Throughput Optimization of Cooperative UAVs Using Adaptive Channel Assignment

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Abstract— **The wireless link represents the bottleneck in the communication of a group of cooperative unmanned airborne vehicles (UAVs). Due to the high speed of the UAVs, the nature of the environments where they are usually deployed and the possible intentional jamming that might exist, the effect of phenomena such as multipath propagation and Doppler spread is more pronounced. In this paper, we propose an adaptive channel assignment (ACA) strategy for allocating the available bandwidth, which is divided into a number of sub-channels, over a number of communications links in a network of UAVs. The proposed ACA algorithm has two main advantages over the static channel assignment (SCA) approach. First, it maximizes the overall throughput of the UAVs network and second, it significantly reduces the probability of outage in the system defined as the percentage of time the links are incapable of supporting a minimum required transmission rate that is determined by the application. The ACA approach is formulated in terms of a binary optimization problem that is solved using the branch-and-bound method. We assume that the links in the network are Rayleigh faded and we use a finite state Markov chain (FSMC) for their modeling. Using Monte Carlo simulations, we show that the proposed channel assignment approach provides a significant gain in the overall throughput and reduction in the outage probability compared to the SCA.**

I. Introduction

Nowadays, unmanned airborne vehicles (UAVs) are being used in many civil applications such as agricultural applications, natural resource management and emergency response in addition to their original role in military applications. The main challenge that the UAVs missions face is the harsh nature of the communication links. The links in a network of UAVs suffer from many problems like power fluctuation of the received signal due to multipath propagation and the Doppler spread which becomes more severe at high speeds and large carrier frequencies. Besides, the limited weight of the UAVs imposes a restriction on the battery weight and consequently, limit their flight times. In [1], Edrich & Schmalenberger proposed using combined direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) to reduce the effect of interference on the UAV wireless links. Using DSSS/FHSS has the advantage of averaging the effect of interference but not avoiding it. Using adaptive channel assignment (ACA) with adaptive modulation and coding [2], it is possible to significantly reduce the effect of interference by assigning sub-channels to the links with better conditions (since these sub-channels experience a better signal-to-interference ratio (SIR) over that link). Two recent contributions [3], [4] showed that using the inherent frequency diversity of OFDM can optimize the network throughput by using adaptive modulation according to the channel state information (CSI) of each sub-channel.

The quality of service (QoS) and the utility-oriented bandwidth allocation was studied by Yaxin in [5]. This previous work can be applied to UAVs networks but with taking into consideration the complexity of the UAV channel. We adopt a finite state Markov chain (FSMC), previously introduced in [6] to model this channel.

In this paper, each UAV is assumed to have a certain QoS requirement, which depends on the application that this UAV is assigned for. Our objective is to maximize the network throughput and to reduce the system outage through adaptive (dynamic) channel assignment of a group of sub-channels while satisfying the minimum rate requirement of each link. We formulate the channel assignment problem as a binary optimization problem that can be solved using the branch-and-bound method.

The rest of this paper is organized as follows. In Section II, the network model of cooperative UAVs master/slave topology is discussed. Then in Section III, the finite state Markov chain model (FSMC) of the Rayleigh fading channel is detailed. In Section IV, the optimization problem is formulated. In Section V, the simulation and numerical results are presented before the paper is finally concluded in Section VI.

II. The Network Model

A. Network Topology

Consider a group of cooperative UAVs located in one spatial layer, the proposed network architecture is shown in Figs. 1 and 2 for the downlink and uplink directions, respectively. In this topology, each slave UAV (such as UAV2, for example) transmits its data to the master UAV (UAV1 in Fig. 1), which in turn relays this information to the ground control unit (GCU). This topology has the advantage of consuming less power than direct transmission to the GCU. Each UAV requires one uplink channel through which the UAV flight control data and control information of the on-board sensor payload ca be transmitted. In the downlink direction, two channels are needed, one provides the position of the UAV, its flight path and navigation data as well as the internal state of the UAV and the sensor payload. The second downlink channel is responsible for providing real time transmission of the captured video data. Based on the collected data from the UAVs, the GCU makes the following decisions:

1) Choice of the Master UAV according to the UAVs position information.

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2) Antenna directivity according to UAV position and traveling path.
3) The sub-channels assignment for each link.
4) The power transmission level used for every link.

This control information is sent directly to all UAVs instantaneously after the decision is made by the GCU.

B. Network CSI

Assuming that we have n links $L_1, L_2, \ldots, L_N$ and that the available bandwidth (BW) is divided into K sub-channels $B_1, B_2, \ldots, B_K$, where $N < K$. The information in each link can be transmitted over any sub-channel. We assume that the channel state information (CSI) is known for each link/sub-channel combination in terms of SIR and is mapped into certain rates by using adaptive modulation. According to CSI, the available rate for each sub-channel is one of m values $R_1, R_2, \ldots, R_m$, where each rate is determined by the type of the modulation/coding used. Mathematically the CSI matrix can be written as

$$\mathbf{CSI}_{K\times N} = \begin{bmatrix} \mathrm{SIR}_{11} & \mathrm{SIR}_{12} & \ldots & \mathrm{SIR}_{1N} \\ \mathrm{SIR}_{21} & \mathrm{SIR}_{22} & \ldots & \mathrm{SIR}_{2N} \\ . & . & . & . \\ . & . & . & . \\ \mathrm{SIR}_{K1} & \mathrm{SIR}_{K2} & \ldots & \mathrm{SIR}_{KN} \end{bmatrix} \quad (1)$$

where SIR_{ij} is the received SIR when using sub-channel B_i over link L_j. The data rate matrix, $R_{K\times N}$, can be written as

$$\mathbf{R}_{K\times N} = \begin{bmatrix} r_{11} & r_{12} & \ldots & r_{1N} \\ r_{21} & r_{22} & \ldots & r_{2N} \\ . & . & . & . \\ . & . & . & . \\ r_{K1} & r_{K2} & \ldots & r_{KN} \end{bmatrix} \quad (2)$$

where r_{ij} is the available rate when using sub-channel B_i over link L_j and $r_{ij} \in \{R_1, R_2, \ldots, R_m\}$. The mapping between $\mathbf{CSI}_{K\times N}$ and $\mathbf{R}_{K\times N}$ can be achieved by using adaptive modulation and coding [7], [8], where a higher order modulation can be used over a sub-channel with better SIR while not exceeding a target bit error rate (BER) value. This will improve the rate for this sub-channel, and consequently, increase the overall throughput of the system. Now, if continuous rate adaptation [9] is used, r_{ij} can be expressed as

$$r_{ij} = \log_2(1 + \beta \times \mathrm{SIR}_{ij}) \quad (3)$$

where β is calculated from

$$\beta = \frac{-1.5}{\ln(5 \times \mathrm{BER}_{\mathrm{target}})} \quad (4)$$

and $\mathrm{BER}_{\mathrm{target}}$ is the required minimum bit error rate.

III. Channel Model

The transmission channel used in UAVs communication will suffer from scattering and reflection that results in multipath propagation. Each path will be associated with a specific propagation delay and attenuation factor depending on the path conditions. The received signal envelope fluctuations can usually be modeled by a Rayleigh distribution [10]. Moreover, the motion of UAVs in space will result in variations in the transmitted signal level, which is known as Doppler frequency shift.

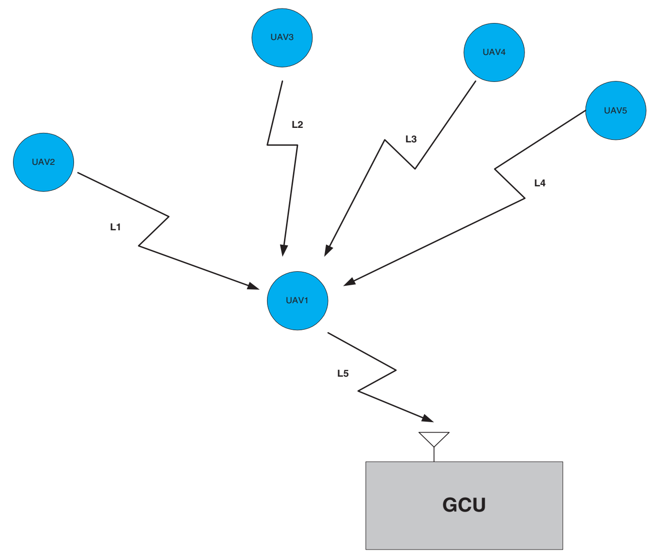

Fig. 1. Downlink transmission for one GCU with one spatial layer scenario.

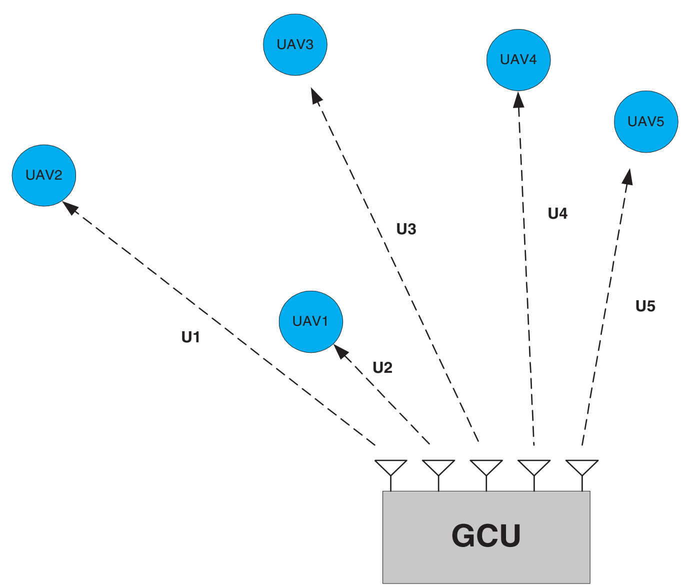

Fig. 2. Uplink transmission for one GCU with one spatial layer scenario.

Based on the fact that the received SIR, is proportional to the square of the received signal envelope, which is Rayleigh distributed, SIR has the following exponential probability density function (PDF) [10]:

$$P(\gamma) = \frac{1}{\rho} \exp\left(\frac{-\gamma}{\rho}\right) \quad (5)$$

where ρ is the average value of the received SIR. The worst case value (maximum value) of the Doppler spread, f_m on the

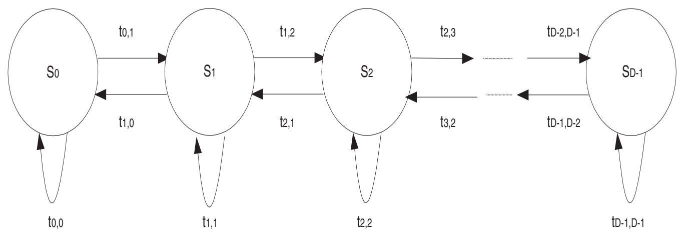

Fig. 3. D-State FSMC modeling of a Rayleigh fading channel.

link can be taken as

$$f_m = \frac{v}{\lambda} = \frac{v \times f_c}{c}. \tag{6}$$

where v is the velocity, f_c is the carrier frequency and $c = 3\times10^8$ m/s is the speed of light. From [6], the expected number of times per second that the received SIR passes downward across a given SIR threshold γ_i is given by

$$N_i = \sqrt{\frac{2\pi \times \gamma_i}{\rho}} \times f_m \times \exp\left(\frac{-\gamma_i}{\rho}\right). \tag{7}$$

We choose to model our channel using an FSMC model as explained in [6]. Towards that end, we need to find the state transition matrix $\mathbf{T}$ and the steady state probability vector $\mathbf{P}$. We assume that the SIR range is divided into D with SIR thresholds $\gamma_0 = 0 < \gamma_1 < \gamma_2 < \ldots < \gamma_{D-1} = \infty$. The Rayleigh fading channel is said to be in state $S_k, k = 0, 1, \ldots, D-1$, if the received SIR is in the interval $[\gamma_k, \gamma_{k+1}]$. Recall that according to (3) and using the lower limit, γ_k, of each SIR bin (as a worst case value of the SIR over the whole range), a certain rate can be achieved while in state S_k. The FSMC of the Rayleigh fading channel with D states can be represented as shown in Fig. (3). Note that, the only possible transition from any state is to either the same state or to its adjacent neighbors, which mathematically can be written as

$$t_{i,j} = 0, \quad \forall \quad |i-j| > 1 \tag{8}$$

where t_{ij} is the transition probability from state i to state j.

For our system we propose using OFDM sub-channels to transmit information over links between UAVs. Given that R_b is the available rate per sub-channel, then on average the rate achieved by this sub-channel while being in state k is $R_b^{(k)} = R_b P_k$, where P_k, the steady state probability of being in state k is given by

$$P_k = \exp\left(\frac{-\gamma_k}{\rho}\right) - \exp\left(\frac{-\gamma_{k+1}}{\rho}\right). \tag{9}$$

The Markov transition probabilities can be approximated by [6]

$$t_{i,i+1} \simeq \frac{N_{i+1}}{R_b^{(i)}}, \quad i = 0, 1, 2, \ldots, D-2 \tag{10}$$

$$t_{i,i-1} \simeq \frac{N_i}{R_b^{(i)}}, \quad i = 1, 2, 3, \ldots, D-1 \tag{11}$$

$$t_{0,0} \simeq 1 - t_{0,1} \tag{12}$$

$$t_{D-1,D-1} = 1 - t_{D-1,D-2} \tag{13}$$

$$t_{i,i} = 1 - t_{i,i-1} - t_{i,i+1}, \quad i = 1, 2, \ldots, D-2. \tag{14}$$

According to the previous discussion, the steady state probability vector $\mathbf{P}$ and the transition probability matrix $\mathbf{T}$ can be written as

$$\mathbf{P} = \begin{bmatrix} P_0 \\ P_1 \\ \vdots \\ P_{D-1} \end{bmatrix} \tag{15}$$

$$\mathbf{T} = \begin{bmatrix} t_{0,0} & t_{0,1} & 0 & \ldots & 0 \\ t_{1,0} & t_{1,1} & t_{1,2} & 0 & \ldots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \ldots & t_{D-2,D-3} & t_{D-2,D-2} & t_{D-2,D-1} \\ 0 & \ldots & 0 & t_{D-1,D-2} & t_{D-1,D-1} \end{bmatrix} \tag{16}$$

Transitioning to the adjacent states is based on the assumption of slow fading where the envelope of SIR changes slowly enough to stay in the same state or jump up or down to the adjacent state as it is clear in (16).

IV. Optimization Problem

After the GCU obtains the channel state information $\mathbf{CSI}_{K\times N}$, it maps it into the rate matrix $\mathbf{R}_{K\times N}$ for a certain acceptable BER using (3). We define an assignment matrix, $\mathbf{X}_{K\times N}$, which is given by

$$\mathbf{X}_{K\times N} = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1N} \\ x_{21} & x_{22} & \ldots & x_{2N} \\ . & . & . & . \\ . & . & . & . \\ x_{K1} & x_{K2} & \ldots & x_{KN} \end{bmatrix}. \tag{17}$$

where $x_{kn} = 1$ indicates that the sub-channel n is assigned to link k and $x_{kn} = 0$ otherwise. Now, the total throughput, THR($\mathbf{X}$), of the network can be obtained as

$$\mathrm{THR}(\mathbf{X}) = \sum_{k=1}^{K}\sum_{n=1}^{N} r_{kn} \times x_{kn} \tag{18}$$

where any sub-channel is used by only one link at any time to avoid any interference. This requirement can be formulated in the form of the following constraint:

$$\sum_{n=1}^{N} x_{kn} \leq 1, \quad \forall \quad k = 1, 2, \ldots, K. \tag{19}$$

The downlink topology shown in Fig. 1, in addition to the nature of the application for which the system of UAVs is used enforce an extra set of constraints as follows. Firstly, the application might require a minimum, $R_{n,\min}$, and a maximum value, $R_{n,\max}$, for the data rate R_n over link l_n. The minimum data rate is determined according to the nature of the application and is selected to satisfy a specific quality of service metric. On the other hand, the maximum rate represents the maximum utility that can be achieved for this application where any increase of the rate over this maximum value will result in a waste in the bandwidth and will provide no extra benefit for the application that this UAV is operated for. Hence, to get maximum utility of our available bandwidth the following constraints should be added to all links except the Master-GCU link (link j).

$$R_n \geq R_{n,\min}, \quad \forall \quad n \neq j$$
$$R_n \leq R_{n,\max}, \quad \forall \quad n \neq j. \tag{20}$$

Secondly, the use of a of Master-GCU link as a backbone of the network in the downlink transmission dictates the following constraint

$$\sum_{\substack{n=1 \\ n \neq j}}^{N} R_n + R_{j,min} \leq R_j. \tag{21}$$

It can be seen from (21) that the extra available rate when all non Master-GCU links reach their maximum rate will be assigned to the Master-GCU link. The optimization problem can now be summarized as follows:

$$\text{Maximize THR}(\mathbf{X}) = \sum_{k=1}^{K}\sum_{n=1}^{N} r_{kn}x_{kn}$$

Subject to

$$(1) \sum_{n=1}^{N} x_{kn} \leq 1, \quad \forall \quad k = 1, 2, \ldots, K$$
$$(2)\, x_{kn} \in [0, 1], \quad \forall \quad n = 1, 2, \ldots, N,\ k = 1, 2, \ldots, K$$
$$(3)\, R_{n,min} \leq \sum_{k=1}^{K} r_{kn}x_{kn} \leq R_{n,max}, \quad \forall \quad n \neq j$$
$$(4) \sum_{k=1}^{K}\sum_{\substack{n=1 \\ n \neq j}}^{N} r_{kn}x_{kn} + R_{j,min} \leq \sum_{k=1}^{K} r_{kj}x_{kj} \tag{22}$$

This adaptive channel assignment (ASA) scheme has two main advantages. The first is the reduction of the system outage time, which is a very critical issue in UAVs communications. The outage of any UAV means that the assigned bandwidth to this UAV is not enough to send the required minimum rate. This will produce some delay in acquiring the sensors and video data, so using adaptive OFDM channel assignment of the available bandwidth for all links will prevent or at least reduce the outage probability. The second advantage is maximizing the total throughput of the system which, in turn, increases the amount of collected data. This adaptive scheme will be compared with the static channel assignment (SCA) of the available bandwidth over all links for the same link conditions.

V. Simulation and Numerical Results

As an example, we assume a three-link topology as shown in Fig. (4). In our simulations, the three links L_1, L_2 and L_3 are assumed to experience Rayleigh fading with $\rho = 15$. We assume a 16-State FSMC model with SIR thresholds $[0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30]$. The SIR

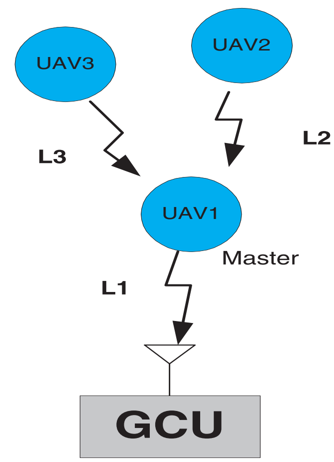

Fig. 4. A Three-Link UAV network Example.

TABLE I
Threshold & State-Rate Mapping

SNR Range	State	Rate(Mbps)
0-2	1	0
2-4	2	3.054
4-5	3	5.461
5-6	4	7.461
6-8	5	9.161
8-10	6	10.064
10-12	7	11.955
12-14	8	13.134
14-16	9	14.203
16-18	10	15.182
18-20	11	16.084
20-22	12	16.921
22-24	13	17.701
24-26	14	18.431
26-28	15	19.119
28-30	16	19.767

TABLE II
System parameters

Carrier Frequency	2.4 GHz
Total Bandwidth	80 MHz
Subchannel Bandwidth	8 MHz
Number of Subchannels	10
Number of links	3

TABLE III
Links parameters

Link Number	Velocity[m/s]	Average SNR
1	10	15
2	50	15
3	100	15

TABLE IV

TRANSITION MATRIX & STEADY STATE PROBABILITY VECTOR

k	$t_{k,k-1}$	$t_{k,k1}$	$t_{k,k+1}$	p_k
1	-	0.9993	0.0007	0.1248
2	0.0008	0.9983	0.0009	0.1092
3	0.0011	0.9978	0.0011	0.0956
4	0.0013	0.9974	0.0013	0.0837
5	0.0015	0.9970	0.0015	0.0732
6	0.0017	0.9967	0.0016	0.0641
7	0.0018	0.9964	0.0017	0.0561
8	0.0020	0.9961	0.0019	0.0491
9	0.0021	0.9959	0.0020	0.0430
10	0.0023	0.9956	0.0021	0.0376
11	0.0024	0.9954	0.0022	0.0329
12	0.0025	0.9952	0.0023	0.0288
13	0.0025	0.9952	0.0023	0.0252
14	0.0027	0.9948	0.0025	0.0221
15	0.0028	0.9946	0.0026	0.0193
16	0.0004	0.9996	-	0.1353

thresholds related to the FSMC model and the mapping of these states into rates are given in Table I. It is important to note that the rates shown in Table II might not be physically realizable. In other words, it might be difficult to find a mo-sulation/coding scheme that exactly provides such rates. The system parameters used in our simulations as well as the link parameters are summarized in Tables II and III, respectively. In Table III, the velocity entry corresponding to L_1 is the velocity of the master UAV relative to the GCU, while the entries corresponding to L_2 and L_3 are the velocities of UAV2 and UAV3, respectively, relative to UAV1. The transition probability matrix and the steady state probability vector for L_3 are given in Table IVas an example. We conducted 25000 simulation runs and the optimization algorithm was invoked in each run. We assume that the minimum required rates over L_1, L_2 and L_3 are $R_{1,\min} = 25$ Mbps, $R_{2,\min} = 25$ Mbps and $R_{3,\min} = 10$ Mbps, respectively. Also, the maximum rate constraint was relaxed in the example we are presenting. Figs. 5, 6 and 7 depict the changes in the achievable rate over links L_1, L_2 and L_3, respectively, vs. the simulation run with both ACA and SCA. We use these figures to calculate the outage probability in each of ACA and SCA. We consider that the system is in outage if any of the links fail to support their minimum rate constraint. Also, it is important to note that the Master-GCU link (L_1 in our example) needs to support its minimum requirement as well as the achievable rates over the other links in the network. From these figures, and based on the minimum rate requirements on each link mentioned earlier, we can arrive at the interesting observation that the outage probability using ACA is found to be 0% while it reaches about 98% in the SCA case, which clearly proves the superiority of the proposed ACA scheme.

In Fig. 8, the overall throughput of the UAVs network is shown. The average throughput and the average rate of the three links were calculated and are shown in Table V. The advantage of using ACA over SCA is, again, very obvious where a 26% improvement in the overall average throughput is observed when using ACA. We expect to obtain even more

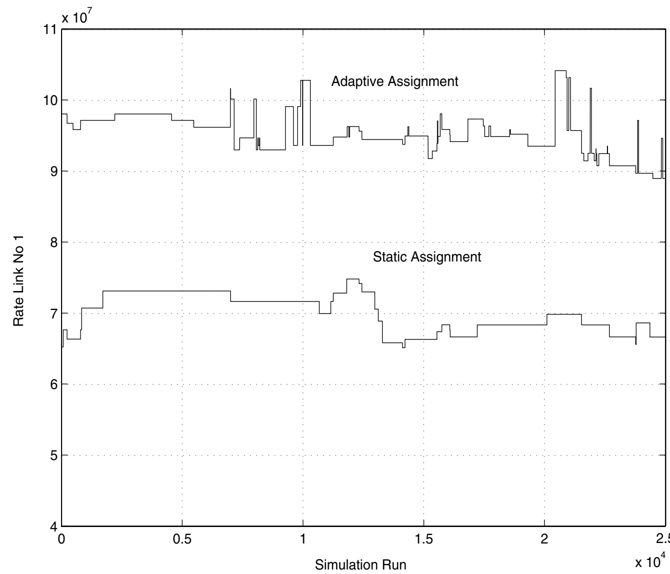

Fig. 5. Rate of Link No.1 Using ACA and SCA.

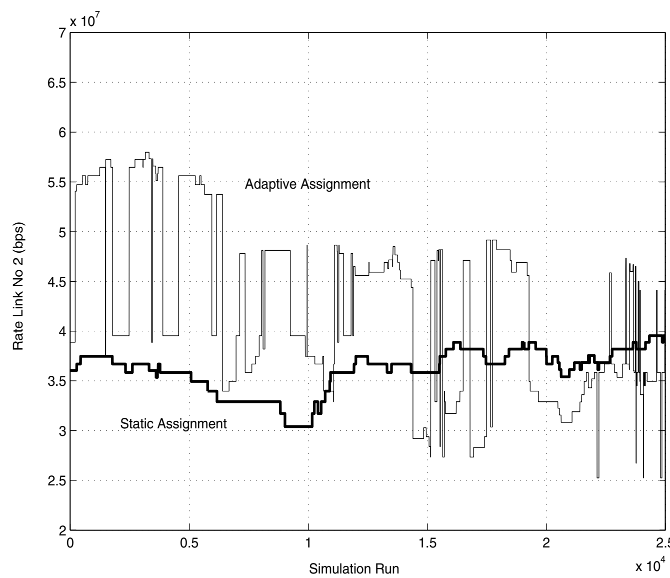

Fig. 6. Rate of Link No.2 Using ACA and SCA.

improvement in the overall average throughout as we increase the number of sub-channels. It should also be mentioned here that the mechanism of getting the CSI, the required rate in downlink to transmit such information, in addition to the required rate in uplink needed to provide control information about the assigned sub-channels will reduce the expected 26% throughput gain. This reduction will further investigated and is beyond the interest of this paper.

VI. CONCLUSIONS

The UAVs wireless channel has a very complex nature because of their high speed and their limited power capabilities. In this paper, adaptive channel assignment was studied in UAV communications to maximize the network throughput

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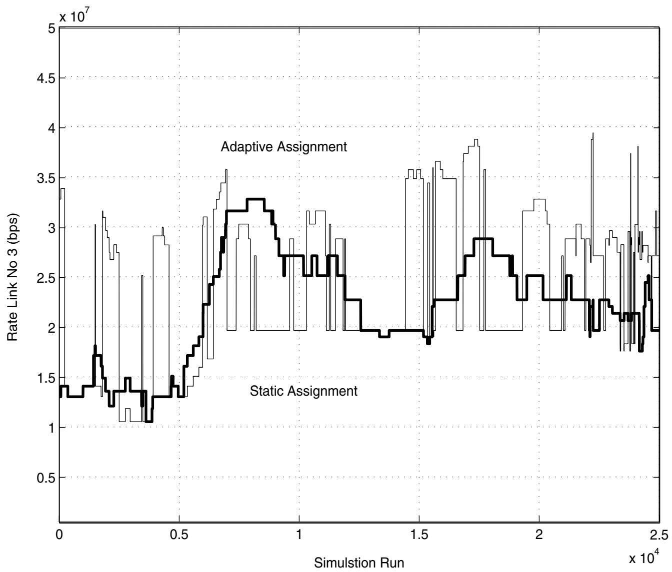

Fig. 7. Rate of Link No.3 Using ACA and SCA.

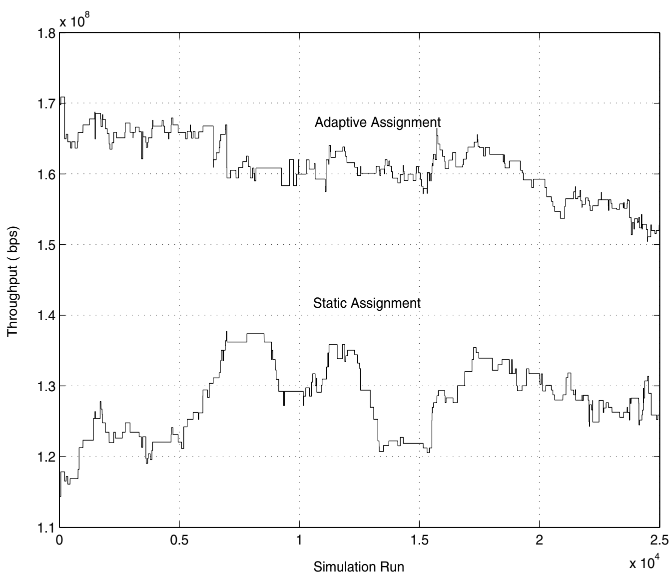

Fig. 8. Overall network throughput using ACA and SCA

TABLE V
AVERAGE THROUGHPUT WITH ACA & SCA

Link Number	ACA [Mbps]	SCA [Mpbs]
1	95.222	69.909
2	42.122	36.056
3	23.869	22.011
All	161.213	127.976

and reduce the outage probability of the system. The use of adaptive channel assignment helps to avoid interference, which can cause the loss of valuable information that might affect critical decisions if a UAV goes out of the GCU control. Using Monte Carlo simulations, we showed how our proposed scheme can result in significant gains in the achieved throughput and reduction in the overall system outage probability. We expect more improvement in the overall average throughput using more sub-channels given the same available bandwidth.

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