A Queuing Theoretic Framework for Flying Mesh Network Assisted IoT Environments

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***Abstract*—The proliferation of connected objects is leading to new ways of using unmanned aerial vehicles (UAV) as wireless relay. As this novel application of drone in wireless communications is currently under development, many challenges must be dealt with, and discussed for the most efficient deployment. This paper proposes an analytic model of Drones Flying Mesh Network which act collaboratively in multi-hop manner to provide connectivity, gather and forward data to an end system. This model take into consideration topology, UAV parameters and the interaction between layers (PHY,MAC). Our main outcome in this work is to predict the average end-to-end throughput as well as stability of intermediate UAV queue under saturated network and using the balance rate. The proposed model was evaluated with simulation using Matlab. We show the interval values of model parameters within which the stability region is find out.**

***Index Terms*—UAV, Weighted fair queuing, Traffic intensity, End-to-end Throughput.**

I. INTRODUCTION

Unmanned aerial vehicles (UAV) also called drones, are proliferating in divers domains. Nowadays, UAV is be harnessed for forest fire monitoring, agriculture, video surveillance, parcel delivery, Safety inspection, etc... Among these several applications, the UAV presents recently a promising integral component in wireless communication. On-demand deployment, low cost, and the hovering capability of UAV were the major encouragements to make this equipment adaptive as flying base station. With the help of this novel use of drone in wireless communications, there has been a countless research works in the literature for successful UAV deployment, in terms of coverage [1], altitude [2], positioning [3], routing [4], energy-efficiency [5] and throughput [6]. Otherwise, the drones can serve in wireless communication through three typical use cases: (1) UAV-assisted ubiquitous coverage: They play the role of aerial base station to provide connectivity to ground devices. e.g: during temporary events where huge audience members (Festivals, Concert ...) are connected to internet. (2) UAV-assisted relaying, to enhance connectivity in a nomadic wireless environment spurred by connected objects (IoT), that lack of a direct link between them. (3) UAV-assisted data collection: when multi-UAV positioned to collect data from a many wireless devices, e.g: sensors in precision agriculture [7]. However, as the number of connected objects increases, the data traffic generated by each device covered by drone grow explosively, which underlined mainly the need to evaluate the performance of UAV-Network. In other words, the development of a virtual network to study and analyze preliminary the reality performance is primordial. This model allows operator to get a clearer vision about UAV parameters setting, capacity of network in terms of traffic, coverage and obviously other advantages. In such UAV-Network with a massive data acquired from ground IoT devices, the relevant metrics that ought to be tackled are Throughput, Delay, Packet loss.

In [8], they study the impact of network size on throughput, transmission range and energy consumption. Whereas, authors in [9] propose an optimal positioning drones that maximize throughput of individual users, their proposed solution can arise in extended UAV communication system. In [15] design a network using directional antennas to maximize throughput and minimize end-to-end delay. The performance of UAV-based wireless sensors network using discrete time Markov chain is evaluated in [11].

This paper is predominantly focuses on the end-to-end throughput in multi-hop routes of the network and the impact of various system parameters on this metric. Toward this vision, we consider a drones flying mesh network (DFMN) assisting an IoT environment. Working with the above mentioned system architecture, we propose a queuing theoretic framework to characterize the average load of drones in network in steady state by using rate equation balance, also to study the end to end throughput as a function of several model parameters.

The remainder of this paper is organized as follows: Section 2 gives a description of our proposed architecture. The drones network stability and the performance are derives by using a balance equation in section 3. Section 4 states numerical results and their analysis and Section 5 provides the conclusion and futures works.

II. SYSTEM MODEL

A. Drones Flying Mesh Network model

A Drones Flying Mesh Network model (DFMN) as shown in figure 1, comprises IoT devices, UAVs network, satellite, Cellular 4G\5G and Processing Unit (PU) that are interconnected. A set of IoT devices are randomly distributed in a remote area (set, desert), which is not covered by any service provider. A set consisting by m UAV act as a Base Station (BS), forms a flying mesh network, which hovers in a circular motion above the grounds IoT objects. Like any BS, when a UAV in the position to cover a group of IoT objects, its collects their data and forwards it to its drones neighbors. Otherwise, the packets from IoT devices traverses UAVs network until them reaches the processing unit, after being passed through a gateway.

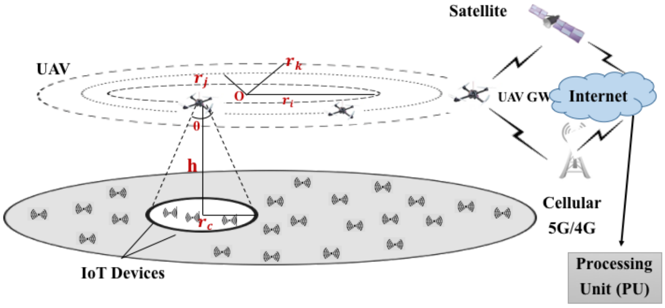

Fig. 1. DFMN Architecture.

That's beyond the scope of this Paper: modeling what is happening between the gateway and the processing unit.

Each UAV_i (proper to drone i) hovers over Nt_i IoT devices while it follows a predefined path. At each position on the path its covers N_i objects as shown in figure 2 according to homogeneous Poisson Point Process (PPP), which can be expressed as:

$$N_i = \lambda_i \pi r_{c_i}^2 = \lambda \pi \tan^2\left(\frac{\theta_i}{2}\right) h_i^2 \tag{1}$$

Where λ ,r_{c_i} , θ_i and h_i present respectively the density, the radius of coverage area, the angle of aperture of the antenna inside drone and the altitude of UAV_i. Therefore, each UAV_i cover Nt_i IoT devices in each round as shown in figure 2.

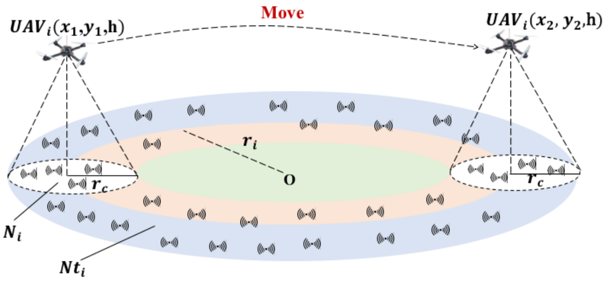

Fig. 2. UAV Coverage

Then:

$$Nt_i = \frac{4\pi\, r_i}{r_{c_i}} N, \tag{2}$$

r_i is the radius of rotation of the UAV_i.

$$r_i = \frac{V_i}{\omega_i}, \tag{3}$$

Where V_i is the linear velocity, ω_i is the angular velocity.

As stated earlier, each UAV_i hovers over N_i in each round in order to collect their data using uplink association. The drones can successfully gather the data from IoT devices if only signal-to-noise ratio (SNR) uplink is above the threshold.

$$P_{cov} = P(SNR \geq SNR_{th}), \tag{4}$$

SNR_{th} is the SNR threshold. We consider only the Line of sight in our case then the coverage probability can be written as. see Ref [12]:

$$P_{cov}(h,\lambda) = 2\pi\lambda h^2 \int_0^{\frac{\theta}{2}} Q\left(\frac{\mu_{LoS} - \psi(\theta_c)}{\sigma_{LoS}(\theta_c)}\right) \underbrace{\beta_1\left(\frac{5\pi}{12} - \theta_c\right)^{\beta_2}}_{P_{LoS}} \times \frac{\sin(\theta_c)}{\cos^3(\theta_c)} e^{-\lambda\pi h^2 \tan^2(\theta_c)} \; d\theta_c, \tag{5}$$

where μ_{LoS} describes the excessive path loss which is depending on frequency and the propagation environment, and σ_{LoS} is the shadow fading $\sigma_{LoS}= a_{LoS}\, e^{b_{LoS}\,\theta_c}$, with a_{LoS} and b_{LoS} being frequency and environment dependent, θ_c is the random variable angle that connect any IoT in N to the closest UAV, β_1 and β_2 are the environment constants. And $\psi(\theta_c)$ is given by:

$$\psi(\theta_c) = 10\, log_{(10)}\left(\frac{P_t}{N_o\, L_f\, SNR_{th}}\right), \tag{6}$$

P_t is the transmit power of IoT device, N_o is the noise and L_f is the free-space path loss which is can be represented as:

$$L_f = \left(\frac{4\pi f d}{c}\right)^2 \tag{7}$$

with f being the frequency of operation, c the speed of light and d distance between transmitter (IoT) and receiver (UAV). We don't consider the interference between the IoT devices.

Moreover, the total throughput system when the UAV is positioned at a given position can be formulated as follows [13].

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr} P_s^{IoT} T_s + P_{tr}(1-P_s^{IoT}) T_c}, \tag{8}$$

Where P_{tr} is the probability that at least one slot time contains a transmission, $E[P]$ refers to the average packet payload size and σ, T_s, T_c, refer respectively to times for an empty slot, time for successful transmission and time for a collision and P_s^{IoT} is the probability of transmitting successfully by an IoT which can be expressed by:

$$P_s = N\, q_j\, P_{cov_j} \prod_{k \in N \setminus j} (1 - q_k P_{cov_k}) \tag{9}$$

With j is an IoT and q is the probability to transmit on the channel, the station access the channel according to Distributed Coordination Function (DCF) scheme [8].

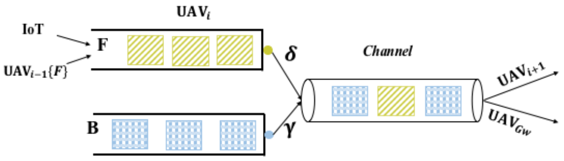

Fig. 3. UAV_i Configuration.

B. The queuing model

In our model, each UAV_i associate two queues. The first one is the *Forwarding* queue F_i that carries data packets originated from IoT device in order to send it to a Processing Unit (PU) through UAV network and a gateway. The queue F_i sends a packet with a probability δ_i. The second one is the *Beacon* queue B_i who carries beacon packets in order to announce the presence of UAV_i as stated in figure 3. Also the B_i chooses to send a packet with a probability γ_i. Furthermore, the network layer always has a beacon frame to send it periodically, unlike the queues F_i which can be empty. At any time, a drone have two kinds of packets: packet from F_i or B_i. Consequently, an UAV_i decide on which a packet wants to forwarded while using Weighted fair queuing (WFQ) [18].

The assumptions used in this paper are asserted below:

- **Network communications:** There are two types of communication channel in our model: Ground-to-UAV (G2UAV) and UAV-to-Ground (UAV2G). Both communications use different frequencies and channels access schemes. We deploy a standard IEEE 802.11s in our model, where the IoT_s refer to the station STA, UAV_s represent Mesh AP (MAP) and the gateway is Mesh Portal (MP).[10]
- **Saturated nodes:** Each UAV has always a beacon packet to send it toward an UAV or IoT. Also, all the ground IoT devices N are covered by an UAV, have always packet to transmit. we assume that all the packets has the same size.
- **Storage capacity of UAV:** Consider that the queues have a infinite capacity storage in order to overcome that the packets arrive to the queue found it full which lead to drop packets.
- **Neighbors of UAV:** We assume that each UAV_i has the same number of neighbors $Ng(i)$, we therefore talk about ”Boundary effect”.
- **UAV numbering:** In the following, the drones are numbered in an ascending way depending to the direction of packet traffic. The smallest index shall be assigned to the UAV which has the smallest radius of rotation, This way the highest index takes place at the edge of the UAV network; the closest to the gateway.
- **Routing:** In this paper, we assume that each UAV_i (i^{th} index) is configured to send their packets to a next hop index UAV_{i+1}, when the destination desired is a gateway.

For any given UAV_i the success probability of a transmission occurring on the channel is [16] :

$$P_{i,j} = q_i\, \xi_{i,j} \prod_{k \in Ng(i) \setminus i} (1 - q_k \xi_{k,j}), \tag{10}$$

where q_i is the transmission probability on the channel either for an IoT or drones and $\xi_{i,j}$ refer to the contact probability of two UAV_s i and j which is given by [17]:

$$\xi_{i,j} = \frac{1}{\pi} \arccos\left(\frac{r_i^2 + r_j^2 - d_{tx}^2}{2 r_i r_j}\right), \tag{11}$$

the d_{tx} represent the transmission range and j can be the next or the previous $UAV$of $UAVi$.

III. QUEUING ANALYSIS

The specific aim in this section is to find out some properties of the queues F_i, while using the rate balance equation for each drone. In order to derive these properties, we are interested to provide an expression of inner flows and departure flows for each drone and also the end-to-end throughput between a couple of drones.
For a way of thinking, each drone possesses a several system parameters such as: θ_i, δ_i, h_i, λ_i which can be regulated in such a way to preserve stability of flows and improve the end-to-end throughput. In the following, we will obtain the stability of the queue F_i in terms of the cited parameters above.
We assume, at any instant, the queue F_i has π_i^F load to be transmitted to the other UAV, and the queue B_i has always a packets to sent it periodically.

Knowing the π_i^F of each drones, we can reveal the margin of each parameters that ensure stability.

A. Departure flow

Departure flow is the probability that a packet leaves the queue F_i relaying from UAV_i to any UAV situated in the network, we denote by $d_{i,s,d}^F$ the departure rate of packets originating from node UAV_s (drone source) to reach the destination d which can be expressed by:

$$d_{i,s,d}^F = \frac{\pi_{i,s,d}^F\, \delta_i}{C_i}\, q_i\, \xi_{i,i+1}, \tag{12}$$

Also, let [17] :

$$C_i = \sum_s \pi_{i,s}^F\, \delta_i L_{i,s} + (1 - \pi_i^F\, \delta_i) L_{i,i} \tag{13}$$

be the average length in slots rime. of a cycle and L_i is the number of attempts till success or failure.

$$L_{i,s} = \frac{1 - (1 - P_{i,i+1})^K}{P_{i,i+1}} \tag{14}$$

While K represent the maximum number of collision after K attempts the packet is dropped.

In our case we have one destination which is the Processing Unit (PU) ($d^F_{i,s} = d^F_{i,s,PU}$).

$$d^F_{i,s} = \frac{\pi^F_{i,s}\,\delta_i}{C_i}\, q_i\, \xi_{i,i+1}, \tag{15}$$

Let $\pi^F_{i,s}$ be the probability that the queue F_i has at least one packet in the first position to be transmitted from source UAV_s. Then, the probability that the queue F has at least one packet to be send it is: $\pi^F_i = \sum_s \pi^F_{i,s}$.

Noted that, the total departure flow is given by:

$$d^F_i = \begin{cases} \displaystyle\sum_{s=1}^{i} \frac{\pi^F_{i,s}\delta_i}{C_i}\, q_i\ \xi_{i,i+1} & if \quad i \neq GW \\ \displaystyle\sum_{s=1}^{i-1} \frac{\pi^F_{i,s}\delta_i}{C_i}\, q_i\ \xi_{i,i+1} & if \quad i = GW \end{cases} \tag{16}$$

B. Inner flow

The inner flow represent the probability that a packet enter to the *Forwarding* queue from the IoT devices and then got transmitted to a gateway reach the PU. Hence, the arrival flow coming from IoT objects to each UAV_i can be given by:

$$a^F_{i,i} = \frac{S}{N_i+1}\, N t_i\, P_{cov}. \tag{17}$$

Then the inner flow arriving from UAV_s to intermediate UAV_i is expressed as:

$$a^F_{i,s} = \frac{S}{N_s+1} N t_s\, P_{cov}\, \pi^F_{s,s}\, \delta_s \prod_{k=s}^{i-1}(1-(1-P_{k,k+1})^K) \tag{18}$$

Note that the gateway doesn't covers ground users. Consequently, the global arrival at node i from several sources can given by:

$$a^F_i = \begin{cases} a^F_{i,i} + \displaystyle\sum_{s=1}^{i-1} a^F_{i,s} & if \quad i \neq GW \\ \displaystyle\sum_{s=1}^{i-1} a^F_{i,s} & if \quad i = GW \end{cases} \tag{19}$$

C. The rate balance equation

We can say that a queues F_i is stable if and only:

$$a^F_i = d^F_i \tag{20}$$

The load of queue F can given by:

$$\pi^F_i f_i = \begin{cases} \dfrac{C_i}{\xi_{i,i+1}} \left(a^F_{s,s} + \displaystyle\sum_{s=1}^{i-1} a^F_{i,s} \right) & if \quad i \neq GW \\ \dfrac{C_i}{\xi_{i,i+1}} \displaystyle\sum_{s=1}^{i-1} a^F_{i,s} & if \quad i = GW \end{cases} \tag{21}$$

D. End-to-End Throughput

The end-to end throughput is the rate at which the packets from UAV_s reaches the desired destination which is Processing Unit, we consider the probability of success between the gateway and PU equal 1, then:

$$Thp^F_{s,PU} = a^F_{PU,s} = a^F_{Gw,s} \tag{22}$$

IV. NUMERICAL RESULTS AND SIMULATIONS

In this section, we show numerical results for traffic intensity of the forwarding queue and the End-to-End Throughput. Furthermore, we consider a symmetric network formed by 4 drones and a gateway as shown in Fig. 4.

A. Symmetric case equations

For the sake of simplicity, the following paragraph exhibits the case of symmetric UAV_s. Each UAV has the same transmit power, Angle of aperture and altitude h. Then:

$$N = \lambda\pi \tan^2\left(\frac{\theta}{2}\right) h^2 \tag{23}$$

The radius of rotation of UAV_i can be expressed as follows

$$r_i = \frac{V_1}{\omega_1} + (i-1)(d_{tx} - z) \tag{24}$$

where z variation of distance and d_{tx} is the transmission range. We can express the contact probability between two UAVs in our system with m UAVs as:

$$\bar{\xi} = \sum_{i=1}^{m} \sum_{j=i+1}^{m+1} \frac{\xi_{i,j}}{m} \tag{25}$$

Transmission from queue F of all successive hops, from UAV_s until the tagged packet arrives to the intermediate UAV_i, are all successful become:

$$D_{i,s} = (1-(1-P_s)^k)^{(i-s)}, \tag{26}$$

where $(i-s)$ represent number of hops between i and s.

B. numerical investigations

We consider a symmetric network formed by 4 drones and a gateway. The major parameters used for simulation are fixed as stated below: V=8 m/s, ω=2 rad/s, d_{tx}=10 m, m=4, B_1= 0.6, B_2= 0.11, N_o= -120 dBm f=2 Ghz, μ_{LoS}=1 dB, B= 36 dBm, P_t=10 dBm, EP =8184 bits, P_{tr}= 0.6, σ= 50 μs, T_s= 8982 μs, T_c= 8713 μs, q=0.6, n=3, K=4.

The figure 4 depicts the relation between the average traffic load of queue (π^F) as a function of forwarding probability δ. From the simulation results, we can observed that our system is not stable when the forwarding probability takes a small values; this means that the queue has a surcharge of packets inside network. Also, the drones nearest to the gateway have more charge in comparison with the furthest drones as shown in figure. They need to transmit their data packets in the fastest way in order to guarantee the stability of UAV Network.

Next we turn our attention to analyzing the end-to-end throughput for F queue as forwarding probability vary for several connections. As depicted in figure 5 the throughput increase up till the system becomes stable around $\delta = 0.5$. However, because of UAV_{Gw} doesn't gather any data directly from an IoT, the load intensity of queue F (π_{Gw}) is more relieved than UAV_4, UAV_3, UAV_2 and UAV_1 .

The figure 6 and 7 illustrate the average load and end-to-end throughput versus altitude h of drones. As shown, when

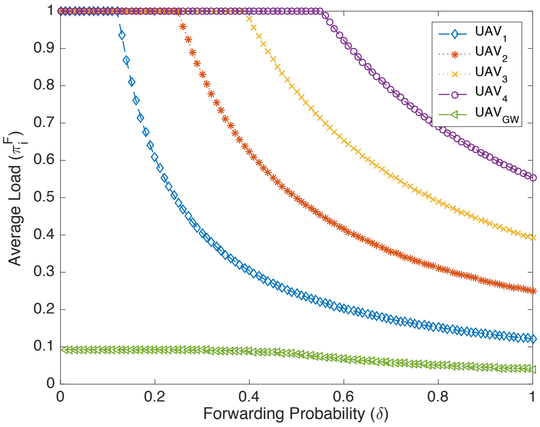

Fig. 4. Load of F queue Vs Forwarding probability.

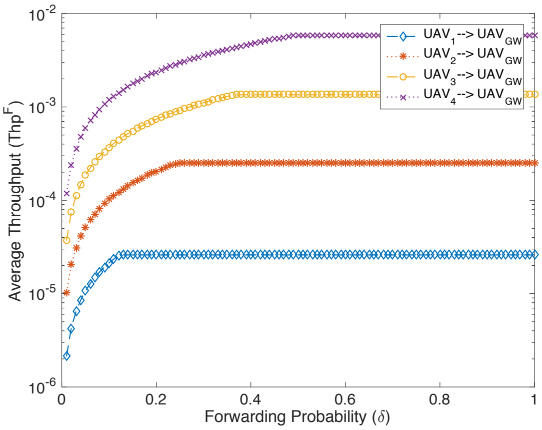

Fig. 5. End-to-end throughput for variable forwarding probability

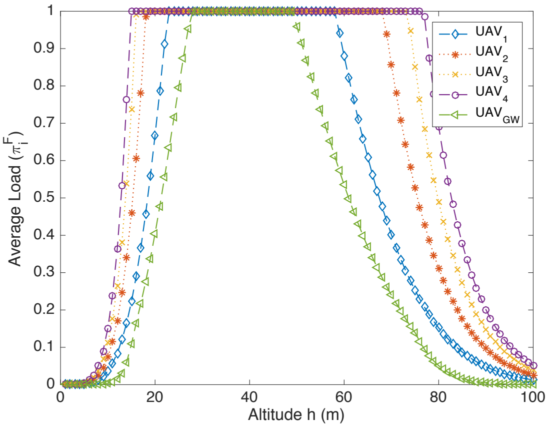

Fig. 6. Load of F queue Vs Altitude.

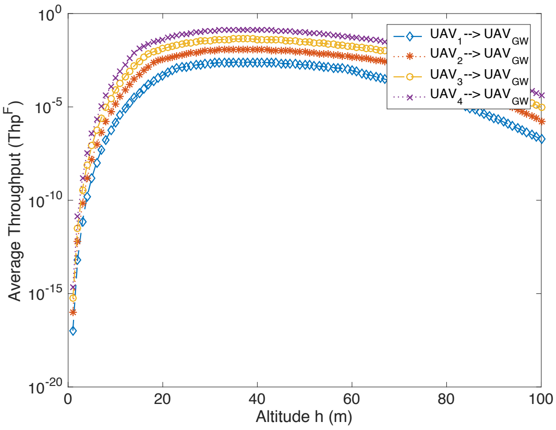

Fig. 7. End-to-end throughput for variable Altitude.

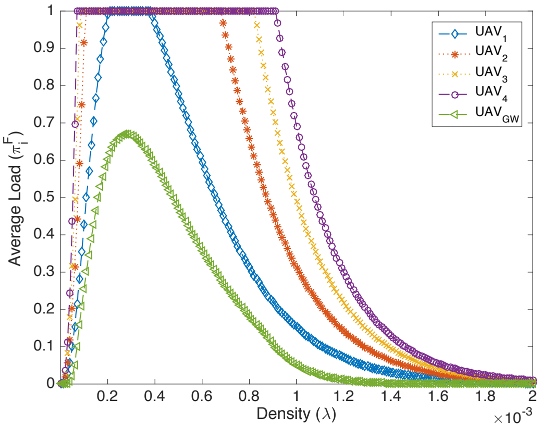

Fig. 8. Load of F queue Vs Density.

h takes the values between $20m$ and $80m$, the throughput for different connection between drones which constitute the network and the gateway is maximized, accordingly, the average load of queue F catch its peak when h take the same values as presented in figure 6. And when drones are placed at high altitude, the two metrics: Load and Throughput decrease. In turn, this corresponds to an increase of the numbers of IoT devices covered by each drones at any position. From a practical point of view, the reduction of load comes with a high number of collision packets.

In figure 8 and 9, we plot the average throughput and load against as function of density λ. In the similar manner as altitude the peak of the performance metrics occurs when λ= [0.0002 0.001] IoT/$m^2$and just after this value the curves decrease, The main reason behind it is, when these performance parameters increase the number of packets circulating in the network evolve, then more packets can be dropped due to the poor coverage.

Similar to the altitude, both figure 10 and 11 shown that increasing the angle of aperture, the load increase and the

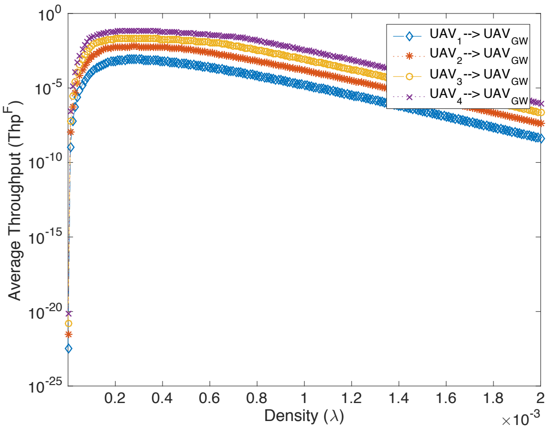

Fig. 9. End-to-end throughput for variable Density.

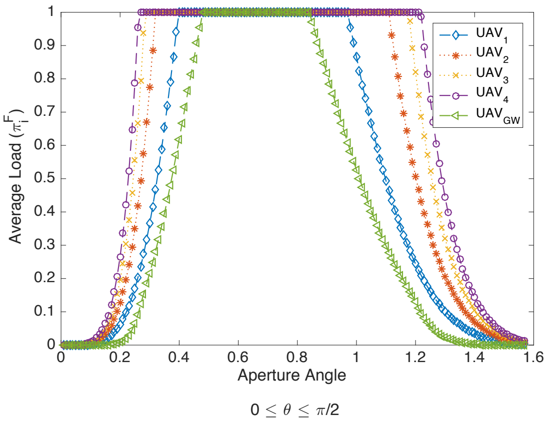

Fig. 10. Load of F queue Vs Angle of Aperture.

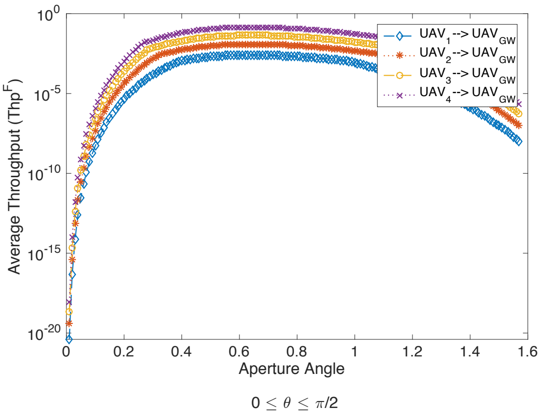

Fig. 11. End-to-end throughput for variable Angle of Aperture.

throughput increase until a margin $[\frac{\pi}{7}....\frac{\pi}{3}]$ and after this two metrics decrease .

V. CONCLUSION

This paper presents a queuing theoretic framework for flying mesh network which is designed to gather and forward data incoming from IoT environment. The mathematical model based on WFQ allows us to study the performance metrics such as traffic intensity and end-to-end throughput as function of altitude, density and angle of aperture. The finding result is the stability region as a function of these parameters. A perspective of this work is to analyze the end-to-delay performance in DFMN to adjust the network metrics in furtherance to ensure the end-to-delay bound.

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