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Original Article

A QoS-Constrained and Utility-Driven Routing Framework with Mobility-Predictive Stability for Flying AD-HOC Networks (QAR)

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Abstract - *Flying Ad-Hoc Networks (FANET) has become popular for many applications that require the exchange of reliable, real-time data, such as environmental monitoring or disaster assessment. Most of the missions that rely on FANETs require traffic to meet strict Quality of Service (QoS) requirements (e.g., low latency, high reliability, etc.) and will also have high mobility and often experience sudden changes in their topology. However, almost all routing algorithms currently used in FANETs were not purpose-built to handle these constraints; consequently, they exhibit reduced performance under both conditions. Variation in link quality and intermittent connectivity make maintaining consistent communication more difficult. The proposed QoS-Aware Routing (QAR) framework incorporates application-specific QoS requirements directly into the routing process, enabling route selection to better satisfy the communication demands of diverse FANET applications. The proposed scheme continuously monitors key QoS metrics, such as delay, packet loss, and throughput, and informs routing decisions based on evolving network conditions. QAR will enhance data delivery reliability within the network and increase overall network efficiency by matching real-time QoS measurements to route selection. The simulations show that the proposed algorithm provides better QoS and more predictable communication behaviour than traditional FANET routing protocols, indicating that it can be used in mission-based Unmanned Aerial Vehicle (UAV) applications.*

Keywords - *FANETs, UAV communication, QoS-aware routing, Dynamic topology, Real-time data transmission, Adaptive routing, Network performance.*

1. Introduction

UAVs have also proven useful, with FANETs receiving considerable attention, as they have been utilised in applications requiring rapid data capture and reliable communication. Information exchange in missions such as surveillance, disaster response, and environmental monitoring depends on real-time communication and, in many cases, on strict Quality of Service requirements [1, 2]. There is no guarantee of low end-to-end delay, high reliability, and sufficient bandwidth in such aerial networks because node mobility is high, nodes move in three dimensions, and link bandwidth varies rapidly [3].

Routing protocols, originally designed to support Mobile Ad-Hoc Networks (MANETs) or Vehicular Ad-Hoc Networks (VANETs), are not appropriate for FANETs. Most conventional routing protocols prioritise network connectivity and hop-count optimisation instead of satisfying application-specific QoS requirements [4, 5]. As UAV mobility continuously alters the network topology, these protocols frequently experience route failures, resulting in packet loss and reduced communication reliability. QoS-aware routing mechanisms for wireless ad hoc networks have been studied extensively, using delay, bandwidth, and packet loss as routing metrics [6, 7]. Most of these methods, however, incur high control overhead when extended to FANETs or employ reactive approaches that perform poorly under rapidly changing network conditions. Geographic routing protocols minimise route discovery latency but are not QoS-aware and are susceptible to void regions and link instability [8]. This means that, to achieve efficient routing, FANETs need to be formally designed with QoS constraints as part of the routing logic, rather than relying on heuristic/ best-effort methods.

Recent FANET-centred literature indicates the need for routing schemes that can jointly accommodate QoS requirements and mobility dynamics [9]. Continuous monitoring of QoS parameters and selection of an adaptive route are imperative for the stable operation of highly active UAV networks [10]. Building on these observations, this paper proposes a framework for implementing a specific QAR model that integrates application-specific QoS into the routing process, thereby enabling increasingly reliable and efficient communication in FANET-based settings [11].

1.1. Research Gap and Novelty

Despite tremendous advances in routing for FANETs, several key challenges remain to be addressed. Currently, traditional protocols like AODV and OLSR are focused mainly on keeping the network connected and identifying the available routes only; the simultaneous satisfaction of multiple QoS requirements is not carefully considered. Although there are extensions that are QoS-aware, they typically enhance only one or a few performance measures e.g. reduction of delay, reliability, bandwidth etc., without combining them to allow for a unified routing strategy that takes into account mobility-aware link stability and measures such as the aforementioned in addition to delay. Moreover, most approaches are reactive and will act only when the route has been degraded, resulting in a high latency, lost packets and a high control overhead in a highly dynamically deployed aerial network. These restrictions make it imperative to find a way to maintain en route QoS feasibility while proactively adapting to topology changes by predicting link instability.

1.2. Problem Statement and Research Questions

FANETs are intended to take advantage of the dynamic conditions of man-made UAVs flying in such fast changing topologies and unstable wireless links. While there have been a lot of modifications in the existing routing protocols to address MANET and VANET scenarios, none of them have taken use of QoS into consideration. Consequently, end-to-end delays, packet losses, and path instability are common in FANETs, particularly in applications requiring real-time or mission-critical data delivery. Current QoS-aware routing strategies rely on reactive schemes that are activated only when performance degrades, or they impose substantial control overhead, making them unsuitable for highly mobile aerial environments. The above set of limitations indicates that the routing framework must be capable of dynamically incorporating QoS requirements into routing decisions and responding to rapid network changes.

According to these challenges, this research addresses the following questions:

1. What are the ways of incorporating application-specific QoS constraints into the routing choices of FANETs?
2. What are the benefits of using real-time network and link conditions to aid in adaptive routing when mobility is high?
3. How much better can a QoS-based routing framework be in terms of reliability and resource usage than the traditional FANET-based routing protocols?
4. What are the mathematical models to model and implement QoS constraints in route discovery and route maintenance in highly dynamic FANET environments?

1.3. Motivation

This work is motivated by the increasing adoption of UAV networks in mission-oriented applications, where communication quality directly influences operational effectiveness. Applications such as aerial surveillance, disaster response, and environmental monitoring depend on the timely and reliable delivery of information to support critical decision making. Even short communication interruptions or excessive delays can significantly reduce mission performance.

Although many works have addressed this challenge, there are still a large number of FANET routing protocols that do not satisfy the QoS demand especially when mobile and link conditions change fast. Existing real-time QoS routing strategies often make routing decisions using limited network information, which can reduce resource utilisation and overall communication reliability. The restrictions inspire the development of an adaptive routing approach that supports a very dynamic routing network, satisfies QoS constraints, and enhances the reliability of communications in mission critical FANET applications.

1.4. Objective

It aims to come up with a QAR solution compatible with the dynamic behavior in the FANET and to evaluate it. The proposed scheme will consider essential QoS metrics like latency, reliability and bandwidth availability in the routing decision making for application-aware communication. It is also intended to enable real-time adoption, by employing an online approach for adaptive adjustment of network conditions, according to the sensed measurements such as end-to-end delay, packet loss, throughput and dynamic changes in link quality.

It is examined the feasibility of the proposed routing scheme as well as its capacity to provide QoS, considering diverse mobility and traffic scenarios. The paper also provides a glimpse of the flexibility of AP topology for rapidly adapting it to the aerial environment provided by QAR, and the opportunities for the improvement of the immunity of communication and network performance in FANET scenarios.

1.5. Major Contributions

- Generate a framework for routing, suitable for QoS support, including delay, bandwidth, reliability and link stability.
- Proactive route selection using the stability of the route to predict mobility.
- Design of an optimization and feasibility-enforcement utility-driven routing mechanism including multi-metric optimization.
- Extensive test against AODV, OLSR and QoS-AODV with different UAV densities.

2. Literature Review

Another field of interest for research pertaining to the FANET routing is the environment's special characteristics like high node mobility, three-dimensional node movement and a very dynamic wireless connectivity. The early proposed FANET routing algorithms are mainly based on the protocols developed for Mobile Ad-hoc Network (MANET) like Ad-hoc On-Demand Distance Vector (AODV) and Temporally Ordered Routing Algorithm (TORA). These protocols provide little mobility connectivity and route maintenance services, but do not explicitly take care of QoS requirements and have a tendency of failing routes easily, and demonstrate high latency in high mobility environments [4, 5]. Later on, geographic routing algorithms were proposed like Greedy Perimeter Stateless Routing (GPSR), which reduces the routing overhead based on the position information of the nodes. The techniques would apply to FANETs, as they are not only scalable but also minimize the number of control messages [8]. However, standard geographic routing relies primarily on proximity and fails to account for QoS parameters such as delay, available bandwidth, and link reliability. This means that such protocols can divert traffic across fragile or faulty links, thereby reducing performance in real-time UAV applications [12]. To deal with these limitations, various ad hoc QoS-based network routing extensions have been proposed. The QoS versions of AODV, commonly called QAODV versions, partially constraint the route discovery process as to end-to-end constraints on minimum bandwidth and maximum delay [13]. Even though QAODV enhances the QoS-conformity as compared to that of original AODV, its reactive route-discovery feature may cause longer delay for the transmission and increase the overhead of management for very dynamic FANETs. On the other hand, QoS-enabled DSR variants with QoS may have delay and bandwidth estimation capabilities that are expected to be relatively unattractive for partially connected or massively dense topologies where enabled paths will be likely invalidated after a topology change [6].

Extensions of proactive routing protocols are also presented to accommodate QoS. Multimedia OLSR (OLSR-QoS) introduces both ETX, bandwidth and delay link-quality metrics into the computation of routes [14]. Despite proactive QoS routing ensures rapid route acquisition with much less delay, there are huge control overhead introduced by intensive topology advertisements that might affect the scalability especially for dense or highly mobile UAV networks [15]. Multi-path mechanisms, e.g. MP-OLSR, may also increase the reliability by maintaining multiple QoS-qualified paths, but at the cost of greater complexity and synchronisation issues [16].

Recent works have investigated cross-layer and mobility-adaptive routing schemes in order to improve QoS support in FANETs. Cross-layer approaches make routing decisions based on physical and MAC layer feedback such as signal-to-noise ratio and queue occupancy [17]. While there are some success stories for cross-layer architecture for changing link conditions, in the real world the logic and control aspects required to make this work across a number of protocol layers can make things difficult to implement. Making use of the mobility-awareness techniques, the pattern of movement of the UAVs is predicted, which enhances path stability [3]. However, prediction accuracy is a critical factor in their effectiveness and cannot easily be assured in the case of highly dynamic flying situations.

Most QoS-aware routing protocols that have been developed in the past couple years focus on provisioning QoS rather than mobility adaptation, and do not integrate both within a single routing protocol. Consequently, the current solutions do not have a large capacity of supporting the changes of the QoS and rapid topology changes in FANETs in real time. To overcome this limitation, the proposed QAR framework reflects the application-specific QoS requirements and uses adaptive selection of routes (based on constant monitoring of the network and an estimation of the link stability based on their mobility information.

Table 1. Comparative analysis of QoS-based routing protocols in FANETs and QAR

Protocol	Routing Category	QoS Metrics Considered	Mobility Awareness	Strengths	Limitations
AODV	Reactive	None	No	Low routing overhead in static scenarios	High route failure under mobility; no QoS support
TORA	Reactive / Adaptive	None	Partial	Fast local route repair	High control overhead; unstable paths
GPSR	Geographic	None	Partial (location-based)	Scalable; low control traffic	No QoS awareness; void region problem
QAODV	Reactive QoS	Delay, bandwidth	No	Supports basic QoS constraints	Increased route discovery latency; reactive recovery
DSR-QoS	Source routing QoS	Delay, bandwidth	No	QoS-aware path selection	Poor scalability; frequent path breakage

OLSR-QoS	Proactive QoS	ETX, delay, bandwidth	No	Faster route availability; link-quality awareness	High periodic control overhead
MP-OLSR	Multipath QoS	Reliability, ETX	No	Improved fault tolerance	Path synchronization complexity
Cross-layer QoS Routing	Cross-layer	Delay, SNR, queue length	Partial	Improved link awareness	Complex implementation
Mobility-aware FANET Routing	Predictive	Link duration, stability	Yes	Stable path selection	Depends on accurate mobility prediction
QAR (Proposed)	QoS-aware FANET routing	Delay, bandwidth, reliability, link stability	Yes	Adaptive, QoS-driven, mobility-resilient	—

As can be seen from the comparison in Table 1, there are some routings that have been made to improve some features like energy efficiency, mobility adaptation, route stability and QoS support etc., Nevertheless, most approaches optimise only individual performance objectives and do not simultaneously consider delay, bandwidth, reliability, and link stability within a unified routing strategy. These observations identify an important research gap and provide the motivation for the proposed QAR framework described in the following section.

2.1. Technological Gap

Despite several studies on routing protocols in FANETs, existing solutions face several technological constraints that limit their ability to deliver QoS in highly mobile aerial networks at any given time. Traditional routing algorithms in MANETs focus on connectivity and the efficiency of route discovery but do not address application-level QoS requirements, leading to unreliable communication performance in high mobility. Geographic routing approaches are very scalable and reduce route-discovery latency, but they rely solely on positional data and do not exploit information about link-quality changes, and they fail to guarantee delay, reliability, or bandwidth.

The QoS extensions are QAODV and OLSR-QoS, which impose some delay and bandwidth bounds on the routing process, but publish topology seldom and only in response to topographic variations (eg. every topographic cycle or every minute), and as such are less responsive to topological changes than their plain equivalents. Cross-layer and multipath routing methods provide greater reliability and link awareness, but incur significant processing and signaling overhead that may not be feasible in resource-constrained UAVs. Mobility-aware routing protocols aim to leverage link stability, though their success depends heavily on accurate mobility modelling, which is not readily available in practical UAV applications.

Additionally, the vast majority of currently available solutions do not provide a formal QoS-based decision model that enables systematic route assessment and selection under competing performance bounds. The existing solutions typically treat QoS provisioning, mobility adaptation, and scalability as independent issues rather than a combined design. This identifies a distinct technological gap in routing architectures that incorporate real-time QoS measurements alongside mobility-driven dynamic linkages, with low control overhead and reasonable implementability. The presented gap is the reason the proposed QAR framework is intended to provide adaptive, constraint-aware routing decisions that depend on the specifics of FANET operation.

2.2. Research Contributions

To address the identified technological gaps, this paper makes the following key contributions:

- A QoS-Conscious Routing system on top of FANETs, which explicitly incorporates the latency, reliability, and bandwidth constraints into the routing decision-making process, and accordingly supports application-on-the-fly communication.
- A live QoS control system that continuously measures delay, packet loss, throughput, and changes in link quality variations to assist in adaptive routing in dynamic network paths.
- A utility-based route selection algorithm that allows a comparative study of candidate routes in a systematic manner and imposes limitations on QoS when doing route discovery and maintenance.
- An extensive performance assessment of the operation of the UAVs in various mobility patterns and traffic conditions, with increased QoS fulfillment, communication dependability, and resource effectiveness compared to the typical routing frameworks.

3. System Model and Design of QAR

The design of QAR is carried out under the assumption of a formal system model that captures the specifics of Flying Ad-Hoc Networks. FANETs are compared with terrestrial ad hoc networks because they have three-dimensional mobility, dynamically unstable links, and non-specialized traffic needs. Therefore, the routing decisions must consider network topology dynamics, link instability caused by mobility and application-specific (application) QoS requirements. In this section, the proposed QAR framework will be presented, along with an analysis of the background and a design justification. The aim is to model the properties of FANETs mathematically, integrate QoS constraints into routing decisions, and account for high mobility and dynamic link behavior characteristic of UAV networks [3, 10].

3.1. Network Model

The FANET is modelled as a directed time-varying graph, as given by Equation (1). This equation explicitly captures temporal changes in the topology. In contrast to stagnant or gradually varying MANETs, the set of accessible wireless connections in FANETs changes rapidly as UAVs move through three-dimensional space. Representing the network as a time-varying graph enables QAR to consider temporary connectivity rather than permanent paths.

$$G(t) = (V, E(t)) \tag{1}$$

Where V=$\{v_1,\ v_2, \ldots.\ v_N\}$ represents the set of UAV nodes, and E(t) ⊆ V × VE(t) denotes the set of wireless links available at time t. A directed link (i,j) ∈ E(t) exists if UAV v_j is within the communication range of the UAV v_i and the received signal quality exceeds a minimum threshold [3].

The existence of the link is defined in Equation (2).

$$d_{ij}(t) \le R \ and\ SNR_{ij}(t) \ge \gamma_{min} \tag{2}$$

Where $d_{ij}(t)$ is the Euclidean distance between UAVs i and j, R is the transmission range, and γ_{min} is the minimum signal-to-noise ratio required for reliable communication.

The connection between two UAVs in flight is based not only on physical proximity but also on the required signal quality. Including distance and SNR thresholds in the model ensures that only links capable of supporting credible data transmission are considered when computing routes. This two-condition model does not require the choice of marginal links, which can be technically feasible but fail to meet the QoS criteria, especially in high mobility or high interference [18].

This network abstraction could be used to incorporate QoS, Mobility prediction and Route optimization.

3.2. Mobility and Link Dynamics

Mobility is the key characteristic in FANETs for sustaining network stability. The path of UAVs is indicated by missions e.g., they can involve which sharp maneuver, altitude adjustment or team. When mobility is not described, a sudden, fragile connection becomes an issue. Therefore, QAR is a 3D visualization of mobility and indicates the positions of vectors which have an associated velocity corresponding to each UAV. This allows the routing protocol to analyze not just the link's current state, but also its future state. Link lifetime estimation is a quantitative assessment of the wireless link's lifespan beyond which it is no longer viable [3]. The position and velocity vectors are used to model UAV mobility in 3D space.

$$p_i(t) = \ (x_i(t), y_i(t), z_i(t)), v_i(t) = \ (v_{xi}, v_{yi}, v_{zi}) \tag{3}$$

Due to continuous motion, links are inherently transient. To quantify link stability, QAR estimates the Link Expiration Time between UAVs i and j, as defined in Equation (4).

$$LET_{ij} = \frac{-(ab+cd)+\sqrt{(a^2+b^2)R^2-\ (ad-bc))^2}}{a^2+c^2} \tag{4}$$

Where

a = $v_{xi} -\ v_{xj}$
b = $x_i -\ x_j$
c = $v_{yi} -\ v_{yj}$
d = $y_i -\ y_j$

QAR limits route-breaking and repeated rediscovery by focusing on links with a longer expected lifetime. Such proactive mobility is what distinguishes QAR from purely reactive routing schemes, which typically respond only after a link failure and, as a result, incur higher packet loss and delay [19].

3.3. Traffic and QoS Requirements Model

FANET applications generate uneven traffic flows with highly dissimilar QoS requirements. Examples include real-time video streaming and command-and-control messages, which require low latency and high reliability, and telemetry or sensor data, which may tolerate longer delays. The unified routing approach should thus not group different traffic classes but identify and separate them.

A QoS requirement vector describes every traffic flow f:

$$Q_f = \left\{D_f^{max}, B_f^{min}, R_f^{min}\right\} \tag{5}$$

Where D_f^{max} denotes the maximum tolerable end-to-end delay, B_f^{min} is the minimum required bandwidth, and R_f^{min} represents the minimum acceptable reliability.

A candidate route P is considered QoS-feasible only if:

$$D(P) \le D_f^{max},\ B(P) \ge B_f^{min},\ R(P)\ \ge R_f^{min} \tag{6}$$

This constraint-based filtering makes routing decisions based on application-level service needs, rather than best-effort provisioning.

QAR models the quality of each traffic flow based on a QoS requirement vector that clearly defines acceptable delay, bandwidth, and reliability limits. Such formalization changes routing from a non-objective process to a constraint-sensitive determination. Routes that do not satisfy a flow's minimum QoS requirements are eliminated early enough to prevent unnecessary resource utilization [20, 21].

Traffic-aware modeling ensures that routing decisions align with application-level goals, thereby enabling QAR to support mission-critical communications better than hop-count-based approaches.

3.4. QoS Metric Estimation

QoS metrics can only be estimated accurately to support informed routing decisions. Nevertheless, FANET nodes are resource-constrained devices that cannot support computationally intensive measurements or excessive signaling overhead. QAR thus embraces lean yet efficient estimation methods that balance precision with realism.

The end-to-end delay of a path P consisting of H hops is expressed in Equation (7).

$$D(P) = \sum_{k=1}^{H}\left(D_k^{tx} + D_k^{prop} + D_k^{queue}\right) \qquad (7)$$

Available bandwidth along the path is approximated by the bottleneck link expressed in Equation (8).

$$B(P) = \min_{(i,j)\in P} B_{ij} \qquad (8)$$

Path reliability is computed as the product of the individual link delivery ratios, as expressed in Equation (9).

$$R(P) = \prod_{(i,j)\in P} PDR_{ij} \qquad (9)$$

These equations enable precise yet easy-to-use approximations of QoS metrics for resource-intensive UAV nodes.

End-to-end delay is the sum of transmission, propagation, and queuing delays along a route. The bandwidth estimation accounts for channel use, which is a real-time measure of contention, rather than assuming a constant capacity. Empirically, reliability is assessed using packet delivery ratios, which provide direct information about the link's current performance [21, 22].

Instead, QAR maintains situational awareness of network conditions by continually updating the metrics (without stale, inert assumptions). It is a dynamic estimation in which routing decisions change over time as traffic load and link quality vary.

3.5. QoS Utility Function

Routing in FANETs currently includes trade-offs among conflicting QoS objectives. For example, a low-delay path would be considered low-reliability, and a high-reliability path would be considered high-latency. QAR uses a multi-metric utility function to control such trade-offs on a system level.

In each trade-off between competing QoS metrics, QAR specifies a utility function, as shown in Equation (10).

$$U(P) = w_d \,.\, \hat{D}(P) + w_b \,.\, \hat{B}(P) + w_r \,.\, \hat{R}(P) + w_l \,.\, \hat{L}(P) \qquad (10)$$

Where w_d, w_b, w_r , w_l are weighting coefficients such that,

$\sum wi = 1$, and $(\hat{\cdot})$ denotes normalized metrics.

$\hat{L}(P)$ is the normalized stability of links based on LET values. This utility formulation will enable flexible prioritization of QoS goals based on the mission's needs.

The utility is a synthesis of normalized QoS metrics with weight variables, thus allowing the routing mechanism to compromise among different performance variables as required by the mission requirements. For delay-sensitive traffic, priority should be given to latency, and reliability-critical flows can focus on successful packet delivery [20, 23].

Such a formulation of utility transforms the routing from a selection process to an optimization problem. It is scalable, flexible, and extensible, meaning that even when operation changes are required, QAR does not require re-architecture work of the routing logic.

3.6. QoS-Aware Routing Algorithm

The QAR algorithm enforces application-specific Quality of Service constraints and optimizes routing decisions in an extremely dynamic FANET. QAR is a routing protocol that contrasts with other, more conservative protocols, such as hop-count and earliest-reply routing; it incorporates constraint checking and utility-based routing to ensure chosen paths meet the QoS requirements of mission-critical UAV applications.

During the route discovery stage, the source node begins a directed search along possible paths to the destination node. For each discovered path P, QAR approximates the end-to-end delay, available bandwidth, and reliability using the QoS metric models in Section 3.4. The estimates are then compared with the QoS requirement vector for the active flow. Paths that violate one of the QoS constraints in Equation (6) are immediately discarded. The early pruning mechanism avoids infeasible routes, thereby minimizing control overhead and avoiding unnecessary resource consumption.

For QoS-feasible paths, QAR uses a composite utility measure to represent a route's overall suitability. The utility function in Equation (10) combines normalized QoS measures with tuned predictors of link stability, weighted. Metric normalization can be used to make fair comparisons between parameters that are not comparable, and weighting can be used to shape routing behaviour to align with mission priorities, such as delay-sensitive surveillance traffic or command-and-control flows that are more reliability-critical.

The utility function is maximized to determine the ideal routing path, as described in Equation (11).

$$P^* = \arg\max_P U(P) \quad (11)$$

This optimization step will ensure that the chosen route provides the best trade-off between competing QoS goals and meets application-level constraints. With the determination of the optimal path, the transmission propagated along the ideal path P^*.

Routes are further reviewed on a periodic basis to report changes in mobility and connectivity conditions. This route-assignment-based dynamic routing guarantees routing stability and evenly distributed QoS in dynamic FANETs [22, 23].

QAR continuously monitors QoS and link stability along the current route to handle topological differences caused by mobility. The routing process is proactively restarted (when a degradation in QoS is identified or the lifetime of the links is estimated to be below a defined threshold), and it once again employs the constraint-based utility-driven selection mechanism. Such adaptive behaviour guarantees a low rate of route failures and packet losses, and a predictable Quality of service in dynamic FANET platforms.

An overview of the overall operating processes of the proposed QoS-Aware Routing mechanism is presented in Algorithm 1.

Algorithm 1: QoS-Aware Routing

Input:
- Time-varying network graph G(t) = (V, E(t))
- Source node s, destination node d
- QoS requirement vector Q_f = $\{D_f^{max}, B_f^{min}, R_f^{min}\}$
- Weight vector W = $\{w_d, w_b, w_r, w_l\}$

Output : QoS-optimal routing path P^*.

Algorithm:
1. Initialize candidate path set $C \leftarrow \emptyset$.
2. Discover candidate paths P_k from s to d using controlled route exploration
3. For each candidate path P_k:
    - Estimate end-to-end delay D(P_k) using Equation (7)
    - Estimate available bandwidth B(P_k) using Equation (8)
    - Estimate path reliability R(P_k) using Equation (9)
    - Compute average link stability L(P_k) from link expiration time estimates
4. If D(P_k) ≤ D_f^{max} and
   B(P_k) ≥ B_f^{min} and
   R(P_k) ≥ R_f^{min}:
    - Add P_k to a feasible path set C.
5. Normalize QoS metrics for all paths in C
6. Compute utility U(P_k) for each $P_k \in$C using Equation (10)
7. Select optimal path :
   $P^* = \arg\max_P U(P)$
8. Establish data transmission along P^*
9. Periodically reevaluate QoS metrics and link stability; trigger rerouting if QoS violation is detected.
10. Return P^*

3.6.1. Time Complexity Analysis of QAR

The computational characteristics of the proposed QAR algorithm depend primarily on the number of candidate paths searched during route finding and on the assessment of QoS indicators assigned to each path. Let N=|V| denote the number of UAV nodes and E = |E(t)| represent the number of active wireless links in the network at a given time.QAR uses controlled exploration during the route-discovery stage, as in on-demand routing protocols, resulting in worst-case path-discovery complexity of O(E). For each possible path P_k, the algorithm calculates end-to-end delay, bandwidth, reliability, and connection stability using per-hop measurements. Assuming H is the average number of hops per path, the cost of estimating the QoS metric is O(H) per path.

Assuming K candidate paths are discovered, the total cost of QoS constraint checking and utility computation is O(K·H). Since H ≪ NH in typical FANET scenarios and infeasible paths are pruned early using constraint-based filtering, the effective number of paths evaluated remains limited. Consequently, the overall time complexity of QAR is given in Equation (12).

$$O(E+K \cdot H) \quad (12)$$

In practice, this is as complex as current QoS-aware on-demand routing protocols and offers improved routing stability and QoS performance. In addition, the proactive route's re-evaluation mechanism is periodic, rerouting only when QoS degrades, thereby keeping computational overhead manageable on resource-constrained UAVs.

3.7. QAR Framework

Figure 1 shows the QAR scheme, which provides an architectural implementation of Algorithm 1 by associating each routing operation with a specific functional block. The QoS Monitoring and Metric Estimation module provides per-path computations based on the definition of the steps as given in Equations (7)-(9). Real-time measurements determine delay, bandwidth, packet delivery properties, and link stability. Mobility-aware link prediction is presented in Section 3.2 and integrated into the Mobility and Link Dynamics stage to provide stability-conscious inputs to the routing stage.

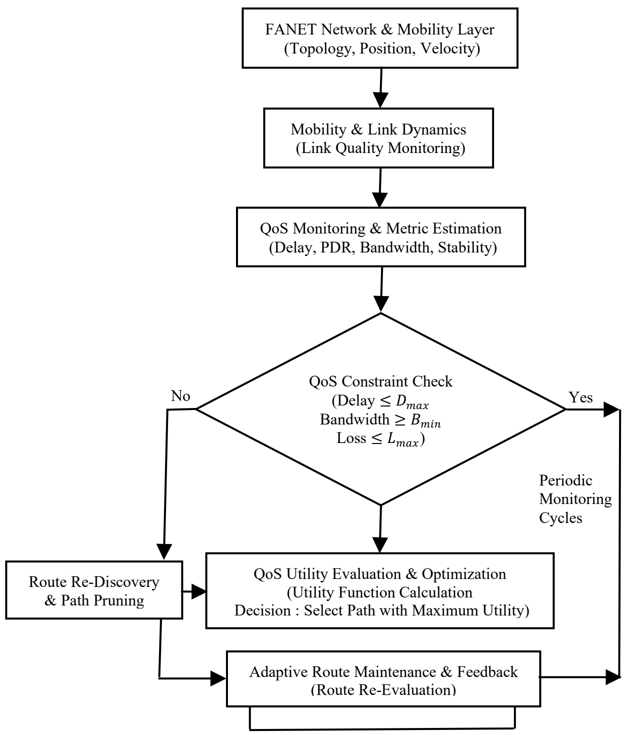

Fig. 1 Framework of QAR

The QoS Constraint Check implements the feasibility conditions in Equation (6) and accepts a path only if it meets application-specific thresholds. Infeasible routes trigger Route Rediscovery and Path Pruning. On the other hand, the utility-based formulation measures the compatibility of applicants. Selected according to the optimized rule of Equation (11) and (10) as well. The Adaptive Route Maintenance module achieves closed-loop adaptation using two feedback loops: An event-based QoS compliance loop and a periodic loop. This algorithmic logic level, being tightly integrated with architectural features, enables efficient decision-making and long-term QoS-based performance in highly dynamic FANET environments.

Meanwhile, the energy function assesses the candidate's feasibility. Selection is made based on the optimization criterion in Equation (10) and Equation (11) as well. The adaptive Route Maintenance module ensures closed-loop adaptation with feedback through two loops, an event-driven QoS compliance loop and a periodic loop. This strong degree of alignment between the logic of the algorithm and architectural elements allows innovative long-term decision making and QoS performance under aggressive and highly dynamic FANET conditions.

3.8. Computational Complexity Analysis of QAR

The QoS Constraint Check enforces the feasibility conditions of Equation (6), allowing only paths that satisfy.

Let |V| denote UAV nodes, |E| active links, K feasible candidate paths, and H the average hop count. Periodic beacon exchange and link monitoring incur.

$$O(|E|)$$

per update interval. Constrained route discovery performs QoS-aware exploration with early pruning, bounded by

$$O(|E|\log|V|)$$

For each candidate path P_k, aggregated QoS metrics are computed as

$$D(P_k) = \sum_{i=1}^{H} d_i,\ B(P_k) = \min_i b_i,\ R(P_k) = \prod_{i=1}^{H} r_i,\ L(P_k) = \frac{1}{H}\sum_{i=1}^{H} l_i \tag{13}$$

yielding a per-path cost of $O(H)$. Total evaluation complexity, therefore, becomes (O(KH).

The overall worst-case complexity of QAR is

$$O(|E|\log|V|+KH) \tag{14}$$

which remains comparable to constrained on-demand routing while benefiting from event-driven re-evaluation triggered only by QoS degradation.

3.9. Weighting Factor Selection and Parameter Tuning

The QAR utility function employs normalized weights.

$$w_d + w_b + w_r + w_l = 1, w_d \geq 0 \tag{15}$$

Where w_d, w_b, w_r, w_l correspond to delay, bandwidth, reliability, and stability.

Weights influence the ranking only, since feasibility is enforced separately via Equation (6). The optimized path is selected as follows.

$$P^* = \arg \max_{P_k \in P_J} U(P_k) \quad (16)$$

Parameter tuning follows simulation-based sensitivity analysis:

$$\Delta U = \frac{\partial \text{U}}{\partial \omega_i} \quad (17)$$

Where weight configurations maximizing average utility while maintaining fairness are selected. Mobility-intensive scenarios increase w_l, whereas latency-critical traffic prioritizes w_d and w_r. This separation between constraint filtering and weight tuning prevents infeasible routes from being selected under any configuration.

3.10. Alignment of Simulation Metrics with the QoS Utility Function

Simulation evaluation directly reflects the utility formulation

$$\text{U(P)} = w_d \,.\, \widehat{D}(P) + w_b \,.\, \hat{B}(P) + w_r \,.\, \hat{R}(P) + w_l \,.\, \hat{L}(P) \quad (10)$$

Measured metrics are mapped as

$$\widehat{D}(P) = \frac{D_{max} - D_P}{D_{max}}, \hat{B}(P) = \frac{B(P)}{B_{max}}, \hat{R}(P) = \text{R(P)}, \hat{L}(P) = \frac{L(P)}{L_{max}} \quad (18)$$

This one-to-one correspondence ensures that improvements in packet delivery ratio, throughput, and route lifetime directly translate into increases in routing utility, enabling a fair comparison with baseline protocols.

3.11. Feasibility and Optimality Analysis

3.11.1. Feasibility

Let P_f denote the feasible path set:

$$P_f = \{P_k \mid D(P_k) \leq D_{max}, \text{B}(P_k) \geq B_{min}, \text{R}(P_k) \geq R_{min} \quad (19)$$

Since all infeasible paths are removed prior to optimization, every selected route satisfies minimum QoS guarantees.

3.11.2. Optimality

Within P_f, QAR solves

$$\max_{P_k \in P_J} U(P_k) \quad (20)$$

Obtaining a Pareto-optimal objective with the given weights.

Due to the dynamic topology, full optimality at the subsequent state is no longer guaranteed; instead, the figure shows event-based QoS feedback processing and a periodic monitoring loop. 1 allows convergence very close to optimality during routing decisions at each new epoch.

4. Simulation Settings

The performance of the QAR in extremely dynamic FANET scenarios was verified by simulation on a discrete-event network simulator. The objective of the simulation study is to evaluate the extent to which QoS constraint enforcement, mobility-aware link stability estimation, and adaptive utility-based route selection improve network performance compared with conventional FANET routing protocols.

The simulator is set up to resemble a real-world UAV swarm scenario: each node in the network must be initialized and all collection/disbursement points are pre-set, but beyond that they take decisions entirely based on their local environment. Particular consideration is given to the evaluation of delay, throughput packet delivery ratio and routing stability associated with these indices which are closely related to the QoS utility formulation in Section 3.

The experimental methodology is repeatable and fair in the sense that all compared protocols are assumed to employ the same mobility patterns, traffic load and radio configurations.

4.1. Simulation Environment

The QAR scheme is implemented in the NS-3 simulator that closely approximates wireless channel capacity, mobility and interactions at the protocol level. The nodes of the aerial network are used to model two or three-dimensional operating scenarios for UAV-based networking tasks such as surveillance, disaster monitoring and cooperative sensing.

Node mobility is defined according to a realistic aerial motion model that includes constant-velocity variability, as well as adjustments in direction, thus emulating the nature of UAV flight. The uplink of all the UAVs adopts wireless communication following the IEEE 802.11S standard (with multi-hop packet forwarding). Path loss interference and stochastic signal variations in the physical layer model the dynamic fluctuations of link quality, which is common for airborne networks.

Application profiles such as CBR(VR) are applied to create traffic flows related to latency-sensitive control messages or high-bandwidth multimedia data streams. This mixed-traffic environment enables us to test how QAR behaves under varying service demands to maintain QoS.

All results are reported by averaging multiple random seeds to support statistical significance. An independent average is performed to combine performance measurements, thereby reducing bias related to transient topology conditions.

4.2. Simulation Parameters

The simulation conditions are chosen to cover those of the moderate-scale FANET deployments, and it is not too computationally expensive or cost-effective. The number of nodes, node mobility, transmission range and traffic load are chosen so that routing disruptions and QoS fluctuations occur very often in the network, which gives a harsh testbed for the proposed routing strategy.

Simulation parameters, including the number of UAVs, network dimensions, mobility speed, transmission power, packet generation rate, and QoS thresholds defined in Section 3, directly influence route discovery complexity, link stability estimation, and the utility-based routing decisions performed by QAR.

The weights of the utility function are consistent with the normalization.

$$w_d + w_b + w_r + w_l = 1 \quad (15)$$

Where w_d, w_b, w_r, w_l denote the importance of delay, bandwidth, reliability, and link stability, respectively. A preliminary sensitivity analysis is employed to adjust parameter settings accordingly to achieve satisfactory power across QoS objectives. The simulation duration will be sufficiently long to allow multiple route-setting and rerouting cycles to drive the evolution of steady-state network dynamics. Adjustment of periodic monitoring intervals is included in the Algorithm 1 to rectify the adaptive monitoring mode, and a timely route update is issued when QoS deteriorates. Overall, the chosen simulation parameters generate a controlled but challenging set-up to show the adaptive and QoS-oriented behavior of the proposed QAR framework that can be directly benchmarked against baseline routing protocols. The simulation parameters, namely Planck's and dark energy's properties, are listed in Table 2.

Table 2. Simulation setting

Parameter	Value	Description / Rationale
Simulation Tool	NS-3	Accurate PHY/MAC and mobility modelling for FANETs
Simulation Area	1000 x 1000 x 300 m³	Represents realistic aerial mission space
Number of UAV Nodes	|V|	50 - 500, Moderate-density FANET topology
Mobility Model	3D Random Waypoint / Gauss-Markov	Captures continuous UAV flight dynamics
UAV Speed	10–30 m/s	Reflects surveillance and monitoring missions
Transmission Range	200–250 m	Multi-hop aerial connectivity
MAC/PHY Standard	IEEE 802.11S	Widely adopted ad-hoc wireless interface
Traffic Type	CBR + Variable Rate	Mixed QoS traffic (control + multimedia)
Packet Size	512–1024 bytes	Balanced payload for delay and throughput analysis
Packet Rate	4–10 packets/s	Generates controllable network load
QoS Delay Threshold	D_{max}	Application-defined latency bound
Bandwidth Threshold	B_{min}	Minimum acceptable throughput
Reliability Threshold	R_{min}	Packet delivery requirement
Monitoring Interval	1–2 s	Matches adaptive rerouting cycle
Simulation Time	600–900 s	Ensures steady-state observation
Utility Weights	w_d, w_b, w_r, w_l	Normalized weights $\sum w_i = 1$

To maintain strict consistency between routing objectives and performance evaluation, all measured simulation metrics are directly mapped to the QoS utility formulation defined in Equation (10). The observed end-to-end delay contributes to the normalised delay component $\widehat{D}(P)$, while measured throughput determines the bandwidth term $\widehat{B}(P)$. Packet delivery statistics are used to derive the reliability metric $\widehat{R}(P)$, and link duration combined with signal variation estimates the stability component $\widehat{L}(P)$. As a result, this measured performance improvement corresponds to the maximization of the utility function.

$$\mathrm{U(P)} = w_d \cdot \widehat{D}(P) + w_b \cdot \widehat{B}(P) + w_r \cdot \widehat{R}(P) + w_l \cdot \widehat{L}(P) \quad (10)$$

Ensures that outcomes of the simulation stay consistent with the routing logic defined in Algorithm 1 and the overall QAR framework. To compare the performances of the routing protocols in an unbiased and equitable manner, the same quality of service requirements is applied to each one.

4.3. Performance Metrics

The performance of the proposed QAR framework is assessed using performance metrics that directly correspond to the utility function defined in Equation (10). This evaluation methodology establishes a clear relationship between the routing objectives and the observed simulation results, thereby enabling a consistent assessment of QoS-aware routing performance.

4.3.1. End-to-End Delay

End-to-end delay is the average duration it takes a data packet to reach the destination UAV from the source UAV. It includes the transmission, propagation, queuing, and processing times for all hops in between. In this measure, it is directly proportional to the normalized delay component \hat{D}\left(P\right) of Equation (10). It has detrimental importance for delay sensitive FANET applications such as real-time surveillance and command-and-control communication.

4.3.2. Throughput

Throughput is the average amount of data that can be delivered per second across the network, in units of kbits or Mbits per second. It is the optimal allocation of bandwidth along the selected routing paths and is equal to the normalised bandwidth factor \hat{B}\left(P\right) in the QAR utility function. Throughput is used as an indicator of effective use of the resources and a consistent path selection under dynamically changing link conditions.

4.3.3. Packet Delivery Ratio

Packet Delivery Ratio (PDR) measures the proportion of data packets successfully received at the destination relative to the total number transmitted by the source. This metric reflects the reliability of the routing protocol in maintaining successful end-to-end communication under dynamic network conditions. PDR is used as a reliability measure and is directly proportional to the normalized reliability measure $\hat{R}(P)$ in Equation (10). This measurement is crucial in mission-critical FANET systems, where good communication reliability is required during mobility-induced disturbances.

4.3.4. Link Stability

The average route lifetime is used to gauge the stability of links between two points, defined as the expected duration over which a selected routing path can be used without rerouting. This measure quantifies the success of mobility-sensitive link selection and equals the normalized link stability measure $\hat{L}(P)$, based on estimates of the link expiration time. Increased route lifetime implies greater resistance to UAV mobility and reduced routing overhead.

4.3.5. Routing Overhead

Routing overhead is the sum of control packets sent during the simulation, divided by the number of data packets successfully transmitted. This metric, though not explicitly given in Equation (10), provides insight into how efficiently and at scale QAR compares with the baseline protocols, particularly under high-mobility and dense-network conditions. The evaluation framework will ensure that the benefits of simulation measurements are directly attributable to the QoS-conscious optimization approach used by QAR, rather than to irrelevant protocol actions.

4.4. Baseline Protocols for Performance Comparison

The performance of the proposed QAR protocol is described in terms of the subset of metrics directly correlated with utility function defined by Equation (10). This estimate is reasonable as the simulated routing goal corresponds to the QAR routing also. It provides a reasonable estimation of QoS-aware selection.

4.4.1. AODV

AODV is an established reactive routing protocol that creates routes on demand; the key optimization parameter is hop count. Although AODV has low control overhead under light traffic conditions, it lacks explicit support for QoS constraints and mobility prediction. It can therefore be easily broken by routes and interfered with in severely dynamic FANET operations. AODV is used to establish a baseline for the advantages of QoS and mobility-sensitive routing decisions.

4.4.2. OLSR

OLSR is an active routing protocol that disseminates routing information to all nodes by periodically broadcasting topology details via multipoint relays. Although OLSR achieves low route-discovery latency, it performs poorly in FANETs due to excessive control overhead and outdated topology under rapid mobility. OLSR is also incorporated to assist the trade-off between proactive routing and adaptive QoS-sensitive decision-making.

4.4.3. QoS-AODV

QoS-AODV is an extension of AODV that adds QoS parameters, such as bandwidth and delay, to the route discovery process. Whereas QoS-AODV can enhance service differentiation relative to AODV, it is usually based on static, single-metric constraints and does not account for service link stability or predictive mobility modelling. The comparison between QAR and QoS-AODV demonstrates the benefits of multi-metric utility maximization and stability awareness based on link expiration time. Adoption of these base-line protocols can ensure an equitable and comprehensive assessment for QAR in reactive, proactive, and QoS extended paths. The comparison of the performance is conducted considering QoS satisfaction, route stability, and adaptation with dynamic FANET conditions that are justified through design choices and premises in analysis within the presented framework for QAR.

5. Results and Discussion

This section compares the efficiency of the proposed QAR framework under highly dynamic FANET conditions in the simulated environment described in Section 4. The analysis considers routing decisions based on the QoS utility in Equation (10), which affects network performance through link delay, throughput, reliability, and stability. QAR is compared against representative baseline protocols, such as

AODV, OLSR, and QoS-AODV, to evaluate its advances in QoS and route robustness. All results are obtained under the same mobility patterns and traffic conditions to ensure fair and consistent comparison. The analysis presented here is based on a multi-metric optimisation approach to QAR, in contrast to the traditional assessment, which analyses performance levels separately. Each realized performance gain is thus associated with the constraint-based path selection and utility-based decision-making proposed in Section 3. The method would enable direct validation of the proposed framework's design objectives.

5.1. End-to-End Delay Analysis

An end-to-end delay is a key performance metric in FANET systems, particularly for mission-critical information such as control signals and situational awareness feedback. Another QAR method is the elimination of delay-violating routes, which are reported as early as possible during the QoS constraint evaluation phase, and thereafter, utility-based path selection, in which congestion-free links are prioritized over delay-inducing links. In contrast to common reactive protocols that rely solely on hop count or route-discovery freshness, QAR uses predictive link stability to minimize route disjuncture without increasing retransmission latency. This reduction in delay is based on two principal design aspects. First, the mobility-sensitive stability estimator eliminates frequent path discontinuities, thereby avoiding repeated route recovery. Second, the normalized delay component in the equation. The scenario in Equation (10) discourages the use of routes with variable bandwidth, which generally cause queuing delays in crowded aerial systems. Although AODV exhibits visible delay spikes during route rediscovery, OLSR incurs higher control overhead at high node density, whereas QAR maintains constant latency as mobility increases. This action demonstrates that applying QoS measurement and predictive routing decisions stabilizes communication delays under changing topologies.

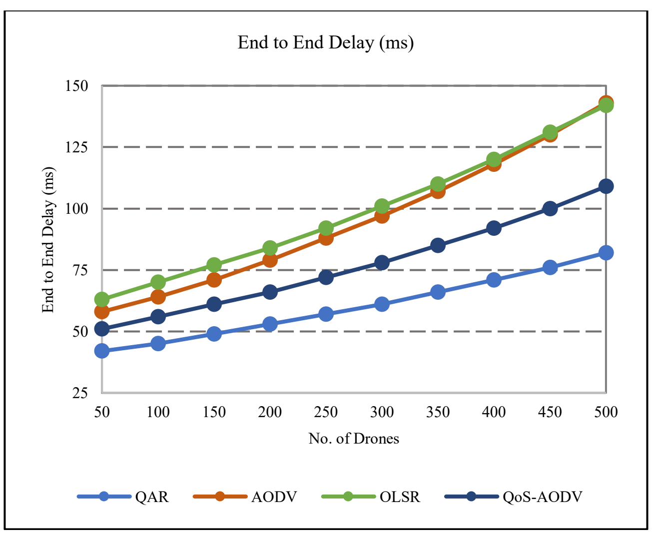

Fig. 2 End-to-End Delay

Table 3. End-to-End delay

End-to-End delay (ms)				
Drones	**QAR**	**AODV**	**OLSR**	**QoS-AODV**
50	42.00	58.00	63.00	51.00
100	45.00	64.00	70.00	56.00
150	49.00	71.00	77.00	61.00
200	53.00	79.00	84.00	66.00
250	57.00	88.00	92.00	72.00
300	61.00	97.00	101.00	78.00
350	66.00	107.00	110.00	85.00
400	71.00	118.00	120.00	92.00
450	76.00	130.00	131.00	100.00
500	82.00	143.00	142.00	109.00
Average	60.20	95.50	99.00	77.00

Figure 2, titled “End-to-End Delay” under Varying UAV Density, plots the number of UAV nodes on the X-axis and the measured latency on the Y-axis. Both routing protocols exhibit higher delay as the network size increases from 50 to 500 UAVs, respectively, and all protocols exhibit higher contention, longer queueing delays, and more frequent topology changes. AODV experiences the largest initial increase in latency because it uses repeated route discovery in response to network contact failures. OLSR exhibits comparably stable delay up to moderate densities, but experiences congestion due to proactive topology updates in dense cases. QoS-AODV exhibits better latency performance by supporting simple QoS requirements, but it is not predictably stable-aware.

The proposed QAR framework has the lowest delay across all densities because it removes infeasible paths during QoS-constrained effectiveness enumeration and prioritizes stable links during link utility assessment. Mobility-aware link stability estimation integrates mobility information to minimize route interruptions and, hence, retransmissions and buffering delays.

The results in Table 3 and Figure 2 indicate that QAR consistently maintains the lowest latency across all evaluated UAV densities, demonstrating its effectiveness in highly dynamic FANET environments.

5.2. Packet Delivery Ratio (PDR)

Packet Delivery Ratio is a measure of data delivery reliability and is directly proportional to the reliability term in the QAR utility function. The proposed framework improves delivery performance by blocking unreliable paths and using QoS to enforce and guarantee link quality. QAR also focuses on routes that are less vulnerable to impromptu disconnections by linking, as well as on estimating route expiration and incorporating reliability weighting into the routing decision process. The findings reveal that QAR has a consistently higher PDR than baseline protocols, particularly when UAV mobility is higher. The conventional AODV suffers from packet loss during route breaks because new paths are established only after failure. The connectivity of OLSR is relatively stable; however, if topology changes exceed its update period, connectivity is lost.

QoS-AODV enhances reliability by performing rudimentary QoS tests but lacks predictive mobility awareness and consequently causes moderate packet loss under high-mobility conditions. QAR, on the other hand, predicts link degradation and reroutes, and pre-emptively recalculates links ahead of failures. This futuristic action reduces retransmission rates and ensures that a large number of packets traverse effective transmission paths, thereby enhancing delivery success.

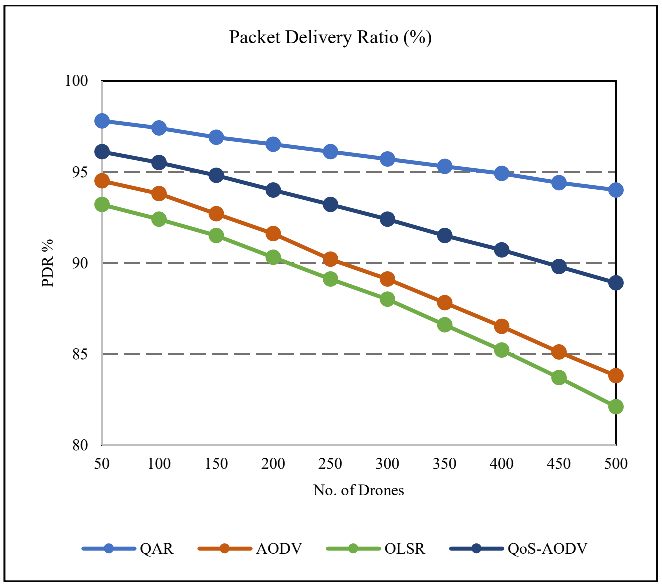

Fig. 3 Packet delivery ratio

Table 4. Packet delivery ratio

Packet Delivery Ratio (PDR, %)				
Drones	**QAR**	**AODV**	**OLSR**	**QoS-AODV**
50	97.80	94.50	93.20	96.10
100	97.40	93.80	92.40	95.50
150	96.90	92.70	91.50	94.80
200	96.50	91.60	90.30	94.00
250	96.10	90.20	89.10	93.20
300	95.70	89.10	88.00	92.40
350	95.30	87.80	86.60	91.50
400	94.90	86.50	85.20	90.70
450	94.40	85.10	83.70	89.80
500	94.00	83.80	82.10	88.90
Average	95.90	89.51	88.21	92.69

Figure 3, "Packet Delivery Ratio (PDR)" at Dense UAVs shows the density of UAV nodes on the X axis and the percentage of successfully delivered packets on the Y-axis. At high UAV density, all the protocols show performance degradation in PDR as a result of congestion, high collision rate factors, and due to mobility-induced link failures. AODV declines the most due to the higher packet loss ratio after rediscovery following corrupted route tables. OLSR works well at low and moderate densities, whereas high-density networks become congested due to control traffic. QoS-AODV improves delivery ratio through the use of constraint-based routing but does not predict mobility that affects its efficiency.

In contrast, QAR always outperforms all other in every situation. This strength is due to its combined QoS-aware feasibility filtering and utility-based route optimization, which prefer stable, low-risk routes.

Moreover, the adaptive monitoring willingness also reduces performance degradation by taking the proactive rerouting before link faults. As can be seen from Table 4 and Figure 3, the QAR is able to enhance the reliability effectively to achieve stable packet delivery even in dense aerial network.

5.3. Throughput

Throughput determines how well a network can deliver data and is the bandwidth term in this normalized utility formulation. QAR increases the network capacity by considering available bandwidth and link stability for determining a route, instead of relying on shortest path metrics only.

Further, the QoS feasibility stage makes sure that potential paths satisfy the minimum bandwidth requirement whereas in the utility optimization phase paths with sustained channel quality are given higher priority. QAR reveals from simulation results that it achieves the maximum average throughput for all considered UAV densities.

The performance gain is even shown to be amplified under congestion, showing the effectiveness of adapting routing choice with respect to the detected congestion. AODV favors short paths which, however, are soon over-loaded with traffic leading to low end-to-end data rates. OLSR maintains the connection but suffers from control overhead which will consume channel capacity, especially when it is deployed in a dense network.

South QoS-AODV does not optimally trade off between bandwidth, delay and link stability even though it considers the bound of bandwidth. QAR's adaptive monitor system re-evaluates the status of the path and allows traffic to migrate onto better routes as channel quality differs. This on-the-fly policy adaptation maintains the same throughput even under changing FANET conditions.

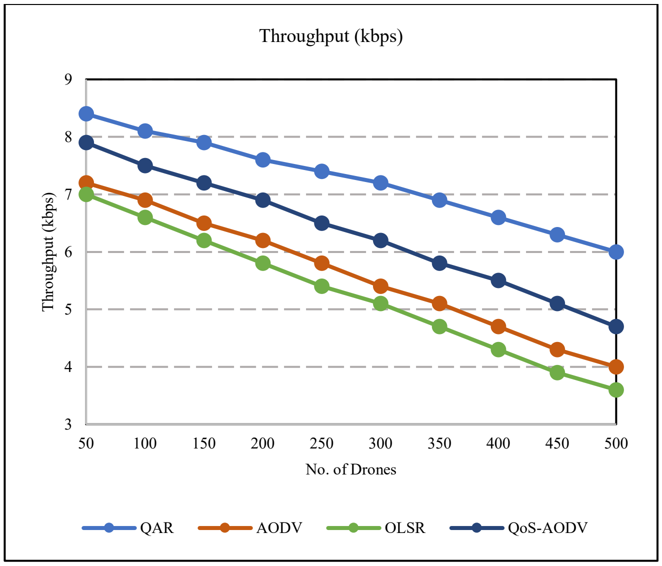

Fig. 4 Throughput

Table 5. Throughput

Throughput (kbps)				
Drones	**QAR**	**AODV**	**OLSR**	**QoS-AODV**
50	8.40	7.20	7.00	7.90
100	8.10	6.90	6.60	7.50
150	7.90	6.50	6.20	7.20
200	7.60	6.20	5.80	6.90
250	7.40	5.80	5.40	6.50
300	7.20	5.40	5.10	6.20
350	6.90	5.10	4.70	5.80
400	6.60	4.70	4.30	5.50
450	6.30	4.30	3.90	5.10
500	6.00	4.00	3.60	4.70
Average	7.24	5.61	5.26	6.33

In Figure 4 labelled as The Proportion of Nodes Versus Aggregation Data Rate, the network "throughput" is shown for different aggregation data rates. The throughput is increased as the UAV density goes up, and it rises and drops when channel contentions become serious. AODV is not throughput-scalable because of the delays and packet loss incurred in reactive route discovery due to changing topology. It has been observed that OLSR works fine when the network is sparsely populated, but throughput decreases in dense networks, where periodic control signaling needs a high bandwidth. QoS-AODV exhibits an improved performance by incorporating bandwidth constraints in route selection, but it does not adapt to the changes of link stability.

The QAR framework is highly scalable and can work on all network scales as it includes bandwidth aware- ness and reliability prediction in its multi-metric utility component. QAR will reduce the retransmission rate and will improve channel utilization efficiency by finding paths that respect QoS constraints while keeping link characteristics. Table 5 shows numerical values and trend graphs (presented in Figure 4) show Q AR gives constant throughput gains even under dynamic behavior of FANETs.

5.4. Link Stability and Route Lifetime Analysis

Another issue to be considered in FANET routing is that of stability as a consequence of the mobility of the UAVs. The presented model considers the expiration of links' lifetime within the routing algorithm itself, resulting in predicting possible changes in topology prior to them impacting data transfer. In the normalized link-stability measure, this condition is present as the denominator in Equation (10) and hence QAR can guide itself so that it may prefer routes with longer lifetime period.

The simulation results show that QAR also has higher number of route lifetime than AODV, OLSR and QoS-AODV as well. Reactive protocol like AODV often re-discover paths as they do not have a priori mobility information, resulting in extra control overhead and performance fluctuation. OLSR uses proactive topology information update mechanism, though the periodic updates will not be able to find out a high aerial speed, and resulted in unstable connections. The QoS-AODV incorporates the QoS checks, but directly issues a response only when there is an observed degradation.

The second phase of the process combines stability prediction with QoS feasibility filtering in developing a procedure for ensuring that the chosen paths are stable and durable. The reduced rate of route breaks results in larger delay, delivery ratio and throughput obtained in above sections.

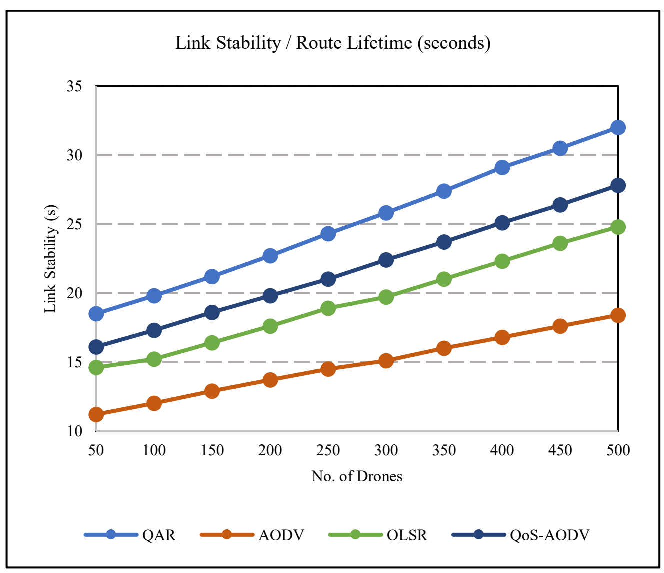

Fig. 5 Link stability (seconds)

Table 6. Link stability

Link Stability / Route Lifetime (seconds)				
Drones	**QAR**	**AODV**	**OLSR**	**QoS-AODV**
50	18.50	11.20	14.60	16.10
100	19.80	12.00	15.20	17.30
150	21.20	12.90	16.40	18.60
200	22.70	13.70	17.60	19.80
250	24.30	14.50	18.90	21.00
300	25.80	15.10	19.70	22.40
350	27.40	16.00	21.00	23.70
400	29.10	16.80	22.30	25.10
450	30.50	17.60	23.60	26.40
500	32.00	18.40	24.80	27.80
Average	25.13	14.82	19.41	21.82

Depicted in Figure 5 under the heading "Link Stability / Route Lifetime" is the average lifetime of an active routing path, as a function of number of UAV nodes varying from 50 to 500 nodes. The x-axis is for, the counter of drones and y-axis for route lifetime in seconds. As network density increases, connectivity generally improves for all routing protocols due to the availability of additional communication links, though 17 distinct differences are visible.

In case of AODV, low route lifetime exists due to its frequent breaking linkages most of the times when mobility is high and moderate stability in OLSR lies because it uses updating topology periodically. QoS-AODV achieves improved route stability by filtering unreliable paths during route discovery. As shown in Table 6 and Figure 5, the QAR framework achieves the highest average link stability across all evaluated UAV densities. This improvement is due to the link prediction based on mobility and utility-driven path selection that preferentially selects routes with a higher expected lifetime. The results support that QAR creates stronger communication links than existing routing schemes, and hence being suitable to dynamic FANETs.

5.5. Routing Overhead

Routing overhead is the amount of control signaling required to establish, maintain, and rebuild routes when they fail. In FANETs, where high dynamism is prevalent, increased control traffic reduces available bandwidth for data traffic and intensifies channel competition. Under the QAR architecture, routing overhead is reduced by predictively estimating link stability and maintaining adjustable per-event monitoring, thereby limiting redundant route rediscovery. QAR relies less on scheduled updates and more on periodic updates or on reacting to flooding; instead, it selectively reevaluates when either QoS deterioration or anticipated unstable links are identified. This decrease in overhead is attributable to the two architectural features introduced in Section 3. The first is enforcing QoS constraints to prevent the routing process from selecting unreliable paths, thereby avoiding repeated control broadcasts caused by path failures. Second, the utility-based decision engine will prioritize long-lived routes, thereby reducing topology updates and route maintenance activities.

Reactive routing in AODV creates significant signalling overhead because route discovery is triggered repeatedly in high-mobility scenarios. OLSR incurs relatively steady overhead from proactive hello and topology-control messages, but periodic signalling becomes more expensive as UAV density increases. QoS-AODV authenticates redundant broadcasts using QoS filtering, but it employs reactive recovery once degradation has already occurred. On the other hand, QAR scales responsiveness to overhead efficiency through predictive mobility analysis coupled with constraint-based optimization, achieving scalable overheads.

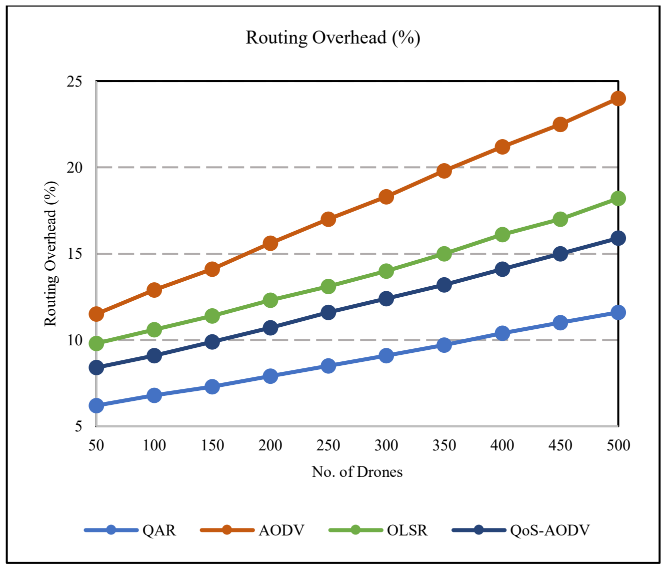

Fig. 6 Routing overhead

Table 7. Routing overhead

Routing Overhead (%)				
Drones	**QAR**	**AODV**	**OLSR**	**QoS-AODV**
50	6.20	11.50	9.80	8.40
100	6.80	12.90	10.60	9.10
150	7.30	14.10	11.40	9.90
200	7.90	15.60	12.30	10.70
250	8.50	17.00	13.10	11.60
300	9.10	18.30	14.00	12.40
350	9.70	19.80	15.00	13.20
400	10.40	21.20	16.10	14.10
450	11.00	22.50	17.00	15.00
500	11.60	24.00	18.20	15.90
Average	8.85	17.69	13.75	12.03

Figure 6, titled "Routing Overhead", in the increasing UAV Density, shows how the network size relates to the normalized control traffic. The first is the X-axis, which depicts the status of UAV nodes (50-500), and the second is the Y-axis, which depicts the routing overhead as a percentage of the total packets relayed. Node density increases overhead across all protocols due to increased topology changes and contention. The steepest increase is observed in AODV, owing to repeated route discovery, which causes substantial broadcast traffic. OLSR has a constant but substantial overhead due to periodic topology dissemination. QoS-AODV yields a moderate improvement by filtering infeasible paths. The presentation of the proposed QAR framework shows the greatest decrease in overhead across all densities, confirming that predictive link monitoring and adaptive rerouting reduce unnecessary signalling. The findings in Table 7 and Figure 6 confirm that QAR is more scalable and achieves high QoS performance under dense FANET deployments.

5.6. Comparative Performance Discussion

As indicated by experimental results presented in Table 3-7 and Figure 2-6, the proposed QAR framework consistently enhances the performance of network for all evaluated QoS metrics values. The QAR unifies mobility-aware link stability prediction, utility-driven route selection and QoS feasibility verification in one routing strategy, rather than optimizing a single routing objective. This combination allows to achieve a balance of performance in the considered FANET for highly dynamic environment, taking into account delay, bandwidth, reliability, as well as route stability.

The "Comparative Evaluation" section emphasizes the drawbacks of the base routing protocols with dense networks. AODV has significant performance degradation due to the reactive route discovery feature that only rebuilds routes after a link failure. Therefore, the more mobile the UAVs are, the higher the Packet Delay, Packet Delivery, lower Throughput, route lifetime, and routing overhead. OLSR is able to keep the network connected by sending out topology updates periodically, but the extra control messages do take up network resources and limit scalability in dense aerial networks. QoS-AODV have incorporated QoS constraints to improve route selection but, it is still dependent on static constraint evaluation without any predictive mobility awareness which hinders to maintain stable communication in such a rapidly changing network.

The enhanced performance of QAR is due to the path establishment strategy used. To cut down on the number of initial candidate routes, the routes are checked against pre-defined QoS requirements, removing those that don't meet application requirements before route optimization starts. For the rest of the feasible options, the utility function given in Equation (10) chooses routes which can offer good compromise between delay, available bandwidth, reliability and expected link lifetime. The two-stage decision process helps to decrease the likelihood of choosing unstable routes, and allows for communications to remain stable even with growing UAV density and mobility.

Additionally, the performance measures are very interdependent. Due to stable communication links, the number of failures on a route and retransmissions are reduced, which leads to reduced end-to-end delay and better packet delivery. A higher delivery success rate leads to improved throughput because of the efficient usage of channel resources, while longer routes will also lead to a reduction in repeated route discovery and hence routing overhead. The results show that QAR brings about improvements that are not just in one dimension or another, but in the combined performance of various routing objectives.

The comparative study shows that QAR is a good QoS based routing solution for highly dynamic FANET environments. It is seen that the QoS-aware route validation with utility-based optimisation and predictive mobility awareness technique successfully obtained desirable and consistent results for all the evaluated scenarios overcame few of the drawbacks of using existing FANET routing protocols.

5.6.1. Performance Improvements over Existing Techniques

The comparative evaluation shows that QAR always outperforms typical FANET routing protocols such as AODV, OLSR and QoS-AODV. QAR combines QoS constraint verification, link stability estimation based on mobility, and utility-based route selection under a common routing framework, which is different from the traditional routing methods that optimize a few routing parameters. This holistic approach allows for simultaneous improvement in latency, reliability, throughput, route lifetime and routing overhead.

An important aspect that plays a part in this improvement is the enforcement of the QoS requirements during route discovery. On the contrary, QAR does not examine all of the available routes; it narrows down to potential routes that do not meet set delay, bandwidth or reliability thresholds. Unlike the conventional routing protocols, this is a pre-feasibility test that helps eliminate routes from the optimisation process that would otherwise be unsuitable. reduces the communication delay while increases the packet delivery performance.

Utility driven routing adds to the performance. Instead of using the smallest hops or just one optimisation metric, all possible routes are considered in QAR and the multi-metric utility formulation of Equation (10) is used. The delay, bandwidth, reliability, and stability of the links can be taken into account simultaneously, enabling the framework to identify the routes that achieve a balance of network performance at continually varying operating conditions. Hence the throughput is less sensitive to the increasing network density and UAV mobility. Another benefit of QAR is its link stability estimation, which is mobile-aware.

Traditional routing protocols typically start routing recovery operations when the quality of the communication has degraded or a link has broken down. QAR implies prediction of link lifetime to the routing process, which is able to predict the deterioration of route before the communication is suspended. In case of choosing longer routes, route reconstruction is less frequent, routing overhead is reduced and communication continuity is improved. This enhances the routes' stability as well, which leads to reduced delay, higher packet delivery, and better throughput due to fewer transmissions. Compared to the state-of-the-art QoS-aware FANET routing techniques reported in the literature, QAR adopts a more complete routing approach, integrating QoS feasibility enforcement, utility-based optimisation and predictive mobility awareness within the same decision framework. The improvements that have been noticed in all the metrics from delay to PDR, from throughput to link stability and from routing overhead to routing control itself are not gains of optimising individual metrics, but are obtained by the coordinated multi-metric optimisation. The outcomes shown in these results confirm the efficiency of the suggested framework, and prove its appropriation for the next generation of FANET applications, which are based on reliable, scalable, and QoS-aware communication.

Table 8. Relationship between QAR design components and performance improvements

QAR Component	Functional Role	Performance Impact
QoS Constraint Enforcement	Eliminates infeasible routes	Lower delay, higher PDR
Utility-based Optimization	Multi-metric route selection	Higher throughput
Link Stability Prediction	Anticipates route degradation	Longer route lifetime
Adaptive Monitoring	Selective route maintenance	Lower routing overhead
Integrated Decision Framework	Joint QoS optimization	Overall network improvement

5.7. Scalability and Practical Deployment Analysis

The ability to scale is a fundamental requirement for the FANET routing protocols designed for the emerging applications like large UAV swarms, disaster management, intelligent surveillance and cooperative aerial sensing. As the network grows, the routing protocol should still ensure accurate routing with minimal delay, route control overhead, and route instability. This makes it important to estimate scalability both based on each individual QoS parameter but, also, on the possibility of maintaining a good network performance when nodes become dense. The simulation result for a network size ranging from 50 to 500 UAVs shows that as the number of UAVs in the network increases, the communication quality in the network remains stable when using QAR. Even with the higher level of channel contention, topology changes, and more complex routing, QAR experiences significantly lower end-to-end delay, higher packet delivery ratio, higher throughput, longer route lifetime, and lower routing overhead than AODV, OLSR and QoS-AODV. These results show that the performance benefits of the QAR are still consistent in both the small and the large-scale deployment of the FANET. The scalability observed is more or less related to the routing strategy used by QAR. Routes to be considered for optimisation are initially filtered based on Quality of Service requirements, excluding any sub-optimal routes from the optimisation process. Bandwidth availability, communication delay, reliability and predicted link stability are then taken into account through a multi-metric utility function, leaving the remaining viable routes. This two-step selection mechanism prevents unstable selection of paths and lowers the number of times a path should be reconstructed, as the network grows which keeps the routing mechanism efficient without adding too much control traffic or increasing the overhead on the route. QAR's traits also render it ideal for implementation of such mission-critical UAVs. Applications like disaster response, environment monitoring, intelligent transportation, border monitoring, emergency coordination and others demand reliable communications when topology constantly changes. In these cases, it is much more crucial to choose communication paths that are reliable and stable than to find the shortest path. QAR integrates the stability estimation and prediction of links with the selection of routes based on QoS information, which helps to maintain robust communication in rapidly changing aerial network conditions.

Section 4 also includes computational complexity analysis, which further shows that the routing algorithm remains a good computational performance as the network scales up. In combination with the simulation results, the proposed framework shows its capability in supporting the future large-scale UAV swarm networks that require scalable routing, reliable communication and QoS provisioning. The results of this research show the viability of QAR as a routing solution that is practical and scalable for next generation FANET environments.

Table 9. Summary of QAR advantages over baseline protocols

Metric	Primary QAR Mechanism	Observed Benefit
End-to-End Delay	QoS constraint filtering	Lower latency
Packet Delivery Ratio	Reliability-aware routing	Higher delivery success
Throughput	Bandwidth-aware utility optimization	Better channel utilization
Link Stability	Mobility-predictive estimation	Longer route lifetime
Routing Overhead	Adaptive rerouting	Reduced control traffic

6. Conclusion

The paper presented a QAR framework for addressing the problem of consistent communication in highly adaptable FANETs. The proposed framework integrates QoS enforcement with a multi-metric utility maximization approach, in contrast to classical routing techniques that consider only a single performance metric. By integrating delay, bandwidth, reliability, and mobility-aware link stability into a single decision-making process, QAR enables routing decisions that withstand rapid topology changes and an unstable wireless environment. The system model in Section 3 defines a mathematically grounded routing architecture in which feasibility checks filter the set of QoS-compliant paths to be considered, while utility maximization selects the most efficient route among the feasible solutions.

Predictive link-expiration modeling is also incorporated to improve routing stability by minimizing route breakage and control overhead. Algorithm 1 presents the integrated operation of constraint-based filtering and adaptive monitoring to ensure stable service quality without imposing an excessive computational burden, thereby enabling implementation in resource-constrained UAV systems.

The simulation results confirm that the proposed design is effective across varying UAV densities. QAR has been found to exhibit lower end-to-end delay, higher packet delivery ratio, higher throughput, longer route lifetime, and lower routing overhead than AODV, OLSR, and QoS-AODV. Such enhancements are directly related to the utility-driven routing logic and the proactive re-evaluation mechanism, which together enable stable communication even in highly dense, highly mobile aerial networks. The strong correlation between the formulation of the QoS utility and the performance measurements provides strong evidence that the proposed framework applies design principles to measurable network value. Overall, constraint-based routing requires multi-metric optimization to provide a scalable, efficient solution for QoS provisioning in FANETs. The future will also focus on extending the framework to support energy-conscious adaptation, lightweight trust provisioning for secure routing, and the edge-based real-time deployment of heterogeneous UAV swarms and edge-based network structures.

6.1. Open Research Issues

The proposed QAR framework can provide high-quality QoS and routing stability, but suffers from significant drawbacks. Future studies on the adaptive design of QoS weighting methods may incorporate mobility patterns and traffic load to update utility parameters, thereby reducing reliance on heuristic parameters. The most complex tasks are optimizing energy consumption and addressing reliability concerns for resource-constrained UAV ground stations. Moreover, QoS routing can be implemented with light security or a trust mechanism to counter attacks by insiders and malicious users. Scalability of ultra-dense UAV swarms, scalability testing using testbeds, and cross-layer integration should also be addressed in establishing viable FANET-based deployments.

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