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A multinational multi-tenant IoT orchestration framework for bioacoustic-driven biota preservation in Royal Belum State Park, Malaysia

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ABSTRACT

The sustenance of life on Earth depends on balanced ecosystems, with forests serving as critical habitats for biodiversity. While IoT-based solutions have enabled remote monitoring and automated conservation actions in single-tenant forest environments, the challenge of shared responsibility in transboundary forests—where multiple nations oversee management—remains unaddressed. This paper proposes a novel holistic IoT framework that employs a bottom-up approach, integrating sensor networks, publish/subscribe data flows, and an action-driven dashboard to facilitate multi-tenant coordination. Designed based on the operational requirements of Malaysia-Thailand's Royal Belum State Park under the World Wildlife Fund (WWF) supervision, this solution ensures credibility and scalability, offering a feasible model for global IoT-driven forest preservation in similar transboundary ecosystems.

1. Introduction

The Internet of Things (IoT) technology has been a popular solution to monitor nature condition in several countries for example, in Malaysia, a river monitoring solution is integrated with mobile application for remote monitoring and alerting, while in high-population countries like India, an urgent IoT-based drinking water monitoring system has also been deployed (Moparthi et al., 2018). Most of nature-related IoT solutions are with the purpose of farming optimization, where farm's condition is sensed with sensors that measure the surrounding natural metrics, such as temperature, humidity, soil's nitrogen content, and many more (Lakhwani et al., 2019; Quy et al., 2022; Ruan et al., 2019; Farooq et al., 2019; Xu et al., 2022; Muangprathub et al. 2019; Balakrishna and Nageshwara, 2019). The focus on nature-based IoT deployment in agriculture is understandable due to the critical importance of global food security. However, another important but less-discussed environmental issue is wildlife preservation. Protecting wildlife is essential for maintaining a balanced ecosystem, supporting the food chain, and preventing the loss of species. IoT platforms can help monitor wildlife by providing near real-time data to remote dashboard applications. For instance, Ross et al. (2022) introduced WildTrack, an IoT-based tracking system utilizing passive RFID technology to monitor small, free-ranging mammals. The system is designed to be minimally invasive, ensuring that the tracking devices do not adversely affect the animals' natural behaviors or health. By employing low-power, lightweight sensors, the researchers successfully monitored species weighing less than 20 grams, demonstrating the system's suitability for fragile wildlife, including newborns. Other solutions are mostly implemented within the proximity of business-owned farms (Akhigbe et al., 2021; Yamsani et al., 2024; Sujitha et al., 2024). This finding is reasonable since applying IoT infrastructure within a confined private environment is more feasible and practical compared to those in the wild forests. At present, there are only a few IoT solution deployments in wild forests, such as the one by Krishnaveni et al. (2023) that monitors animals' biometrics and forecasts forest fires. Their method of putting sensors on animals has well-known side effects, i.e., physical discomfort that could even be deadly due to the intrusive installation of body sensors. While their forest fire detection system utilizes drones that may not be feasible for highly dense forests. Additionally, camera traps to capture motion-driven images are also included in their solution. The previously mentioned multiple sources of images would then be analyzed using machine learning algorithms to produce the classification of visible animals and predict fire presence. A similar but more targeted forest fire monitoring solution was conducted by Wang et al. (2021) in China. Instead of analyzing an untargeted dataset, they focused on data points where temperature had exceeded the specified threshold in the forest. This method had a drawback in the case that the satellite-based temperature sensing received several false positives coming from the surrounding factories and mining sites. These false alarms may waste resources in case manpower assistance and firefighting equipment are to be brought to the triggered location. Therefore, such a method may need to be complemented by additional sensor type/s like a camera trap. In Romania, an IoT-based forest monitoring system was implemented by Marcu et al. (2019). Their system is more advanced than earlier examples because, in addition to common sensors like temperature and humidity, it also includes sound sensors. These sound sensors detect background noises and classify them as either natural forest sounds or external sources, such as vehicles or machinery. This approach was designed to detect forest fires, pollution, and illegal logging activities. However, the system was limited to actions and supervision within a single country. A similar approach using sound sensors was also developed by Olteanu et al. (2018), demonstrating that sound sensing is a feasible technology for forest conservation systems.

Furthermore, a different method of forest monitoring solution has been devised by another group of researchers, who designed a multi-step system, where a forest fire would be detected, followed by the ringing of an alarm in case there was a sign of animal's movement around the fire. This solution brings two benefits, i.e., the fighting of fire through the activated water sprinkler and the avoidance of loss of animal life via the alarm triggered. Such methodology, however, requires complex installation of water piping for the sprinklers; this installation may not be allowed in some forests due to its potential disturbance to nature.

Overall, the current review of forest monitoring practices infers that such IoT-based solutions have not been implemented in a way that orchestrates multiple bordering nations, and even more concerning, they contained methods that were not always feasible and intrusive for animals. Hence, this paper proposes a method that allows countries that are directly separated by natural forests to orchestrate meticulous IoT-driven biota monitoring and preservation.

2. Methodology

The forest monitoring challenges discussed earlier can be addressed by the proposed methodology presented in this section. Our approach aims to overcome the current limitations of IoT-based wildlife monitoring systems, which are often restricted to a single country's resources, can be physically intrusive to animals, and require high maintenance costs for equipment such as drones, satellites, and water piping systems.

Besides the standard camera trap sensor, bioacoustic sensors would also be included since the current commonly deployed sound sensors are insufficient to discern animals' profiles. Bioacoustic sensors can identify complex biological processes and natural interactions among biota (Alberti et al., 2023; Martinez-Rach et al., 2013; Lostanlen et al., 2019). Another advantage of bioacoustic sensors is that they are non-intrusive since no physically embedded sensors would be installed in the biota's body.

Moreover, to make our solution more holistic, thermal sensors would also be incorporated to detect the presence of creatures and the buildup of fire. In addition, location sensors would also be embedded to pinpoint the sensed incident's location.

The proposed IoT solution would also consider the distribution of actions of multiple nations to handle incidents in the bordering forest. This is due to the fact that each involving country may be the better option to handle certain incident engaging specific biota, for examples, an incident involving elephants in Royal Belum state park/forest might be best handled by Thailand instead of Malaysia considering Thailand has more experiences and knowledge regarding elephants, while a different incident concerning tigers had better be handled by Malaysia for the similar reason.

The bioacoustic sensors may also detect the physical invasion of a plant, for example, when insects feed on plants (Alberti et al., 2023; Martinez-Rach et al., 2013). Such detrimental incidents should be mitigated to prevent the perishing of beneficial plants. Research has discovered that in the Southeast Asia region, Thailand, Vietnam, and the Philippines are the most proficient nations when it comes to the treatment of plants. Thus, in the Royal Belum forest case study presented in this paper, Thailand would get the priority to handle detected plant-related incidents.

The plausible past performances of bioacoustic sensors further justify their inclusion in our proposed framework as have been shown by Noh et al. (2022) who recorded 95.89% accuracy and capturing speed of 15 seconds in their biometric use case, while Alberti et al. (2023) obtained 76% accuracy in their insect detection experiment. Some other examples of high accuracy include Lostanlen et al. (2019) in their avian flight detection cases that went as high as 90.5%, and similarly, Kohlberg et al. (2024) consistently reached over 90% accuracy in their insect monitoring case.

The proposed IoT orchestration model in this paper involves multiple stakeholders across different countries. This multi-tenancy approach allows a single organization to operate in multiple nations—in this case, the World Wildlife Fund (WWF), which has a presence in both Malaysia and Thailand. The deployment site is the Royal Belum State Park, located along the Malaysia–Thailand border. In this model, WWF Malaysia is responsible for tiger-related incidents, while WWF Thailand handles elephant- and plant-related incidents. Tigers and elephants are chosen as the main focus due to their protected status within the park.

The term "incident" for animals refers to events that affect their well-being, such as sounds indicating injury or the birth of a newborn. For plants, "incident" refers to situations such as infestation or damage caused by insects or termites. The system also detects human intrusion, such as poaching. In such cases, the WWF team located closest to the incident site will be assigned to respond.

Fig. 1 shows the framework of the proposed multi-tenant IoT orchestration. The flowchart in Fig. 2 includes two main actors—WWF Malaysia and WWF Thailand—and four types of triggers: tiger, elephant, plant, and human.

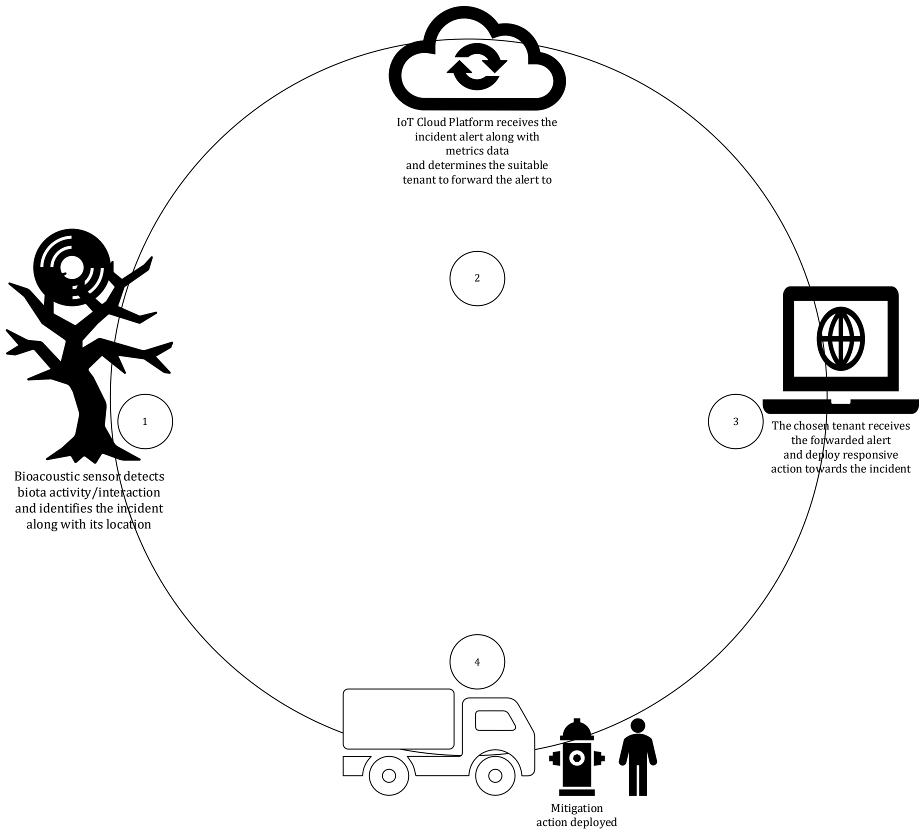

Fig. 1: Multinational multi-tenant IoT orchestration for nature preservation methodology framework; the following flowchart discerns the detailed mechanism of the above multi-tenant IoT orchestration methodology framework

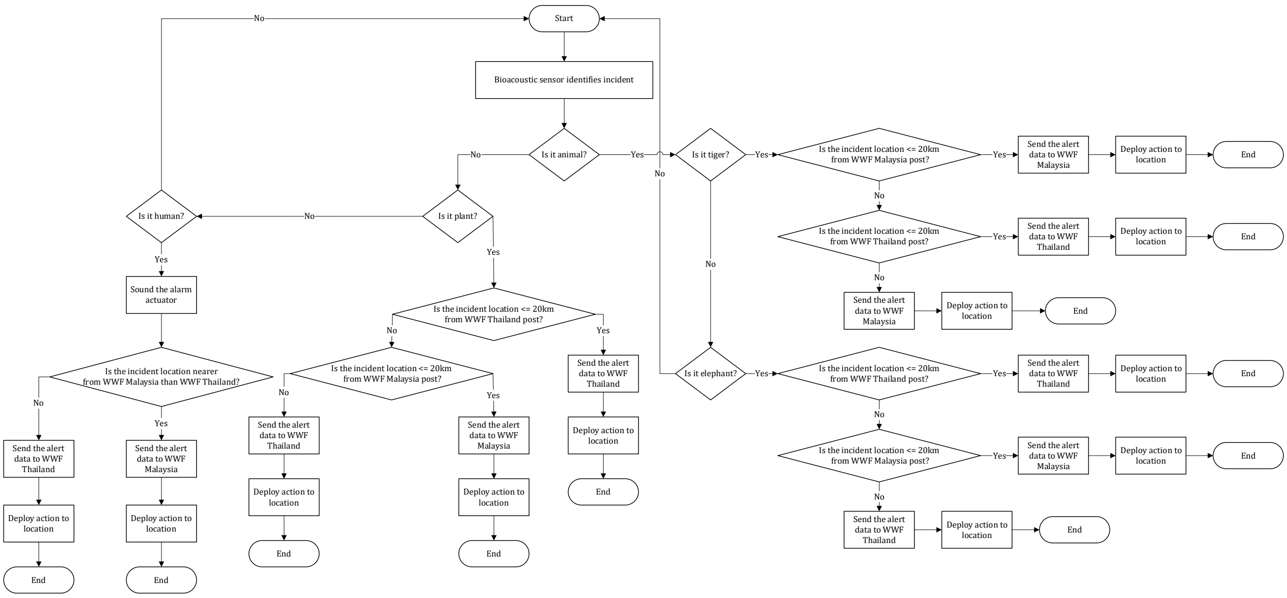

Fig. 2: Multinational multi-tenant IoT orchestration for nature preservation flowchart

A disclaimer is to be stated that the 20km distance mentioned in the framework's flowchart is a pseudo value and does not represent the actual distance on the field since the sensors' locations are confidential information. Instead of merely measuring the nearest country from the incident's location, the constant maximum distance value is specified to emphasize the preferences for specific countries to handle specific incidents when they are in range. Semantically, the flowchart can be explained by the following pseudocode:

1. Bioacoustic sensor detects an incident
2. Check type of incident:

- *If it involves an animal:*
  - *If the animal is a tiger:*
    - *If the incident location is ≤ 20 km from WWF Malaysia:*
    - *Send alert to WWF Malaysia*
    - *Deploy mitigation action*
    - *Else if the incident location is ≤ 20 km from WWF Thailand:*
    - *Send alert to WWF Thailand*
    - *Deploy mitigation action*
    - *Else:*
    - *Assign WWF Malaysia as the responsible actor*
    - *Deploy mitigation action*
  - *If the animal is an elephant:*
    - *If the incident location is ≤ 20 km from WWF Thailand:*
    - *Send alert to WWF Thailand*
    - *Deploy mitigation action*
    - *Else if the incident location is ≤ 20 km from WWF Malaysia:*
    - *Send alert to WWF Malaysia*
    - *Deploy mitigation action*
    - *Else:*
    - *Assign WWF Thailand as the responsible actor*
    - *Deploy mitigation action*
- *If it involves a plant:*
  - *If the incident location is ≤ 20 km from WWF Thailand:*
    - *Send alert to WWF Thailand*
    - *Deploy mitigation action*
  - *Else if the incident location is ≤ 20 km from WWF Malaysia:*
    - *Send alert to WWF Malaysia*
    - *Deploy mitigation action*
  - *Else:*
    - *Assign WWF Thailand as the responsible actor*
    - *Deploy mitigation action*
- *If it involves a human (e.g., poaching):*
  - *Activate alarm actuator*
  - *If the incident location is closer to WWF Malaysia than WWF Thailand:*
    - *Send alert to WWF Malaysia*
    - *Deploy mitigation action*
  - *Else:*
    - *Send alert to WWF Thailand*
    - *Deploy mitigation action*

The previously stated pseudocode is the representation of how the bioacoustic-driven multi-tenant IoT orchestration would be conducted. Besides it, the deployment of this IoT infrastructure would require an operational environment diagram as Fig. 3.

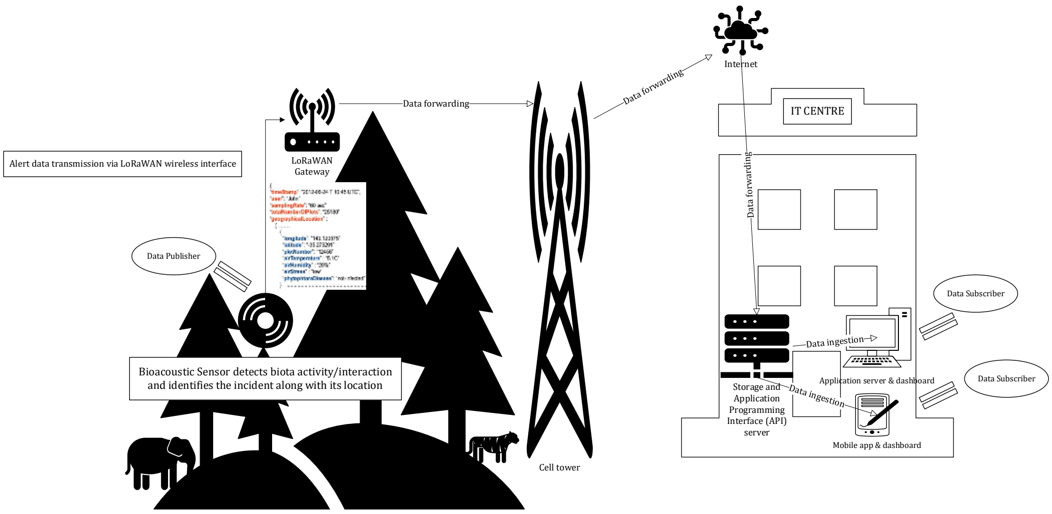

Fig. 3: Multinational multi-tenant IoT orchestration for nature preservation operational environment diagram

The operational environment diagram in Fig. 3 illustrates how the proposed infrastructure could be installed in Royal Belum State Park. Logically, the IoT network is comprised of the same layered protocols (TCP/IP stack) that construct a basic computer network (Abdulazeez et al., 2024). However, it may require renaming of the hardware layer to the sensing layer, because IoT infrastructure at the lowest layer deals with sensing done by sensors instead of conventional receiving of data from a source computer. The details of all the physical and logical layered protocols involved are explained below in a bottom-up manner.

2.1. Sensing layer

This layer is the lowest in the system architecture and corresponds to the hardware layer in the OSI model and the network interface layer in the TCP/IP stack. It is known as the sensing layer and includes various sensing devices, such as bioacoustic sensors, camera traps, thermal sensors, and location sensors.

Among these, bioacoustic sensors are the only type that has not yet been deployed.

Data processing also occurs within this layer, as the recorded input is analyzed using machine learning algorithms to identify the species and determine the type of activity detected. This processing takes place on the edge device, which is directly connected to the sensors. To ensure system reliability, a backup plan is included in case the edge device is compromised; in such situations, data processing is transferred to a cloud-based Data Analytics node.

Various machine learning algorithms can be used for this analysis, particularly classification algorithms such as Convolutional Neural Networks (CNN), Support Vector Machines (SVM), k-Nearest Neighbors (kNN), Random Forests (RF), and Linear Discriminant Analysis (LDA). Based on previous comparative studies, especially those focused on acoustic sensor data (Noh et al., 2022; Salamon and Bello, 2017), CNN has been identified as the most effective option.

2.2. Network layer

Located above the sensing layer is the network layer. This layer manages the network interface selected for the proposed system. Considering the environmental conditions of Royal Belum State Park, the network interface must support wide-area coverage through dense forest and be capable of connecting to existing telecommunications infrastructure.

For this reason, LoRaWAN has been selected as the preferred network interface technology. LoRaWAN offers strong scalability through the use of gateways and can connect to existing cellular towers, which in turn provide access to the Internet. Additionally, LoRaWAN hardware uses less power than other long-range communication technologies, making it suitable for remote deployment.

The LoRaWAN protocol will be embedded in the firmware of all sensors and networked devices, including edge devices, aggregation units, and routers. Furthermore, Internet Protocol (IP) addressing is required for communication. IPv6 will be used, as it offers a large number of available addresses, ensuring the system can scale in the future.

2.3. Transport layer

One step after the network layer is the transport layer, which provides control and reliability of end-to-end network connections using the Transport Control Protocol (TCP).

2.4. Application layer

At the top of the architecture is the application layer. In this layer, a lightweight communication protocol is preferred due to the limited computing capacity of the sensors. Therefore, Message Queuing Telemetry Transport (MQTT) is used instead of the more resource-intensive Hypertext Transfer Protocol (HTTP). In this setup, the sensors act as MQTT brokers (data publishers), while the Data Analytics node functions as the MQTT client (data subscriber or consumer). This analytics node can be located either on-premise or in the cloud.

The data received by the analytics node is processed, and the results are presented through an application dashboard for clear and meaningful visualization. This application can be developed for both desktop and mobile platforms.

For microservices and machine-to-machine communication, this layer uses Application Programming Interface (API) messages. These API messages are transported using MQTT, following the Publish/Subscribe (Pub/Sub) model mentioned earlier. The communication is organized using a Representational State Transfer (REST) architecture, which ensures standardized message formatting and interoperability between different systems. This makes the proposed framework compatible with both web-based and mobile applications designed for visualization.

The API messages, whether for publishing or subscribing, use the JSON (JavaScript Object Notation) format, which consists of key-value pairs. Below is an example of an API publish message sent by a bioacoustic sensor:


```
{
"timeStamp":"2024-10-22 T 11:50 UTC",
"sensorID":"sensor1",
"tigerIncident":"true",
"elephantIncident":"false",
"plantIncident":"false",
"humanIncident":"false",
"longitude":"5.795100332189252",
"latitude":"101.51609913496283"
}
```


Example of API Subscribe message sent by an application client (desktop/mobile):


```
{
"sensorID":"sensor1",
}
```


An intuitive and meaningful dashboard - be it on desktop or mobile application is crucial for seamless monitoring purposes. Hence, this paper also proposes a wireframe design that may achieve such an objective as shown in Fig. 4. The above presented sample wireframe design shows environmental statuses, control adjustments for remote configuration, and remote action executions. The user-friendly Graphical User Interface (GUI) elements are used, such as charts, buttons, and toggles to help users navigate the application. Sequentially, the monitoring statuses are shown first at the top row, followed by control buttons and toggles at the bottom half section. This intuitive arrangement is meant to follow the proper procedural human thinking process, which starts with observation and is followed by decision-making (action).

3. Discussion and conclusion

The above proposed framework in the previous section covers multiple aspects of the novel multi-tenant bioacoustic-driven IoT infrastructure, which includes both physical and logical aspects of the infrastructure. This holistic approach would increase the likelihood of successful deployment. Such a grand design may also be replicated by other parties with a similar purpose in other forests around the world. Regardless, pre-deployment may include an assessment that scores the readiness level of the proposed design. Such assessment has been made by other case studies, such as the one for Malaysia's national IoT infrastructure (Nurika and Jung, 2024) and another one done for Australia's national IoT infrastructure. Both cases were assessed using Key Performance Indicators (KPIs) specified in the enhanced CREATE-IoT standards devised by Nurika and Jung (2021).

Fig. 4: Proposed monitoring dashboard wireframe design

The deployment of similar frameworks worldwide may ease the IoT-driven forest monitoring and preservation orchestration among large geographical areas, because system compatibility and connection could be directly achieved with similarities in chosen technologies and software-based protocols.

However, deployments may not be straightforward as there could be an exchange of sensitive national data; thus, political discussion may have to get underway, and consequently, it may lead to delays in deployments. This concern may be solved by incorporating security policies, for example, end-to-end data encryption, multi-level authorization/permission, security groups, and clear distribution of data ownership. For instance, data ownership may be subject to its origin, however, its regulation will be subject to where it is stored. Selective data sharing may also be controlled by the owner of the data based on request.

Another concern is the possibility of MQTT's blocking approach being implemented. Such a technique may restrict the number of concurrent requests since it would assign a thread for every request and hold it for its entire lifecycle. This could be mitigated by implementing the non-blocking approach that does the opposite.

Overall, the benefits of this framework's deployment would outweigh the inherent security risks that come with it, since global forests' biota would be protected and preserved for sustaining our Earth's ecosystem.

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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