International Journal of Research in Engineering, Science and Management
Volume 8, Issue 10, October 2025
https://www.ijresm.com | ISSN (Online): 2581-5792

Applications and Energy Modelling of UAVs in Mobile Networks

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***Abstract*: Unmanned Aerial Vehicles (UAVs), commonly known as drones, have emerged as transformative tools for enhancing mobile network capabilities. With the rise of 5G networks and the impending implementation of 6G, UAVs play a crucial role in expanding coverage, enhancing connectivity, and facilitating communication in challenging environments. This paper reviews some of the applications of UAVs in mobile networks and, their significance in low-power communication systems. Further arithmetic modelling of energy consumption is also discussed, including ongoing research and technological developments.**

***Keywords*: Communication Systems, Energy modelling, Mobile networks, UAVs.**

1. Introduction

The evolution of wireless communication technologies from first generation to fifth generation (5G), and now progressing toward sixth generation (6G), reflects the continuous need for faster, more reliable, and widely accessible networks [8]. Unmanned Aerial Vehicles (UAVs) are increasingly integrated into these systems because of their flexibility, mobility, and ability to operate in areas where traditional infrastructure is absent or damaged. In mobile networks, UAVs serve multiple roles, from aerial base stations to relay nodes, thereby enhancing their performance, resilience, and reach. Particularly in emergency scenarios and remote areas, UAVs offer immediate solutions to connectivity challenges [1].

However, despite their potential, UAV integration still faces key challenges, such as limited flight time, energy constraints, airspace regulations, and security vulnerabilities. These limitations highlight the need for ongoing improvements in UAV design, energy efficiency, and operation. Addressing these challenges is critical to unlocking the full potential of UAVs in building robust, scalable, and next-generation wireless communication systems.

This paper attempts to examine the applications of UAVs in mobile networks, focusing on their role in low-power communication systems. Additionally, it explores the mathematical models for energy consumption and discusses the current research trends and emerging technological advancements.

2. UAV Applications in Mobile Networks

A. Temporary Base Stations (Flying BTS)

Disasters such as hurricanes, earthquakes and floods can destroy or disable permanent cell towers. UAVs which are unaffected by ground damage can hover and reposition in midair to provide coverage. Verizon offered airborne long term evolution service for disaster recovery, providing cellular coverage after Hurricane Ian 2022 [5].

B. Remote Area/ Emergency Coverage

UAV-based coverage is a real-world and scalable approach for extending mobile networks into difficult-to-reach or underserved areas like in rural or mountainous terrains, without any physical infrastructure. The mobile communication company, EE formerly known as Everything Everywhere demonstrated prototype balloons and drones to provide temporary mobile coverage in emergency situations in the UK in 2017 [2],[3].

UAVs can rapidly restore communication links and support rescue operations [13].

C. Network Support- 5G and 6G

UAVs serve as effective platforms for extending 5G coverage through lightweight antenna deployment and are anticipated to be integral to 6G networks by enabling consistent line-of-sight connectivity in complex environments [5].

D. Infrastructure Monitoring and Maintenance

UAVs outfitted with imaging and sensing technologies offer a safer, more efficient alternative for inspecting telecom infrastructure, particularly in hard-to-reach or hazardous locations. Such systems reduce the need for manual inspections, minimize the operational downtime and risk to field workers. Nokia and Swisscom have implemented a drone-based inspection system in Switzerland that supports public safety operations, infrastructure monitoring, and emergency response. [9].

E. Relay Nodes and Mesh Networking

UAVs can be deployed as relay nodes or to form dynamic mesh networks, offering a reliable communication backbone in regions without terrestrial or satellite connectivity. In such

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networks, the UAVs operate collaboratively, using protocols such as Flying Ad Hoc Networks (FANET) to ensure seamless data routing and adaptive reconfiguration. This enables continuous connectivity, lower latency, and improved network reliability, even in challenging environments. For instance, researchers at IIT-BHU have developed a drone-based mesh communication system to support emergency communication in remote areas [6].

Figure 1 outlines a few applications of UAVs in mobile networks. The dynamic evolution in drones brings the flexibility to quickly adapt to the environmental conditions, independent of preexisting requirements. Apart from the applications mentioned above, UAVs are value add support in mapping and surveying, rescue missions, localization, and logistic delivery.

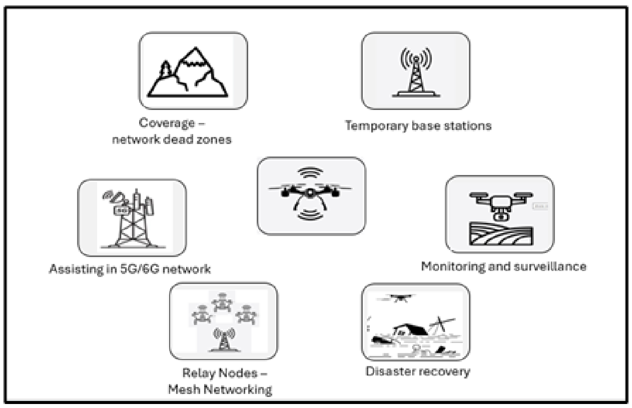

Fig. 1. UAV applications in mobile networks

3. Role of UAVs in Low-Power Mobile Networks

UAVs can also enhance low-power mobile networks such as NB-IoT and LPWAN, which are made for slow data rate and energy-efficient communication devices such as those applied in smart agriculture and remote sensor networks. The drones are fitted with the right modules and can provide energy to the sensors and devices to provide power through energy transfer.

NB-IoT (Narrowband IoT) is a standard for communication that is both horizontally and vertically organized having a long-range, low-power, and superior coverage through robust module systems and signal repetition. In this way, UAVs can not only strengthen the current connectivity by making it aerial via relays or temporary base stations but also automatically expand NB-IoT coverage to off-the-grid or hard-to-reach locations where ground infrastructure is inadequate [8].

LPWAN (Low-Power Wide Area Network), the technology that facilitates huge IoT deployments with the least energy requirement and the lowest data rates possible. In this instance, the UAVs function as mobile access points thereby ensuring the continuity of coverage and enhancing network reliability in areas with no infrastructure [7].

4. Energy Consumption Modeling for UAVs in Mobile Networks

Understanding energy consumption is essential for optimizing UAV performance [4]. The key model is summarized below

Energy Use of UAVs (Simple Formula)

The total energy used by a UAV depends mainly on three factors which are defined as below,

Flying time: The flying time of the UAV is the time that elapses while it is flying from one waypoint to the next or from one mission area to another. This phase usually causes the most energy consumption since there is continuous maneuvering done by the UAV.

Hovering time: The time spent by the UAV in the air doing nothing so that it can do things like data collection, imaging, or being a communication node. Even though the UAV is hovering, it needs energy to keep its altitude and to make the platform stable.

Communication time: The time period when the UAV is sending or receiving data actively. The energy used by the communication payload (for example, antennas) is included in this and it can change depending upon the transmission power and data rate.

Thus, the formula of *E_total* of UAV can be derived as the sum of the energy used during flying, hovering, and communication activities.

$$E\_total = P\_fly \cdot T\_fly + P\_hover \cdot T\_hover + P\_comm \cdot T\_comm$$

Where:

- P is the power used
- T is the time spent doing each task

This helps determine how long the drone can remain in the air before requiring a recharge.

Formulas for UAV Energy Consumption can be defined as below,

Basic Energy Formula is $E = P \times t$

Where:

- E is the energy consumed
- P is the power used
- t is the time of operation

Thus, the total Flight Power Consumption is,

$$P\_total = P\_hover + P\_move + P\_drag$$

Where:

- P_hover is the power needed to hover
- P_move is the power needed to move forward
- P_drag is the power needed to overcome air drag

And Flight Energy Consumption is measured as,

$$E\_fly = (P\_hover + P\_move + P\_drag) \times t$$

The formula for Communication Energy Consumption:

$$E\_comm = P\_comm \times t$$

Total Energy Consumption:

$E\_total = E\_fly + E\_comm$
$E = \int_0^t P\,dt$

The total energy consumed by a UAV during flight by summing up its instantaneous power usage over time.

Where:

- E is the total energy consumed over time
- P is the instantaneous power consumption (in watts)
- t is the time interval of the flight scenario (in seconds)

$E = \int_0^1 P\,dt = P$

It illustrates that when power remains constant over 1 second, the energy consumed is exactly equal to that constant power value.

Where:

- E is the total energy consumed
- P is the constant power consumption over time

The integration is over a unit time interval (from 0 to 1 second)

These energy evaluation models are critical for UAV flight planning and ensuring optimal mission duration as per the requirement [4].

5. UAV integration and Simulation

A. Integration

UAVs can immediately return communication, allow rescue groups and influence people to get in touch again. As shown in Fig 1, the UAV performs the role of a relay node or temporary base station that links the user equipment with the core network and thus provides secure, reliable, and priority-based communication systems for emergency response teams. [11],[12].

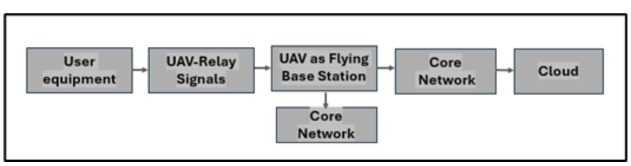

Fig. 2. Mobile network block diagram with UAV integration

B. Simulation and Algorithm Evaluation

To verify UAV deployment strategies and evaluate the impact of different pathfinding algorithms on energy efficiency, a simulation system was developed using Panda3D and a custom-built Drone Sim environment. The simulator modelled:

- UAV take off
- Navigating to assigned waypoints (buildings)
- Hovering behavior
- Real-time energy monitoring and visualization

The software included a visual Heads-Up Display (HUD) to display the energy consumed by each drone and the fleet's total energy usage. Missions could be triggered interactively and monitored for performance across a range of conditions.

1) Algorithms Implemented

The simulator supported multiple pathfinding algorithms selectable via command-line flags. In this context, the shortest path algorithms are referred to as calculating the energy [10]. A few algorithms are listed below,

A:* The A* Search algorithm is one of the most effective techniques in pathfinding. It is a heuristic-based algorithm that provides fast, near-optimal routes, performing best in terms of both energy and time.

Algorithm 1: A*

Input: *A graph, start node s, goal node g, and heuristic h*
Output: *The lowest-cost path from s to g*
Initialize *a priority queue O (open set) with the start node s*
while *O is not empty do*
n ← Node in O with the lowest f-score (cost g + heuristic h)
if n is the goal g, return the path
Remove n from O.
for each neighbor m of n do
if a shorter path to m is found via n then
Update m's path and score, then add/update it in O
end if
end for
end *while*

Dijkstra: This algorithm finds the shortest path from a given source node to every other node, but consumes more energy due to exhaustive search.

Algorithm 2: Dijkstra

Input: *A weighted graph and a start node s*
Output: *The shortest distance from s to every other node*
Initialize *distances to all nodes as ∞ (start s is 0) and a priority queue PQ with s*
while *PQ is not empty do*
u ← Extract node with the minimum distance from PQ
for each neighbor v of u do
if the path through u is shorter then
Update v's distance and add/update it in PQ
end if
end for
end *while*

Breadth-First Search (BFS): BFS is applicable for unweighted graphs, starts with a source node and visits all the nodes level by level; however, in real-world distance

Table 1
Observations on pathfinding algorithms

Algorithm	Time (s)	Energy (J)	Path Efficiency	Notes
A*	15.2	310	High	Best balance
Dijkstra	19.5	390	Highest accuracy	High CPU use
BFS	24.3	420	Low	Inefficient
DFS	27.1	455	Poor	Longest paths
Clustering		280 (total)	Energy-saving	Fewer drones used

optimization, it has limitations in finding the shortest path.

Algorithm 3: Breadth-First Search

Input: *A graph and a start node s*

Output: *A traversal of the graph's nodes*

Initialize *a queue Q with s and a set V to track visited nodes*
while *Q is not empty do*
  n ← Dequeue from Q
  for each unvisited neighbor m of n do
    Mark m as visited and Enqueue m into Q
  end for
end *while*

Depth-First Search (DFS): This algorithm goes deep into one branch before moving to another, thus the paths are long and energy-intensive. It is the least efficient compared to other algorithms.

Algorithm 4: Depth-First Search

Input: *A graph and a start node s*

Output: *A traversal of the graph's nodes*

Initialize *a stack S with s and a set V to track visited nodes*
while *S is not empty do*
  n ← Pop from S
  if n has not been visited then
    Mark n as visited
    Push all neighbors of n onto S
  end for
end *while*
return *failure*

C. Clustering for Energy Efficiency

A custom clustering-based assignment algorithm was also implemented to minimize the number of drones needed and overall energy consumption. In this approach, buildings were grouped into clusters, and each drone was assigned to service a specific cluster. This method ensured more efficient mission planning by reducing redundant flights and improving coverage distribution. This was resulted in:

- Total fleet energy was reduced
- Fewer drones were deployed
- Individual mission lengths increased with efficiency

1) Code Overview

The simulation was coded in Python using Panda3D. Key elements were included:

- Dynamic drone instantiation and take-off sequences
- Real-time energy tracking via HUD
- Waypoint assignment using clustering or 1-to-1 mapping
- Event-triggered mission execution with modular control

Figure 3 describes the Python program used to code the simulation.

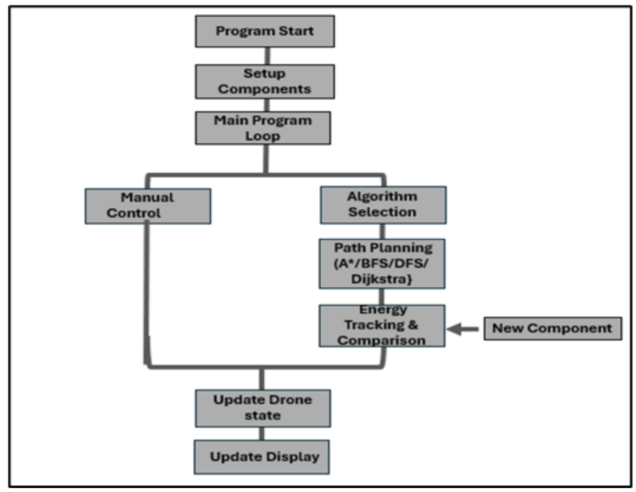

Fig. 3. Simulation through python program

This modular architecture enabled detailed analysis of flight paths, energy metrics, and algorithm behaviors in various mission scenarios, as shown in the Table 1.

6. Conclusion

UAVs have proven to be a transformative addition to modern wireless network infrastructure, enabling rapid deployment of communication services, extending coverage to underserved areas, and supporting the evolution of 5G and future 6G networks. This paper attempts to present a solution in the form of energy modulation formulas for the optimization of power consumption and extending flight time as a means of tackling one of the major problems in the UAV-assisted communication systems, energy efficiency.

These results highlight the importance of designing energy-aware communication strategies to maximize the effectiveness of UAV networks. While challenges such as regulatory constraints, security, and scalability remain, advances in energy-efficient protocols and UAV hardware will play a critical role in overcoming these limitations. The next stage of this research can explore the possibility of the creation of intelligent, self-optimizing UAVs which would, in turn, be the safeguard for the next generation of robust, high-capacity, and sustainable wireless networks.

Acknowledgment

I would like to express my sincere gratitude to Professor Dr.

Rashmi Bhatia, IIT Bombay, for their invaluable guidance and encouragement throughout this project. Her insights and mentorship have been instrumental in helping me learn and grow during this experience.

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