Reliability of Cloud Controlled Multi-UAV Systems for On-Demand Services

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***Abstract*—Unmanned Aerial Vehicle (UAV) technology has been widely applied in both military and civilian applications. With the increasing complexity of application scenarios, the coordination of multiple UAVs has become a hot topic. However, the limited capability of UAVs make it hard to achieve stable and reliable control. Considering this practical problem, we propose a cloud-based UAV system. It extricates the computing and data storage from UAVs and utilizes the cloud to process the sensor data and to maintain the stable operation of multi-UAV systems. Firstly, we analyze the cloud-based system's on-demand service ability and its impact on UAVs' control procedure. Secondly, we propose a UAV cloud control system (CCS) which serves as a network control system. Moreover, the stable condition of the UAV cloud control system is derived. It reveals the relationship between the acquisition rate of sensor data and the stability of the cloud-based UAV system. Finally, simulations are conducted to verify the effectiveness of previous theoretical analysis.**

***Index Terms*—Cloud-based UAV system, mobile cloud computing, network control system, queueing theory.**

I. Introduction

Unmanned Aerial Vehicle (UAV) has been actively developed around the world. It can be used in many fields such as reconnaissance, fire fighting and disaster rescue, etc. As the application scenarios of UAV are becoming more and more intricate, it is difficult for a single UAV to meet the demand of such challenging tasks. Therefore, how to cooperate and coordinate multiple UAVs to accomplish complicated missions has become a hot topic [1].

When an UAV is executing tasks, it will collect and process sensor data as well as communicate with other UAVs. According to the plan of the United States Navy (USN), American warships may launch swarms of up to 30 UAVs coordinating in the future battle [2]. However, with the increasing of sensor's performance, task's complexity and swarm's size, challenges comes from the limited capability of UAVs such as resource scarceness, finite energy and low connectivity [3], [4]. As a result, mobile cloud computing (MCC), which can provide mobile users with data processing and storage services on the cloud [5], [6], is appropriate for multi-UAV systems. Relying on the architecture of MCC, we propose a cloud-based UAV system which incorporates the cloud computing capability into multi-UAV systems to improve the flexibility and scalability of the system.

As is shown in Fig. 1, the cloud-based UAV system is composed of the UAV front-end, the access network and the general static cloud (GSC). UAVs in the front-end form multiple cloudlets according to their location. They can communicate with other UAVs through wireless channel or connect to the GSC for computing services through access networks. The GSC is composed of a series of powerful immovable devices which can supply on-demand computing service for UAVs permanently to fulfill the control of the multi-UAV system. In each cloudlet, a UAV resource controller (URC) is selected, which allocates communication resources to other UAVs to improve the on-demand service capability.

In this system, data processing can be divided into two parts—the front-end computing within cloudlets for simple services, and the back-end computing supported by GSC for complicated services. Therefore, the performance of control also depends on the on-demand service capability of these two parts. The more and faster the sensor data is collected, the longer the processing response time of the system will be, which prolongs control delay and reduces stability. In order to analyze the stable condition of the multi-UAV system's control, we consider the control process of this system as a network control system [7], named UAV cloud control system (CCS) in this paper. In a nutshell, the contribution of this paper can be summarized as follows:

- We constitute the architecture of the cloud-based multi-UAV system and elaborate each part of the system.
- We define the on-demand service capability of the UAV front-end and GSC respectively. Moreover, we quantify the front-end on-demand service capability based on the resource allocation model, as well as the GSC service capability based on Jackson queue network.
- Relying on the impact of the time delay on the cloud-based multi-UAV system's control, we model the UAV's cloud control system as a switched control system and figure out the stable condition based on quantitative analysis.

The rest of this paper is organized as follows. The system model is described in Section II. The on-demand service capability of the UAV front-end and the GSC are analyzed in Section III. In Section IV, the stability condition of the CCS is derived. In section V, the relationship between the rate of data generation and system's stability is verified through sufficient simulations, followed by our conclusion in Section VI.

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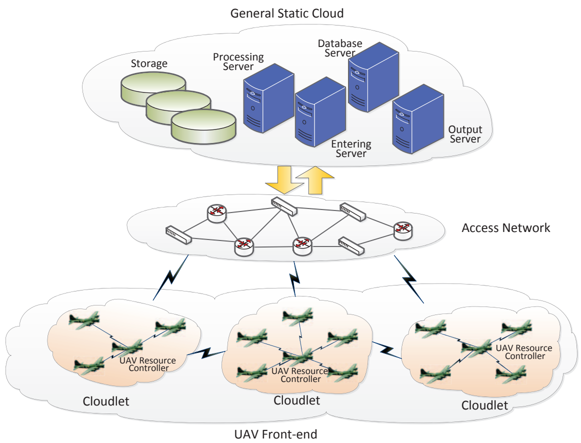


Fig. 1. The structure of the cloud-based multi-UAV system.

II. System Model

A. The on-demand service model of the UAV front-end

As is mentioned above, the UAVs are capable of communicating with the GSC through the URC. This indirect communication scheme is beneficial for information pre-fusion, which relieves the traffic load of access networks. Relying on the clustering and gateway selection algorithm [8],we assume that the URC in each cloudlet has already been selected and every cloudlet operates independently.

In the following, we will analyze one cloudlet for example. The UAV front-end can be considered as a slotted system, where the length of a time slot is the transmission time of a single packet . The URC schedules the allocation of each slot for other UAVs. If the wireless channel is time-varying, the resource allocation in each UAV cloudlet can be formulated as a adaptive slot allocation system. The left side of Fig. 2 shows the resource allocation scheme of a cloudlet. We can conclude that a high rate of data generation from UAVs will cause traffic congestion. In this case, the URC may break down and the UAV front-end cannot provide on-demand services efficiently. Hence, the highest rate of data generation supported by the URC can be deemed as the on-demand service capability of the UAV front-end.

At each time slot t, the URC can either support one of other UAVs or stay in an idle state. The control variable $U(t)$ represents the index of the UAV served by the URC at time slot t, and $U(t) = e$ when the URC is idle. The binary variable $C_i(t) = 1$ denotes that UAV i is connected to the URC at time slot t, while $C_i(t) = 0$ represents the opposite. When a UAV is supported by the URC, service will be completed with a certain probability. The random variable $M_i(t)$, which is related with the bandwidth of the communication link to URC, denotes whether the service is completed. Let $L_i(t)$ be the length of the queue in UAV i at time slot t. The arrival of the queue in UAV i is assumed to obey the Poisson distribution with parameter λ_i.

In this paper, we assume that the buffer capacity of each UAV is unlimited. Therefore, the stability analysis is mainly based on the sojourn time of UAV's queueing system. Let the independent and identically distributed (i.i.d.) stochastic process $A_i(t)$ denote the number of packets arriving at the queue of UAV i at time slot t and we get:

$$E\left[A_i^2(t)\right] \le A_{\max}^2. \tag{1}$$

The state of these parallel queues can be given by:

$$L_i(t) = \left[L_i(t-1) - I\left[U(t)=i\right]\cdot C_i(t)\right]\cdot M_i(t)^+ + A_i(t), \tag{2}$$

where $I[\boldsymbol{.}]$ is the indicator function of the event enclosed in the brackets, and $(\boldsymbol{.})^+$ is equal to the maximum value between $(\boldsymbol{.})$ and 0.

B. The on-demand service model of GSC

As is shown in Fig. 2, the data process procedure is modeled as a queueing system. In this model, GSC is composed of four parts. Specifically, the entering sever (ES) is the entry of the cloud. The processing server (PS) provides physical computational resources. The database server (DS) provides load balancer modules. Data accesses the DS with a probability δ according to the load balancing strategy, which is critical to enhance the congestion control and data availability of the system [9]. Finally, the output server (OS) transmits the control command back and the URC forwards the control command to the assigned UAV. Therefore, the sojourn time of the whole queueing system can be defined as the on-demand service capability.

Without loss of generality, ES, PS, DS and OS can be modeled as $4\ M/M/1$ queues with service rates relying on exponential probability density functions characterized by μ_e, μ_p, μ_d and μ_o, respectively. Considering the GSC is a powerful platform, we assume that each cloudlet is capable of obtaining the cloud service independently, and hence the queueing systems are stable with the arrival of the sensor data from UAV front-end. Let T_u, T_e, T_p, T_d and T_o represent the sojourn time for the five parts portrayed in Fig. 2. The sojourn time of the whole system can be described as:

$$T = T_u + T_e + T_p + T_d + T_o. \tag{3}$$

In this model, we focus our attention mainly on the response time of the system and the transmission delay is ignored.

C. The UAV structure of CCS

We model the operation processes of the system as a network control system, called CCS in this paper. In the CCS, GSC plays as a controller who receives and processes the data collected by UAVs and sends the control command back through access networks and the URC. After receiving the control command from GSC, the UAV adjusts its relevant parameters correspondingly. Since the data and the control command are both encapsulated into packets, we model CCS as a discrete-time linear time-invariant system, which can be described by:

$$\begin{cases} \mathbf{s}(k+1) = A\mathbf{s}(k) + B\mathbf{u}(k), \\ \mathbf{u}(k) = K\mathbf{s}(k-1), \end{cases} \tag{4}$$

where $\mathbf{s}(k) \in \mathbb{R}^n$ represents the state vector, and $\mathbf{u}(k) \in \mathbb{R}^n$ denotes the control input. Furthermore, A, B and K are the adjustment matrices of the CCS. Here we assume that the duration between time slots is the same as the control period. However, if the control command cannot reach the UAV in time, the UAVs will adopt the zero-control strategy, and we can get:

$$\mathbf{s}(k+1) = A\mathbf{s}(k). \tag{5}$$

Here, we provide a toy example of motion control to illustrate Eq. (4). We describe the state of each UAV as its position in a three-dimension space, i.e. $\mathbf{s}(k) = (x(k), y(k), z(k))^T$. Then, A is an adjustment matrix of the UAVs formulated as:

$$A = \begin{bmatrix} A'_1 \\ A'_2 \\ A'_3 \end{bmatrix} = \begin{bmatrix} a_{1x} & a_{1y} & a_{1z} \\ a_{2x} & a_{2y} & a_{2z} \\ a_{3x} & a_{3y} & a_{3z} \end{bmatrix}, \tag{6}$$

where vector A_1, A_2 and A_3 can be deemed as the adjustment vector of the UAV's speed, moving direction and noise, respectively. Moreover, K is another the adjustment matrix of GSC system described as:

$$K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} = \begin{bmatrix} k_{1x} & k_{1y} & k_{1z} \\ k_{2x} & k_{2y} & k_{2z} \\ k_{3x} & k_{3y} & k_{3z} \end{bmatrix}. \tag{7}$$

where the adjustment vectors K_1, K_2 and K_3 are similar to A_1, A_2 and A_3. The difference is that A focuses on UAVs, while K describes the whole system. Finally, B is a modification matrix of the received control command, which is a constant matrix.

III. The Analysis of On-Demand Service Capability

A. The on-demand service capability of the UAV front-end

We model the wireless channel between UAVs as a Rice fading channel. According to the path loss of the electromagnetic wave, if the gain of the transmitting and receiving antenna equal 1, the power of the received signal, which is transmitted between the URC and UAV i at the time slot t, can be formulated as:

$$GR_i^t = \left(\frac{3 \times 10^8 h_i^t}{4\pi r_i f}\right)^2 GT, \tag{8}$$

where GT is a constant transmitting power of UAVs. r_i denotes the distance between the URC and UAV i. f denotes the frequency of the signal. h_i^t represents the channel fading coefficient at time slot t complied to Rice distribution characterized by parameter (v, σ). Here we take $\sigma = 1$ for simplicity and h_i^t can be represented by two i.i.d zero-mean Gaussian variables as:

$$\left|h_i^t\right|^2 = x^2 + (y+v)^2, \tag{9}$$

where $x \sim N(0,1)$ and $y \sim N(0,1)$. Moreover, in the system which has been operating for a while, the arrival of the sensor data and the channel gain can be assumed to be stable. Therefore, the index t can be thrown away without loss of generality.

In order to judge whether the data is received successfully by the receiver, let β indicate the sensitivity of the UAV and the data can be received successfully only if $GR_i \geq \beta$. Additionally, let R present the service radius of the URC. Other UAVs distribute uniformly around the URC with distance $r_i \sim U(0, R)$. Since x, y and r_i are all independent, the connection probability between the URC and UAV i can be formulated as a function of v and R as:

$$\begin{aligned} &P_s(v,R) = \Pr\left[GR_i \geq \beta\right] \\ &= \iint\limits_{\substack{\left(\frac{0.3 h_i^t}{4\pi r_i f}\right)^2 GT \geq \beta \\ 0 < r_i \leq R}} \frac{1}{R} f(h_i)\, \mathrm{d}h_i\, \mathrm{d}r_i = \iiint\limits_{\substack{x^2+(y+v)^2 \geq \left(\frac{4\pi r_i f}{0.3}\right)^2 \frac{\beta}{GT} \\ 0 < r_i \leq R}} \frac{1}{2\pi R} e^{-\frac{x^2+y^2}{2}}\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}r_i, \end{aligned} \tag{10}$$

where $f(h_i)$ is the probability density function of h_i. The unit of r_i and R is kilometer and the unit of f is MHz.

As described in Section II-A, the UAV front-end can provide on-demand services while the queueing system is stable. The stability of queueing systems [10] can be defined as follows:

Definition 1. *The queueing system i is stable, if*

$$\lim_{t\to\infty} \Pr[L_i(t) < l] = F(l) \quad \textit{and} \quad \lim_{l\to\infty} \Pr F(l) = 1. \tag{11}$$

Here, we adopt a feasible policy named as fixed probability policy (FPP) for this parallel queueing system within the stability region [11]. Under the FPP, UAV i is capable of receiving the service from the URC with a fixed probability ω_i. At time slot t, if the service of the URC is allocated to UAV i and they are connected (i.e. $L_i(t) \neq 0$), a packet will be sent to the URC from UAV i. As a result, the state of each parallel queue can be considered as a Markov chain.

Let μ_g indicate the service rate of URC's output, which is also called the bandwidth of the URC's output. The arrival rate and service rate of each parallel queueing system are under negative exponential distribution characterized by λ_i and $\omega_i P_s(v,R)\mu_g$, respectively. Thus, the stability region of the UAV front-end with N queues can be described as:

$$\lambda_i \leq \omega_i P_s(v,R)\,\mu_g, \quad 1 \leq i \leq N, \tag{12}$$

where $\sum_{i=1}^N \omega_i = 1$.

B. The On-Demand Service Capability of GSC

In this section, we assume that the UAV front-end is stable. Therefore, the input to ES is the sum of the input from N queues. Since the data from each UAV is collected independently, the distribution of the data collected can be deemed as i.i.d, and the arrival of the data in ES is a Poisson process characterized by λ_e, which can be calculated as:

$$\lambda_e = \sum_{1\leq i\leq N} \lambda_i = N\lambda. \tag{13}$$

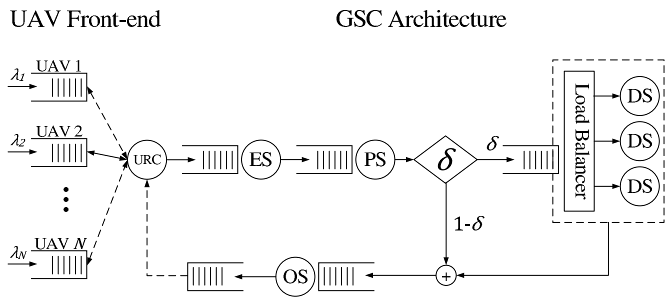


Fig. 2. The data processing structure of the cloud-based multi-UAV system.

Then, we assume that when the control command is sent back to the URC from OS, the URC will put it into buffer, which can be considered as the $(N+1)$th queue of the UAV front-end. Moreover, the URC allocates services to the control command queue with the probability of ω_{N+1}. When the control command queue obtain the service at a certain time slot, the URC will send the first packet of the control command queue to the corresponding UAV. Given that ES, PS, DS and OS are 4 $M/M/1$ queues and operate in proper order with a Poisson process based arrival, the architecture of GSC satisfies the requirement of an open Jackson network. According to the Jackson's theorem, the arrival of each queueing system in an open Jackson network is independent with each other. Hence, the arrival of the control command queue is independent with the other N parallel queues in the UAV front-end and the departure rate of the control command queue is $\omega_{N+1}P_s(v,R)\mu_g$, where v and R can be set as two constants for the operation ranges of UAVs are similar at the same time slot. Therefore, the control command queue can be modeled as an $M/M/1$ queue with the arrival rate $N\lambda$ and the service rate $\omega_{N+1}P_s(v,R)\mu_g$. Then the stability region defined in Eq. (12) can be rewritten as:

$$\begin{cases}\lambda \le \omega_i P_s(v,R)\mu_g, & 1\le i\le N,\\ \lambda \le \frac{\omega_i}{N}P_s(v,R)\mu_g, & i=N+1,\end{cases} \tag{14}$$

where $\sum_{i=1}^{N+1}\omega_i=1$. The floor of λ can be maximized when $\omega_1=\cdots=\omega_N={}^{\omega_{N+1}}/_N={}^1/_{2N}$.

Let T_{us} and T_{uc} represent the time delay of sensor data queue and the control commands queue in the URC, respectively. We can get $T_{us}\sim\exp\left({}^{P_s(v,R)\mu_g}/_{2N}-\lambda\right)$ and $T_{uc}\sim\exp\left({}^{P_s(v,R)\mu_g}/_{2}-N\lambda\right)$ [12]. As the arrival and the processing of each part in the GSC is independent, T_e, T_p, T_d and T_o are independent with each other. Relying on the arrival rate $N\lambda$ of ES, PS and OS, as well as $\delta N\lambda$ of DS, the total sojourn time of the system can be rewritten as:

$$T=T_{us}+T_{uc}+T_e+T_p+aT_d+T_o, \tag{15}$$

where $T_e\sim\exp(\mu_e-N\lambda)$, $T_p\sim\exp(\mu_p-N\lambda)$, $T_d\sim\exp(\mu_d-\delta N\lambda)$, $T_o\sim\exp(\mu_o-N\lambda)$ and $a\sim B(1,\delta)$. Since other parameters are constants in a certain system, the distribution of T is a function of λ, N and R [13], which can be reformulated as:

$$F(t)=\Pr(T\le t)=\delta f_6(t)+(1-\delta)f_5(t), \tag{16}$$

where $f_n(t)=\sum_{i=1}^n\prod_{j=1,j\ne i}^n\frac{\beta_j}{\beta_j-\beta_i}\left(1-e^{-\beta_i t}\right)$, and

$$\begin{cases}\beta_1=\frac{P_s(v,R)\mu_g}{2N-\lambda}, & \beta_2=\frac{P_s(v,R)\mu_g}{2-N\lambda}, & \beta_3=\mu_e-N\lambda,\\ \beta_4=\mu_p-N\lambda, & \beta_5=\mu_o-N\lambda, & \beta_6=\mu_d-\delta N\lambda.\end{cases} \tag{17}$$

IV. Stability Analysis of CCS

In this paper, the stability of the CCS is represented by the state of UAVs, i.e. $\mathbf{s}(k)$ in Eq. (4). Here, we adopt the definition of system stability [14] as follows:

Definition 2. *The system described in Eq. (4) is a globally exponentially stable system (with the stability degree $0<\sigma<1$) if there is a constant $\alpha>0$ such that $\|\mathbf{s}(k)\|\le\alpha\sigma^{-k}\|\mathbf{s}_0\|$ holds for all $k\ge0$. Here, $\|\centerdot\|$ presents the Euclidean norm.*

According to Eq. (4) and Eq. (5), the CCS can be considered as a discrete-time switched system with two subsystems. Let $A_1=A+BK$ and $A_2=A$ and the subsystem i can be rewritten as $\mathbf{s}(k+1)=A_i\mathbf{s}(k)$. In this paper, we assume the robust of the UAV is controlled very well, and the transfer function matrix of each subsystem is a normal matrix, which are the conditions to minimize the offset upper bound of a matrix's eigenvalues.

Let $l(k)$, which is not less than 1, denotes the number of switchovers between two systems in the interval $[0,k)$, and $k_1<\cdots<k_{l(k)}$ be the switching point over the interval $[0,k)$. During $[k_j,k_{j+1})$, where $j=0,\ldots,l(k)$ and $k_0=0$. we assume that the i_j-th subsystem is working. The switched system can be described as:

$$\mathbf{s}(k)=A_{i_{l(k)}}^{k-k_{l(k)}}A_{i_{l(k)-1}}^{k_{l(k)}-k_{l(k)-1}}\ldots A_{i_1}^{k_2-k_1}A_{i_0}^{k_1}\mathbf{s}_0. \tag{18}$$

In order to analyze the stability of this system, we come up with Lemma 1.

Lemma 1. *C is a $n\times n$ normal matrix, $\sigma_1,\sigma_2,\ldots,\sigma_n$ denote the eigenvalues of matrix C, and we have $\sigma_{\max}=\max(\sigma_1,\ldots,\sigma_n)$, $\forall k\in\mathbb{N}$. Then, we can get:*

$$\left\|C^k\right\|\le\sqrt{n}\left|\sigma_{\max}\right|^k. \tag{19}$$

Proof: Let $(C)^H$ denote the conjugate transpose of matrix C, and $tr(C)$ denote the trace of C. Since C is a normal matrix, according to the Cauchy-Schwarz inequality, we have:

$$\left[tr\left[\left(C^k\right)^HC^k\right]\right]^2\le tr\left[\left[\left(C^k\right)^H\right]^2\right]tr\left[\left(C^k\right)^2\right], \tag{20}$$

i.e.,

$$tr\left[\left(C^k\right)^HC^k\right]\le tr\left[C^{2k}\right]=\sum_{i=1}^n\sigma_i^{2k}. \tag{21}$$

Therefore, $\left\|C^k\right\|$ can be derived as:

$$\left\|C^k\right\|=\sqrt{tr\left[\left(C^k\right)^HC^k\right]}\le\sqrt{\sum_{i=1}^n\sigma_i^{2k}}\le\sqrt{n}\left|\sigma_{\max}\right|^k. \tag{22}$$

■

Then, let K_1 and K_2 represent the activated time of two subsystems during $[0, k)$, where $K_1+K_2 = k$. Furthermore, σ_1 and σ_2 denote the max eigenvalues of two subsystems, which benchmark the variance of the UAV's state in a subsystem. According to Lemma 1, Eq. (18) can be deduced as:

$$\begin{aligned} \|\mathbf{s}(k)\| &\le \left\| A_{i_{l(k)}}^{k-k_{l(k)}} \right\| \cdots \left\| A_{i_1}^{k_2-k_1} \right\| \left\| A_{i_0}^{k_1} \right\| \|\mathbf{s}_0\| \\ &\le 3^{\frac{l(k)+1}{2}} \sigma_1^{K_1} \sigma_2^{K_2} \|\mathbf{s}_0\| . \end{aligned} \tag{23}$$

Hence, we can conclude that the stability of the whole system mainly depends on σ_1, σ_2 and $l(k)$. Let τ_a denote the average dwell time of the system. It indicates that there may exist consecutive switchovers separated by the interval less than τ_a, but the average time interval between consecutive switchovers is not less than τ_a, i.e. $l(k) \le k/\tau_a$.

Let τ represent the length of one control period. Moreover, $F(\tau)$ and $1 - F(\tau)$ defined in Eq. (16) are the probability for the subsystem A_1 and A_2 to be activated, respectively. Let τ_i be the random variable which denotes the continuous-time for subsystem A_i to be activated in two adjacent switching interval. The joint probability of these two variables can be given by:

$$\Pr(\tau_1 = n_1, \tau_1 = n_2) = 2F(\tau)^{n_1+1}(1 - F(\tau))^{n_2+1}. \tag{24}$$

and the average dwell time can be calculated as:

$$\begin{aligned} \tau_a &= \frac{1}{2} E\left[(n_1 + n_2)\Pr(\tau_1 = n_1, \tau_1 = n_2)\right] \\ &= \frac{F(\tau)^2 + \left(1 - F(\tau)\right)^2}{F(\tau)\left(1 - F(\tau)\right)}. \end{aligned} \tag{25}$$

Since the subsystem A_1 indicates the complete process of the CCS. It is reasonable to assume that all eigenvalues of A_1 are in the open unit circle. In other words, A_1 is Schur stable and $\sigma_1 < 1$. Then we can conclude the stability condition of our switched system as follows:

Theorem 1. *If $\sigma_1 < 1$, then for any given $\sigma \in (\sigma_1, 1)$, the CCS is globally exponentially stable with the stability degree $n^{1/2\tau_a}\sigma$, if the switching scheme satisfies:*

$$F(\tau) > \max(a_1, a_2). \tag{26}$$

where a_1 and a_2 can be calculated as:

$$a_1 = \begin{cases} \frac{2-b+\sqrt{b^2-4}}{2(2-b)}, & 3^{-\frac{1}{4}} < \sigma < 1, \\ 0, & 0 < \sigma \le 3^{-\frac{1}{4}}, \end{cases} \tag{27}$$

where $b = {}^{\ln 3}/_{2\ln\sigma}$, as well as

$$a_2 = \begin{cases} \frac{\ln\sigma_2 - \ln\sigma}{\ln\sigma_2 - \ln\sigma_1}, & \sigma < \sigma_2, \\ 0, & \sigma \ge \sigma_2. \end{cases} \tag{28}$$

Proof: Eq. (23) can be deduced as:

$$\|\mathbf{s}(k)\| \le 3^{\frac{l(k)+1}{2}} \sigma_1^{K_1} \sigma_2^{K_2} \|\mathbf{s}_0\| \le \sqrt{3}\left(3^{\frac{1}{2\tau_a}}\sigma\right)^k \|\mathbf{s}_0\|. \tag{29}$$

Since $F(\tau)$ satisfies Eq. (26), then we have $F(\tau) > a_1$. According to Eq. (25) and Eq. (27), we obtain:

$$\tau_a > -\frac{\ln 3}{2\ln\sigma}. \tag{30}$$

Hence, we have:

$$3^{\frac{1}{2\tau_a}}\sigma < 1. \tag{31}$$

Hence the switched system is globally exponentially stable. ■

Then, we can analyze the physical meaning of Theorem 1. There are two factors to affect the variance of the state of the whole system. One is the switching of the whole system, the other is the variance caused by each subsystem. Specifically, a_1 restrains the average dwell time of the switched system in order to control the first effect factor, and a_2 restrains the proportion of two subsystems' working time.

V. Simulation Results

In this section, we verify the performance of our proposed cloud-based multi-UAV system relying on OPNET. The simulation time is set as 1000 s and the total number of UAVs is 30. Other important parameters are summarized in Table I.

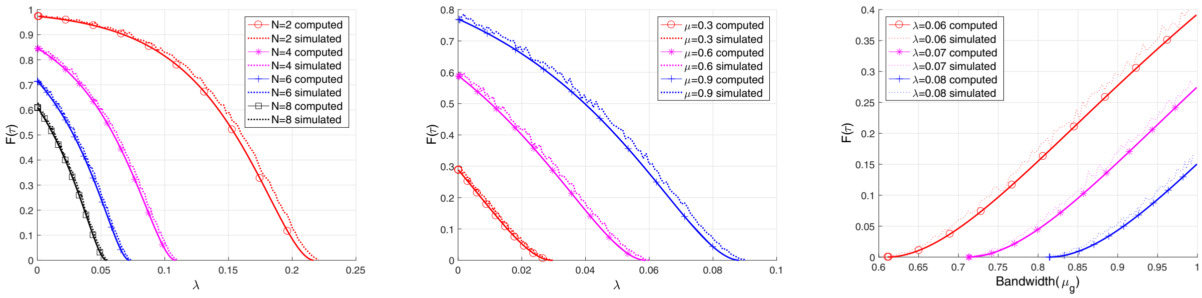
TABLE I
Simulation Parameters

	Description	Value
R	Service radius of the URC	3000 m
β	Receiving sensitivity	0.005 W
GT	Transmitting power	1 W
v	Speed of UAV	1 m/s
τ	Control period	20 ms
σ_1	Max eigenvalue of subsystems 1	0.6
σ_2	Max eigenvalue of subsystems 2	$(0, 3)$
N	Number of UAVs in a cloudlet	$2, 4, 6$
σ	Variance of the system's state	$(0.6, 1)$
λ	Average packet arrival rate per ms	$[0, 0.25]$
μ_g	URC's output bandwidth per ms	$[0, 1]$

Fig. 3(a) shows $F(\tau)$ versus λ characterized by different N. $F(\tau)$ indicates the probability of the response time of the whole system to be smaller than one control period of the UAV. The theoretical results and the simulation results are consistent. We can conclude that within the stability region, the probability decreases with the increasing of the rate of data generation λ and N. That is because the system should be more congested with a large λ and N and the response time will be prolonged.

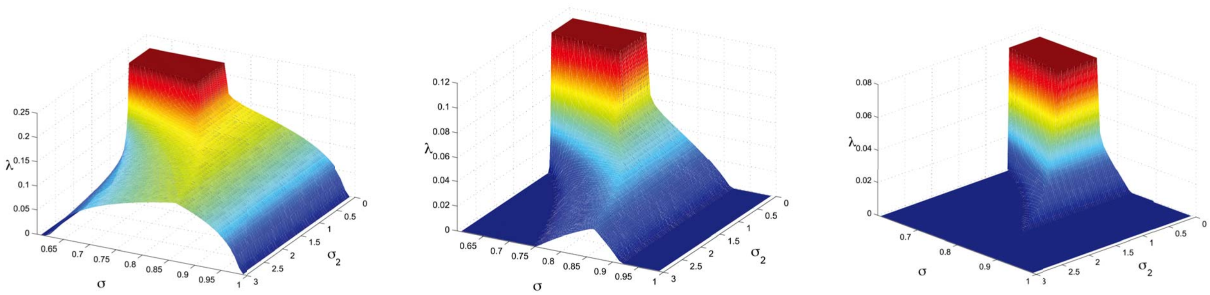
When $N = 4$, The effect of the bandwidth of the URC's output on the system's response time is shown in Fig.3(b) and Fig.3(c). When the μ_g is fixed, the increasing of data traffic will prolong the system's response time. By contrast, when λ is fixed, the increasing of the bandwidth will decrease the system's response time.

When $\sigma_1 = 0.6$, the relationship among λ, σ and σ_2 with different N is shown in Fig. 4. We can conclude that when σ and σ_2 are small, λ can achieve the maximum value. Specifically, when the state of the UAV varies gently, the data generation ratio can reach the maximum value indicated by the stability region of the UAV front-end. On the other hand, when the state of the UAV varies dramatically, the traffic of data should be reduced to stabilize the CCS. Moreover, the number of UAVs controlled by each URC will also restrain the rate of data generation. Specifically, when $a_1 = a_2$, λ will be much larger. It means that the control result of the average



(a) $F(\tau)$ versus λ characterized by N. (b) $F(\tau)$ versus λ characterized by μ_g. (c) $F(\tau)$ versus μ_g characterized by λ.

Fig. 3. Simulation results of time delay.



(a) $N = 2$. (b) $N = 4$. (c) $N = 6$.

Fig. 4. The relationship among λ, σ and σ_2.

dwell time and the proportion of the two subsystems' total working time are identical.

VI. Conclusion

In this paper, we proposed a cloud-based multi-UAV system. We analyzed the on-demand service capability of both the URC and GSC as well as the control procedure in order to find out the maximum rate of data generation that UAVs can achieve while the system works stably and reliably. Furthermore, relying on the open Jackson network theory, the on-demand service capability of the cloud system was proposed by analyzing each queueing system. We modeled the CCS as a discrete-time switched system and presented the stability condition of the CCS. Finally, we verified our theoretical analysis by sufficient simulations. The relationship of the rate of data generation and the stability of the cloud-based multi-UAV system was summarized.

Acknowledgement

This research was supported by NSFC China under projects 61371079 and 61471025.

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