Routing with Multi-Criteria QoS for Flying Ad-hoc Networks (FANETs)

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***Abstract*—Flying Ad-hoc Network (FANET) is a type of Ad-hoc network on backbone of Unmanned Aerial Vehicle (UAV). These networks are used for providing communication services in case of natural disasters. Dynamic changes in link quality and mobility distort the Quality of Service (QoS) for routing in FANETs. This work proposed a Multi Criteria QoS Optimal Routing (MCQOR) guided by prediction of link quality and three-dimensional (3D) movement of FANET nodes. The network is clustered based on prediction of movement of nodes. Over the clustered topology, routing path is selected in reactive manner with joint optimization of packet delivery ratio, delay, and network overhead. In addition, cross layer feedback is used to reduce the packet generation rate and congestion in network. Through simulation analysis, the proposed routing protocol is found to have 3.8% higher packet delivery ratio, 26% lower delay and 14% lower network overhead compared to existing works.**

Keywords—Flying ad-hoc Network; multi-criteria QoS; unmanned aerial vehicles; joint optimization

I. INTRODUCTION

FANET is a kind of ad-hoc network formed by Unmanned Aerial Vehicles (UAV). These UAVs are small sized, light weight flying nodes with dynamic speed and altitude. The network is characterized by frequency disconnections of links and partitioning of network. High-speed three-dimensional mobility introduces frequent link distortions in the network [1]. Unreliable packet delivery and high end to end latency are very common in FANET networks. Most traditional routing protocols designed for Mobile Ad-hoc Networks (MANETs) and Vehicular Ad-hoc Networks (VANETs) does not address the challenges in FANET. Challenges like flying in three dimensions, high mobility, low node density, rapid topology changes, unstable links, network partitioning and limited resources makes it difficult to achieve higher QoS in FANET [2].

The major factors to be considered in designing routing protocols for FANET are high mobility, unstable links, and low energy capacity of nodes. UAV nodes have greater mobility ranging from 30 to 460km/hour [3]. The higher mobility creates low link quality. Frequent link disconnections and network partitions increase route discovery and maintenance overhead [4]. The paths must be planned based on predicted positions of UAV to ensure higher packet delivery ratio and lower latency. Also packet collisions and congestion must be effectively controlled to ensure higher QoS. UAV nodes have limited energy and the routing protocols must not drain the energy faster. Depleting the energy faster can create network partitions and reduce the reliability of the network. Most existing routing protocols for FANET (detailed in Section II) does not address all these factors of high mobility, unstable links, and low energy capacity of nodes in designing multi criteria QoS optimal routing paths. The joint optimization of multiple QoS criteria like delivery ratio, delay and network overhead has not been considered in most of the existing FANET routing protocols. This work addresses these problems.

This work proposes a multi criteria QoS optimal routing protocol for FANET. The network is clustered to accommodate dynamic topology and unstable links. The clustering is done based on prediction of three-dimensional mobility of nodes. Over the clustered topology, geographic routing with next relay selection based on joint optimization of multi criteria is done. Cross layer feedback of network dynamics is used to dynamically adjust the source rate of packet generation. By this way congestion is reduced in the network.

A. Following are the Novel Contributions of this Work

1) A novel clustering topology for FANET based on prediction of three-dimensional mobility of UAV nodes. Many existing works have been proposed for clustering in FANET based on current mobility. Different from it, this work proposes a clustering topology with joint consideration of density and predicted mobility. Nodes with higher stability based predicted mobility is selected as cluster heads and network is clustered based on them.

2) A novel geographic routing with next hop relay selection based on joint optimization of multi criteria QoS factors. Compared to links state based routing protocols, the proposed geographic routing has lower overhead. Relay selection in proposed work is based on QoS considering both delay and link reliability compared to distance based relay selection is existing geographic routing protocols.

3) A novel source rate control based on probability function of delay distribution to vary the packet flow on the routing path adaptive to traffic and application characteristics. By this packet loss due to congestion is reduced and reliability of the routing path is increased.

The paper is organized as follows. Section II presents the survey of exiting routing protocols for FANET. Section III presents the proposed multi criteria QoS optimal routing protocol for FANET. Section IV presents the results of proposed routing protocol and its comparison to existing routing protocols. Section V presents the conclusion and scope of future research.

II. RELATED WORK

Lin et al. [5] proposed a shortest path routing algorithm based on grid position for FANET. Instead of Euclidean Distance, logical grid distance is used in route computation which is less sensitive to high mobility of UAV nodes. Adjacency relationship is constructed automatically, and Dijkstra's shortest path algorithm is used to construct the routing paths. Routing paths are further optimized using a region reconstruction strategy. The route selection considered link stability as the only criteria to be maximized. Xie et al. [6] proposed a new form of optimized link state routing protocol to handle dynamic topology changes in FANET. Link expiration time was predicted based on current position. The next hops were selected with higher link expiration time and higher residual energy. The network overhead to maintain the OLSR routing table is higher in this approach. Hou et al. [7] constructed OLSR routing table with trajectory prediction information of UAV. The optimal route is selected from OLSR using Q-learning. The approach considered link stability as the only criteria in route selection. Yang et al. [8] proposed a routing protocol for FANET using Q-learning and fuzzy logic. Routing path selection is based on fuzzy logic decision on both link and path performances.

Link parameters considered were transmission rate, energy state and flight status between neighbor UAV's. Path parameters considered were hop count and packet delivery time. The routing was done with objective of maximizing the lifetime. Oubbati et al. [9] proposed a route discovery mechanism for FANET. The routing paths with balanced energy consumption, link breakage prediction and higher connectivity degree are found. Packet delay and reliability were not considered in route discovery process. Sharma et al. [10] proposed a Distributed Priority Tree-based Routing protocol (DPTR) for FANET. The routing protocol addresses the problem of network partitioning and organizes the nodes in form of distributed Red-black tree. The appropriate node and channel for relaying are selected depending on application requirement. The approach considered link stability as the only parameters in routing decision. Usman et al. [11] proposed a forwarding protocol for FANET with next hop selection based on lifetime improvement.

A forwarding zone is created to spot the front relative nodes through forwarding angle and effective approximate node is selected with higher energy state. Packet reliability and delay were not considered in forwarding decision. Zafar et al. [12] proposed a multi cluster FANET topology to reduce the communication cost and optimize the network performance. Within clusters, transmission slot scheduling is done to reduce the packet collision and improve energy utilization. Authors considered only scalable network as the criteria in clustering decision and did not focus on routing protocols. Mariyappan et al. [13] proposed an energy aware routing protocol for FANET with Residual Energy Minimum (REM), Total Residual Energy (TRE), and Hop count as a routing cost metric. The next hop is selected based the routing metric, so that routing path is energy balanced. Packet reliability, congestion and delay were not considered in the routing decision. Khan et al. [14] explored various topology-based routing protocols for FANET. Protocols were analyzed in terms of throughput, end-to-end delay, and network load. Authors found that zonal routing protocol were found to have lower delay and better throughput compared to other protocols.

But study did not consider various mobility models. Zhang et al. [15] proposed a three-dimensional Q-learning routing protocol to improve QoS and guarantee packet delivery ratio. The proposed solution has two important functionalities: link state prediction and routing decision. Three-dimensional mobile pattern is predicted to calculate link lifetime. Routing path is constructed with higher link lifetime. Energy, congestion, and packet delay etc. were not considered in the routing decision. Usman et al. [16] proposed a reliable link adaptive position-based routing protocol for FANET. The routing is based on multiple criteria of node speed, signal strength, energy, and geographic distance towards destination. The geographic distance is calculated along the forwarding angle. The relay node is optimal in terms of energy, relative speed and connectivity duration is selected and packets are forwarded. The forwarding angle is decided at source and there is no deviation in next hop. This results in sub optimal routes. Choi et al. [17] proposed a multi hop geo location-based routing protocol for FANETs. The method uses the geo-location of neighbors and finds the next hop to destination based only neighbor information. Though the method has low overhead and robustness to dynamic network topology, it does not include other factors like stability, congestion, energy availability in the path. Li et al. [18] proposed a preemptive protocol based on link stability.

Authors introduced a stability metric based on link quality, safety degree and mobility predictor factor. Multiple robust link disjoint paths are computed, and route maintenance is triggered when link is broken. Routing is done by selecting the most reliable path. The overhead for route maintenance is high and the method is suitable only for limited mobility scenarios. Hong et al. [19] proposed a topology change aware routing protocol. The topology changes are monitored continuously, and route is constructed based on the mobility mode.

Among the multiple routing modes, the best one is selected based on the predicted topology changes. The thresholds used in topology change monitoring in this approach is not generic and applies only for certain mobility models. Pu et al. [20] proposed link state routing protocol adaptive to link quality and traffic load. Link quality is estimated using statistical information of received signal strength. Traffic load is estimated using MAC layer channel contention information. The path with higher reliability and light load is selected for routing. The maintenance overhead is high in this approach. Zhang et al. [21] proposed a deep-reinforcement-learning-based geographical routing protocol based on link stability and energy prediction. The next hop selection decision was done using reinforcement learning. The reward for reinforcement learning was on maximization of packet delivery ratio, without consideration for factors like delay, overhead reduction etc. Souza et al. [22] used fuzzy logic to improve the route discovery process in FANET. The routing decision is based on received signal strength indicator and mobility level. The factors like load on routing path, delay etc. was not considered in next hop selection in this work. He et al. [23] proposed an opportunistic routing protocol with distributed decision making. Each node exchanges aeronautical data with other nodes. From this, each node calculates the transfer probabilities to different neighbors jointly considering the position of neighbors and the destination node. Each node selects the neighbors with higher transfer probabilities as the next hop relay nodes for routing. The overhead in exchange of aeronautical data is higher in this approach. Xinchen et al. [24] used Q-learning for routing decision in FANETs. Nodes exchange routing metric information with neighbors. Based on this information, reward function which maximizes reliability is triggered to select the next hop node. Authors considered reliability as the only metric in the routing decision.

From the survey, most of the FANET routing protocols are OLSR based with high maintenance overhead. Very few opportunistic routing protocols are available but their relay selection policies are very limited and they don't consider multi criteria QoS factors in relay selection. Also after the route path selected, there is no continuous adaptation of packet rate based on application/network dynamics. Based on these observations, this work proposes a routing protocol for FANET.

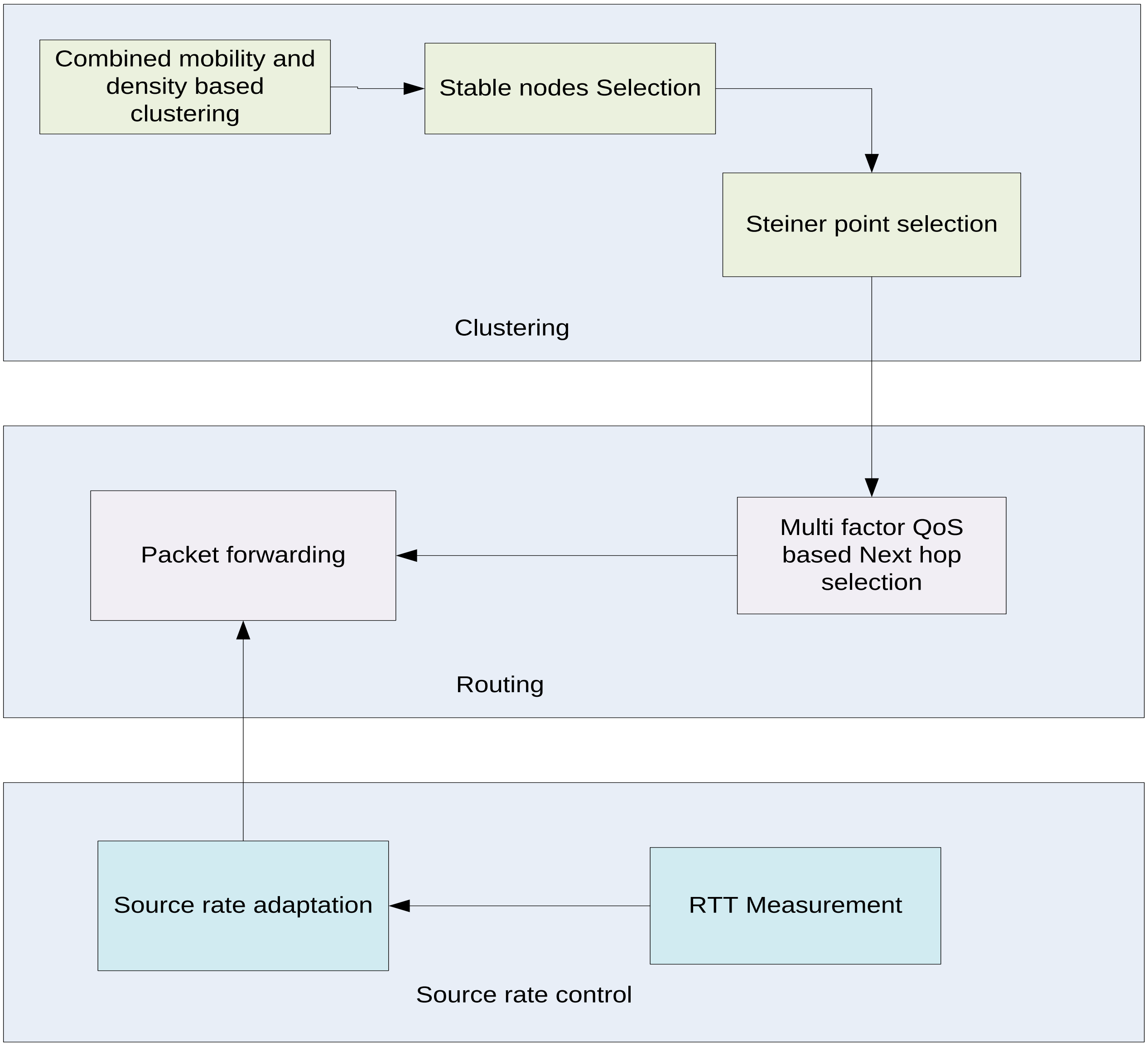

Fig. 1. Architecture of Multi Criteria QoS Optimal Routing.

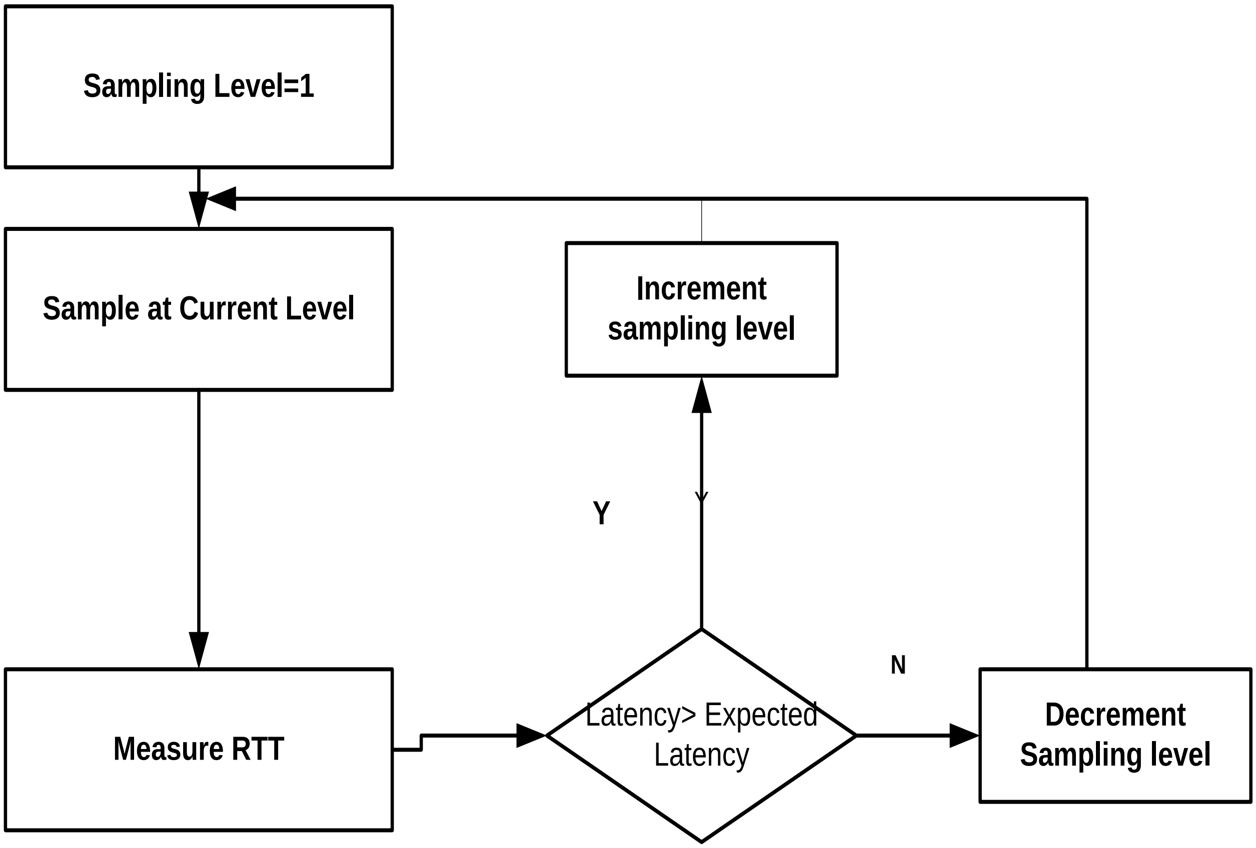

Fig. 2. Source Rate Control.

III. MULTI CRITERIA QOS OPTIMAL ROUTING

The proposed Multi Criteria QoS Optimal Routing (MCQOR) is constructed on clustering topology. The functionality of the proposed solution is given in Fig. 1. The proposed solution has three stages: clustering, routing, and source rate control.

The FANET network is first clustered using combined mobility and density-based clustering. The stable nodes in the clusters are selected and a routing backbone optimally connecting these stable nodes is constructed using Steiner Tree algorithm in 3D space. Geographic routing with next hop selection of nodes near the Steiner tree satisfying the multi criteria QoS factors is used for routing from source node to destination. Cross layer feedback from physical layer is collected at application layer to adopt the source data generation rate depending on traffic dynamics. Each of the stages of the proposed solution is detailed in below subsections.

A. Clustering

The FANET network is clustered by jointly considering mobility and density. For any two nodes i and , the mobility factor is calculated as:

$$M_{ij} = e^{1-\frac{V_r}{2V_{max}}} \quad (1)$$

Where V_r is the relative speed between nodes i and$j$, calculated over the period of time Δt as:

$$V_r = \frac{d_t - d_{t-\Delta t}}{\Delta t} \quad (2)$$

d_t and $d_{t-\Delta t}$ are the distance between the nodes observed in time between t and Δt. V_{max} is the maximum speed a node can move.

The distance between nodes is calculated in Euclidean 3D space as:

$$d_t = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y(t))^2 + (z_i(t) - z(t))^2}$$
(3)

Higher the value of M_{ij} , the link between nodes i and j is highly stable.

M_{ij} is calculated between each pair of nodes in a communication radius of R and when the nodes having consistent M_{ij} are grouped as cluster. The R value is selected based on the density of nodes within the network area. It is calculated as:

$$R = T \times \frac{N_{CH}}{M} \quad (4)$$

Where T is total area, N_{CH} is the maximum number of clusters and M is the total number of UAV nodes. Once cluster are formed, the UAV nodes with consistent M_{ij} values to all other nodes are selected as stable nodes in the cluster.

Existing Link state-based routing protocols for FANETs have higher maintenance overhead but link state-based routing protocol provide reduced route discovery time compared to ad-hoc search. This work adopts link state-based routing with a concept of routing backbone establishment with comparatively lower maintenance overhead. This work uses a graph theory concept called Steiner minimal tree to construct the routing backbone.

A Steiner Minimal Tree (SMT) is created with S points referred as Steiner points such that cost of N ∪ S is minimal. A weighted graph with vertex corresponding to each of N stable nodes and weight between the vertexes is set as the Received Signal Strength Index (RSSI) value between them is constructed and Steiner minimal is constructed for this graph.

A sample SMT in 2D space is shown in Fig. 3. In this, the hollow points are the vertexes, and the dotted points are the corresponding Steiner Points. The line connecting the Steiner points is the Steiner minimal tree. The tree is almost near to each of vertexes.

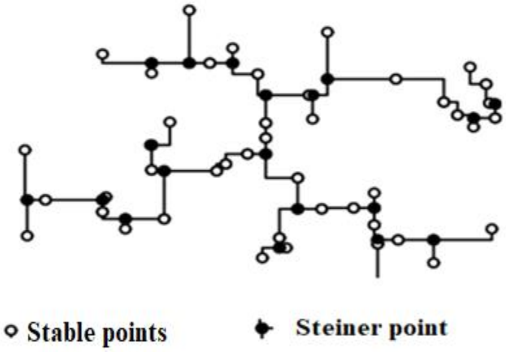

Fig. 3. Steiner Point in a Graph.

Since the stable points are in 3D space, this work adopts improved smith algorithm [25]. With stable nodes given as input, Steiner minimal tree is constructed optimally connecting the stable nodes.

B. Routing

Geographic routing with next hop selection based on multi criteria QoS factor over the Steiner minimal tree is proposed for routing the packets.

The QoS (Q) is calculated as...

$$Q = \alpha \times DF + (1 - \alpha) \times RF \tag{5}$$

Where DF is the Delay Factor. It is calculated in terms number of packets in queue (np_i) and Transmission failure Probability (P_i) and Packet transmission Time (pt_i) over the link i as

$$DF = \sum_{i=1}^{n} \{(np_i + 1).\left(\frac{1}{1-P_i}\right).pt_i\} \tag{6}$$

In terms of throughput, pt_i is calculated as

$$pt_i = \frac{L}{(1-R_i)B_i} \tag{7}$$

Where B_i is the Channel Bandwidth for link i under the influence of interference and L is the packet size. The net bandwidth usage is expressed as $(1 - R_i)$.

Reliability Factor (RF) is calculated in terms of exponential moving average of past delivery ratio (ψ) and Recent Delivery Ratio (DR).

$$RF = \alpha * \psi + (1 - \alpha) * DR \tag{8}$$

α is the weight factor with value in range of 0 to1.

Any node which wants to forward the packet to next hop selects the nodes close to Steiner tree with highest value for Q and uses that node as the relay node for packet forwarding.

C. Source Rate Control

Though routing paths with better QoS are selected, the QoS can be affected due to congestion. This work adopts source rate control based on cross layer feedback to reduce congestion on the routing path.

On routing path, congestion is measured in terms of round trip delay. It is calculated in terms of probability mass function of delay distribution between nodes A and B as

$$RTT = \begin{cases} \sum_{i=0}^{\infty} f_i(a).f_i(b)\ , x = 0 \\ \sum_{i=0}^{\infty} f_i(a).f_{2x+i}(b) + \sum_{i=0}^{\infty} f_i(b).f_{2x+i}(a), x > 0 \end{cases} \tag{9}$$

$f_i(a)$ is the probability mass function of delay in direction of A to B and $f_i(b)$ is the probability mass function of delay indirection of B to A.

The data sampling level is set in discrete interval from lowest to highest. The flow of source rate control is given in Fig. 2. Initially the UAV node operates in the default sampling level. RTT is measured periodically, and it is compared against expected latency. If the latency is higher than expected latency, the sampling level is decreased; this reduces the number of packets transmitted from source thereby attempting to reduce congestion. If the latency is lower than expected latency, then sampling level is increased, thereby increasing the number of packets in the network. Thus, source control rate is adaptive to traffic dynamics of the network.

IV. RESULTS

NS2 platform was used for simulation of the proposed solution. Simulation was conducted for configuration parameters given in Table I.

TABLE I. SIMULATION CONFIGURATION

Parameters	**Values**
Number of UAV	50 to 250
Communication range	100m
Area of simulation	1000m*1000m
Node distribution	Random distribution
Simulation time	30 minutes
Interface Queue Length	50
MAC	802.11
Number of Data collection point	1
UAV Speed	20-50 m/sec

Comparison of proposed solution's performance is done against Q-learning based QoS routing proposed by Xinchen et al. [24], link stability-based routing proposed by Zhang et al. [21], trajectory aided OLSR routing proposed by Hou et al. [7].

The simulation was conducted to measure the QoS parameters and compare the solutions in terms of their QoS performance.

Performance is measured and compared in terms of (i) packet delivery ratio (ii) delay (iii) throughput and (iv) network overhead. The QoS parameters were measured in two conditions of varying the number of UAV and varying the speed. By varying the number of UAV, QoS performance in relation to density of UAV in the network was compared. By varying the speed, QoS performance in relation to mobility of UAV was compared.

The packet delivery ratio is measured by varying the number of UAV and the result is given in Table II.

As in Fig. 4, in the proposed solution, the average packet delivery is 6.8% higher compared to Hou et al., 3.8% higher compared to Zhang et al. and 4.2% higher compared to Xinchen et al. The packet delivery ratio has increased in proposed solution due to three factors of selection of stable routing backbone, selection of multi criteria QoS based next hop and source rate control. These three factors have reduction the effective packet loss.

Varying the number of UE, the average delay is measured and given in Table III.

TABLE II. COMPARISON OF PACKET DELIVERY RATIO

Number of UAV	**Proposed**	**Hou et al [7]**	**Zhang et al [21]**	**Xinchen et al [24]**
50	93	86	89	88
100	94	87	90	90
150	95	88	91	91
200	95	89	92	91
250	96	89	92	92
Average	94.6	87.8	90.8	90.4

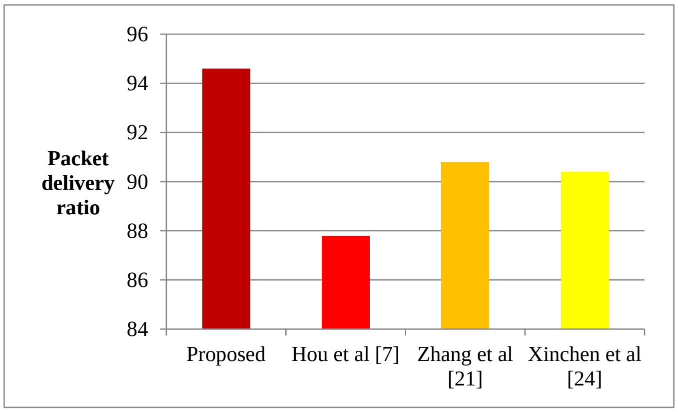

Fig. 4. Comparison of Packet Delivery Ratio.

TABLE III. COMPARISON OF DELAY

Number of UAV	**Proposed**	**Hou et al [7]**	**Zhang et al [21]**	**Xinchen et al [24]**
50	8	10	12	11
100	10	12	14	12
150	11	14	17	14
200	12.5	17	20	16
250	14	20	22	17
Average	11.1	14.6	17	14

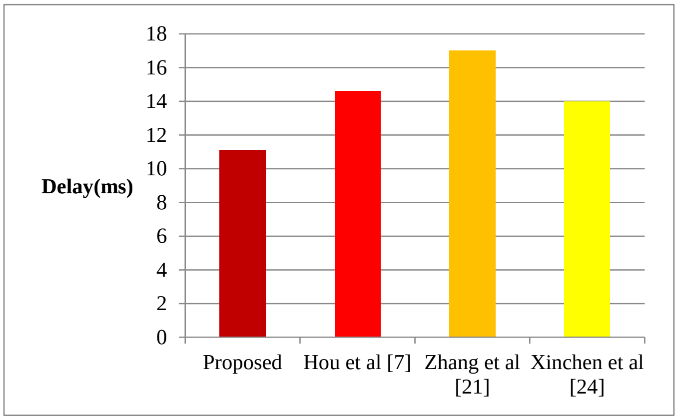

Fig. 5. Comparison of Delay.

As shown in Fig. 5, in the proposed solution, the average delay is 31% lower compared to Hou et al., 53% lower compared to Zhang et al. and 26% lower compared to Xinchen et al. The delay in proposed solution has reduced due to selection of Steiner minimal tree constructed based on delay minimization in the proposed solution.

Varying the number of UAV, throughput is measured and given in Table IV.

As shown in Fig. 6, the throughput is almost same across the solutions. Throughput has not increased much in proposed solution due to source rate control. Source rate control effectively controls the congestion in network but due is aggressive control also reduces the throughput marginally.

Network overhead apart from data payloads packets is measured varying the number of UAV and the result is given in Table V.

TABLE IV. COMPARISON OF THROUGHPUT

Number of UAV	**Proposed**	**Hou et al [7]**	**Zhang et al [21]**	**Xinchen et al [24]**
50	197	185	182	188
100	206	193	191	195
150	211	201	194	204
200	220	209	196	210
250	226	211	197	215
Average	212	199.8	192	202.4

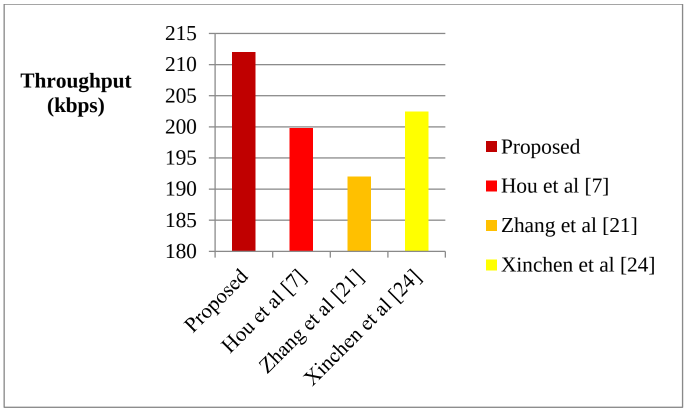

Fig. 6. Comparison of Throughput.

TABLE V. COMPARISON OF NETWORK OVERHEAD

Number of UAV	**Proposed**	**Hou et al [7]**	**Zhang et al [21]**	**Xinchen et al [24]**
50	130	145	150	147
100	140	164	167	170
150	151	175	187	190
200	160	184	194	198
250	168	192	198	210
Average	149.8	172	179.2	183

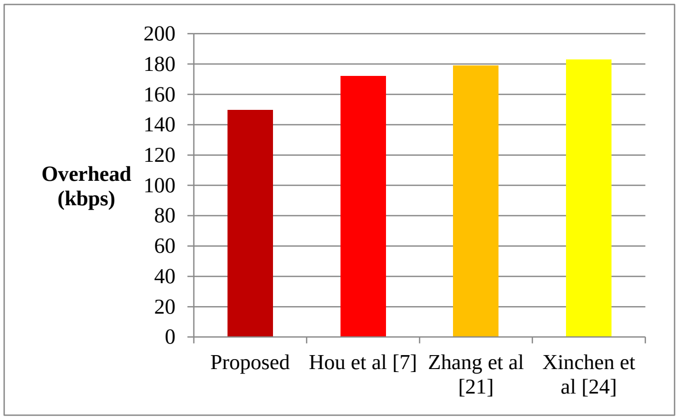

Fig. 7. Comparison of Overhead.

As shown in Fig. 7, the network overhead in proposed solution is 14% lower compared to Hou et al., 19.6% lower compared to Zhang et al., 22% lower compared to Xinchen et al. The network overhead has reduced due to construction of routing backbone using Steiner minimal tree which involves only stable nodes.

The packet delivery ratio is measured by varying the speed of UAV and the result is given in Fig. 8.

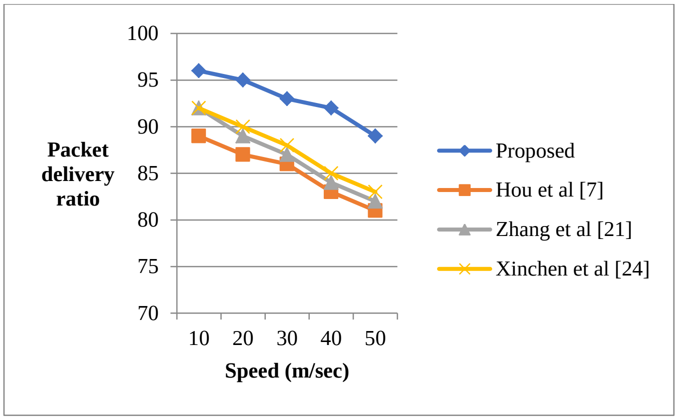

Fig. 8. Packet Delivery Ratio vs. Speed.

As shown in Fig. 8, packet delivery ratio drops with increase in speed of UAV. But even in drop, the packet delivery ratio is higher in proposed solution compared to existing works.

The delay is measured by varying the speed of UAV and the result is given in Fig. 9.

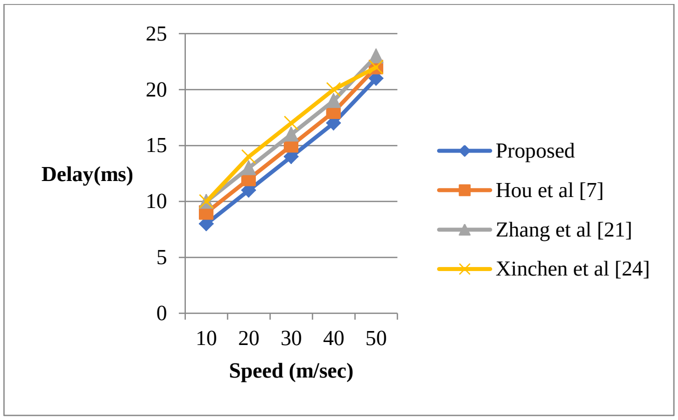

Fig. 9. Comparison of Delay.

With increase in speed delay increases in all existing works. But in comparison to existing works, the delay increases at slower rate in proposed solution.

The delay is lower due to use of Steiner Minimal Tree-based routing in proposed solution.

Network overhead is measured by varying the speed and the result is given in Fig. 10.

The network overhead increases with speed of UAV but the overhead is lower in proposed solution compared to existing works. Overhead has reduced in proposed solution, due to use of less maintenance overhead.

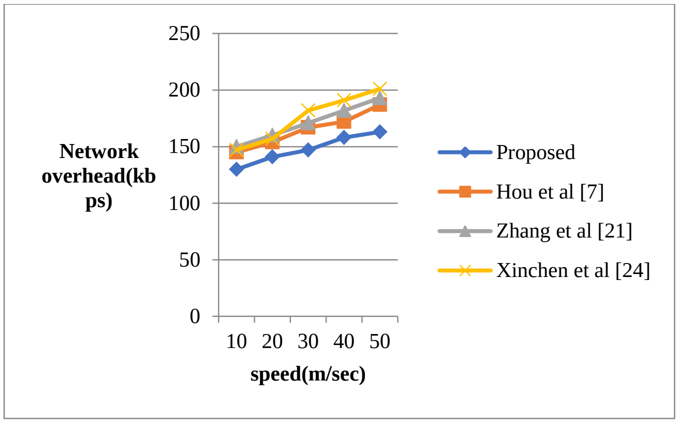

Fig. 10. Comparison of Network Overhead.

V. DISCUSSION AND RESULTS

The proposed solution performed better in all QoS metrics of packet delivery ratio, delay and throughput. Packet delivery has increased in proposed solution due to selection of more stable paths for routing and source rate control adaptable to network/application dynamics. Though Xinchen et al. used Q-learning to select the stable paths, it required high overhead to maintain the paths. Also the packet flow on the paths was not controlled based on application/network characteristics. Zhang et al. used OLSR based proactive routing protocol. Link stability was given more importance in route construction. But without packet rate control, congestion increases and affects the path reliability. Hou et al. solution was also based on OLSR. Similar to Zhang et al., the solution proposed by Hou et al. did not consider reliability after path establishment.

Delay has reduced in proposed solution due to use of geographic routing. Though Hou et al. and Zhang et al. used shorted OLSR path, due to node movement, the path has to be reconstructed. This created more packets in the network and as result, delay increased. The network overhead has increased in Hou et al. and Zhang et al. due to more route maintenance packets needed to keep OLSR link state fresh. Since the proposed solution used opportunistic routing, the overhead is lower in proposed solution.

The QoS performance was better in proposed solution compared to existing works even in higher speed. At higher speed, the link state maintenance overhead is higher in Hou et al. and Zhang et al. Due to this, number of packets increased in the network, creating congestion and reducing the reliability of the network. Proposed solution has source rate control mechanism to reduce the packet flow during congestion times, but this mechanism was lacking in the existing works.

VI. CONCLUSION

A Multi Criteria QoS Optimal Routing (MCQOR) for FANET is proposed in this work. The proposed solution has three stages of clustering, routing, and source rate control. The FANET network is clustered using combined mobility and density information. Over the clustered network, routing backbone is constructed using Steiner Minimal Tree (SMT) and Multi Criteria QoS based routing is done over the Steiner routing backbone. Due to stability consideration in clustering and routing, the packet reliability has increased in the network. The proposed solution achieves 3.8% higher packet delivery ratio, 26% lower delay and 14% lower network overhead compared to existing works. Though QoS factors have been considered in this work, energy minimization and life time improvement has not been considered in this work. Life time maximization with joint consideration for QoS is in scope of future work.

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