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Research Article

# A Dual-Channel MAC Protocol with Fibonacci Backoff for Enhanced Efficiency in UAV-Based Sensor Networks

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**Abstract:** Unmanned aerial vehicles (UAVs) are highly effective in collecting data from challenging environments equipped with Wireless Sensor Networks (WSNs), overcoming retrieval challenges. However, using a single-channel Medium Access Control (MAC) protocol for synchronization can lead to potential data collisions among multiple sensors sharing the same medium and result in high power consumption. In this article, we propose a dual-channel MAC protocol specifically designed for UAV-based data collection from WSNs. The protocol includes features such as varying transmission power levels for UAVs, dedicated channels for control and data packets, and a Fibonacci Backoff strategy. The UAV optimizes power usage by initially using low-power transmission and gradually increasing it. The dual-channel communication allows for separate channels for wakeup signals and data transmission, enhancing efficiency. Additionally, the sleep and wakeup mechanism conserves sensor node battery power during inactivity. We developed a discrete event simulator to evaluate the proposed protocol's performance. Our simulation results show that the average for each node count, the proposed protocol with the Fibonacci Backoff strategy improves network throughput by 20.68%, reduces delay by 22.32%, and decreases power consumption by 21.84% compared to the conventional Exponential Backoff method.

**Keywords:** Wireless Sensor Networks, Unmanned Air Vehicles, Dual-Channel MAC Protocol, Fibonacci Backoff Strategy.

## 1. INTRODUCTION

In the era of wireless connectivity, the wireless sensor network (WSN) stands as a technological marvel, interlinking sensor nodes with a central sink/base station node [1]. These sensor nodes diligently collect data from their surroundings, orchestrating a symphony of information transmitted to the sink. WSNs are utilized in a variety of fields, including military operations, geographic location tracking, transportation monitoring, healthcare applications, environmental and maritime surveillance, construction project management, cost efficiency initiatives, and agricultural operations. [2]. Presently, a significant emphasis is placed on establishing network connectivity among deployed sensors. This enables the transmission of collected data to a central location for subsequent processing and implementation of necessary actions [3]. Significant strides have been made in data collection from sensors in WSNs, particularly for scenarios where sensors are deployed in challenging environments lacking adequate network infrastructure for data transmission [4]. The provision of permanent network infrastructure proves cost-prohibitive in such scenarios, prompting the exploration of alternative mechanisms [5]. Unmanned aerial vehicles (UAVs) have emerged as a recent solution for data collection in these challenging environments [6]. UAVs, controlled remotely or autonomously, have garnered attention for their ability to navigate areas such as forests, deserts, mountains, glaciers, seas, battlefields, and borders, where conventional infrastructure is lacking [7]. Khan *et al*. [8] explored the use of UAVs and Intelligent Reflecting Surfaces to enhance Public Safety Communication networks in disaster scenarios where cellular base stations fail.

Numerous studies have delved into the realm of Medium Access Control (MAC) protocols for data collection, with a specific focus on enhancing

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the capabilities of UAVs in WSNs. Notable contributions include genetic algorithm-based protocols ensuring optimal UAV path selection for power conservation [9]. Distributed Aerial Data Collection Algorithm has been proposed as a coordinated approach to streamline data collection processes involving multiple UAVs [10]. A cross-layer protocol is introduced to boost efficiency and reliability in UAV-sensor node communication [11]. Pan *et al.* [12] dynamically adjusted UAV speed to maximize data collection efficiency. Goudarzi *et al.* [13] addressed the shortest path problem using the Traveling Salesman's approach and introduced an adaptation system for autonomous flight re-planning, effectively reducing UAV power consumption and optimizing network throughput. These diverse strategies collectively contribute to an overarching improvement in the efficiency of UAV-assisted data collection from WSNs.

Existing MAC protocols for UAV-based data collection in WSNs face several significant challenges. They rely on a single channel for synchronization and data collection. This can result in high power consumption and potential data collisions when multiple sensors attempt to transmit data simultaneously on the same channel. Also, the standard Binary Exponential Backoff (or simply, Exponential Backoff) algorithm used in protocols such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is not effective in high-density sensor networks, leading to increased collisions and retransmissions [14]. Moreover, high power consumption is a critical issue in WSNs, especially in remote or challenging environments. Existing protocols do not sufficiently address energy conservation while maintaining efficient data transmission. This situation demands a novel approach to enhance efficiency, reduce power consumption, and address the collision problem in WSNs.

In response to the significant challenges posed by existing MAC protocols, this article proposes a dual-channel MAC protocol leveraging the Fibonacci series to address these issues. We propose a dual-channel MAC protocol that uses a dedicated control channel for wakeup signals and synchronization, and a separate primary channel for data transmission. This separation reduces collisions and lowers power consumption. This innovative protocol incorporates two distinct channels for the data collection procedure: a designated control channel for sensor wakeup and synchronization, and a primary channel for transmitting the accumulated data to the UAV. Communication initiation involves transmitting a wakeup signal on the control channel, followed by the actual data transmission on the main channel. Before data transmission, individual nodes undergo a backoff process, during which a random backoff time is selected within the contention window (CW) range, calculated using the Fibonacci series [15].

Our protocol incorporates a Fibonacci Backoff strategy, which provides a more adaptive and effective backoff mechanism. Using Fibonacci intervals for the backoff time reduces collision probability and improves network throughput and efficiency. This approach aims to enhance network performance by avoiding collisions in UAV-based sensor networks and increasing throughput through the implementation of a Fibonacci-based backoff strategy. The proposed protocol optimizes power usage by dynamically adjusting transmission power. The UAV starts with low-power transmission and increases power only when necessary. Additionally, the dual-channel approach and sleep/wakeup mechanism for sensor nodes reduce power consumption by allowing nodes to remain inactive when not transmitting data.

To address the problem of potential data collisions and high power consumption in UAV-based WSNs using a single-channel MAC protocol, this article presents the following contributions:

i. We introduce a dual-channel MAC protocol featuring a Fibonacci Backoff strategy that leverages Fibonacci distribution for collision avoidance in wireless networks deployed on UAVs. The use of a dedicated control channel for wakeup signals and synchronization, and a separate primary channel for data transmission, reduces collisions and lowers power consumption.

ii. Our protocol optimizes power usage by dynamically adjusting transmission power. The UAV starts with low-power transmission and increases power only when necessary. Additionally, the dual-channel approach and sleep/wakeup mechanism for sensor nodes reduce power consumption by allowing nodes to remain inactive when not transmitting data.

iii. We develop an event simulator to assess the protocol's performance, considering factors such as throughput, delay, and power consumption. Our simulation results show that the average for each node count, the proposed protocol with the Fibonacci Backoff strategy improves network throughput by 20.68%, reduces delay by 22.32%, and decreases power consumption by 21.84% compared to the conventional Exponential Backoff method.

## 2. PROPOSED PROTOCOL

In this section, we present the proposed dual-channel protocol and its pseudocode.

### 2.1. Dual Channel MAC Protocol With Fibonacci Backoff Strategy

The proposed protocol is specifically designed for situations where a network of sensors is deployed in a field to gather data related to environmental factors such as fire, movement, temperature, and pollution levels. Following the data collection, the acquired information is then transmitted to a central base station for thorough analysis. In regions with limited or no existing network infrastructure, retrieving data from sensor nodes becomes a formidable challenge. To tackle this issue, the proposed solution involves periodically deploying a UAV to the field. The UAV is tasked with collecting data from the sensors and returning, with the frequency of these UAV visits dictated by the specific requirements of the data collection process.

In the context of this protocol, the CSMA [16] strategy plays a pivotal role. CSMA minimizes collision risks by requiring stations to sense the medium before transmitting, significantly reducing collision probabilities. While Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [16] addresses collisions post-occurrence, the wireless network-oriented CSMA/CA [17] employs interframe space, contention window, and acknowledgments to avoid collisions. It introduces a delay, Interframe Space (IFS), before transmission to prevent collisions with distant nodes. Despite prioritizing stations with shorter IFS, the risk of collisions persists, necessitating acknowledgments and timeout timers to ensure successful frame reception. The proposed protocol incorporates dual-channel communication, utilizing both a low-power control channel for synchronization and a high-power main channel for data transmission. During idle periods, sensor nodes conserve power by entering sleep mode and deactivating the main channel. The always-active control channel receives control signals and wakeup signals, prompting sensor nodes to resume full functionality. This dual-channel approach effectively reduces power consumption, particularly beneficial for low-powered devices like sensor nodes. With modern low-power transmission antennas capable of sustaining sensor nodes for extended periods, this strategy significantly prolongs the lifespan of WSNs.

The dual-channel MAC protocol facilitates UAVs in collecting data from sensor nodes in a field, where each sensor is equipped with two channels. One channel is dedicated to UAVs for data collection, while the other serves as a low-power wake-up channel, ensuring prolonged battery life. In their default state, sensors operate in sleep mode, preserving power by deactivating all resources except the wakeup antenna. Upon the UAV's arrival in the field, it transmits a wakeup radio signal to all sensors using its dedicated wakeup channel. Upon receiving this signal, sensors activate all resources, including their primary transmission antenna. Communication between the UAV and sensor nodes on the main channel utilizes the CSMA/CA protocol.

The proposed protocol introduces a novel approach by employing the Fibonacci series to determine the CW in the CSMA/CA protocol on the main channel. Traditionally, CSMA/CA relies on the Exponential Backoff mechanism, where the contention window size doubles on each unsuccessful attempt, leading to increased network latency and performance degradation as the number of nodes rises. In contrast, the Fibonacci-based backoff strategy offers advantages, particularly in small-sized networks. The CW size in the Fibonacci series is calculated using equation (1):

$$\mathrm{CW}_k = \mathrm{CW}_{k-1} + \mathrm{CW}_{k-2} \tag{1}$$

where $k$ denotes the number of attempts a node makes to sense the medium before determining its idleness. Initially, $\mathrm{CW}_{k-1}$ and $\mathrm{CW}_{k-2}$ are set to 1, resulting in an initial CW of 2.

The Fibonacci series leads to a gradual start with smaller contention windows, providing transmitting nodes more opportunities to sense the medium frequently and a higher probability of early data transmission attempts. As the process continues, the CW grows by following the Fibonacci sequence (3, 5, 8, ….), while ensuring $max\mathrm{CW}k \leq \mathrm{CW}max$ where $k$ represents the number of attempts. This approach optimizes network performance, particularly in a smaller network context. In the illustrated data flow diagram (Figure 1), the interaction between the UAV and a sensor node is depicted. Upon arriving at the location where sensor nodes are deployed, the UAV initiates the process by broadcasting a wake-up radio signal to all nodes. The nodes, equipped with wakeup antennas, receive this signal and activate their main antennas for subsequent data transmission. Following the activation, each node engages in a backoff process on the main channel, CSMA/CA, and utilizes Fibonacci distribution. Subsequently, the node transmits the collected data and awaits acknowledgment from the UAV to complete the communication cycle.

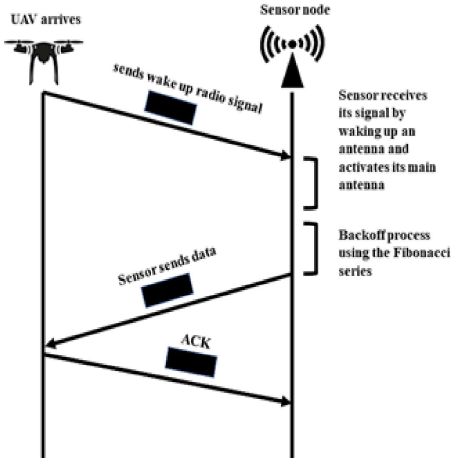

**Fig. 1.** Data flow diagram illustrating the interaction between UAV and sensors and sensors.

## 2.2. Proposed Protocol Pseudocode

The pseudocode outlined in Table 1 describes a recursive strategy for the proposed protocol, where nodes repeatedly attempt data transmission. Key elements guiding the transmission process include

**Table 1.** Procedural Pseducode depicting the operation of the proposed dual-channel protocol.

```
Step  Pseudocode
1     Input: X, prevBackoff, prevPrevBackoff, CWmin, CWmax, backoffCounter, maxTries
2     Output: True if data transmission successful, False otherwise
3     Initialization: boPrev = 0, boPrevPrev = 0, CWmin = 0, CWmax = 12, backoffCounter = 0, maxTry = 5,
      P = initialPower, ΔP = powerIncrement
4     while (P < Pmax) and (N < Nmix) do
5         Send signal S with power P
6         P = P + ΔP
7     data ← prepareData()
8     procedure DualChannelTransmission(data, boPrev, boPrevPrev, CWmin, CWmax, backoffCounter, maxTry)
9         if backoffCounter == 0 then CW ← CWmin + CWmax, boPrev ← CWmax else CW ← boPrev +
            boPrevPrev
10        backoffTime ← random (0, CW)
11        while backoffTime > 0 do wait (),
                backoffTime ← backoffTime - 1
12        if CCA () == idle then sendPackets(data),
          return True
13        boPrevPrev ← boPrev, boPrev ← CW,
          backoffCounter ← backoffCounter + 1
14          if backoffCounter > maxTry then return False else        DualChannelTransmission(data, boPrev,
            boPrevPrev, CWmin, CWmax, backoffCounter, maxTry)
15    if DualChannelTransmission(data, boPrev, boPrevPrev, CWmin, CWmax, backoffCounter, maxTry) ==
      True then sleep() else stopTransmission()
```

parameters such as X, previous backoff values, CWmin, CWmax, the backoff counter, and the maximum number of attempts.The desired output is a binary indication: True if data transmission succeeds, and False if it fails.

In the initial phase, the UAV engages in a repetitive process of sending signals with increasing power until the power, P, is less than Pmax and the number of responses, N, is less than Nmix (Lines 4-6). Following this, input variables are initialized: backoff parameters boPrev and boPrevPrev are set to 0, CW size limits CWmin and CWmax are established, and counters for backoff attempts (backoffCounter) and a threshold for maximum attempts (maxTry) are initialized, and data is prepared for transmission (Line 7).

The dual-channel transmission procedure is then defined and invoked with the initialized input variables (Line 8). During the first backoff attempt, if the backoff counter is 0, the CW is set to the sum of CWmin and CWmax, and boPrev is assigned the value of CWmax (Line 9). For subsequent backoff attempts, CW is calculated as the sum of boPrev and boPrevPrev (Line 9), and a random backoff time is chosen (Line 10).

The procedure then waits during this backoff time by decrementing it in a loop. Following the wait, a Clear Channel Assessment (CCA) is performed (Line 11). If the channel is idle, packets are sent one by one, and the procedure returns True, indicating successful transmission (Line 12). If the channel is busy, boPrevPrev is updated to the value of boPrev, boPrev is updated to the current CW value, and the backoff counter is incremented. If the backoff counter exceeds maxTry, the transmission is terminated (Line 13). Otherwise, the procedure is called again with updated values (Line 14).

After the dual-channel transmission procedure, the algorithm checks if the returned value is True (Line 15). If True, the node goes to sleep again. If False, the node quits transmission for an indefinite time. In cases where the channel is not idle, the node re-enters the backoff process. In such instances, the CW is calculated using the Fibonacci series, relying on CW values stored in the previous backoff processes. The backoff timer, a countdown timer, expires upon reaching zero, leading to a resumption of the channel assessment. The sensor node exits the backoff loop only when an idle channel is detected during channel assessment, allowing data transmission to the UAV to commence.

The proposed protocol, using a Fibonacci backoff mechanism, has a computational complexity of O(CWmax). This is more efficient compared to the exponential backoff algorithm which has a complexity of O($2^k$), where k is the number of attempts. The Fibonacci backoff mechanism provides a more predictable and controlled backoff time, leading to better performance and lower collision probability.

## 3. MATERIALS AND METHODS

### 3.1. Simulation Setting

We design an event-driven simulator in Python to evaluate the performance of the proposed protocol. The simulation outcomes are geared towards analyzing network throughput, delay, and power consumption. A comparative analysis is conducted against the standard CSMA/CA protocol. This Python simulator, crafted for wireless communication, introduces a modified CSMA/CA protocol, substituting the Exponential Backoff strategy with a more sophisticated Fibonacci Backoff strategy.

The simulation specifically focuses on communication within the MAC layer, disregarding any complexities associated with other layers of the OSI model. Throughout the simulation, the channel bandwidth and packet size remain constant. Various transmission overheads are overlooked, and the calculation of packet transmission time spans from the initiation of Clear Channel Assessment (CCA) by a node to the moment an acknowledgment is received for the respective packet. The hardware used for the simulation includes an Intel Core i7-9700K CPU @ 3.60GHz, 32GB of DDR4 RAM, and a 1TB SSD, running on Ubuntu 20.04 LTS. The software environment consists of Python 3.8 as the programming language, SimPy 4.0.1 for simulation, and NumPy 1.19.2 and Matplotlib 3.3.2 for data analysis and visualization.

Notably, the simulation entails multiple runs, progressively increasing the number of network nodes. Each simulation involves an increment of 10 nodes, with a total of 50 simulation runs, each having a distinct node count. The packet size remains consistent at 60 bits, and the network initiates with two nodes. Subsequently, in each simulation run, one node is added to the network. Our protocol optimizes power use with a sleep and wake-up strategy, activating nodes only when data is ready and the UAV is available. It utilizes two channels, i.e., a low-power receptor channel and a main channel for data transmission—accounting for power consumption in both. For simplicity, we assume constant data rates and fixed transmission ranges, focusing on comparing power efficiency across backoff mechanisms.

### 3.2. Evaluation Metrics

In this article, we employ several key metrics to assess the performance of the proposed protocol:

**Throughput**: Throughput, expressed in bits per second (bit/s), quantifies the rate at which data bits are successfully delivered over a communication channel. The formula used for calculating throughput is:

$$Throughput = \frac{No\ of\ bits\ transfered}{Total\ time}$$

This formula quantifies how efficiently bits can be sent across the network in a given unit of time.

**Delay:** In our simulation, delay refers to the time taken for a packet to travel from the source to the destination and receive confirmation through an acknowledgment. Although the distance is not a factor in our simulation, the delay is dissected into various components, including processing delay, queuing delay, transmission delay, and any additional delays. The total network delay is computed using the following formula:

$$Network\ Delay = Transmission\ Delay + Propagation\ Delay + Processing\ Delay$$

This formula considers the entire cycle, from the initiation of the packet send the process to the receipt of the acknowledgment.

**Power Consumption:** Power consumption refers to the amount of energy utilized by sensor nodes during their operation. It is a critical performance metric as it directly influences the lifespan and efficiency of the network.

These metrics collectively provide a comprehensive evaluation of the proposed protocol's effectiveness, considering factors such as data delivery rate, network delay, and power efficiency.

## 4. RESULTS AND DISCUSSIONS

Fibonacci Backoff strategy provides higher throughput**.** Figure 2 presents a comparative analysis between networks utilizing Fibonacci and Exponential Backoff strategies. The red solid line represents the throughput of the network employing the Fibonacci Backoff algorithm, while the green dotted line represents a network utilizing the traditional Exponential Backoff strategy. The initial increase in throughput with the addition of more nodes is observed, as the higher number of nodes leads to increased frame transmission within the network. This leads to a more efficient delivery of bits across the network. However, around a network size of 20, the trend reverses due to the network's limited capacity caused by backoff and collision issues. Beyond a network size of three, a noticeable disparity in throughput becomes evident between the Fibonacci and exponential networks.

Consistently, the Fibonacci network demonstrates superior throughput compared to the exponential network. Throughput increases for both the Fibonacci Backoff and Exponential Backoff strategies as nodes increase from 2 to 17 due to lower congestion. The throughput peaks around 17 nodes, after which it gradually declines, with the Fibonacci Backoff strategy showing better performance due to superior collision avoidance. There is a slight dip around 20 nodes, likely from temporary congestion, and a significant decline as the node count nears 47, where the Fibonacci Backoff strategy still manages

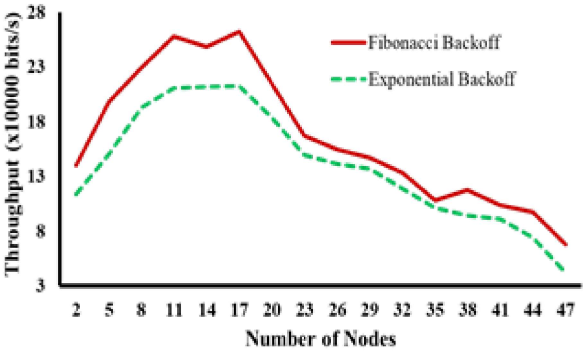

**Fig. 2.** Comparison of throughput vs. number of nodes using Fibonacci and Exponential Backoffs.

collisions more effectively than the Exponential Backoff strategy. The average for each node count, the proposed protocol with the Fibonacci Backoff strategy improves network throughput by 20.68% compared to the conventional Exponential Backoff method.

The Fibonacci Backoff strategy has lower network delay. Figure 3 presents the delay in seconds for networks employing the Fibonacci Backoff mechanism and the conventional Exponential Backoff strategy. The findings illustrate the enhanced performance of Fibonacci concerning delay. With a network size of up to 40 nodes, the delay within the Fibonacci-based network consistently maintains a lower profile compared to the exponential-based network. However, beyond 40 nodes, Fibonacci-based networks experience higher delays than their exponential-based counterparts. Occasional spikes in the graph denote variations in network conditions, yet the overarching pattern indicates that as the number of nodes increases, so does the delay. This upsurge in nodes results in an increased number of frames for transmission, leading to heightened traffic. Given the limited capacity of a transmission channel, increased traffic inevitably extends the time it takes for a frame to travel from one point in the network to another. Consequently, it can be inferred that Fibonacci networks exhibit commendable performance concerning delay. These results show that the average for each node count, the proposed protocol with the Fibonacci Backoff reduces the delay by 22.32%, compared to the conventional Exponential Backoff method.

Figure 4 illustrates a comprehensive comparison of the power consumption of nodes in two distinct types of networks: one employing the Fibonacci Backoff mechanism and the other utilizing the Exponential Backoff strategy. Power measurements are expressed in milli-watts. Our protocol employs a sleep and wake-up strategy to conserve power. In the absence of data to transmit, sensor nodes enter sleep mode, turning off all resources. They activate when the UAV is available and data is ready for transmission. This approach incorporates the utilization of two channels: a low-power unidirectional receptor channel, consistently accessible, and a main channel designated for data transmission to the UAV. The computation of power consumption is carried out using the pertinent formula. It is crucial to acknowledge the intricate interplay between power consumption and network throughput. Typically, higher throughput results in increased power consumption, establishing a proportional connection. Conversely, lower throughput is associated with reduced power consumption. These results show that the average for each node count, the proposed protocol with the Fibonacci Backoff strategy decreases power consumption by 21.84% compared to the conventional Exponential Backoff method.

Fibonacci Backoff strategy provides a higher throughput-to-power ratio. Nevertheless, the proposed protocol demonstrates lower power consumption compared to the baseline for the same throughput. To illustrate this, we present the throughput-to-power ratio plotted against the number of nodes in Figure 5. The Efficiency Ratio, calculated as throughput divided by power consumption, serves as a metric for the effectiveness of each protocol in balancing data transfer capacity with energy usage. Analyzing Figure 5, a higher Efficiency ratio for the proposed protocol indicates superior efficiency, emphasizing

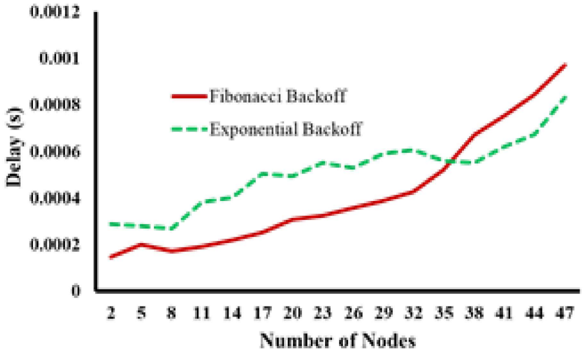

**Fig. 3.** Comparison of delay vs. number of nodes using Fibonacci and Exponential Backoffs.

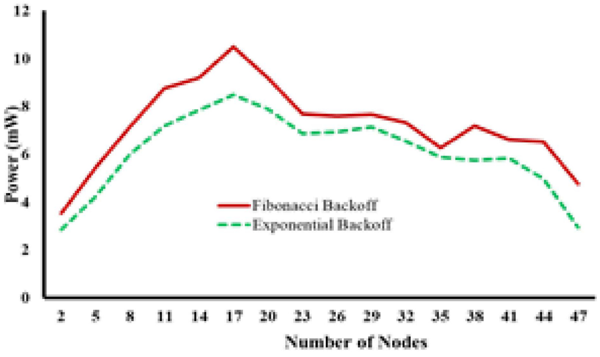

**Fig. 4.** Comparison of power consumption vs. number of nodes using Fibonacci and Exponential Backoffs.

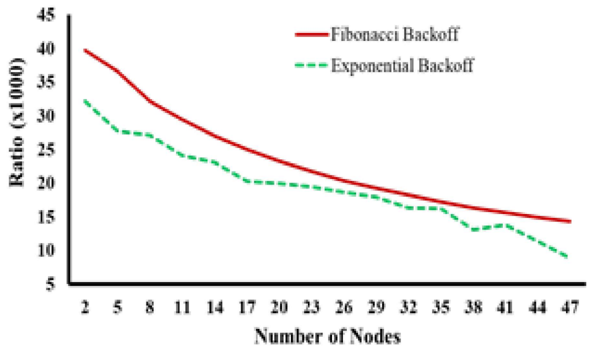

**Fig. 5.** Comparison of throughput-to-power ratio vs. number of nodes using Fibonacci and Exponential Backoffs.

its ability to achieve greater throughput relative to power consumption.

The empirical observations from our study affirm the superior performance of the dual-channel approach combined with the Fibonacci Backoff strategy compared to the conventional method. Moreover, this innovative approach not only enhances network efficiency but also ensures an extended operational lifespan for both UAVs.

## 5. CONCLUSIONS

Our proposed protocol enhances data collection from sensor nodes in infrastructure-limited areas using UAVs. Key contributions include the implementation of a dual-channel communication strategy and the use of the Fibonacci series for contention window size calculation, which collectively improve network performance and efficiency. The UAV's dynamic power adjustment and the sensor nodes' sleep mode contribute to significant power conservation. Simulation results show that the protocol achieves nearly 100% efficiency with about 20 nodes and extends network lifespan through its dual-channel approach. This provides a robust solution for UAV-assisted data collection from WSNs. Future research directions include exploring dual-channel communication in UAV swarms, developing UAV power conservation strategies, optimizing data collection routes, implementing geometric backoff for collision avoidance, and investigating cluster-based methods for energy-efficient multi-stage data collection.

## 6. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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