Cooperation between Unmanned Aerial Vehicles and Wireless Cellular System

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***Abstract*—We consider the cooperation of Unmanned Aerial Vehicles (UAV) with wireless cellular mobile systems. UAVs collaborate closely with Base Stations (BSs) when they are occasionally present in the coverage area of a BS. From the tele-traffic point of view, UAVs can provide additional capacity to cellular BSs such as to alleviate saturation conditions during periods of high traffic congestion. The assignment of traffic channels works as follows; when a call arrives to the system it is assigned to any free channel of the BS. If all channels of the BS are busy, the call is assigned to any free channel of any present UAV. If all channels of the present UAVs are busy, the call is lost. When a call served by a given BS ends, any other call in progress on a UAV, if any, is transferred to the released channel of that BS. When a UAV leaves the coverage area of the BS, the calls in progress in that UAV are transferred to the idle channels of other UAVs, as many as possible; and calls that cannot be transferred are lost. The scenario under study is modeled as a 2-D Markov process. One dimension takes into account the number of UAVs present in the system and the other dimension deals with the number of calls in progress. We evaluate, i) the blocking probability of new calls, ii) the forced termination probability of ongoing calls, iii) when an ongoing call ends at the BS, the probability of transferring an ongoing call from a given UAV to that BS, and iv) when a UAV leaves the service area, the probability of transferring its ongoing calls to another UAV.**

***Keywords*—Unmanned Aerial Vehicle, Quasi-Birth-Death process.**

I. INTRODUCTION

Unmanned Aerial Vehicles (UAV) are identified as aircraf without humans on board. They can support a variety of services such as agriculture applications [1], remote sensing [2], wireless internet services and telephone services, the support to cellular system during high traffic load situation [3], among others private business [4]-[7]. Also, see [8] for a nice survey.

The concept of UAV also has been commonly recognized as Remotely Piloted Aerial System (RPAS), more commonly known as "drones". In fact, the term "autonomous helicopter" was predominant until 2015 when the term drone became more usual when referring to unmanned aircrafts [1]. UAVs are located at the troposphere, with a maximum altitude of 10 Km. roughly speaking. We also mention the concept of High-Altitude Platform Stations (HAPS). HAPS are usually Unmanned Aerial Systems (UAS) located above the commercial jet air planes, in the stratosphere, between 10 Km and 50 Km altitude, approximately [9]. HAPS can provide intensive computing and can endure at a fixed position in opposite with the lower computing capacity and less endure or presence of UAVs; but they can closely cooperate in a hierarchical manner for various Internet of Things (IoT) applications [10].

In this paper, we analyze the use of such UAVs that from time to time are present in the coverage area of a given cellular Base Station (BS). When one BS is fully busy, the new traffic load is offered to some UAV present in the coverage area of the BS. If all the present UAV are fully busy, the traffic is lost.

As soon as a call in progress on the BS ends, any call in progress on any UAV is handed over the released channel of the BS. In fact, it is a reassignment to a new channel of a call in progress, a repacking procedure. When one UAV leaves the coverage area of a BS, as many calls as possible in progress at the UVA are transferred to other free channels of the present UAVs, while the rest are forced to finish.

Key Performance Indicator (KPIs) parameters are, among others, the blocking probability of initial fresh calls, the probability that one ongoing call in a UAV be transferred to a BS, a handover procedure, and due to the exit of one UVA from the system, the forced termination probability of admitted calls in progress, the probability distribution function of the number of interrupted call in progress in one UAV, and the probability distribution function of the number of calls that are transferred from the leaving UAV to the other present UAVs.

The analysis is carried out using Markovian tools. In particular, we identify the scenario of a single BS with several UAVs potentially present in the coverage area. A Quasi-Birth-Death (QBD) process is obtained and the mentioned KPIs are expressed in a closed form solution.

The structure of the paper is as follows. After Section I, the analytical model is presented in Section II. Section III shows the key system parameters, such as the blocking probability of new calls, the forced termination probability, the distribution of calls that are forced to terminate and the handover signaling traffic load. Numerical results derived from the analytical model are presented in Section IV. The paper ends with some basic conclusions in Section V.

II. THE MODEL

We assume a single BS with a total number of P primary channels. A finite number of V UAVs are occasionally present in the coverage area of the BS. The presence versus absence of

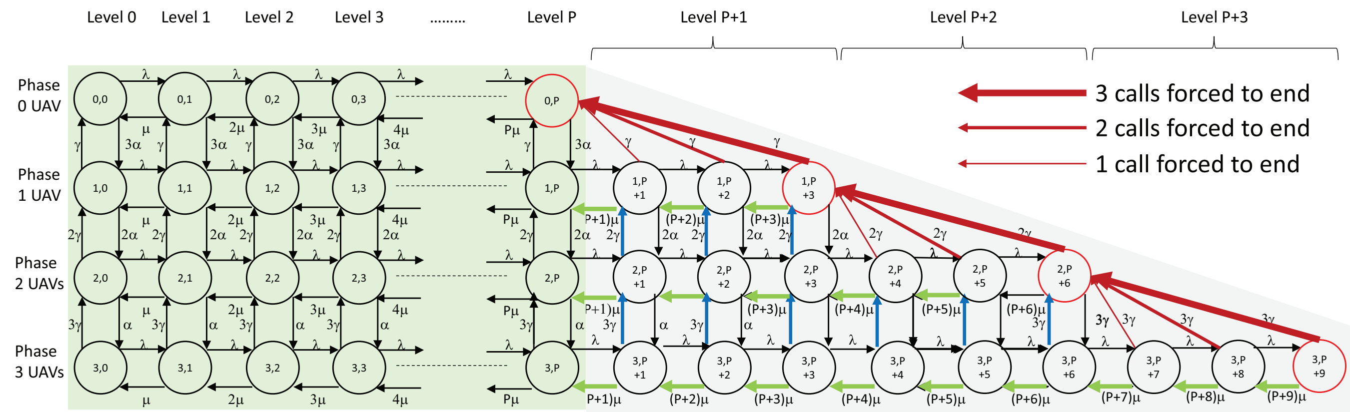

Fig. 1. The 2D Markov process for a number of $UAVs$, $V = 3$, for a number of secondary channels per UAV, $S = 3$ and for a generic number of primary channels, P.

one UAV follows an ON-OFF process. Each UAV is equipped with S secondary channels.

A. The admission of arrival calls

When a new or fresh call arrives to the system, first, it will be allocated to one idle primary channel of the BS, if any. If all primary channels are busy, the call will be allocated to one idle secondary channel of one UAV, if any. Otherwise, the call is lost.

B. The departure of calls. The repacking of ongoing calls

When one call in progress in a given primary channel ends, the released primary channel will be assigned to any call in progress in the secondary channels of an arbitrary UAV, if any. This is, in fact, a handover procedure of a call in progress in any UAV to the BS.

C. The departure of a UAV from the coverage area of a BS

When one UAV abandons the system, as many calls as possible that are in progress in this UAV will be reallocated to other UAVs, that is, a handover process is performed from the leaving UAV to others UAV with some free secondary channels. Other calls that are not possible to be reassigned are forced to terminate.

D. The analytical model

Arrival calls follow a Poisson process with rate λ. The service call is assumed to be exponentially distributed with rate equal to μ. Individually, the presence of one UAV in the coverage area of the BS follows an exponential distribution with rate γ and the absence of the system of this UAV is also exponentially distributed, with rate α.

E. The Quasi-Birth-Death process

Figure 1 illustrates the Markov process for an arbitrary number of primary channels, P, and a total of $V = 3\ UAVs$, each one equipped with $S = 3$ secondary channels. Easily, we identify a Quasi-Birth-Death process (QBD) process where the *levels* are the block structure, from 0 to $P + V$ and the *phases* are the intra-block structure, from 0 to V. To be more precise, according to Figure 1, each level between 0 and P is composed of a single column of states, while each level between $P + 1$ and $P + V$ is composed of S columns of states. Notice that each block in the *level* interval $[0, P]$ has $V + 1$ phases, and the range of phases on each block in the level interval $l \in [P + 1, P + V]$ is $[l - P, V]$. Observe that the block size in the level interval $l \in [0, P]$ is $V + 1$ states while the block size in the level interval $l \in [P + 1, P + V]$ is $S * (V + P + 1 - l)$ states. In other words, the top first row of states in Figure 1 reflects that there are no UAVs active in the system, the second row reflects that there is a single UAV active in the system, and so on.

The states located in the green area, on the left, indicate that the UAV devices do not support any calls in progress. Thick red arrows show the forced termination of ongoing calls. The horizontal thick green arrows show the task, although not always, of transferring one call in progress on the UAVs to the BS, a handover execution. The vertical thick blue arrows show the task, although not always, of transferring one call in progress in one UAV to another UAV, an inter-UAV handover execution.

Let $\pi_{k,n}$ denote the probability that $k\ UAVs$ be present in the system and with a total of n calls in progress. Clearly, from the above comments, the number of calls in progress carried by the BS is $\min(P, n)$ and the number of calls carried by the UAVs is $\max(0, n - P) \leq S * V$. Notice that the value of k is coincident with the phase of the QBD process. These 2D-Markov processes can be solved numerically using some basic algorithm for a QBD process; see [11][12] for details.

III. KEY SYSTEM PARAMETERS

Here, we present some parameters of interest. Obviously, the fraction of time a given UAV is present in the coverage area of the BS is given by,

$$Pr(\text{One UAV is present}) = \frac{\alpha}{\gamma + \alpha} \quad (1)$$

and the mean number of UAVs that are present in the system is given by,

$$\text{Mean number of UAVs present in the system} = \frac{V\alpha}{\gamma + \alpha} \quad (2)$$

A. The blocking probability

Since the arrival process is Poisson, taking into account the Poisson Arrivals See Time Averages (PASTA) property [13], the blocking probability of new calls, i.e., the fraction of offered calls that are blocked due to the lack of resources, is given by

$$\begin{aligned} P_b &= \pi_{0,P} + \pi_{1,P+S} + \pi_{2,P+2S} + \dots \\ &\dots + \pi_{V-1,P+(V-1)S} + \pi_{V,P+VS} = \sum_{k=0}^{V} \pi_{k,P+kS} \end{aligned} \quad (3)$$

Observe that P_b is evaluated by adding all the probabilities that take into account the saturation of the system, that is, at the arrival time of one incoming call, all primary channels of the BS and all secondary channels of all UAV are busy, (in Figure 1, the states with red circle).

B. The forced termination probability

The fraction of offered calls that are forced to terminate when one UAV abandons the system is expressed as, (in Figure 1, the transitions with red arrows),

$$\begin{aligned} P_{ft} &= \frac{\text{Rate of forced termination}}{\text{Rate of admitted calls}} = \\ &= \frac{\gamma \sum_{k=1}^{V} k \sum_{m=1}^{S} m \pi_{k,P+(k-1)S+m}}{\lambda(1-P_b)} \end{aligned} \quad (4)$$

C. The distribution of calls that are forced to terminate

Let $f_{m;V,S}$ be the probability that just immediately after one UAV leaves the coverage area, m ongoing calls are forced to terminate. Since each UAV is equipped with a maximum of S secondary channels, clearly, the domain of $f_{m;V,S}$ is the set of integer numbers $m \in [0, S]$. Then, the Probability Distribution Function (PDF) of $f_{m;V,S}$ is given by, (in Figure 1, the transitions with red arrow show the forced interruption of at least one call in progress),

$$f_{m;V,S} = \begin{cases} \dfrac{\sum_{k=1}^{V} k \sum_{n=0}^{P+(k-1)S} \pi_{k,n}}{\sum_{k=1}^{V} k \sum_{n=0}^{P+kS} \pi_{k,n}}, & \text{for } m = 0 \\[2ex] \dfrac{\sum_{k=1}^{V} k \pi_{k,P+(k-1)S+m}}{\sum_{k=1}^{V} k \sum_{n=0}^{P+kS} \pi_{k,n}}, & \text{for } m = 1, \dots, S \end{cases} \quad (5)$$

D. The handover signalling traffic load

It is interesting to see the signalling traffic load due the rearrangement, repacking or re-switching of ongoing calls. We distinguish two cases; first, when a call in progress in one UAV is transferred to the BS and second, when a call in progress in one UAV is transferred to another UAV. In the first case, the handover is produced when one ongoing call carried by the BS ends. In the second case, the handover occurs because a UAV leaves the system. Next, we deal with the corresponding analytical formulation.

1) The handover to the BS: We observe the end of ongoing calls on the BS (calls that are carried by any UAV do not cause any handover task when they finish). When one ongoing call in the BS ends, one call carried by one UAV, if any, is transferred to the released channel of the BS. Since calls ends one at a time, the fraction of calls that are transferred from any secondary channel to the released primary channel is expressed as, (in Figure 1, horizontal transitions with blue colour),

$$\begin{aligned} P_{hd-BS} &= \frac{\text{Rate of handovers to the BS}}{\text{Rate of admitted calls}} = \\ &= \frac{\mu P(\sum_{k=1}^{V}\sum_{j=1}^{kS} \pi_{k,P+j})}{\lambda(1-P_b)} = \frac{P(\sum_{k=1}^{V}\sum_{j=1}^{kS} \pi_{k,P+j})}{A(1-P_b)} = \\ &= \frac{P(1 - \sum_{k=0}^{V}\sum_{j=0}^{P} \pi_{k,j})}{A(1-P_b)} \end{aligned} \quad (6)$$

In other words, Eq. (6) gives the probability that, when one call carried by a primary channel ends, the system performs a handover of another call in progress in a secondary channel to the released primary channel. So, the rate of handover to the BS is given by

$$\text{Rate of handovers to the BS} = P_{hd-BS}\lambda(1-P_b) \quad (7)$$

2) The distribution of handovers between UAVs: When one UAV leaves the coverage area of the BS, probably not all ongoing calls in the UAV are forced to terminate. If any other UAV that is present in the coverage area has any free channels, any ongoing call in the leaving UAV can be transferred to this second UAV, (in Figure 1, see the vertical transitions with green colour). Notice that it is possible to handover more than one call in progress at the same time.

First, we assume that just immediately before one UAV abandons the coverage area of the BS, there are v UAVs in this area with a total of m calls in progress in all the *UAVs*. Clearly, $0 \le v \le V$ and $0 \le m \le vS$. Let $r_{i;m,v,S}$ be the probability that this specific UAV is holding i calls in progress ($0 \le i \le S$). Then, $r_{i;m,v,S}$ is given by

TABLE I. # OF HANDOVERS BETWEEN *UAVs*, $\boldsymbol{H}$, AND # OF CALLS FORCED TO TERMINATE, $\boldsymbol{F}$, FOR $v = 1, 2, \ldots, V = 3$ AND $S = 3$

	level →	$P+1$	$P+2$	$P+3$	$P+4$	$P+5$	$P+6$	$P+7$	$P+8$	$P+9$
	m →	1	2	3	4	5	6	7	8	9
phase ↓	$r_{i;m,v,S}$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$
$v=1$	$r_{0;m,1,3}$									
	$r_{1;m,1,3}$	$(0,1)$								
	$r_{2;m,1,3}$		$(0,2)$							
	$r_{3;m,1,3}$			$(0,3)$						
$v=2$	$r_{0;m,2,3}$	$(0,0)$	$(0,0)$	$(0,0)$						
	$r_{1;m,2,3}$	$(1,0)$	$(1,0)$	$(1,0)$	$(0,1)$					
	$r_{2;m,2,3}$		$(2,0)$	$(2,0)$	$(1,1)$	$(0,2)$				
	$r_{3;m,2,3}$			$(3,0)$	$(2,1)$	$(1,2)$	$(0,3)$			
$v=3$	$r_{0;m,3,3}$	$(0,0)$	$(0,0)$	$(0,0)$	$(0,0)$	$(0,0)$	$(0,0)$			
	$r_{1;m,3,3}$	$(1,0)$	$(1,0)$	$(1,0)$	$(1,0)$	$(1,0)$	$(1,0)$	$(0,1)$		
	$r_{2;m,3,3}$		$(2,0)$	$(2,0)$	$(2,0)$	$(2,0)$	$(2,0)$	$(1,1)$	$(0,2)$	
	$r_{3;m,3,3}$			$(3,0)$	$(3,0)$	$(3,0)$	$(3,0)$	$(2,1)$	$(1,2)$	$(0,3)$

TABLE II. RESPECTIVE PROBABILITIES OF ELEMENTS IN TABLE I FOR $(\boldsymbol{H},\boldsymbol{F})$, FOR $v = 1, 2, \ldots, V = 3$ AND $S = 3$

	level →	$P+1$	$P+2$	$P+3$	$P+4$	$P+5$	$P+6$	$P+7$	$P+8$	$P+9$
	m →	1	2	3	4	5	6	7	8	9
phase ↓	$r_{i;m,v,S}$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$	$(\boldsymbol{H},\boldsymbol{F})$
$v=1$	$r_{0;m,1,3}$									
	$r_{1;m,1,3}$	1.000								
	$r_{2;m,1,3}$		1.000							
	$r_{3;m,1,3}$			1.000						
$v=2$	$r_{0;m,2,3}$	0.500	0.200	0.050						
	$r_{1;m,2,3}$	0.500	0.600	0.450	0.200					
	$r_{2;m,2,3}$		0.200	0.450	0.600	0.500				
	$r_{3;m,2,3}$			0.050	0.200	0.500	1.000			
$v=3$	$r_{0;m,3,3}$	0.6666	0.4166	0.2380	0.1190	0.0476	0.0119			
	$r_{1;m,3,3}$	0.3333	0.5000	0.5357	0.4761	0.3571	0.2142	0.0833		
	$r_{2;m,3,3}$		0.0833	0.2142	0.3571	0.4761	0.5357	0.5000	0.3333	
	$r_{3;m,3,3}$			0.0119	0.0476	0.1190	0.2380	0.4166	0.6666	1.000

$$r_{i;m,v,S} = \frac{\binom{S}{i}\binom{S(v-1)}{m-i}}{\binom{vS}{m}}, \tag{8}$$

with $\max(0, m - S(v-1)) \le i \le \min(m, S)$

being $\binom{y}{x} = \dfrac{y!}{x!(y-x)!}$ $(0 \le x \le y)$, the binomial coefficient.

In other words, at the instant one specific UAV exits from the coverage are of the BS and there are i calls in progress in this UAV, the number of busy channels in other UAVs is $\max(m-i, 0)$, and the number of free channels in other UAVs is $S(v-1) - \max(m-i, 0)$. Then, the number of handovers from the UAV that leaves the system to other present UAVs is equal to $\min(S(v-1) - \max(m-i, 0), i)$ and the number of calls that are forced to terminate is $\max(0, i - \min(S(v-1) - \max(m-i, 0), i))$.

As one example, let us consider a maximum number of $V = 3$ UAVs, each one with $S = 3$ secondary channels, see Figure 1. When the system leaves, for example, the state $(v, P+m) = (3, P+7)$ because of the departure of one UAV, 1 ongoing call is forced to terminate and the number of possible handovers can be 0 or 1 or 2. And when the system leaves the state $(v, P+m) = (2, P+5)$ due to the departure of one UAV, 2 ongoing calls are forced to terminate and the number of possible handovers can be 0 or 1. Table I shows the different options.

The following fact is clearly satisfied:

$$\sum_{i=\max(0,m-S(v-1))}^{\min(m,S)} r_{i;m,v,S} = 1 \tag{9}$$

Second, knowing the probabilities $\pi_{k,n}$ of the QBD process of Figure 1, the rate of handovers from the specific UAV to other UAVs, that are executed just immediately after that specific UAV leaves the system, is given by

$$\begin{aligned} g_{z;V,S} &= \\ &= \sum_{v=1}^{V} v\gamma \sum_{m=0}^{P} \pi_{v,m} + \sum_{v=2}^{V} v\gamma \sum_{m=1}^{(v-1)S} \pi_{v,P+m} r_{0;m,v,S} \\ &+ \sum_{v=1}^{V} v\gamma \sum_{m=(v-1)S+1}^{vS} \pi_{v,P+m} r_{m-(v-1)S;m,v,S} \\ &\quad \text{for } z = 0 \text{ handovers} \end{aligned} \tag{10}$$

and

$$\begin{aligned} g_{z;V,S} &= \sum_{v=2}^{V} v\gamma \Bigg(\sum_{m=1}^{(v-1)S} \pi_{v,P+m} r_{z;m,v,S} \\ &+ \sum_{m=(v-1)S+1}^{vS-z} \pi_{v,P+m} r_{m-(v-1)S;m,v,S} \Bigg) \\ &\quad \text{for } z = 1, \ldots, S \text{ handovers} \end{aligned} \tag{11}$$

Then, the probability to execute z handovers between UAVs is expressed as, from (10) and (11),

$$h_{z;V,S} = \frac{g_{z;V,S}}{\sum_{n=0}^{S} g_{n;V,S}} \quad \text{for } z = 0, \ldots, S \text{ handovers} \tag{12}$$

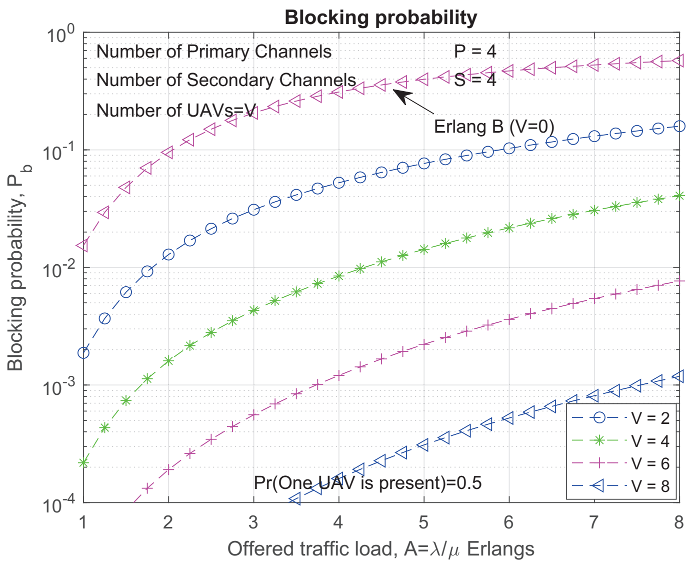

Fig. 2. Blocking probability for a number of primary and secondary channels, respectively $P = 4$ and $S = 4$ and for several numbers, V, of UAV.

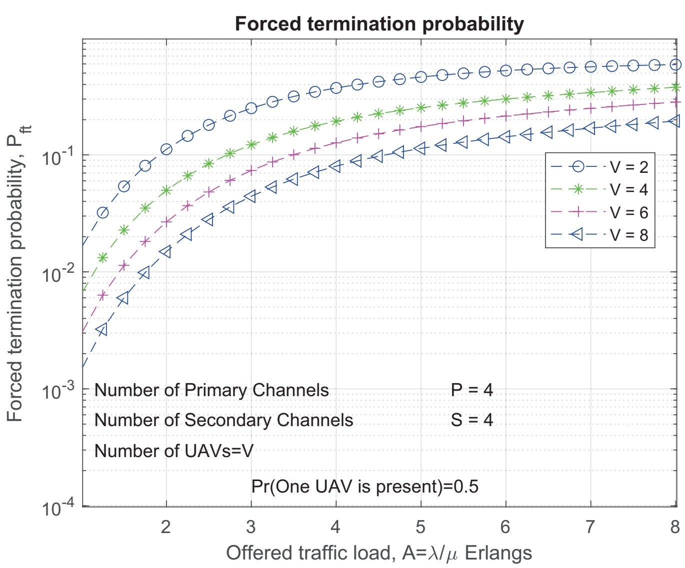

Fig. 3. Forced termination probability for a number of primary and secondary channels, respectively $P = 4$ and $S = 4$ and for several numbers of UAV (V).

IV. NUMERICAL ANALYSIS

Here, we perform the evaluation of the KPI parameters mentioned in previous section. Without loss of generality, we set $P = 4$ primary channels, $S = 4$ secondary channels per UAV and $V = 2, 4, 6, 8$ UAVs. The fraction of time one UAV

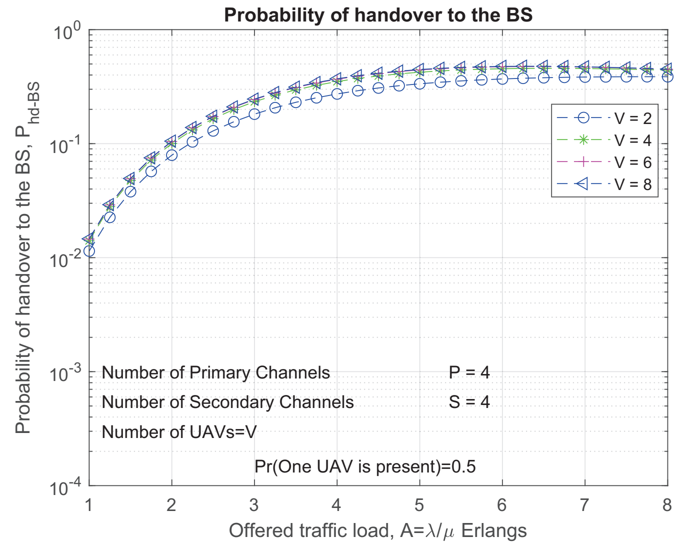

Fig. 4. Handover probability to the BS for a number of primary and secondary channels, respectively $P = 4$ and $S = 4$ and for several numbers of UAV (V).

is in the system is equal to 0.5, see Eq. (1). Figure 2 shows the blocking probability, Eq. (3). The offered traffic is $A \in [1 : 0.25 : 8]$ Erlangs. Clearly, the lost probability increases when the offered traffic A increases. Here, for instance, if we fix the blocking probability to be no greater than 0.01 and no UAV are used, this goal is not achieved for a traffic $A \geq 1$ Erlangs. But this objective is achieved with the help of $V = 2$ UAVs, when the traffic is not greater than $A = 1.75$ Erlangs. With $V = 4$ UAVs, the traffic can be increased until $A = 4.75$ Erlangs, approximately. Also, notice the significant reduction of the blocking probability when V increases.

Figure 3 deals with the forced termination, see Eq. (4). This is the probability that one arbitrary admitted call be forced to terminate because one UAV exits from the coverage area of the BS. Obviously, this probability increases as the offered traffic increases, as expected.

Figure 4 reflects the probability that one admitted call be transferred from a secondary channel of one UAV to a primary channel of the BS, see Eq. (6). We observe that, for a given offered traffic, this handover probability increases when the number V of UAVs increases; but this increase is very small.

Figure 5 shows the Probability Distribution Function (PDF) given by Eq. (5). It gives the the number of calls forced to terminate when one UAV leaves the system. The plots are obtained for a number of primary channels $P = 4$, a number of UAVs $V = 4$, a number of secondary channels per each UAV equal to $S = 4$ and for an offered traffic equal to $A = [1.0 : 0.5 : 3.0]$ Erlangs. In general, the probability decreases when the number of calls forced to terminate increases. Better performance is achieved when the offered traffic is low, as expected.

Finally, Figure 6 gives the PDF of the number of calls transferred from one leaving UAV to the other UAVs that are present in the system. Here, the parameters are the same as for Figure 5. As we can see from the last two figures, when a UAV leaves the system, 97% of the time there is no handover

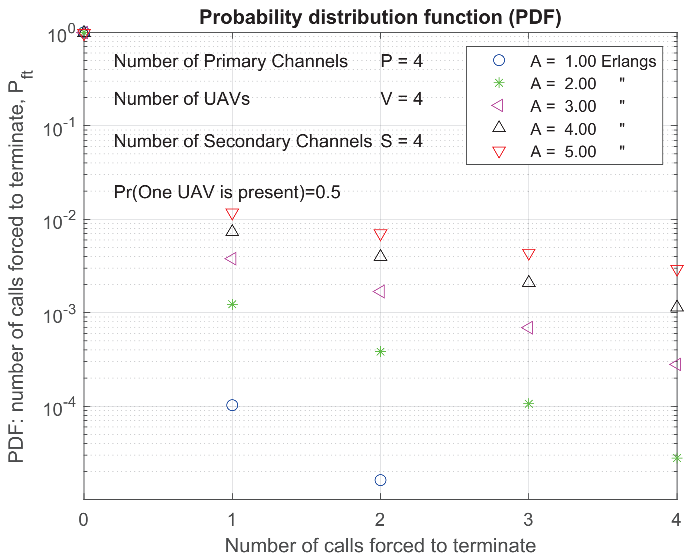

Fig. 5. Probability Distribution Function of the number of calls forced to terminate when on UAV leaves the coverage area of the BS.

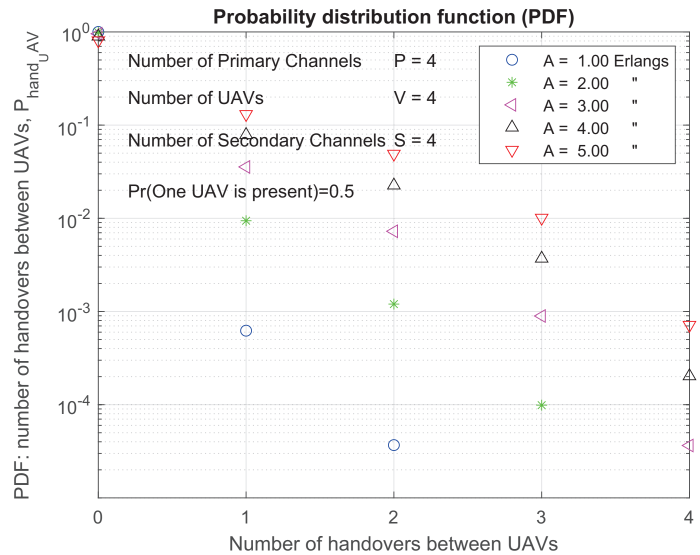

Fig. 6. Probability Distribution Function of the number of calls transferred from one leaving UAV to the others.

to execute.

V. Conclusions

In this paper, we have analyzed a system composed of a single Base Station (BS) and several Unmanned Aerial Vehicles (UAVs) individually and independently of each other, that, from time to time are present in the coverage area of the BS. The main Key Performance Indicator (KPI) parameters we have evaluated are, first, the blocking probability of fresh calls, second, the probability of handing over a call to the BS when one ongoing call in the BS ends and when one UAV abandons the coverage area of the BS, third, the forced termination probability of calls in progress, fourth, the probability distribution function of the number of interrupted calls, and fifth, the probability distribution function of the number of calls transferred from the leaving UAV to other UAVs.

The analysis has been carried out using Markovian assumptions, therefore, an analytically close expression of the KPI parameters is obtained. The evaluation has been conducted using the model of a QBD process. Clear guidelines are given for the design of the number of primary channels, P, installed in the BS, for the number of UAVs, V, present/absent in the coverage area and for the number of secondary channels, S, available on each UAV.

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