fog level requires fast and efficient data processing methods to detect the fire outbreak as soon as possible. Whereas the cloud level requires more sophisticated data analysis methods to determine the fire vulnerability level of each forest area. Therefore, we can decide on future directives to better preserve our forests.

The transfer and data exchange in the IoT ecosystem are frequently confronted with security and privacy issues. The case of FFDS is not an exception. Through this paper, the authors have evoked several applications where the main concern was privacy preservation and security on the network. Preserving privacy and enhancing the security level on the IoT network is another research guideline to exploit. The authors in (Gadekallu et al., 2022; Prabadevi et al., 2021) discuss this issue and propose the involvement of the Blockchain concept in Edge of Things (EoT) applications. The main reason behind the use of blockchain in EoT applications is its unique properties. Decentralization in blockchain will multiply the number of access points in the EoT network, thus eliminating the single point of failure of traditional centralized systems and reducing the system's vulnerability to attacks. Due to the blockchain's consensus algorithms, the immutability aspect of data on the network will reinforce the preservation of anonymity in an EoT system. Despite the use of open-source technology in the blockchain, which will bring transparency to the data on the network, critical information is kept secure by complex cryptography algorithms.

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