

Power Efficient Mathematical Model for UAV Communication Networks

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KEY WORDS	ABSTRACT
UAV (Unmanned Aerial Vehicle) UAV Communication Efficient Power Mathematic Model Power Efficient Mathematical Model	The recent development in unmanned aerial vehicles (UAVs) plays an imperative role in the field of wireless communication networks. These UAVs communicate with each other in the air for various substantial applications. However, after a certain duration, this network faces power issues due to inadequate power resources. Hence, a power-efficient mechanism is required for routing the information in UAV communication. However, in this research study, we propose a power-efficient mathematical model for UAV communication networks. By using a power-efficient mathematical model, the UAVs can determine the power information and route the data packets efficiently. The implementation has been carried out by using the simulator tool OPNET modeler. We have run the EPOLSR routing protocol, as well as the prevailing routing protocols OLSR using this model. The performance of the network has been significantly improved, and the results show that the EPOLSR outperforms OLSR, enhancing the lifetime and performance of UAVs' communication networks in terms of increased throughput and minimized delay by utilizing the proposed power-efficient mathematical model environment. Furthermore, the protocol EPOLSR was compared with OLSR, DSR, and AODV, and the results were observed. Consequently, EPOLSR outperforms OLSR, DSR, and AODV in terms of throughput and delay by utilizing a power-efficient mathematical model.

1. Introduction

UAVs' communication networks are widely used for both military and civilian applications. Additionally, due to their ease of deployment and rapid mission completion, these nodes can be utilized to carry out tasks; however, this increases the demand for UAVCN (Unmanned Aerial Vehicle Communication Networks). Generally, these nodes can be used for real-time [1] surveillance of huge crowds, public rallies inspections [2], vehicle inspections [3], airports [4], road traffics automatically monitoring [5], disaster rescue [6], remote sensing [7], cargo services [8], forestry rescue communication,

detection of wildfire [9], agriculture[10], power line fault detections [11], livestock monitoring [12], medicine delivery [13] and video streaming [14]. By considering these applications in UAVCN, one critical problem is the inadequate power of UAV nodes, which limits the communication capabilities of UAVs [15]. The power consumption model was developed theoretically for UAS (Unmanned Aerial Systems) by [16], which estimates and validates the energy consumption. The proposed and developed algorithm for the hovering mechanism design of UAVs predicts the location and duration of hovering. The authors explored the use of rotary wings for improving the energy efficiency of UAVs' communication. The

power consumption rotary wing model is derived. The problem is formulated using an optimization method to minimize the energy consumption of UAVs. In this research authors used a new path discretization method, which transforms the problem by using a finite number of variables into a discretized equivalent. Through which a suboptimal solution was obtained with high quality using the successive convex (SC) approximation technique [17]. A power consumption model for efficient UAV communication is presented, which can be used for mission planning. The authors attempted to explore the causes that impact power consumption in UAVs. Moreover, they tried to familiarize themselves with the empirical power consumption model (EPCM) for horizontal and vertical hovering, speed, and payload requirements of unmanned aerial vehicles. However, a new model is projected for the prediction of the requirements of energy consumption and efficient energy mechanism of planning of UAVs' mission using 5 generation (5G) networks communication. The proposed model utilized optimal paths to minimize energy consumption during the communication of UAVs for various scenarios and applications [18]. In [19], a model was proposed that improves the Transmit TxPwr power and the path or trajectory during interaction. The authors describe UAVs as research hotspots nowadays. The emerging 5 G technology networks have accelerated the diversified mechanisms for UAV communication. The ITU recommends 5G-assisted devices for communication. The recent deployment of UAVs has aerial base stations for interaction. The ABS has outstanding structures, for example, a strong line of sight for connectivity and flexible deployment capability. However, UAV-assisted devices require energy for both flight operations and communication processes. Consequently, the energy consumption factor is a significant problem. However, the authors investigated the vertical-to-horizontal communication of a UAV network that uses multi-type ABSs. Due to the heterogeneity of ABSs of UAVs, the problem was formulated using a mean-field-type game (MFTG) framework. The problem was simplified by discretizing the MFTG problem and developing an algorithm, namely MFQ learning. The algorithm obtains the trajectory and transmission power information of each ABS of the UAVs. This technique provides the solution for coverage and reduces the energy consumption of each ABS of UAVs. A distribution system power loss diminution model, introduced to minimize it for the distribution network [20], is an efficient mathematical model. A novel technique is proposed to estimate the energy consumption of a group of UAVs [21]. For the user, a mathematical model is proposed that utilizes a relay

between the UAV user equipment and the gNB, as well as a direct path between the gNB and the UE, employing a long-distance path loss model in free space. The amplification and UAV position parameters are specified to increase coverage by utilizing the AF relay, which optimizes the efficiency of UAV communication. An algorithm was developed for UAV routes having characteristics of controllability and obstacle avoidance. That can replenish energy for sensors in wireless networks. If the sensor runs out of energy, it can be recharged using the charging technology found in UAVs. In [22], the authors proposed a power control mechanism for UAVs to regulate the uplink transmit power (TxPwr) to compensate for the path loss of different propagation types, thereby achieving precise power control. An algorithm developed by the authors, which can be applied in 5G networks utilizing an exponential power control mechanism for both open-loop and closed-loop phases. The proposed solution focuses on coverage, spectrum, and energy efficiency. By using 3D distance, energy efficiency was evaluated and analyzed. In this research [23], the authors introduced the concept of circuit onboard power consumption. They highlighted the optimal situation, which reduces the recall frequency of UAVs, thereby increasing the lifespan of the UAV network. In [24], a mathematical model was introduced for monitoring the power supply of UAVs. Moreover, an experimental analysis was conducted at various temperatures to determine the average life expectancy. It was shown that the life expectancy curve fits with actual curve. By considering network capacity and topology structure, it was concluded that reliability analysis is a more important factor for monitoring UAV network communication. In [23], the authors proposed a scheme to minimize the power consumption of UAVs.

In this study the research gap highlighted as UAVs facing the power issue due to less battery time. However, we have focused on UAV battery and efficiently power management.

In this study, a power-efficient mathematical model is proposed for routing in UAV communication. This solution is implemented using EPOLSR, OLSR, DSR, and AODV protocols, and the evaluation is carried out based on performance metrics throughput and delay using the OPNET Modeler simulation tool. Moreover, this paper is organized into sections. Section 1 presents the introduction. In addition, Section 2 presents methodology and methods that propose a power-efficient mathematical model, highlighting the optimal lifetime of the network, UAV design, UAV power efficient Model, routing protocols, and experimental work carried out. Moreover, section 3 presents the results and

discussion. Furthermore, Section 4 presents the conclusion, Section 5 highlighting the findings and outlining future research directions, Section 6 highlighted the conflict of interest, and last section 7 consists the references.

2. Methodology and Methods

2.1 Power-Efficient Mathematical Model

The UAVCN is described as a network graph $G_n = (UAVs, L)$. UAVs are a collection of unmanned aerial vehicles, and L is a collection of connected links (x, y) , where $x, y \in UAVs$. The transmission power of the link (x, y) from UAV_x to UAV_y , P_{xy} in w (watts) is $\geq$ than $\beta \cdot d_{xy}^\alpha$ (for example, $P_{xy} \geq \beta \cdot d_{xy}^\alpha$). The β represents the transmission quality parameter, d_{xy} represents the Euclidean distance between UAV x and UAV y , and α is the parameter of gradient power. In-network, for all nodes $x \in UAVs$, let the E_x and the residual energy be denoted as $\bar{E}_x$ in joules. Suppose $Q_x^{(a)}$ is the rate in bits per second (bps) generated at UAV_x for application $a \in A$, where A is considered as the set of all applications. In a multi-application flow, the dissimilar flows are assumed to be transmitted concurrently from source to destination. (For example, more than one flow or stream can split the bandwidth concurrently). It represents the energy required to transmit a bit from UAV_x to UAV_y by e_{xy} in joules. The flow of application a is transmitted from UAV_x to UAV_y in bps and expressed by $f_{xy}^{(a)}$. The cumulative flow of all commodities $f_{xy} = \sum_{a \in A} f_{xy}^{(a)}$ represents a source UAVs by $S^{(a)}$ wherever the bits are generated for each application, for example, $S^{(a)} = \{x | Q_x^{(a)} > 0, x \in UAVs\}$, and $D^{(a)}$ represents the set of destination UAVs. Suppose the UAV x does not belong to the source or destination; in this situation, the flow-in should equal the flow-out. For UAV $x \in D^{(a)}$, in this condition, the flow-out should equal the flow-in - $Q_x^{(a)}$. The flow conservation is known as:

$$\sum_{(x,y) \in L} f_{xy}^{(a)} - \sum_{(k,x) \in L} f_{kx}^{(a)} = \begin{cases} Q_x^{(a)} & \text{if } x \in S^{(a)}, \\ -Q_x^{(a)} & \text{if } x \in D^{(a)}, \forall a \in A, \\ 0 & \text{otherwise} \end{cases}$$

Equation (1)

2.2 Optimal Network Life Time

In UAVCN, the UAV nodes face limited power issues, making it challenging to recharge them in flight. However, it is essential to maximize the network lifetime; hence, we need to increase the maximum lifetime of all UAVs in the network while minimizing delay and increasing throughput.

Let UAV x lifetime denote the time to drain the battery at UAV x , and $T_x(F)$ be the lifetime during flow F .

$$T_x(F) = \frac{E_x}{\sum_{y \in UAV} e_{xy} \sum_{a \in A} f_{xy}^{(a)}} \quad \text{Equation (2)}$$

The minimum lifetime of the battery overall UAVs at the lifetime of G_n is:

$$\begin{aligned} T_{Gn}(F) &= \min_{x \in UAV} T_x(F) \\ &= \min_{x \in UAV} \frac{E_x}{\sum_{y \in UAV} e_{xy} \sum_{a \in A} f_{xy}^{(a)}} \end{aligned} \quad \text{Equation (3)}$$

Objective function:

$$T_{Gn}(F) = \min_{x \in UAV} \frac{E_x}{\sum_{y \in UAV} e_{xy} \sum_{a \in A} f_{xy}^{(a)}}$$

Subject to:

$$\begin{aligned} \sum_{(x,y) \in L} f_{xy}^{(a)} - \sum_{(k,x) \in L} f_{kx}^{(a)} &= \begin{cases} Q_x^{(a)} & \text{if } x \in S^{(a)}, \\ -Q_x^{(a)} & \text{if } x \in D^{(a)}, \forall a \in A, \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad \text{Equation (4)}$$

$$f_{xy}^{(a)} \geq 0, \quad \forall x \in UAV, \forall (x, y) \in L, \forall a \in A$$

Out-Flow: The network lifetime (T) indicates the time it takes for the outflow of the first UAV, which is represented by $\hat{f}_{xy}^{(a)} = T f_{xy}^{(a)}$. However, time should be maximized subject to:

$$\sum_{(x,y) \in L} e_{xy} \sum_{a \in A} \hat{f}_{xy}^{(a)} \leq E_x, \forall x, y \in UAV \quad \text{Equation (5)}$$

$$\begin{aligned} \sum_{(x,y) \in L} \hat{f}_{xy}^{(a)} - \sum_{(k,x) \in L} \hat{f}_{kx}^{(a)} &= \begin{cases} TQ_x^{(a)} & \text{if } x \in S^{(a)}, \\ -TQ_x^{(a)} & \text{if } x \in D^{(a)}, \forall a \in A, \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad \text{Equation (6)}$$

$$\hat{f}_{xy}^{(a)} \geq 0, \quad \forall (x, y) \in L, \forall a \in A,$$

$$E_x > 0, \forall x \in UAV$$

To maximize the P_{xy} , the SINR should be minimized by reducing interference between the UAV_{xy} and minimizing P_{xy} .

Subject to:

$$P_{xy} \geq \beta \cdot d_{xy}^\alpha \quad \text{Equation (7)}$$

$$\text{SINR } R_{xy} = \frac{\frac{P_{xy}}{d_{xy}^\alpha}}{\sum_{(k,y) \in L} \frac{P_{ky}}{d_{ky}^\alpha + \sigma}} \geq \gamma_{xy}, \quad \text{Equation (8)}$$

$$P_{\max} \geq P_{xy} \geq 0, \forall x \in \text{UAV}, \forall (x, y) \in L$$

The following expression represents the route from source to destination. Where $x_0, x_1, \dots, x_h$ are UAVs and h represents the hops.

$$R = \{(x_0, x_1), \dots, (x_{h-1}, x_h)\}, \forall (x_k, x_{k+1}) \in L, \quad \text{Equation (9)}$$

The best route is considered, which has the maximum residual energy among the UAV_{xy} .

$$E_r = \text{Min}(E_{x_0}, E_{x_1}, \dots, E_{x_{h-1}}) \quad \text{Equation (10)}$$

$$r(E_{r_1}, E_{r_2}, \dots, E_{r_m})_{\max} \quad \text{Equation (11)}$$

2.3. Design of UAV

The design of the unmanned aerial vehicle UAV consists of 3 parts, which ensure minimal energy consumption in this work, including the energy part, power management part, and communication part. This system manages energy consumption through bidirectional link connectivity during communication while regulating power. The layout of each UAV consists of these parts. The energy part is responsible for gathering and storing energy from strengthened signals and updating the power management part to regulate the UAV's function. PMU is responsible for shifting the UAV into low-power mode when the battery is low. Moreover, the communication part comprises radio transceivers and protocols, adaptive modulation, and directional antennas, which facilitate power management during UAV-to-UAV communication.

The bidirectional link connectivity between two UAVs enables the adjustment of power through adaptive power transmission, depending on residual energy or the battery or link quality. Moreover, the concept of adaptive modulation plays a vital role in both robust and weak links. It is also responsible for

monitoring link quality using RSSI, SNR, or BER for communication and power savings, and the UAV acts as a relay to extend the communication range. Furthermore, when the link is strong, it uses less power. When the battery is low and the link is found to be weak, it temporarily increases power and employs robust modulation for communication. The directional smart antennas reduce energy consumption and ensure robust, focused communication. Through this mechanism, the power is robustly used during communication.

This model offers robust, focused, adaptive, and power-efficient communication during aerial missions. The Fig.1. presents the Power efficient model for UAVCN.

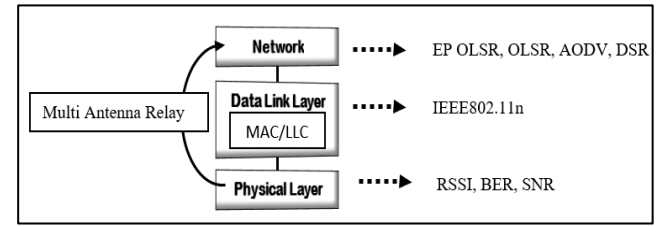


Fig. 1. Power Efficient Model

2.4 Routing Protocol

Routing protocols are the mechanisms that facilitate data communication in a network environment. In the UAV network scenario, table-driven and event-driven protocols support data communication. Moreover, the table-driven protocol is similar to OLSR, and event-driven routing protocols include AODV [25] and DSR [26, 27]. The EPOLSR [28] has distinctive features; we have modified the OLSR by utilizing a power efficient mechanism and incorporating the received signal strength, thereby terming it EP OLSR.

We have implemented this protocol by using the mathematical model and improved the performance of this routing protocol. And modification of hello and topology control message in which power information is added in the reserved field of OLSR, which carries the signal power strength received at the receiver. Through this process, the power information is communicated by each node in the network. By utilizing the power efficient model concept and modifying the Hello and TC messages, we have introduced the concept of the EP-OLSR protocol, an extended version of OLSR. In this work, we have run the protocols mentioned above using the efficient mathematical model for UAVs and observed the performance of the routing protocols.

2.5 Experimental Work

The experimental work has been carried out by developing the scenario through 8(eight) nodes of UAVs. For this scenario, we utilized the OPNET Modeler simulator tool for performance analysis of routing protocols. By utilizing a power-efficient mathematical model in the nodes of UAVs, the OLSR, AODV, DSR, and EP OLSR protocols were implemented using the 802.11n WLAN environment. Table 1 presents the network parameters used in the simulation.

Table 1

Network parameters

Parameters	Value
Simulator Tool	OPNET 18.5
Scenario Network Size	2000x1000 m ²
Scenario Simulation time	4000 s
Number of UAVs	8
Routing Protocols	EP OLSR, OLSR, DSR, AODV
Application Description	Video Streaming
Mobility Model	Random Waypoint
WLAN Environment	802.11n
Channel Setting	Auto Assigned
Power of Transmitter	0.050 watt
Data rate	65 (base)/600 (Max) Mbps

A network scenario of 2000 x 1000 m² was developed for eight nodes, and the profile definition, application definition, mob: configuration, and movable nodes were dragged and dropped at the workplace.

Further application attributes were updated for video streaming by utilizing FTP and HTTP services, as indicated in the profile definition. The movement pattern of UAVs was a random waypoint selected in mobility configuration. Whereas, the WLAN 802.11n was used at a rate of 65 Mbps (base) with auto channel setting. The transmitter power is set to 0.05 watts, and the simulation time is 4000 seconds.

The OLSR, DSR, and AODV protocols were configured accordingly. The simulation was conducted to evaluate the performance of the protocols. Furthermore, the EPOLSR was configured with similar attributes and parameters, and the simulation was rerun. The performance parameters, including throughput and delay were considered, and simulation carried out and observed, and collected the results

3. Results and Discussion

The simulation results were carried out and described the observations. Experimentally, network performance was evaluated in terms of throughput and delay parameters.

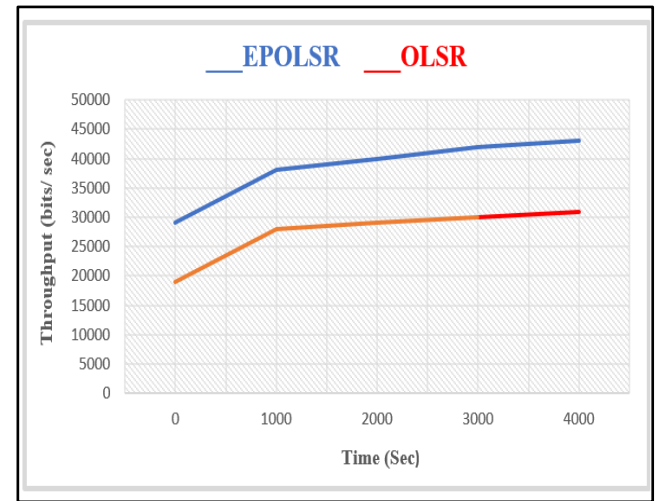


Fig. 2. The EPOLSR vs. OLSR comparison in terms of throughput

Fig. 2 presents the results of a 802.11n wireless LAN environment using a power-efficient mathematical model. The graph shows that the EPOLSR performance achieves a throughput of 0.043 Mbps during the communication of 8 UAVs. Additionally, the OLSR performance achieves a throughput of 0.031 Mbps during the communication of 8 UAVs.

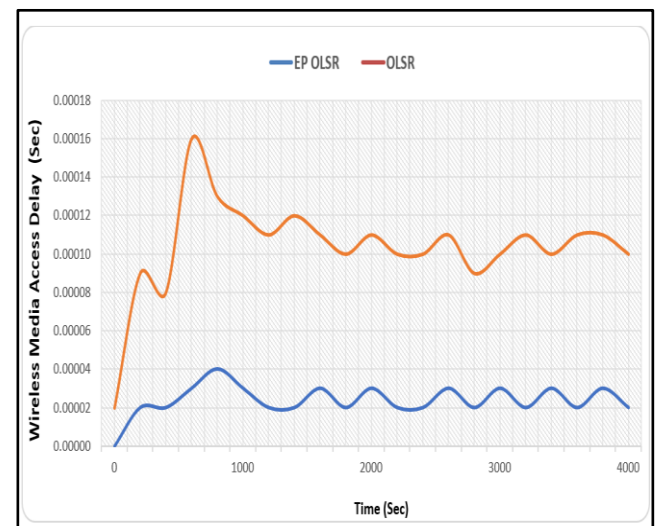


Fig. 3. The EPOLSR vs. OLSR comparison in terms of media access delay

Fig. 3 presents the performance of 802.11n wireless LAN using a power-efficient mathematical model for UAV communication. The graph shows that the EPOLSR media access delay performance was observed at 0.00003 seconds during the

communication of 8 UAVs. Additionally, the OLSR performance results in a 0.00011 sec media access delay during the communication of 8 UAVs.

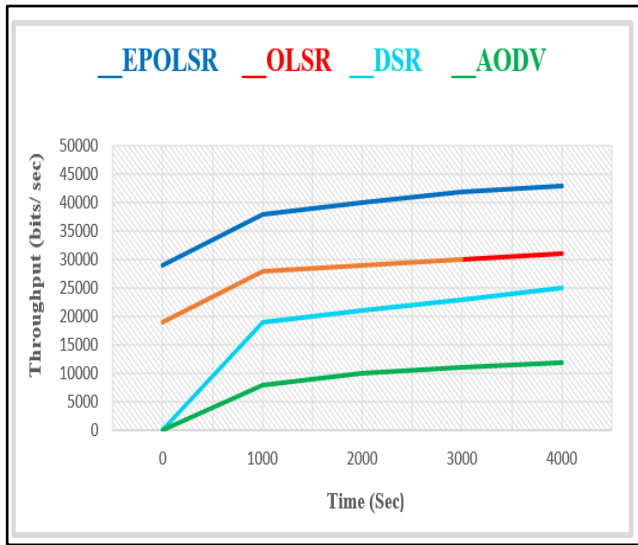


Fig. 4. The EPOLSR vs. OLSR, DSR, AODV comparison in terms of throughput.

Fig. 4 presents the performance of 802.11n wireless LAN in an environment using a power-efficient mathematical model. The graph shows that EPOLSR achieves a throughput of 0.04 Mbps during communication among 8 UAVs. Additionally, the OLSR performance yields 0.03 Mbps, the DSR performance yields 0.025 Mbps, and the AODV performance yields 0.0011

Mbps during the communication of 8 UAVs.

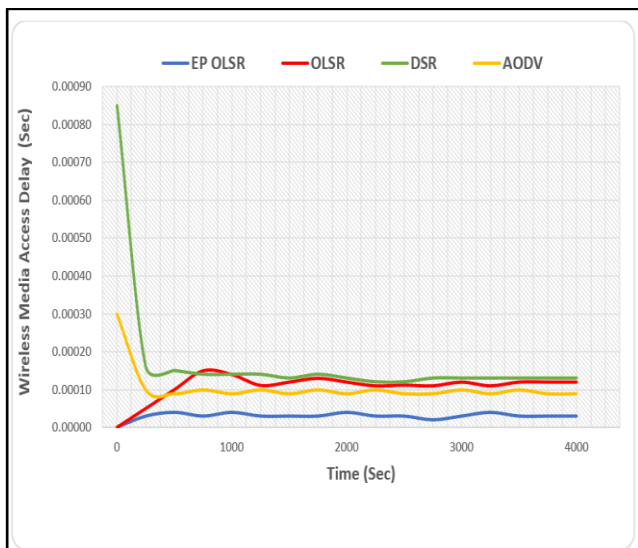


Fig. 5. The OLSR, DSR, AODV vs. EPOLSR comparison in terms of media access delay.

Fig. 5. Presents that in the environment of 802.11n wireless LAN performance using a power-efficient mathematical model, the graph shows that the EPOLSR performance produces a media access delay of 0.00003 sec during the communication of 8 UAVs.

Additionally, the OLSR performance results in a media access delay of 0.00012 seconds, the DSR performance achieves 0.00013 seconds and the AODV performance yields 0.00009 seconds media access delay during the communication of 8 UAVs.

The analysis results present that the Media access delay found less in EPOLSR as compared to OLS, AODV, and DSR. In comparative analysis of UAV network, it has been observed overall EPOLSR (efficient power optimized link state routing) protocol perform well.

3.1. Results Analysis

Table 2 provide the comprehensive comparison of UAV network performance for video streaming using the proposed model in the 802.11n environment. The OLSR protocol and EPOLSR protocol were implemented first and the simulated the results in terms of throughput and media access delay. The EPOLSR protocol perform well as compared to OLSR. Moreover, these protocols also compared with the DSR and AODV. The overall comparative analysis presents that EPOLSR performs well as compared to OLSR, DSR and AODV in terms of throughput.

Table 2

Results Analysis

Experimental Work Result Analysis				
UAV Network Parameter	Description			
Traffic				
Application				
Description	Video Streaming			
WLAN				
Environment	802.11n			
Data rate	65 (base)/600 (Max) Mbps			
Number of UAVs	8			
Transmit Power (w)	0.050 watt			
Scenario	2000x1000 m2			
Network Size				
2 Protocol	EP OLSR	OLSR		
Throughput	0.043 Mbps	0.031 Mbps		
Media Access Delay	0.00003 sec	0.00011 sec		
4 Protocol	EPOLSR	OLSR	DSR	AODV
Throughput	0.04 Mbps	0.03 Mbps	0.025 Mbps	0.0011 Mbps
Media Access Delay	0.00003 sec	0.0001 sec	0.0001 sec	0.00009 sec

4. Conclusion

In this research study, a power-efficient mathematical model is proposed for UAV communication that utilizes power information. By

using a power-efficient mathematical model, the EPOLSR protocol is implemented and compared with OLSR. The performance of the network has been significantly improved, with results showing that the EPOLSR outperforms OLSR in terms of enhancing the lifetime and performance of UAVs' communication networks, as measured by metrics such as throughput and delay. Furthermore, the EPOLSR routing protocol was compared with OLSR, DSR, and AODV, and the results were observed. Consequently, EPOLSR outperforms OLSR, DSR, and AODV in terms of throughput and delay by utilizing a power-efficient mathematical model.

5. Future work

Future research work can be focused on many directions, such as:

1. Developing novel algorithms that help in real-time swarm UAVs' communication.
2. Improving and proposing new location-aware, mobility-aware, and energy-aware protocols that will help and ensure real-time communication among flocks of UAVs.
3. By developing novel algorithms and utilizing emerging simulation tools, the quality of service, reliability, and security issues in this area can be explored, and new solutions will be highlighted.
4. The AI integration is the most important area to explore for algorithms that predict the position of UAVs hovering and packet losses during real-time communication.
5. Innovative and real-time swarm UAV communication mechanisms could be introduced and further develop the novel routing protocols and propose new models that enhance swarm UAV communication using artificial intelligence techniques.

6. Conflict of interest

The authors declared that there is no conflict of interest in this paper.

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