Command and Control of UAV Swarms via Satellite

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Abstract. Unmanned Aerial Vehicles (UAVs) are attracting an increasing interest from both the industrial and the research fields, because of the large number of scenarios and applications that they can support. One of the big challenges of the next future is the use of UAV swarms, in order to exploit the advantages that coordinated actions of multiple drones can provide. In this work, we propose an analytical framework to evaluate the probability of a reliable command and control message delivery from a Ground Control Station to a UAV swarm via satellite, also exploiting intra-swarm gossiping.

1 Introduction

Nowadays, UAVs, or drones, are attracting a lot of attention from industrial and research fields. They are suited to a large number of applications, from military to civilian ones, thus the advantages that they can provide are eagerly exploited by several actors. UAVs have been largely used in the military field in the past, but, nowadays, the cost reduction makes them of interest also in several civilian fields: for instance, in the precision agriculture [1,2], in the surveillance field or environmental monitoring [3], and in search and rescue applications [4]. The use of UAVs has proved to be particularly effective in otherwise impervious areas, or each time their use can remove the need for expensive temporary scaffolding, such as in the case of the inspection of historical or cultural areas and buildings. In the latter scenarios, UAVs are typically equipped with the needed sensors in order to facilitate an inspection: for instance, cameras, but also short-range communication radios, in order to collect data from previously installed sensors or to deliver commands, in the case of actuators. Up to now, the largest fraction of civilian applications is based on the use of Line of Sight (LoS) communications, so that the operator remotely controlling the drone can avoid any close obstacles. In fact, a strict regulation is quickly spreading in several European countries, in order to control the use of these devices, mainly in areas where poor experienced personnel can improperly use UAVs, such as close to airports or in the presence of crowd, with possibly disastrous consequences. When considering Non Line of Sight (NLoS) or Beyond Line of Sight (BLoS) communications, the use of the satellites is a possibility, but the following limiting factors should be taken into

P. Pillai et al. (Eds.): WiSATS 2017, LNICST 231, pp. 86–95, 2018.
https://doi.org/10.1007/978-3-319-76571-6_9

account: a larger delay than in LoS communications; the absence of a direct visual feedback; the need of always available bandwidth, in order to control the drone and to collect data; furthermore, the availability of automatic collision avoidance systems to compensate the operators' maneuvering delay. The aforementioned requirements make more expensive the design, the manufacturing, and the use of these devices. In several contexts, the use of a single UAV can be a limiting factor; for instance, in search and rescue applications, if several drones can be rapidly deployed, the probability of a successfully rescue mission may increase. The use of UAV swarms is of interest in several fields, if the task previously assigned to a single drone can be parceled and parallelized. A number of advantages are provided by the use of UAV swarms, as pointed out in [5]: (*i*) likely, the overall cost of acquisition and maintenance of several small Commercial Off-the-Shelf (COTS) UAVs is lower than the overall cost of a single large UAV; (*ii*) scalability, which is a key feature of UAV swarms, instead absent in single UAV missions; (*iii*) fault-tolerance, because a single malfunction has a limited impact on the swarm; (*iv*) faster operations, thanks to the parallelization of the work.

The scenario under consideration in this work is built upon UAV swarms remotely controlled via satellite. Although some works in the literature deal with the use of the drone swarms [6–8], the issues posed by Command and Control (C2) via satellite require further investigations. The main contribution of this work is providing an analytical framework to estimate both coverage probability and delivery delay, when an UAV swarm receives C2 data via satellite, which can be further forwarded (*gossiped*) inside the UAV swarm, in order to increase the probability of a reliable data delivery. The rest of the paper is structured as follows: Sect. 2 provides some background and discusses the related works. Section 3 deals with the description of the problem and of the analytical model needed to address it. Section 4 provides some preliminary numerical results; the conclusions are in Sect. 5.

2 Related Works

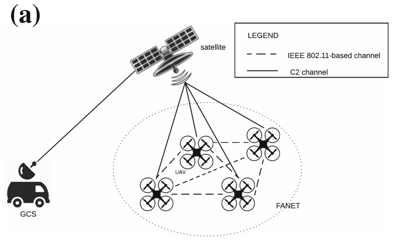
Several works can be identified in the literature on Flying Ad-Hoc Networks (FANETs), mainly focusing on the communications within the swarm and on the issues posed by the communications with a terrestrial station. The survey in [5] provides a very valuable overview of both the issues and the advantages provided by FANETs. The communication link quality within a swarm exhibits a complex behavior that depends on several factors: the distance between any couple of nodes, the shadowing due to the UAV itself, the drone attitude, and the environmental conditions. The last ones play a major role in the link quality, if UAVs fly above or below the clouds. Typically, small UAVs fly below the clouds, therefore the rain fading can impair the communications. Furthermore, because of the wind, small UAVs can frequently change their attitude, thus modifying the relative orientation on the pitch, roll and yaw angles; this impacts on the link quality, as well, because the power loss due to the antenna mismatch can be sometimes severe [5].

In [6], four basic communication architectures for Unmanned Aerial Systems (UASs) are discussed: direct link, satellite, cellular, and mesh networking. Satellite-based and mesh networks may be the most promising solutions. In a mesh network, each node acts as a relay to forward data, thus a control station can be reached via several intermediate hops. Anyway, it requires a path, i.e., nodes in place, in order to work, thus it can be feasible only in areas with a large nodes' density. The use of satellites can provide a better coverage than the use of the direct links, so that the UAV swarm remains well connected. The typical limited bandwidth in satellite links does not really pose here an issue, because C2 protocols should not require large amount of available bandwidth. On the other hand, if user data were to be delivered, larger bandwidth may be required to meet the requirements of high data rate applications. Geostationary Orbit (GEO) and Low Earth Orbit (LEO) satellites can be employed; if considered, a large delay should be taken into account in the former case, while temporary disconnections are expected in the latter case. Despite the challenges characterizing satellite-controlled UAV systems (especially for civilian purposes), research and industrial communities are still investigating the feasibility of the introduction of UAVs in non-segregated airspace. The DeSIRE project[1] is aimed at demonstrating maritime surveillance services using Remotely Piloted Aircraft System (RPAS), by exploiting BLoS communications.

3 System Model

In the scenario under consideration, visible in Fig. 1a, a Ground Control Station (GCS) transmits C2 messages, each composed of k control blocks, towards a swarm composed of n drones. Therefore, we assume that each C2 message (for instance, new navigation data) is split in k fragments that must be successfully received. An average loss probability PL_{SAT} is considered, in order to take into account possible impairments on the satellite channel. Therefore, a successful

(a)



(b)

		s_1	s_2	s_3	s_4
		2	2	1	1
u_1	4	1	1	1	1
u_2	2	1	1	0	0
u_3	0	0	0	0	0
u_4	0	0	0	0	0
u_5	0	0	0	0	0

(a)

		s_1	s_2	s_3	s_4
		2	2	1	1
u_1	3	1	1	1	0
u_2	1	0	0	0	1
u_3	1	1	0	0	0
u_4	1	0	1	0	0
u_5	0	0	0	0	0

(b)

Fig. 1. (a) The scenario under consideration in this work. (b) Examples of received blocks per UAV in the swarm, when $h = 6$ (sum of the margins), $k = 4$ columns (number of blocks), and $n = 5$ rows (number of UAVs).

[1] DeSIRE stands for *Demonstration of Satellites enabling the Insertion of RPAS in Europe*, a joint ESA-EDA initiative.

transmission probability P_{SAT} of k blocks (i.e., a single C2 message) towards each node of the swarm can be written as $P_{SAT} = (1-PL_{SAT})^k$. In the scenario under consideration (see Fig. 1a), the UAVs cooperate in propagating C2 data, in order to increase the probability that each UAV in the swarm can correctly decodes C2 messages. If an UAV has correctly received the C2 message (i.e., all k blocks), then it can *gossip* them to the neighbors. We call *gossiping user* an UAV that forwards data within the swarm. For the sake of clarity, all drones (neighbors) are potentially gossiping users. The gossiped blocks can be lost with an average loss probability $PL_{FAN} = PL_{fs} + PL_{coll} - PL_{fs}\, PL_{coll}$, where PL_{fs} is the average free-space loss probability at a given distance d between UAVs, and PL_{coll} is the average collision probability due to the medium contention. Therefore, PL_{FAN} is the average loss probability when UAVs cooperate in gossiping C2 messages received via satellite, in order to compensate for any losses.

In the following, we derive the analytical formulation of the throughput within the FANET. Then, we estimate the coverage probability and the average delivery delay of a C2 message. The medium access mechanism among UAVs is here based on the use of the 802.11 standard: 802.11 frames are transmitted on the channel, and each frame is composed of several time-slots. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mediates the access to the shared medium. CSMA/CA uses a backoff time randomly chosen from a contention window of length W [slots], whose range is $[W_{min}, W_{max}]$. W is doubled after each unsuccessful transmission, up to the maximum value equal to $(W_{max} + 1)$. A two-dimensional Markov chain of $(b + 1)$ stages is used in [9] to model the backoff time of a node. That model assumes that each block collides in a time-slot with constant and independent probability PL_{coll}, whereas τ, which is the stationary probability that the node transmits a packet in a generic randomly chosen time-slot, is derived as a function of the number of backoff stages b, of the minimum contention window value W_{min}, and of the collision probability. In [9], a system of non linear equations allows a unique solution (PL_{coll}, τ), that in turns is used to compute the normalized throughput:

$$Thr = \frac{P_s P_{tr} L}{P_s P_{tr} T_s + P_{tr}(1 - P_s)T_c + (1 - P_{tr})T_{id}}, \tag{1}$$

where $P_{tr} = 1-(1-\tau)^n$ is the probability that there is at least one transmission in a time-slot; $P_s = (n\,\tau(1-\tau)^{n-1})/(1-(1-\tau)^n)$ is the probability of a successfully transmission on the channel, given that at least one node has transmitted; T_{id} is the duration of a time-slot; L is the payload size; $T_s = MAC_{header} + L + SIFS + 2T_{id} + ACK + DIFS$ is the average duration of the busy period of the channel because of a successful transmission; $T_c = MAC_{header} + L + DIFS + T_{id}$ is the average duration of the busy period of the channel because of a collision. $SIFS$, $DIFS$ and ACK parameters in use in this work are provided in Table 1.

By using (1), we can compute the delivery delay of the gossiped blocks on the 802.11 channel. We are interested in evaluating the coverage probability P^{cov}, which is the probability that each node receives all the k blocks composing a C2 message. It is defined by the following equation:

$$P^{cov} = P_{SAT} + (1 - P_{SAT})\, P^{cov}_{FAN}. \tag{2}$$

Equation (2) is composed of two terms: the probability P_{SAT} that a node successfully receives the blocks via satellite, and the probability P^{cov}_{FAN} that the blocks are successfully received from the gossiping neighbors. In order to estimate P^{cov}_{FAN}, we need to enumerate the coverage events. *A coverage event* occurs if all k blocks are received by a single UAV thanks to gossiping. In order for a coverage event to occur, the UAV must receive at least once each of the k control blocks[2]. Assuming that a coverage event has occurred, the total number of control blocks received by the UAV, namely h, is bounded as follows: $k \leq h \leq k\,(n-1)$.

In order to enumerate the coverage events, we need the following definitions: a *row* (column) *margin* is defined as the sum of the entries, rows by rows (columns by columns). The coverage events can be enumerated by counting the number of receiving matrices $\mathcal{M}(R(h), C(h))$. A receiving matrix is composed of vectors $R(h) = \{r_1(h), ,..., r_n(h)\}$ and $C(h) = \{c_1(h), ,..., c_k(h)\}$, which are the row and column matrix margins, respectively, for a given h. Matrices $\mathcal{M}(R(h), C(h))$ are $(n-1) \times k$ binary matrices, where the entry (i, j) is 1 or 0, if the i-th neighbor successfully transmits (or not) the j-th block. An example of a receiving matrix $\mathcal{M}$ is shown in Fig. 1b(a), for $k = 4$ and $n = 5$, with margins $R(h) = \{4, 2, 0, 0, 0\}$, $C(h) = \{2, 2, 1, 1\}$. The sum of the elements of $R(h)$ and $C(h)$ in Fig. 1b(a) is $h = 6$. The set of margins $\mathcal{C}(h)$, corresponding to the coverage events, can be enumerated by evaluating all the k integer partitions of h with $h = k, \cdots, k\,(n-1)$. We recall that the integer partitions of h are the ways of writing h as a sum of k positive integers $C(h) = \{c_1(h), \cdots, c_k(h)\}$. Some of the partitions may not be feasible; a partition is said to be *feasible* if and only if $\sum_i c_i(h) \geq k$ and $c_i(h) \geq 1$, for $i \in [1, k]$. In order to enumerate only the feasible partitions, some constraints are needed. Those constraints can be written as follows:

$$\begin{gathered} h = \sum_{i=1}^{k} c_i(h), \forall\, C(h) \in \mathcal{C}(h),\; h = k, \cdots, k(n-1); \\ 1 \leq c_i(h) \leq n-1,\; \forall\, C(h) \in \mathcal{C}(h). \end{gathered} \tag{3}$$

The constraints in (3) guarantee that the maximum number of transmissions per block is equal to the number of the gossiping nodes, and that the minimum number of successfully transmitted blocks must be k for a coverage event to occur. For instance, the matrix in Fig. 1b(a) shows the symbols s_k received (entries equal to 1) or not received (entries equal to 0) from each user u_n for one of the two feasible column margins $C_1(6) = \{2, 2, 1, 1\}$ and $C_2(6) = \{3, 1, 1, 1\}$ for $h = 6$. Furthermore, given that any column margin $C_l(h)$ has a finite number of entries, namely $c_{li}(h)$, $c_{li}(h)$ can appear with multiplicity m_i, thus all the permutations with repetition ϵ_r of $C_l(h)$ must be evaluated, because these margins

[2] Because of gossiping, each block can be received more than once.

still represent feasible solutions. These permutations can be calculated as:

$$\epsilon_r := \binom{k}{m_1, m_2, \cdots, m_j} = \frac{k!}{m_1! m_2! \cdots m_l!} \tag{4}$$

Note that P_{FAN}^{cov} depends on the number of nodes that transmit with success. Therefore, for any $C_l(h) \in \mathcal{C}(h)$, several configurations of successfully transmitting neighbors $\mathcal{R}_l(h) = \{R_{l,j}(h),\ j = 1, \cdots, J\}$ are possible, where $R_{l,j}(h) = \{r_{l,j,1}(h), \cdots, r_{l,j,n-1}(h)\}$.

Figure 1b shows two of the possible configurations of transmitting users for the column margin $C_1(6) = \{2, 2, 1, 1\}$: $R_{1,1}(6) = \{4, 2, 0, 0, 0\}$ and $R_{1,2}(6) = \{3, 1, 1, 1, 0\}$. Again, we can notice that $R_{1,2}(6)$ can be achieved from $R_{1,1}(6)$ as follows: $\{a_{1,4} \rightarrow a_{2,4}, a_{2,1} \rightarrow a_{3,1}, a_{2,2} \rightarrow a_{4,2}\}$. Hence, the set of feasible row margins in $\mathcal{R}_l(h)$ can be enumerated by evaluating the permutations with repetition ϵ_r of the binary column vectors of the receiving matrix. Then, arranging those permutations in groups large k, the disposition groups are obtained from the obtained $R_{l,j}(h)$ row margin. A *disposition group* is a permutation group where each permutation is taken only once. For the sake of clarity, in Fig. 1b(a), we have $s_1 = \{1, 1, 0, 0, 0\}$, $s_2 = \{1, 1, 0, 0, 0\}$, $s_3 = \{1, 0, 0, 0, 0\}$, $s_4 = \{1, 0, 0, 0, 0\}$, with sets of permutations $\epsilon_r(s_1)$, $\epsilon_r(s_2)$, $\epsilon_r(s_3)$, $\epsilon_r(s_4)$. The number of permuted elements is 6 for $\epsilon_r(s_1)$ and $\epsilon_r(s_2)$, 4 for $\epsilon_r(s_3)$ and $\epsilon_r(s_4)$. The total number of arrangements in the groups of 4 permuted vectors is $6 \cdot 6 \cdot 4 \cdot 4 = 576$, but several of these arrangements provide the same row margin $R_{l,j}(h)$, which must be counted only once in order to obtain a disposition group. For each column margin $C_l(h)$, the set of row margins $\mathcal{R}_l(h)$ can be now evaluated. However, we still need to enumerate all the possible matrices $M_i(C_l(h),\ R_{l,j}(h))$ for a given pair of margins $C_l(h)$, $R_{l,j}(h)$. The matrices $M_i(C_l(h),\ R_{l,j}(h))$ correspond to the feasible coverage events. In fact, there exists a set of matrices $\mathcal{M}(C_l(h),\ R_{l,j}(h))$, where $M_i(C_l(h),\ R_{l,j}(h))$ differs from $M_j(C_l(h),\ R_{l,j}(h))$ by a sequence of *elementary circuit sub-matrices*, as proved in [10]. In Fig. 1b(b), the sub-matrix $\{\{u_1,\ u_2\}, \{s_3,\ s_4\}\}$ can be changed in another one through an elementary circuit matrix, as follows:

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

and the relative margins $C_l(h)$, $R_{l,j}(h)$ do not change. An algorithm to efficiently count the matrices of the set $\mathcal{M}(C_l(h),\ R_{l,j}(h))$, hereafter referred to as $|\mathcal{M}(C_l(h),\ R_{l,j}(h))|$, is provided in [11]. To summarize, the coverage events can be evaluated according to the following steps:

1. enumerate all feasible column margins in $\mathcal{C}(h)$ and its permutations $\epsilon_r(\mathcal{C}(h))$ for a fixed h value;
2. enumerate all feasible row margins $R_{i,j}(h)$, $\forall\, C_i(h) \in \mathcal{C}(h)$;
3. count the number of matrices $\mathcal{M}(C_i(h),\ \mathcal{R}_i(h))$ that correspond to the coverage events in the sets $(C_i(h), \mathcal{R}_i(h))$;

4. count all the matrices corresponding to the coverage events related to all the feasible partitions. The number of those matrices is Ω, and can be estimated as in the following formula:

$$\Omega(h, \mathcal{C}(h), \mathcal{R}(h)) = \epsilon_r(\mathcal{C}(h)) \sum_{C_l(h) \in \mathcal{C}(h)} \sum_{R_{l,j} \in \mathcal{R}_l(h)} |\mathcal{M}(C_i(h),\, R_{i,j}(h))|.$$

So far, we are able to enumerate all the possible coverage events for the parameters h and the number of gossiping users U_{tx}. Finally, the occurrence probability of a coverage events is:

$$Pr(h|U_{tx}) = \Omega(h, \mathcal{C}(h), \mathcal{R}(h))(1 - PL_{FAN})^h (PL_{FAN})^{U_{tx}k-h}. \tag{5}$$

In other words, (5) allows evaluating the probability that an UAV receives h blocks given U_{tx} transmitting neighbors. The remaining $(n - 1 - U_{tx})$ UAVs do not contribute to h, because the blocks transmitted via satellite and via gossiping have been lost. Let $Pr(U_{tx})$ be the probability of having U_{tx} gossiping neighbors. The coverage probability can be written as:

$$P_{FAN}^{cov} = \sum_h Pr(h|U_{tx})\, Pr(U_{tx}),$$
$$Pr(U_{tx}) = (P_{SAT})^{U_{tx}} \left[(1 - P_{SAT}) + P_{SAT} PL_{FAN}^k\right]^{n-U_{tx}-1}.$$

4 Numerical Results

In this section, we provide some numerical results for the scenario under consideration. We consider an UAV swarm composed of n nodes, $PL_{SAT} \in [0.01, 0.1]$, and an average free-space loss probability in the FANET $PL_{fs} = 0.07$. It is worth noting that the largest contribution to the average loss rate PL_{FAN} within the swarm is due to the collision probability PL_{coll}. Table 1 provides the settings used in the performance evaluation, which provide the following results. Two performance metrics are here considered: the coverage probability and the delivery delay. In fact, when dealing with C2 data, a timely and correct reception of the commands is of primary importance.

Table 1. Settings of the 802.11-based intra-UAVs channel.

Carrier frequency	Channel bit rate	Propagation delay	Slot time	SIFS/DIFS	Payload	MAC/PHY header	ACK	W_{min}/ W_{max}	b
2.4 [GHz]	1 [Mbps]	1 [µs]	50 [µs]	28/128 [µs]	1024 [B]	272/128 [b]	112 [b] + PHY header	15/1023 [time-slots]	$\log_2 \frac{W_{max}+1}{W_{min}+1}$

Figure 3 shows that the coverage probability vs. the number of gossiping neighbors, when a C2 packet composed of $k = 4$ blocks is sent. The use of a gossiping algorithm can significantly increase the coverage probability. However, when considering severe impairments on the satellite channel ($PL_{SAT} = 0.1$), the coverage cannot be guaranteed, as shown in Fig. 3 with 10 UAVs. Different approaches, such as either forward error correction techniques for real-time traffic as in [12,13], or the use of Network Coding (NC) as in [14], can be employed to increase the coverage probability; such investigation is left out for future works.

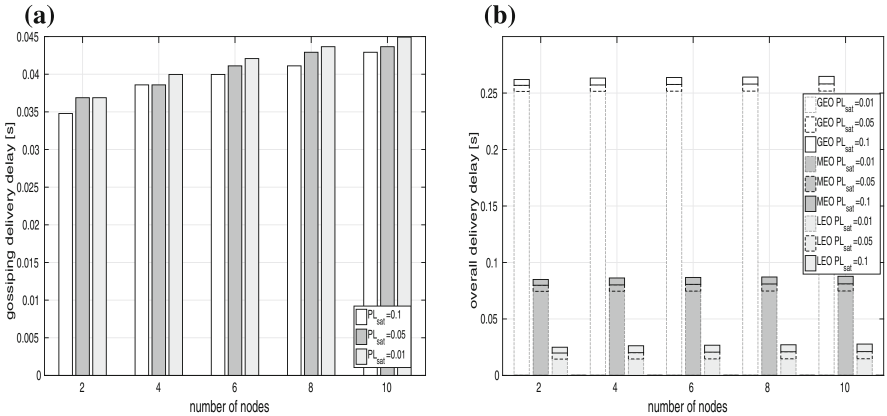


Fig. 2. (a) 802.11 delivery message delay vs. number of gossiping nodes (b) Overall message delivery delay vs. number of gossiping nodes

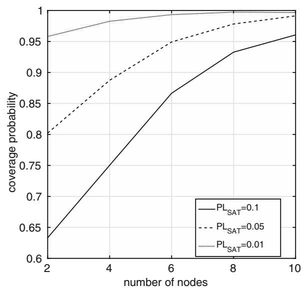


Fig. 3. Coverage probability vs. number of gossiping nodes

Figure 2a shows the impact (defined as *gossiping delay*) of increasing the number of gossiping nodes on the average delivery delay, due to 802.11 backoff mechanism, which reduces the time a node contends for the medium, to reduce the collision probability. Figure 2b shows the one-way-delay for delivering a C2 message from the GCS to the UAV swarm, in case of GEO, MEO and LEO satellite. This delay is the sum of two components: the satellite latency, weighted by P_{SAT}, and the gossiping delay (in Fig. 2a), when the message is received via gossiping. The use of a gossiping algorithm does not significantly impact on the delivery delay; in fact, the largest component is due to the latency of the satellite. However, the channel latency is still higher than the gossiping delay in case of LEOs, but the latter is no more so negligible w.r.t. the former.

5 Conclusions

This study provides an analytical framework for evaluating the probability of a reliable C2 message delivery via satellite, as well as the relative delivery delay, when a gossiping algorithm is used within the swarm to increase the probability of a successfully transmission. Such a framework provides a simple but effective tool for future studies, both theoretical and empirical ones. Future works will be devoted to the development of an actual test-bed, in order to validate the results provided in this work and, furthermore, to the extension of the proposed analytical framework to the case of an UAV swarm controlled by a single GCS, when LoS communications are considered.

Acknowledgments. This work has been supported by the Tuscany region in the frameworks of SCIADRO and MOSCARDO projects (FAR-FAS 2014–2016).

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