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Availability of Services in Wireless Sensor Network with Aerial Base Station Placement

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Abstract: Internet of Things technologies use many sensors combined with wireless networks for cyber-physical systems in various applications. Mobility is an essential characteristic for many objects that use sensors. In mobile sensor networks, the availability of communication channels is crucial, especially for mission-critical applications. This article presents models for analyzing the availability of sensor services in a wireless network with aerial base station placement (ABSP), considering the real conditions for using unmanned aerial vehicles (UAVs). The studied system uses a UAV-assisted mobile edge computing architecture, including ABSP and a ground station for restoring the energy capacity of the UAVs, to maintain the availability of interaction with the sensors. The architecture includes a fleet of additional replacement UAVs to ensure continuous communication coverage for the sensor network during the charging period of the air-based station UAVs. Analytical expressions were obtained to determine the availability of sensor services in the system studied.

Keywords: wireless sensor networks; aerial base station; unmanned aerial vehicle; availability

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1. Introduction

Wireless sensor networks (WSNs) are a fast-growing technology with many potential applications in cyber-physical systems (CPS) and the Internet of Things (IoT). These networks are made up of hundreds or even thousands sensor nodes, each with limited information processing and communication capacities, which are connected wirelessly to form a distributed system [1]. To overcome these limitations, sensor nodes can be clustered together, with each cluster headed by a cluster head (CH) that collects local information and transmits it to the base station (BS). Clustering is an important method for extending the network lifetimes of WSNs. A cluster-based model of WSNs is shown in Figure 1. CPS involves the integration of cybernetic and physical components, with WSNs providing the sensing and communication systems. WSNs are designed to operate autonomously, as they are not accessible to external agents once deployed.

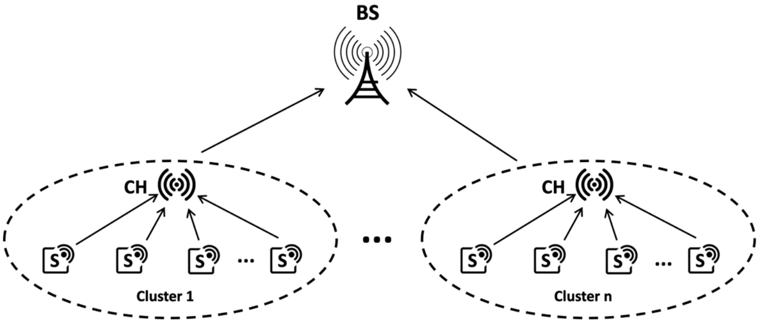

Figure 1. Architecture of cluster-based wireless sensor network.

WSNs have different applications, such as critical infrastructure monitoring, health care, military, inter-vehicular, and infrastructure monitoring [2,3]. To improve data collection efficiency, mobile sensors or robots can be deployed to support static sensor nodes [4,5]. Mobile robots can work in different scenarios, including collecting data in a sensing area to send to a base station (BS) or collecting data from sensor nodes and sending it along with their own data to the BS [6,7]. This approach takes advantage of the mobility of the robots to reach areas that static sensors cannot and to reduce the energy burden on static sensors during data transmission. Mobile robots have limited battery life and cannot communicate over long distances when the BS with an information processing center is located at a distance from the zone with sensors, which may lead to disconnections or packet loss [8].

To overcome the challenges of information transfer over long distances, unmanned aerial vehicles (UAVs) are suggested as a solution for WSNs [9]. With their mobility and adaptive altitude, UAVs can act as a wireless mobile backbone to collect information from the ground sensors and transmit it to a BS for analysis. The dependability of data exchange via aerial base station placement (ABSP) in mobile sensor networks is the most crucial [10].

This paper presents models for analyzing the availability of sensor services in wireless networks with aerial base station placement, considering the real conditions of UAV use. The multi-tier network architecture in Figure 2 includes ground mobile sensors with unknown mobility location. A group of UAVs are responsible for collecting the data by moving around in a controlled manner to track the sensors. Every sensor communicates with UAV via a ground-to-air link directly or through a cluster head. The collected data is then transmitted by the UAVs to the BS. The communication link from the UAVs to the BS must provide a continuous data stream. The base station performs primary data processing and transmits the integrated information to a single cloud processing and analysis center (CPA).

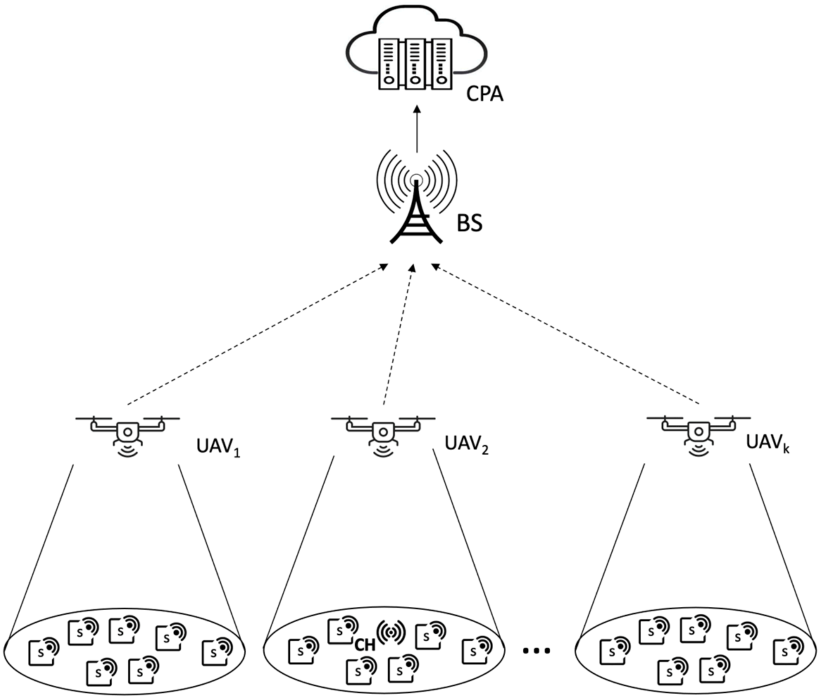

Figure 2. Architecture of the multi-tier network with aerial base station placement.

The proposed architecture of sensor services in wireless networks with aerial base station placement using unmanned aerial vehicles has a wide range of potential applications. There are some examples of use cases in various sectors:

- Agriculture. In precision agriculture, the ABSP architecture can be utilized for monitoring soil conditions, crop health, and growth. The ground sensors can collect data on soil moisture, temperature, and nutrient levels, and the UAVs can gather information on plant health through aerial imagery. The UAVs can then transmit this data to the base station and cloud processing center for further analysis, allowing farmers to optimize irrigation, fertilization, and pest control strategies.

- Environmental monitoring. The ABSP architecture can be used to monitor air quality, water pollution, and wildlife habitats. Ground sensors can collect data on air pollutants, water quality indicators, and wildlife movement patterns, and UAVs can provide aerial imagery and additional environmental data. By transmitting this information to the base station and cloud processing center, authorities and researchers can analyze the data and develop strategies for environmental conservation and pollution control.
- Disaster management. In the event of natural disasters such as floods, wildfires, or earthquakes, the ABSP architecture can help in rapid response and damage assessment. Ground sensors can collect data on the affected areas, and UAVs can provide real-time aerial imagery and assess the extent of the damage. This information can be sent to the base station and cloud processing center for processing, enabling authorities to make informed decisions about rescue and relief operations.
- Infrastructure monitoring. The proposed architecture can be employed to monitor the structural health of bridges, roads, railways, and other critical infrastructure. Ground sensors can measure vibrations, strain, and temperature, and UAVs can inspect these structures visually and through various imaging techniques. The gathered data can be transmitted to the base station and cloud processing center for analysis, allowing maintenance teams to detect and address potential issues before they become critical.
- Border security and surveillance. In border security applications, the ABSP architecture can help monitor and detect unauthorized activity along borders. Ground sensors can detect motion, sound, and other indicators of human presence, and UAVs can provide aerial surveillance and tracking. The data collected by the sensors and UAVs can be transmitted to the base station and cloud processing center for real-time analysis, enabling security forces to respond quickly to potential threats.

These are just a few examples of the many applications that can benefit from the proposed architecture of sensor services in wireless networks with aerial base station placement using unmanned aerial vehicles. The versatility and adaptability of this architecture make it a promising solution for various sectors and industries that require efficient, reliable, and scalable data collection and analysis.

2. Related Works

The development of unmanned aerial vehicle technology has allowed their application in different areas. In [9], the main applications of UAVs in wireless sensor networks are examined and divided them into three categories: auxiliary data gathering, collaborative sensing, and autonomous deployment. Each category is discussed in detail along with engineering application examples. The paper [10] contains an analysis of the development trend of future hybrid systems made up of UAVs and wireless sensor networks, which can enhance sensing, communication, and deployment capabilities and offer new service methods. [11] contains a review of the literature on UAV networks' applications as well as their classifications. The paper also contains an analysis of typical problems related to UAV control, navigation, and deployment optimization, and research gaps and future directions are identified.

The article [12] provides a review of the literature on the possibilities of using UAVs for IoT tasks, and it contains a proposed classification of services in IoT systems into four categories. The article discusses the problems of using UAVs in IoT systems and the possibility of developing new applications for these systems.

In wireless sensor networks, data collection is of key interest to researchers. In [13], this problem is considered in relation to aerial photography applications. The goal of the study was to find optimal solutions of deploying a UAV network and choosing its configuration when transmitting information from sensors via ground-to-air communication channels.

UAVs in systems with an aerial BS are being developed to provide internet connectivity in areas without sufficient terrestrial infrastructure, such as remote locations or areas affected by natural disasters. In the article [9], the aerial BS placement problem is introduced and explored, and the trade-offs and challenges associated with it are discussed. The article also presents various approaches to addressing these challenges in 2D and 3D spaces, and the concept of adaptive placement is discussed.

To ensure optimal altitude for UAV nodes to cover the cellular network, the accurate estimation of nodes' air timing is critical. The article [14] contains a proposed decision-making model for cellular networks to create an effective coverage area using UAVs. The model proposes a dynamic reconfiguration of network nodes based on UAVs to achieve the target criteria of the network.

The article [15] examines the effective placement and movement of several UAVs operated as aerial BS to acquire data from ground-based IoT devices. To guarantee dependable communication from the IoT devices to the UAVs with the lowest overall transmission power, a new approach is introduced that optimizes the 3D positioning and mobility of the UAVs, the connections of UAVs with IoT components, and uplink power control.

For devices to operate efficiently, it is crucial to have communication channels of optimal quality. To tackle this issue, the authors of [16] utilized UAVs and machine learning to detect coverage gaps in each area independently. Then, based on the user's demand and wireless backhaul with the core network, they deployed UAV-based base stations.

The paper [17] introduces a new relay system called the tethered unmanned aerial vehicle to ground user to ground system, in which UAV is used as a relay station. This system is a viable alternative to a base station.

UAVs are widely used as repeaters in high-quality broadband networks. The article [18] explores flying peer-to-peer networks (FANETs) using UAVs as repeater clusters that can be used in new generations of cellular networks.

UAVs offer a fast and easy deployment option as drone cells, but efficient placement is a critical issue. In [19], the authors discuss the challenges in efficiently placing drone cells. Mobile base stations based on UAVs have several specific features compared to the stationary terrestrial base stations of the same networks. The authors formulated the task of achieving the maximum network efficiency depending on the three-dimensional placement of the UAV.

The article [20] offers a comprehensive survey of the various applications and algorithms that pertain to using UAVs as aerial BSs. The purpose of article is to review each research area in detail, covering the major technology and applications oriented around the development of UAVs serving as base stations.

The article [21] presents a tutorial on the possible application areas of UAVs in wireless communications. The tutorial offers essential guidelines for analyzing, optimizing, and developing a UAV-based WSN.

Several advantages of using UAVs in wireless sensor networks, however, also encounters several practical technical problems. One of these problems is determining the availability of an end-to-end communication channel when using ABSP. This article proposes an approach to solving this problem.

3. Materials and Methods

The multi-tier studied WSN architecture consists of ground sensors, UAVs, and a ground base station with cloud processing and analysis capabilities, as shown in Figure 3. There are k clusters of sensors, each of which is serviced by a fleet of k UAVs. The base station collects information from UAVs and, after preliminary processing, transmits data to the final location for cloud processing and analysis. Due to the limited flight time of UAVs, the replacement fleet of m additional UAVs is utilized to maintain the availability of channels for sensor data collection. These additional UAVs take over from the primary UAVs while they recharge at L designated recovery places at the ground recovery center.

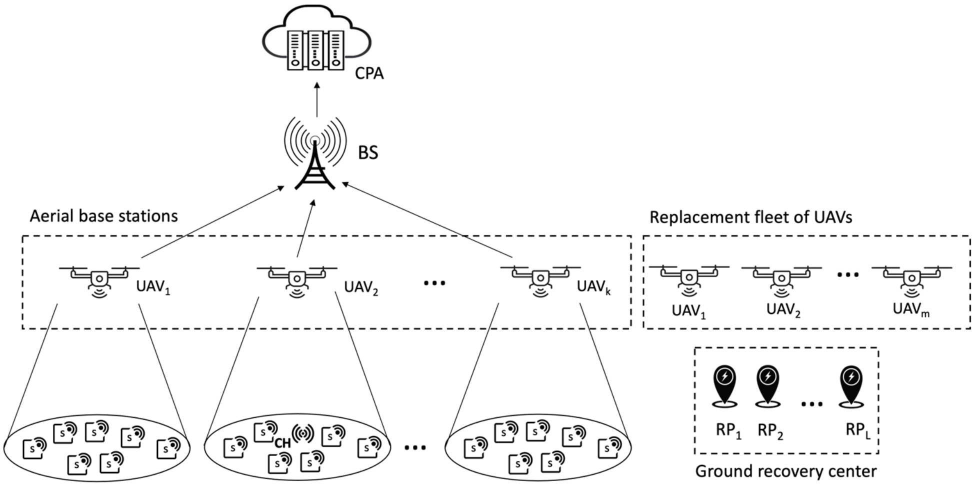

Figure 3. The multi-tier studied architecture of sensor wireless network using ABSP.

This architecture of sensor services in a wireless network with ABSP is significant because it leverages the capabilities of UAVs to improve the performance and efficiency of wireless networks. By deploying UAVs as aerial base stations, it becomes possible to extend the coverage area, enhance network capacity and throughput, and provide reliable connectivity in areas where terrestrial infrastructure is limited. Moreover, the proposed architecture considers the real-world conditions of using UAVs, such as the mobility of the UAVs, their limited battery life, and the challenges of communication in air-to-ground and air-to-air channels. The architecture aims to optimize the deployment and mobility of UAVs to maximize network performance while minimizing its deployment cost [22–24].

The model is required to analyze the level of service provided by the sensors in this aerial base station placement system. The level of service provided by the sensors in this architecture is determined by the availability of communication channels.

The primary problem addressed in this research is ensuring the availability of sensor services in wireless networks with aerial base station placement (ABSP), specifically focusing on the use of unmanned aerial vehicles (UAVs) to facilitate communication between ground sensors and a base station (BS). The objectives of this study are as follows:

1. Develop a multi-tier WSN architecture incorporating UAVs for data collection, transmission, and processing, considering the real-world constraints of UAV operation.
2. Analyze the availability of sensor services in different ABSP system configurations, considering ground sensors, UAVs, and ground base stations with cloud processing and analysis capabilities.
3. Propose a model to calculate the availability of dedicated sensor services provided by UAVs in the ABSP system based on Markov chain analysis.

Table 1 contains the main designations used in the model.

Table 1. Notations used in the model.

Notations	Parameters
p_i	Stationary probability of the state H_i
A	Availability of end-to-end information channel from sensor to cloud processing
$U = 1 - A$	Unavailability of end-to-end information channel from sensor to cloud processing
A_c	Availability of service provided by the base station and cloud
A_a	Availability of WSN information service at ABSP level

Table 1. *Cont.*

Notations	Parameters
A_{cs}	Availability of information services provided by cluster sensor
A_s	Availability of information services provided by sensor
A_{ch}	Availability of data services provided by cluster head
λ	Failure rate of UAV service
μ	Repair rate of UAV service
$\gamma = \lambda / \mu$	UAV reliability parameter 1
$\omega = \gamma / L$	UAV reliability parameter 2
$MTBF$	Mean Time Between Failures
$MTTR$	Mean Time to Repair
k	Number of UAVs in ABSP system
m	Number of additional UAVs in backup fleet
$N = k + m$	Number of UAVs in ABSP system
L	Number of repair places in ground recovery center

The availability of an end-to-end information channel from sensor to cloud processing can be determined by expression:

$$A = A_c A_a A_{cs} \ , \tag{1}$$

where $A_{cs} = \begin{cases} A_s \text{ in clusters without cluster head,} \\ A_s A_{ch} \text{ in clusters with cluster heads.} \end{cases}$

The availability of single equipment (sensors and cluster heads) is determined by its dependability parameters [25]:

$$A_s = \frac{MTBF_s}{MTBF_s + MTTR_s} \ , \quad A_{ch} = \frac{MTBF_{ch}}{MTBF_{ch} + MTTR_{ch}}$$

The reliability of cloud services, denoted as A_c, is determined by various factors such as redundancy and system architecture. The assessment of cloud service reliability is discussed in detail in [26]. Typically, the availability services provided by the cloud for users is set as a constant value. To ensure the hosting services provided by cloud providers, a Service Level Agreement (SLA) is offered, which guarantees a certain percentage of uptime. The industry standard SLA guarantees range from 99% for the routine category to 99.99999% for the safety-critical category, as stated in [27].

The focus of this study is on defining the availability of services provided by the UAVs in an ABSP system. When a sensor network is used, a unique interaction channel with the CPA is created for each sensor (Figure 4). The availability of this interaction channel is important for determining the availability of the service provided. In an ABSP system, the focus is on the dedicated UAV responsible for receiving information from this interaction channel. The states of other channels for the service provided by this dedicated sensor are not important. The model for analyzing the performance of services in separate subsystems in an ABSP system depends on the set of additional UAVs in the fleet and the number of ground stations available to replenish the UAVs' energy resources.

To assess the availability of a dedicated sensor service (DSS) provided by a single UAV in an ABSP system, it is essential to analyze the availability of service for the particular UAV. This analysis is of interest to the user of a specific sensor cluster who only cares about the availability of the service provided by the selected UAV without being concerned about other UAVs or applications in other sensor clusters. To determine the availability of the DSS in the ABSP system, a model based on the Markov chain was used [28,29].

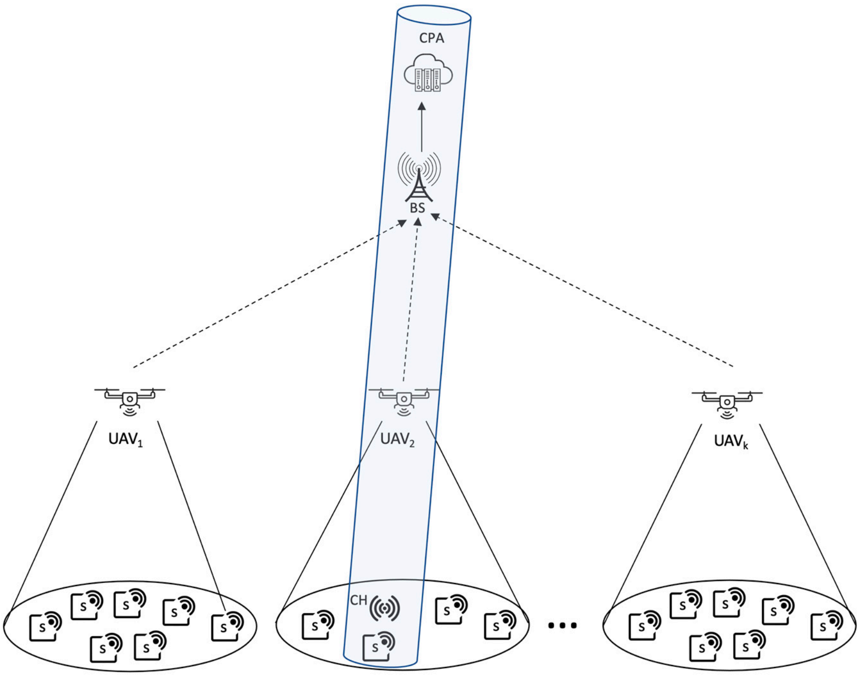

Figure 4. End-to-end channel of sensor interaction with CPA.

The Markov chain was used to describe the examined system, which has two types of states: H_i, where i UAVs have failed but the dedicated sensor service provided by the selected UAV is still working, and H_{if}, where $i+1$ UAVs have failed, including the one providing service for the selected sensor. The ABSP system requires periodic restoration of power supply for UAVs to ensure channel availability. Depending on the resource capacity of the ground recovery center, the model can have two configurations. The first configuration has $1 \leq L \leq m$ ground recovery points, and its state transition diagram is shown in Figure 5. The second configuration has $m < L \leq k+m$ ground recovery points, and its state transition diagram is shown in Figure 6. The availability analysis of sensor services for each configuration was done using Markov models with classical Kolmogorov–Chapman differential equations for the system in a stationary state [29].

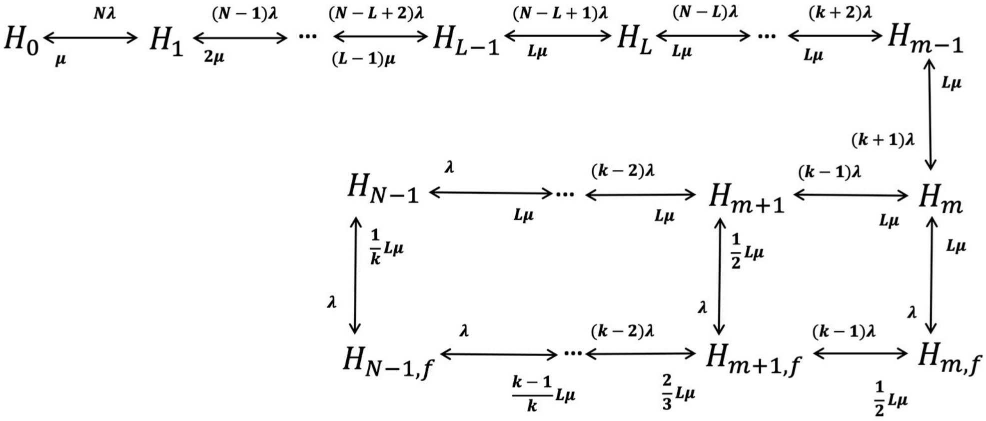

Figure 5. Transition graph of the Markov model of the ABSP architecture with a limited number of recovery places at the ground recovery center.

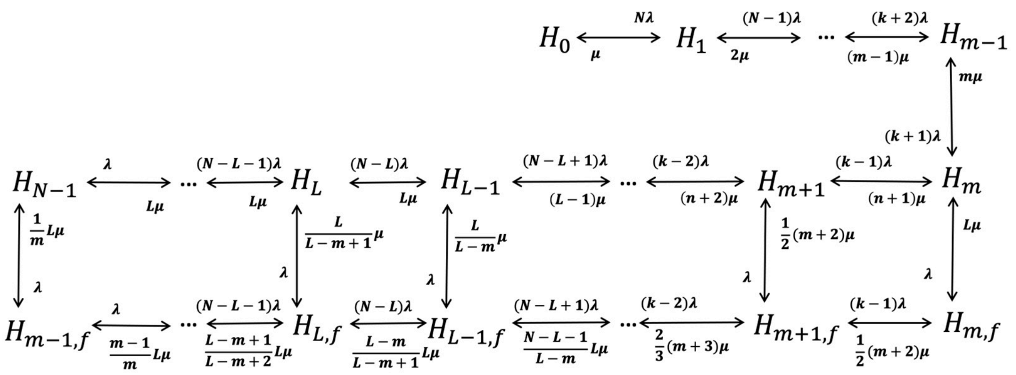

Figure 6. Transition graph of the Markov model of the ABSP architecture with an unlimited number of recovery places at the ground recovery center.

4. Results

We needed to calculate the availability of the information channel that the dedicated UAV provides for a particular sensor in the aerial base station placement system.

1. Configuration of ABSP system with $1 \le L \le m$ ground recovery points (Figure 5).

By composing a system of equations corresponding to a given graph, the following solutions were obtained.

Compiling and solving the system of Kolmogorov–Chapman equations corresponding to the graph in Figure 5, we obtained as its solution the following values of stationary probabilities of states:

$$p_i = \begin{cases} C_N^i \gamma^i p_0\,, & 1 \le i \le L\,, \\ \dfrac{N!L^L\omega^i}{(N-i)!L!}p_0\,, & L < i \le m\,, \end{cases}$$

$$p_{m+j} = \frac{N!L^L\omega^{m+j}}{(k-j-1)!L!k}p_0\ , \qquad 0 \le j \le k-1\ ,$$

$$p_{m+j,f} = \frac{N!L^L(j+1)\omega^{m+j+1}}{(k-j-1)!L!k}p_0\ , \quad 0 \le j \le k-1\ .$$

The probability p_0 is determined from the rationing condition

$$p_0 + \sum_{i=1}^{m} p_i + \sum_{j=0}^{k-1}(p_{m+j} + p_{m+j,f}) = 1$$

and is equal to

$$p_0^{-1} = \sum_{i=0}^{L} C_N^i \gamma^i + \frac{N!L^L\omega^N}{L!}\left\{\sum_{i=k}^{N-L-1}\left(j!\omega^i\right)^{-1} + k^{-1}\left[\frac{1}{(k-1)!\omega^{k-1}} + \sum_{i=0}^{k-2}\frac{k+\omega^{-1}-i}{i!\omega^i}\right]\right\}.$$

For the ABSP architecture under study, the service availability of the dedicated sensor was determined with the expression

$$A_a = 1 - U = 1 - \sum_{i=m}^{N-1} P_{i,f} = \frac{v_1 + v_2}{v_1 + v_2 + v_3}\,, \tag{2}$$

where

$$v_1 = \begin{cases} \sum\limits_{i=0}^{L} C_N^i \gamma^i + \frac{N!L^L}{L!} \sum\limits_{i=L+1}^{m-1} \frac{\omega^i}{(N-i)!} \ , & L \le m-3 \, , \\ \sum\limits_{i=0}^{L} C_N^i \gamma^i \ , & L = m-2 \, , \\ \sum\limits_{i=0}^{L-1} C_N^i \gamma^i \ , & L = m-1 \, , \end{cases}$$

$$v_2 = \frac{N!L^L}{L!k} \sum_{i=0}^{k-1} \frac{\omega^{m+i}}{(k-i-1)!} \ ,$$

$$v_3 = \frac{N!L^L}{L!k} \sum_{i=0}^{k-1} \frac{(i+1)\omega^{m+i+1}}{(k-i-1)!} \ ,$$

Substituting expression (2) into expression (1), we got a formula for determining the desired availability of services for each of the sensors in a wireless sensor network with aerial base station placement.

2. Configuration of ABSP system with $m \le L \le k+m$ ground recovery points.

By composing a system of equations corresponding to a given graph (Figure 6), the following solutions were obtained.

Compiling and solving the system of Kolmogorov–Chapman equations corresponding to the graph in Figure 6, we obtained as its solution the following values of stationary probabilities of states:

$$p_i = C_N^i \gamma^L p_0 \ , \qquad 0 \le i \le m \ ,$$

$$p_{m+i} = \frac{k-i}{k} C_N^{k-i} \gamma^{m+i} p_0 \ , \qquad 1 \le i \le L-m \ ,$$

$$p_{m+i,f} = \frac{i+1}{k} C_N^{k-i-1} \gamma^{m+L+1} p_0 \ , \qquad 0 \le i \le L-m \ ,$$

$$p_{L+i} = \frac{N!L^L \omega^{L+i}}{L!(N-L-i-1)!k} p_0 \ , \qquad 1 \le i \le N-L-1 \ ,$$

$$p_{L+i,f} = \frac{N!L^L (L-m+i+1)\omega^{L+i+1}}{L!(N-L-i-1)!k} p_0 \ , \quad 1 \le i \le N-L-1 \, .$$

The probability p_0 is determined from the rationing condition and is equal to

$$p_0^{-1} = \sum_{i=0}^{m} C_N^i \gamma^i + k^{-1} \left\{ C_N^{m+1} \gamma^{m+1} + \sum_{i=1}^{L-m} [(m+1+\gamma) + i(1+\gamma)] C_N^{m+i+1} \gamma^{m+1} + \frac{N!L^L}{L!} \sum_{i=1}^{N-L-1} [1 + (L-m+1)\omega] \frac{\omega^{L+i}}{(N-L-i-1)!} \right\} .$$

For the ABSP architecture under study, the service availability of the dedicated sensor was determined with expression (2), where

$$v_1 = \sum_{i=0}^{m-1} C_N^i \gamma^i \ ,$$

$$v_2 = \frac{N!}{k} \left[\sum_{i=0}^{L-m} \frac{\gamma^{m+i}}{(k-i-1)!(m+i)!} + \frac{L^L}{L!} \sum_{i=1}^{N-L-1} \frac{\omega^{L+i}}{(N-L-i-1)!} \right] ,$$

$$v_3 = \frac{N!}{k} \left[\sum_{i=0}^{L-m-1} \frac{(i+1)\gamma^{m+i+1}}{(k-i-1)!(m+1+i)!} + \frac{L^L}{L!} \sum_{i=0}^{N-L-1} \frac{(L+i-m+1)\omega}{(N-L-i-1)!} \right] .$$

5. Discussion

We investigated the availability of a DSS at the UAV level in the ABSP system. The graph in Figure 7 shows the unavailability of the selected sensor service at the UAV level $U = 1 - A_a$ as a function of the number k of UAV channels in the system for a single replacement place ($L = 1$) and different UAV reliability parameters, which are represented by reliability parameter γ (the first family of curves for $\gamma_1 = 10^{-1}$ and the second family of curves for $\gamma_2 = 10^{-2}$). By analyzing the curves in Figure 7, we can see that the availability A of the end-to-end information service at the UAV level in the ABSP system is inversely proportional to the growth of the number of UAVs providing communication with sensors of clusters and is directly proportional to the increase in the UAVs' dependability of operation.

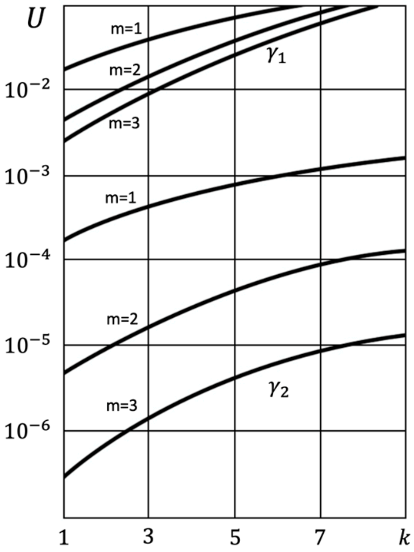

Figure 7. Function of unavailability of the selected sensor service at the UAV level.

In some cases, the architecture of the ABSP system may include more than one UAV level, forming a UAV cluster that provides a fog node for a cloud-based network. This approach can improve the balance of information flows in the network, increase the fault tolerance of data processing, and minimize the load on cloud computing. For example, intelligent transport systems often have three fog levels [30]. In such scenarios, we are not dealing with single UAVs but rather a swarm of UAVs.

In the aviation field, UAV swarms consisting of multiple UAVs are a common application in mobile ad hoc networks [31]. As intelligent, low-cost, and miniaturized UAVs have become increasingly available, multi-tier UAV swarms have obtained new research interest for different applications [32,33]. This ABSP architecture has additional advantages, such as a reliable ad hoc network, wide land coverage, and enhanced operation performance [34].

According to a study [35], the clustering structure is appropriate for managing multi-tier UAV swarms. As an example, Figure 8 shows the ABSP architecture of a system with a two-level UAV swarm. In a multi-tier UAV swarm system, the availability of the dedicated end user service at the drone swarm level A_a can be calculated using the equation:

$$A_a = \prod_{i=1}^{n} A_{ai}$$

where n is the number of swarm levels, and A_{ai} represents the availability of the UAV swarm at the i $(i = 1, \ldots n)$ level. The availability of each swarm level can be determined using expression (2).

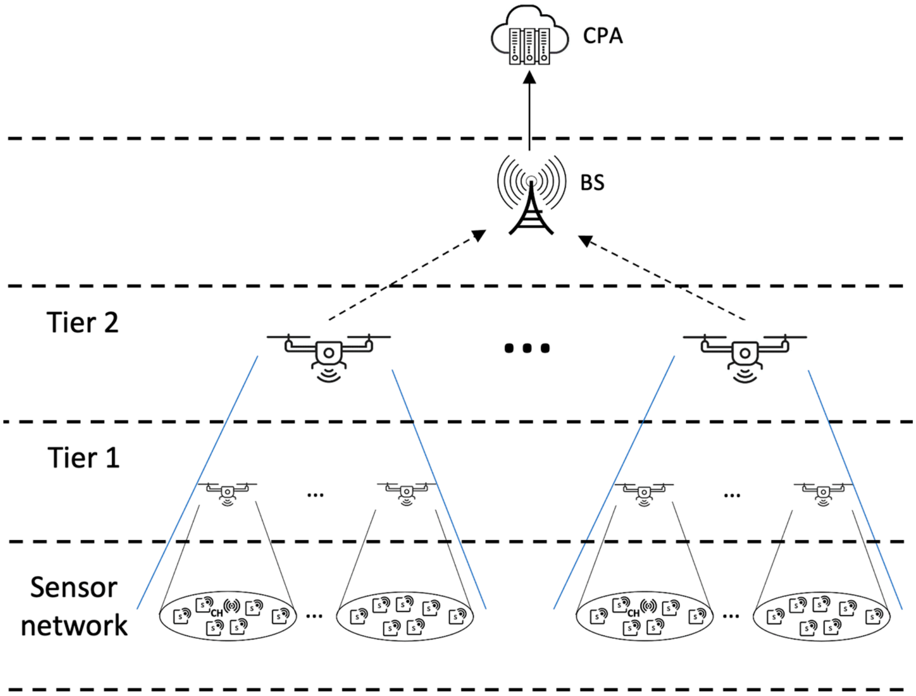

Figure 8. ABSP architecture with multi-tier UAV swarms.

Figure 8 represents a hierarchical ABSP architecture for fog computing that consists of some levels. At the first level, the sensor network is responsible for acquiring and collecting sensor data as well as controlling sensors and actuators. The second level consists of two tiers of UAV swarms. It is focused on filtering, compressing, and transforming data, and the higher levels (BS and CPA) are responsible for aggregating data. With an increase in the number of UAV tiers, each tier is capable of filtering and extracting valuable data, thereby enhancing the performance and intelligence of the entire system.

The proposed architecture of sensor services in a wireless network with aerial base station placement has several potential applications, including:

- Disaster management: In the event of a natural disaster, such as an earthquake or hurricane, communication networks can be disrupted or destroyed. UAVs equipped with communication equipment can be deployed as aerial base stations to restore communication networks and provide first responders with crucial information.
- Precision agriculture: UAVs can be used to collect data on crop health, soil moisture, and other environmental factors. With the help of ABSP, the collected data can be transmitted to a central server, where it can be analyzed and used to make informed decisions regarding crop management.
- Surveillance and security: UAVs equipped with cameras and other sensors can be used for surveillance and security purposes, such as monitoring borders, critical infrastructure, and public events. ABSP can be used to provide a reliable and secure communication link between the UAVs and the ground station, enabling real-time video transmission and control of the UAVs.
- Search and rescue: UAVs equipped with thermal imaging cameras and other sensors can be used to search for missing persons in remote or dangerous locations. ABSP can be used to provide a communication link between the UAVs and the ground station, enabling real-time transmission of data and control of the UAVs.
- Environmental monitoring: UAVs can be used to collect data on air quality, water quality, and other environmental factors. ABSP can be used to provide a communication link between the UAVs and the ground station, enabling real-time transmission of data and control of the UAVs.

The described technology of Aerial Base Station Placement can, under certain conditions, become an alternative or addition to other ones such as, for example, the Long Range (LoRa) technology developed for IoT [36].

In a LoRa network, sensors equipped with LoRa modules transmit data to a LoRa gateway, which acts as a bridge between the sensors and the cloud. The LoRa gateway receives the data from the sensors and sends it to a cloud-based server for processing and analysis. The LoRa gateway can cover a large area up to several kilometers in range, making it suitable for IoT applications that require long-range communication. LoRa technology can be used in a variety of applications, including smart cities, industrial IoT, and asset tracking [37].

The Aerial Base Station Placement and LoRa technologies are both wireless communication technologies that have been widely used in IoT and WSNs. Although both technologies have their advantages and limitations, ABSP offers several unique advantages over LoRa technology. One of the primary advantages of ABSP is its ability to provide a much larger coverage area compared to ground-based LoRa gateways. The use of unmanned aerial vehicles as base stations enables ABSP to cover vast areas, making it suitable for applications such as precision agriculture or disaster management and in military applications. Another advantage of ABSP is its mobility. ABSP enables mobility for both the sensors and the base stations, making it suitable for scenarios where objects equipped with sensors are in motion. ABSP can be a valuable addition to the wireless sensor network's toolbox, providing new possibilities and use cases for IoT and WSN applications.

At the same time, it is possible to use both the Aerial Base Station Placement and LoRa technologies together in a hybrid solution, which can provide the benefits of both technologies [38]. For instance, LoRa technology can be used to connect stationary objects equipped with sensors, and the ABSP architecture can be used to connect mobile objects equipped with sensors. In this hybrid solution, the ABSP architecture can provide additional coverage and reliability to the LoRa network, especially in scenarios where a large coverage area is required. Additionally, the ABSP architecture can also provide mobility to LoRa gateways, enabling them to be moved to areas with better coverage or where temporary coverage is required. This can be particularly useful in scenarios where the coverage needs to be extended temporarily, such as during an event or emergency.

ABSP can be a valuable addition to the wireless sensor network's toolbox, providing new possibilities and use cases for IoT and WSN applications.

Although the proposed models and architectures in this article offer several valuable contributions to the field of wireless sensor networks with aerial base station placement, there are some limitations and potential challenges that need to be addressed:

- Security. This article does not address the security challenges associated with the deployment of UAVs in wireless sensor networks. As these networks become more widespread, they may become more susceptible to cyberattacks or malicious interference. Ensuring the security and privacy of data transmitted between sensors, UAVs, and the cloud is crucial for the successful implementation of these models.
- Environmental factors. The impact of environmental factors, such as weather conditions, terrain, and signal interference, on the performance of UAVs and ground sensors is not considered in the models. These factors can significantly affect the efficiency, reliability, and availability of the wireless sensor network, and thus, they should be taken into account when implementing the proposed architectures.
- Energy management. Although the models consider the limited flight time of UAVs and propose a fleet of additional UAVs for maintaining the availability of communication channels, the overall energy efficiency of the system is not thoroughly addressed. Further research is needed to optimize the energy consumption of UAVs and ground sensors as well as to develop more energy-efficient communication protocols for the proposed architectures.
- Cost-effectiveness. The deployment of multiple UAVs and ground recovery points can be expensive, especially for large-scale wireless sensor networks. A more in-depth

cost–benefit analysis is necessary to determine the practicality and cost-effectiveness of implementing the proposed models in real-world applications.
- Regulatory and legal concerns. The operation of UAVs is subject to various regulations and legal restrictions, which can vary depending on the country or region. These limitations can impact the feasibility of the proposed architectures and should be considered during the design and implementation stages.

To address the limitations of the study and further enhance the performance of the proposed architecture, several future research directions can be considered:

- Create realistic UAV models that account for factors such as battery life, flight dynamics, and communication constraints.
- Investigate security aspects of the proposed architecture, including data encryption, authentication, and intrusion detection mechanisms.
- Evaluate the scalability of the proposed architecture for large-scale networks and its performance under high node density conditions.
- Explore adaptive clustering algorithms that can dynamically adjust cluster size and structure based on network conditions and requirements.
- Investigate the integration of advanced communication technologies, such as 5G and 6G, to further enhance the performance of WSNs.

Overall, the proposed architecture of sensor services in a wireless network with the ABSP has the potential to revolutionize several industries by enabling reliable, efficient, and secure communication networks using unmanned aerial vehicles.

The proposed architecture can be adapted to various application scenarios by modifying the parameters and features of the UAVs, sensor nodes, and clustering techniques. For instance, in environmental monitoring applications, the UAVs could be equipped with sensors to collect data on air quality, temperature, and humidity. In disaster management scenarios, the UAVs could be used for the real-time monitoring of affected areas, enabling rapid response and decision-making. In security surveillance applications, the UAVs could be integrated with advanced imaging and tracking systems to detect and track potential threats. By tailoring the proposed architecture to specific application requirements, its performance and effectiveness can be further optimized.

6. Conclusions

This paper discusses a model for evaluating the availability of sensor services in a wireless network that uses UAVs as base stations. The system employs a mobile edge computing architecture with an aerial base station placement system and a ground station for recharging the UAVs. The architecture includes additional replacement UAVs to ensure uninterrupted communication coverage for the sensor network during the charging period. Analytical expressions were derived to calculate the availability of sensor services in the system. The study reveals that the availability of end-to-end information service at the UAV level in the ABSP system is inversely proportional to the growth of the number of UAVs providing communication with sensors of clusters, and that it is directly proportional to the increase in the UAVs' dependability of operation. This paper also proposes an extension of the model for a multi-level ABSP architecture and provides a general expression for calculating the desired availability of services for each sensor in the wireless sensor network with aerial base station placement.

In this paper, several key contributions are made to the field of wireless sensor networks with aerial base station placement:

1. The availability model of multi-tier WSN architecture is proposed, which integrates ground sensors, UAVs, and a ground base station with cloud processing and analysis. This architecture is particularly suited for applications in cyber-physical systems (CPS) and the Internet of Things (IoT).
2. The comprehensive model for analyzing the availability of sensor services in this ABSP architecture is presented. The model takes into account various factors, such as

the availability of end-to-end information channels, the dependability of equipment, and the reliability of cloud services.

3. Two different configurations of ABSP systems were examined, one with a limited number of ground recovery points and another with a larger number of ground recovery points. The availability of the DSS in each configuration was assessed using Markov chain models.
4. The effect of the number of UAVs, their reliability parameters, and the number of UAV levels on the availability of the DSS in the ABSP system were analyzed. This analysis provides valuable insights for designing more efficient WSNs with UAV support.
5. The hierarchical ABSP architecture for fog computing has been proposed, which consists of multiple levels of UAV swarms. This architecture has the potential to enhance the performance and intelligence of the entire system by filtering and extracting valuable data at each UAV tier.

These contributions provide a foundation for future research in wireless sensor networks with aerial base station placement and have the potential to improve the efficiency and reliability of various applications in cyber-physical systems and the Internet of Things.

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