QoS-aware Dynamic Controller Implantation over vSDN-enabled UAV Networks for Real-Time Service Delivery

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ABSTRACT

The advancement of wireless communication networks has been highly influenced by the development of UAV networks. The real-time realization and quick installation of UAV networks make it extremely suitable for emergency services. Due to limited energy and processing memory, vSDN-enabled UAV networks are brought into the picture where the central SDN controller is used to manage the Data Plane UAV activities. The placement of the controller is a critical issue due to random mobility and distant coverage. In this work, we have proposed a controller implantation technique for low latency communication and service delivery. A two-tier hierarchical data plane (D-plane) segmentation has been introduced to place the UAV entities at D-plane. Our algorithmic approach shows that the centralization of SDN controller causes comparatively low latency with respect to other potential regions. We have relaxed the traffic overheads considering minimal data exchange between D-plane and C-plane. The latency trade-off significantly helps to identify the most suitable positions to deploy the Controller units. This work also contributes towards the CPP-UAV (Controller Placement Problem in UAV-networks).

CCS CONCEPTS

• **Networks** → **Network Architecture**; *Network design principles*; Layering; • **Network** → Network Algorithm; Network performance.

KEYWORDS

vSDN, UAV network, URLLC, Controller, Control Plane, Data Plane

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1 INTRODUCTION

In recent days, the research interests on Unmanned Aerial Vehicle (UAV) based communication systems are gaining rapid momentum. 5G or fifth generation of wireless communication systems intensify the growth of Drone or UAV networking [14, 19]. The major key performance indicators of 5G support the UAV network deployment which targets to server URLLC (Ultra-Reliable Low Latency Communication) network services to end-users. The UAV-networks are extremely helpful to provide services to remote areas or hard-to-reach areas. High mobility and flexibility are the potential enablers for UAV-networks. The UAV instances are used to carry the required load or sometimes they are deployed as WiFi access points inside a network. UAV-driven wireless communication networks are the best alternative for post-disaster management issues [17]. They are capable enough to provide emergency services where human interventions are difficult or impossible in some extreme cases. Apart from search and rescue operations, the communication service range provided by the UAVs is minimal due to various reasons which include mobility, data processing capacity, energy utilization, etc. The drone networks or UAVs have low processing capacity and limited energy accessibility. There are chances of a power outage and sudden service unavailability. Due to limited space and other constraints, it is necessary to control the UAVs using a centralization unit and provide minimal task offload to the UAV-plane. The low buffer storage is also a hindrance here. The centralization of such networks makes such networks flexible and efficient enough to deliver the required QoS and QoE to the end-users. Exhaustive research works are still going on to resolve such critical deployments.

Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are two key technology enablers that have the ability to upgrade the UAV-networks to the next level [3, 9]. SDN and NFV have emerged exclusively to be the most important technology enablers for creating such user-friendly communication systems where the deployment as well as the utilization of various network services are dynamic and can be customized according to the never-ending user demands [4]. Both these technologies together form vSDNs or virtualized-Software Defined Networks. SDN

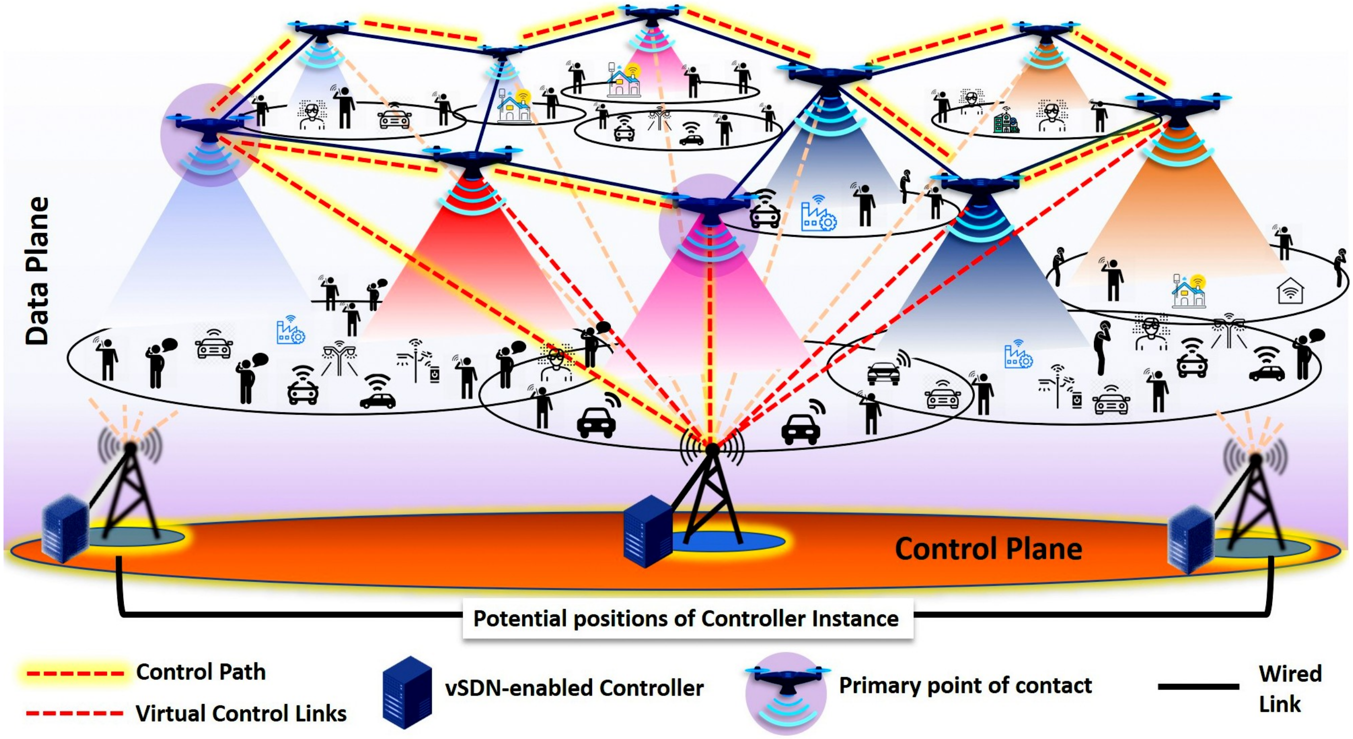

Figure 1: vSDN-enabled UAV network architecture

decouples the controller and the user data planes from one another. On the ground level, the SDN functions are hosted at the physical nodes where at each node one, multiple or zero virtual nodes can be embedded. A vast amount of virtual networks can be deployed on a single substrate physical topology and consequently, a wide array of services can be provided to the end-user [5, 13]. NFV allows multiple TSPs to abstract a variety of virtual network functions (VNFs). They are software implementations of network protocols that consist of high-capacity servers or switches instead of customized hardware on top of which one or more virtual machines may be operating while running different applications. These VNFs can be easily migrated from one machine to another providing flexibility in resource allocation. The TSPs can orchestrate and deploy their private operating systems by using their own controllers and also modify them in accordance with the user demands. These SDN and NFV enabled models to allow notable pruning in the operating expenditure OPEX and capital expenditure CAPEX [6].

In SDN, the central controllers are placed at the Control Plane (C-plane) and it manages the flow statistics in Data Plane (D-plane) elements. The controllers are updated with all essential topological configurations. In the case of vSDN-enabled UAV networks (as shown in figure 1), the UAV instances are distributed over the D-plane, and maintaining stable connectivity between the controller and the D-plane is extremely important here. UAVs are acting as the data forwarding elements and provide services to the regions that fall within their transmission range. In this work, we have proposed a hop-based communication inside the UAV network. This type of mechanism causes huge data overhead within the network. On the other hand, it is also very important to make the network ready for low latency communication. Coverage is always one of the major issues within UAV-networks, we have proposed a two-tier multi-hop control flow mechanism over the vSDN-driven UAV networks. The next sections will explain in detail the system model and problem formulation.

Contributions: In this paper, we have proposed a two-layer hop by hop control function flow mechanism over a weighted Watts_ strogatz_ graph. The UAV instances are considered to be distributed over the data plane which has been controlled by the nearest Control plane unit wirelessly. We have done exhaustive search operations to find out the following objectives:

- Initially, we have successfully identified the set of potential nodes which can be used as the access points for service delivery. Over a geographical distribution, it is extremely difficult to randomly select the controller locations which may cause high service delay, service unavailability, or sometimes poor bandwidth utilization. So, it is important to identify the most feasible locations for optimum service delivery.
- We have executed the shortest path routing algorithm (Dijkstra's Algorithm) over each UAV instance to find out the most suitable entity for the first tier. The rests are shifted to the second tier. It is important to keep this selection dynamic to make the network mobility high.
- Next we have studied the flow of control requests over the entire network by varying the potential controller locations from one region to another for real-time service delivery.

- Finally, our test cases have come up with conclusive shreds of evidence. It has been shown from our result analysis that, the centralization of the control plane instances is the most effective orientation for a low latency service flow. The graphical analysis over latency criterion also satisfies our claims.

Paper organization: The rest of the paper is organized as follows. Section 2 demonstrates major research works, critical drawbacks, and main motivation towards this contribution. Section 3 explains our proposed two-tier hierarchical system model for vSDN-driven UAV Networks. Section 4 formulates the problem definition and Section 5 explains our algorithmic two-tier multi-hop shortest path control flow preparation approach. Section 6 evaluates the entire procedure and analyzes the results to show the effectiveness of our proposed method. Finally, Section 6 concludes the work with a few important future directions.

2 RELATED WORK

The evolution of SDN-driven UAV networks has started almost half a decade ago [10]. Since then it has evolved as an emerging technology in the field of various public and civil applications. UAVs are used in certain cases where human intervention becomes difficult. Disaster management, areal surveillance, military applications, war stations, and other remote areas. Even though UAV networks show promising outreach with a wide range of service functionalities, it encounters serious challenges due to some of the major limitations. Different varieties of UAVs are there. Depending on size, mobility, use cases, processing speed, energy efficiency, etc. the UAV or drone networks can be categorized. The manufacturing cost is also a matter of concern here. The entity with additional features draws more cost which further results in higher CAPEX and OPEX. UAVs have limited capacity, storage, energy, mobility, and coverage area, and that is why multiple instances are required to cover a large geographical area. The non-existence of any central controlling system causes inconsistent service delivery and poor network performance. SDN and NFV play a crucial role in resolving these issues inside any UAV network.

2.1 Software-Defined UAV Networks

The concept of SDN is not new, and researchers from academia and industry are exploiting the possible use cases of programmable networks in various fields [1, 21]. The scope of introducing the SDN paradigm in UAV surveillance applications or drone-assisted networks can not be overlooked. SDN brings exclusive advantages that further motivates us to design advanced UAV networks. Though getting UAVs over the open platform of SDN enables vulnerability and cyber threats inside the network, that is not our main area of concern as different study groups are looking into this matter. SDN network architecture contains three layers: Application Layer or Management Layer, Control Layer, and Data Layer. Various network service providers primarily control the application layer instances. The application layer uses Northbound-API to communicate with the Control plane where the main central controller is placed. The drones are distributed over the data plane, and they act as the data forwarding entity. The behavior and features of data plane entities (drones) are configured using the management layer as per the network requirements. OpenFlow protocol is used to exchange instructions between the control plane and drones. The drone layer (Data plane layer) receives all data forwarding instructions, rules, and regulations from the central controller. Figure 2 shows a simple SDN-enabled UAV network model.

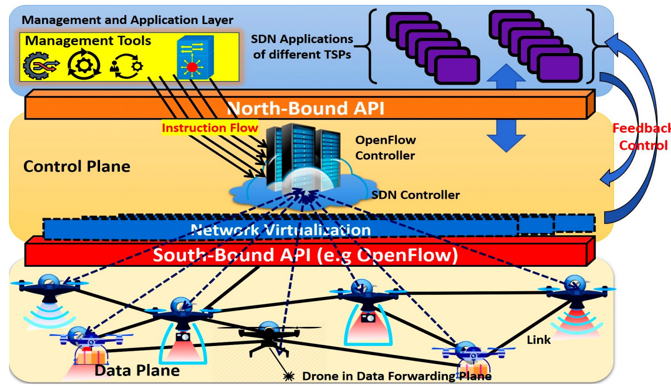

Figure 2: SDN-driven UAV network Architecture

2.2 CPP over Software-Defined UAV Networks

The Controller Placement Problem (CPP) is one of the fundamental optimization problems of SDN. Depending on network applications and requirements the constraints vary. In UAV networks also CPP plays a major role and that is why researchers are intensively working in this field. Fadi Al-Turjman *et al.* in [2] has done a comprehensive survey over software-defined IoT networks in the context of UAVs assessment. They have analogically explained how a UAV network can be realized using the SDN configurations. A more detailed study has been done in [18] by W.Shi *et al.* explaining the wide use cases, applications, recent challenges, opportunities, and future of UAVs. Dvir *et al.* in [8] demonstrates a heuristic solution to minimize the link failure probability with a low latency environment. An ant colony approach along with an extrinsic memory algorithm is used by Llerena *et al.* to deploy the SDN controllers for D2D (Device to Device) Communication [12]. Deployment of SDN controllers to prevent malicious attacks is explored by Santos *et al.* in [16] using the ILP method. Petale *et al.* have minimized the Maximum Worst-Case Latency objective and maximum memory utilization of SDN controllers by solving the optimal model for CPP. Limited contributions are observed in the wireless communication field (e.g UAV assisted 5G Networks) using SDN and NFV. Our work mainly focuses on wireless communication to make the network ready to work using 5G and beyond 5G technologies.

2.3 vSDN-enabled UAV Networks for Real-time Applications

The inclusion of NFV within SDN makes the network more flexible, programmable, and agile. However, the concept of vSDN approach within the UAV network is relatively new. In [15] authors have done a detailed study to provide various use cases, applications, challenges, and opportunities for vSDN-enabled UAV networks. The future generation wireless communication networks are focusing more on URLLC, real-time service delivery becomes an important aspect. Chai *et al.* in [7] have proposed an approach to minimize the control plane propagation latency. Kyle J. S. White *et al.* have performed a study combining SDN and NFV concepts to build a robust migration of network services via UAV network, which also confronts high mobility requirements [20]. Most of the works performed so far do not consider the potential deployment of the virtual controllers inside any UAV-SDN network. Considering the distribution of UAVs may arbitrarily degrade network performance. UAVs may go out of the coverage, which triggers service outage problems. The limited capacity of UAVs restricts us from continuously exchange complete topological information among them. A virtualized SDN controller is the best solution in this case. Our work primarily contributes towards localizing the optimum positions for such networks. A similar approach can be followed to design economic network infrastructure as well.

3 PROPOSED SYSTEM MODEL OVER VSDN-DRIVEN UAV NETWORKS

In vSDN-driven UAV networks, SDN controller acts as the brain of the network and takes all the necessary routing decisions. The D-plane UAVs only perform the data forwarding events. In our proposed two-tier hierarchical topology as shown in Figure 3, the first hop master UAV performs the information exchange with the nearest SDN station. The master UAV then delivers the topological information to the second-tier UAV instances. The central monitoring system helps the UAVs to exchange the updated information very quickly. If any routing path needs to be updated, that decision is taken by the controller and the same has been distributed over the D-plane UAVs via the master UAV. Other statistical information like link capacity, type of network function, memory requirement, etc. UAV updates to the corresponding controller. Data packets are routed in the D-plane between the UAVs following the rules of SDN controller.

Table 1

List of Simulation Parameters	
Parameters	**values**
Topology	Watts_ strogatz_ graph
No. of Nodes (N)	Random in [9,15]
No. of nearest neighbors (k)	Random in [4,7]
Probability of rewiring each edge(p)	Random (0.4,0.6)
Potential Controller Locations	N
Edge weights (E_w)	Random [1,5]
Node capacity (C_{cap_k})	10-35 Mbps
Path latency ($\mathbb{L}_{ij}$)	1 to 5 msec.

The UAV network is considered as a graph ($\mathbb{G}$) over which the UAV instances are distributed. The network specifications are mentioned in Table 1. The parameters and corresponding values may vary depending on the requirement and geographical orientation. The test case followed by us considers the system configurations according to Table 1.

Uninterrupted communication between C-plane and D-plane is extremely necessary. It is obvious that, direct transmission of control signals from the controller to all other UAVs is not possible because of limited transmission power, path losses, etc. Now,

Algorithm 1: TMSPA - Algorithm for real time routing over a given drone assisted communication network (two step pseudo-code)

Input: $G_{drone} = (\mathcal{N} \cup \mathcal{E}) where |\mathcal{N}| \rightarrow N_{node} \& |\mathcal{E}| \rightarrow N_{edge}$
$n_i \in \mathcal{N} \;\; \forall \;\; i = 1, 2, ...N_{node} \quad at \; i^{th} \; drone \; position$
$e_i \in \mathcal{E} \;\; \forall \;\; i = 1, 2, ...N_{edge} \quad for \; i^{th} \; logical \; links$
initialization: $cont - lat \rightarrow [None] \times N_{edge}$
$cont - node \rightarrow None, \{l_1, l_2, l_3, i, j, k\} \rightarrow local \; variables$
Output: $Optimized \; re - arrangements : G_{drone}$
Given: $i \leftarrow 1, j \leftarrow 1$
while $i \leq N_{edge}$ **do**
  while $j \leq N_{edge}$ **do**
    if $i \neq j$ **then**
      $first - hop \; append \; (dist(i, j))$,
      shortest-path distance between i & j
    else
      $distance \; path \; skip$
    end
    $j \leftarrow j + 1$
  end
  $i \leftarrow i + 1$ & $j \leftarrow 1, l_1 \rightarrow$ *min(first-hop)*
  $tier_1 \rightarrow [\forall j \in N_{node} \; for \; which \; dist(i, j) = l_1]$
  while $i \in tier_1$ **do**
    while $k \in N_{node}$ && $k \neq$ && $i \neq j$ **do**
      temp = temp + dist(k,j) *second-hop append(temp)*
    end
  end
  $l_2 \rightarrow min(second - hop), cont - lat[i] = l_1 + l_2$
end
$l_3 = min(cont - lat), cont - node = [\forall i \in N_{node}, \; such \; that \; cont - lat[i] = l_3]$

positioning the controller is a challenge here. We need to give proper attention so that the overall average network delay becomes minimum. Our prime task is to identify such locations inside the network. The next section explains the multi-hop control function propagation technique which ultimately results in low propagation delay as well as identifying the optimal controller positions.

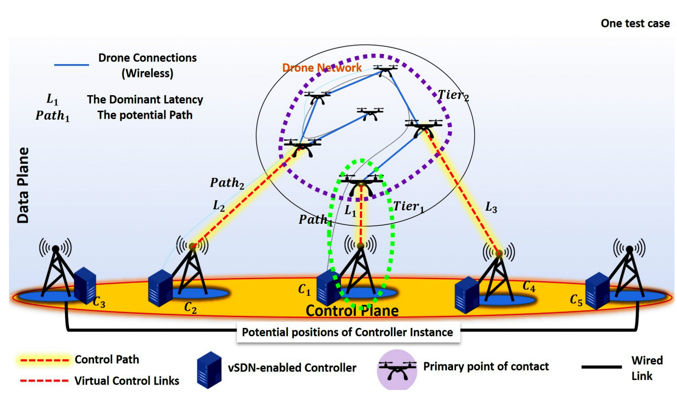

Figure 3: The two-tier hierarchical model of vSDN-driven UAV Network

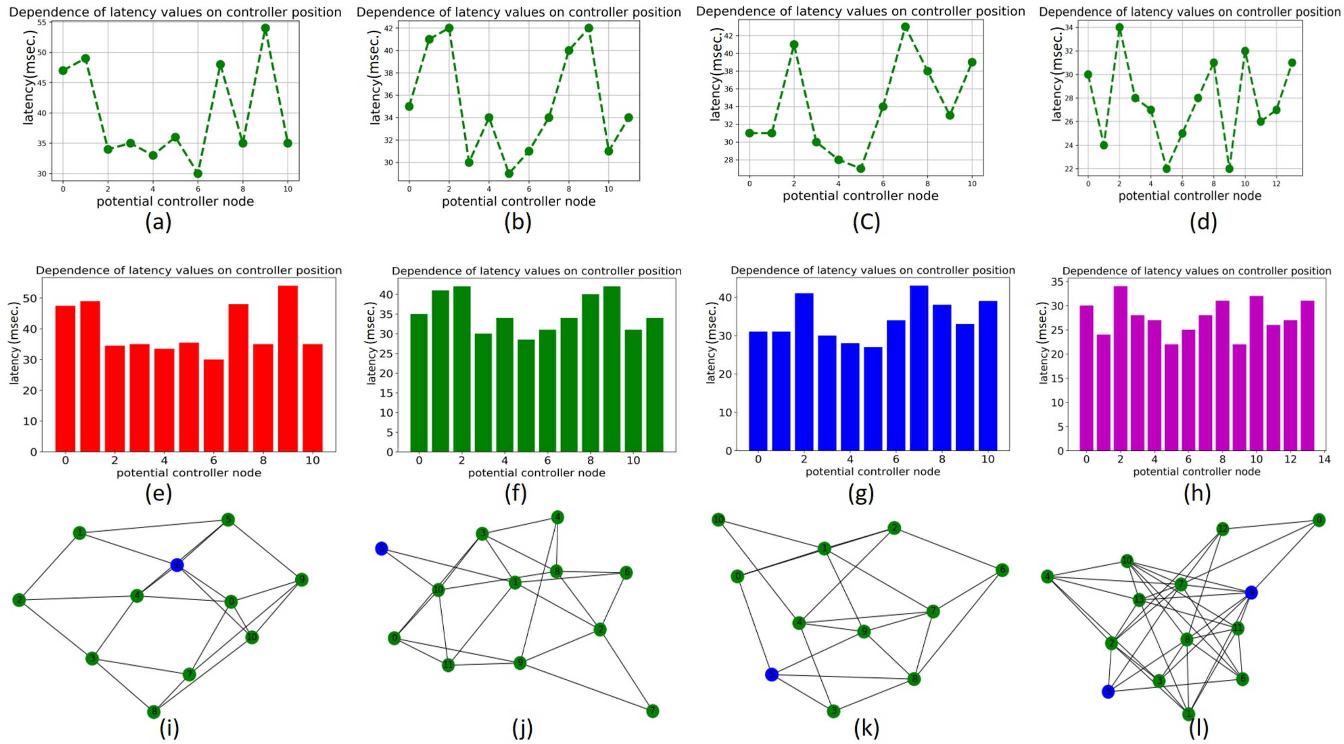

Figure 4: 4(a)-4(h) show comparative latency analysis for different potential positions of the Controllers; 4(i)-4(l) show random weighted graphs and associated links of for D-plane and C-plane instances

4 TWO-TIER MULTI-HOP SHORTEST PATH ALGORITHMIC APPROACH

The $Tier_1$ UAV communicates with the SDN controller and also passes the information of its neighbors. This method is energy efficient as well because high power is required for direct transmission but UAVs run in batteries with restricted power usage. Though, we are relaxing the complexity by considering a small-scale UAV network. In the case of large-scale networks, this approach will definitely drag complexity and data overhead conditions. We keep that area as one of our future research domains.

The forwarding of the data packet from the controller to the master UAV is done through a single-hop wireless transmission. Special care is taken while setting up the network so that at a time at least one drone must be within the direct transmission range of the controller. We have discarded all unprecedented cases of signal outage for simple architecture. The arrowhead flowchart shown above within this section is the two-tier multi-hop shortest path algorithm to find out the most suitable controller positions. It is a key feature of any network to provide services to the end-users in real-time. Through our approach, we have found 20-30% of average latency reduction. This is observed if the potential position is taken at the center of the UAV network or in another way the distribution of the D-plane can be done keeping the controller at the central region to achieve maximum efficiency. Next-generation wireless communication technology such as 5G,6G focuses on URLLC function exchange. Keeping this key criterion in mind we have tried to introduce an algorithmic approach to solve UAV-CPP in a vSDN-assisted UAV network.

Our proposed TMSPA (Two-tier Multi-hop Shortest Path Algorithm) as shown in section 3 finds out the optimal potential positions of the SDN controllers with time complexity of $O(N_{node} \times N_{edge})$. The drone (UAV network) topology will be taken as the input, and the ground access points act as the C-plane potential positions. The final G_{drone} orients the UAV topology according to the best ULL arrangements. Considering a simplistic case, a two-step hop-by-hop routing is shown in the algorithm that can be generalized as per the requirement. We have restricted the hop step to maintain the quality of the signal.

5 RESULT EVALUATION AND DISCUSSION

The procedure shown in section 4 was implemented using a Python3 script over a weighted Watts_ strogatz_ graph [11]. A total of 15 nodes (UAVs) are placed above a plane with an area of 1000x1000 m^2. The controllers are also positioned at the C-plane within the transmission range of 200 m. The periodic message delivery interval was set to 1 sec for each UAV. The distribution of the potential controller positions is kept within the interval of a feasible range. The D-plane to C-plane distribution model can be understood from figure 3. The packet update within the UAVs is done following the shortest path algorithm as explained in section 4. Considering a single potential controller location on the C-plane the nearest first level UAV section is done. The second level communication is done using the master UAV of the first level. Delay increases with increasing hop numbers. Equation (1) represents the relationship between latency (L) and the number of hops (n). If the controller can be placed in some central location, that further reduce the end-to-end network latency.

$$L = 0.001n^4 + 0.011n^3 - 0.0556n^2 + 0.1181n - 0.0775 \quad (1)$$

Figure 4 shows the latency characteristics of the network depending on various controller positions. It can be observed that the average latency gets minimized when the controller positions are considered near the central points. At certain points, it gets the lowest value. Two sides of the graph show comparatively higher latency concerning the middle region. This study is quite intuitive which also claims that once the D-plane UAV distribution becomes symmetric with respect to the C-plane entity, the entire network faces an overall latency efficiency. Service availability also increases which further improves network QoS. The four sets of graphs 4(a)-4(d) also show similar effectiveness. The analogical graphs 4(e)-4(h) represent the reduction of average latency for the same. The random distribution of the D-plane and C-plane entities is done considering the weighted random graphical model as explained at the beginning of this section. In some cases, more than one potential position does exist inside the network but that does not violate our claims. Figure 4(l) shows the existence of two potential positions of SDN controller over C-plane that too following the central symmetry. These results validate our claim and act as key indicators for the TSPs (Telecommunication Service Providers) and MNOs (Mobile Network Operators) to deploy any new UAV network.

6 CONCLUSION AND FUTURE WORKS

The domain of wireless communication using UAV networks is expanding rapidly but limited energy, low processing capacity, and restricted storage media are acting as some of the major challenges in such networks. Through this work, we have contributed towards vSDN-driven UAV networks deployment for low latency communication. We have proposed a two-tier hierarchical UAV network architecture that is driven by the control plane instance wirelessly. We have assumed the channel condition, drone mobility, and access medium within favorable conditions. Our proposed approach primarily targets identifying the distribution of UAV instances at the D-plane and under the C-plane. We have used a hop-by-hop shortest path algorithm to prove that the central alignment of the Controller acts as the most suitable position for maximum coverage. We have targeted minimizing the average control flow latency between C-plane to D-plane so that the quality of service can be maintained properly. The data redundancy might be a critical issue here, as we have considered the master Drone act as the single point of contact with the C-plane unit. We will be looking into this issue in the future as well. The results and distributive latency curves show that the average latency requirement is cooperatively less in the middle region. Selecting the best position of the controller is still an open issue in the research field. Our contributions towards this approach will be more significantly justified if the simulation model can be applied over some real network topology. In the future, we will be further improving the model with a suitable federated learning approach to make the network more efficient and flexible.

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