A Survey on Network Architectures and Applications for Nanosat and UAV Swarms

Manlio Bacco[1], Pietro Cassará[1], Marco Colucci[1], Alberto Gotta[1], Mario Marchese[2], Fabio Patrone[2]

[1] Institute of Information Science and Technologies (ISTI) of National Research Council (CNR), via Moruzzi, 1, Pisa, Italy
`{manlio.bacco,pietro.cassara,marco.colucci,alberto.gotta}@isti.cnr.it`
[2] Satellite Communications and Networking Laboratory (SCNL) of the University of Genoa, via all'Opera Pia, 13, Genoa, Italy
`{mario.marchese@,f.patrone@edu.}unige.it`

Summary. Nanosatellites and unmanned aerial vehicles are attracting more and more the interest of both industrial and research fields. They are low-cost and easy deployable items, therefore their use is expected to quickly grow in the next few years. This work proposes a survey on the network architectures and the applications for nanosatellite swarms and constellations, as well as for flying ad hoc networks, by characterizing distinctive features and issues yet to be resolved in order to take advantage from both technologies in a joint fashion.

Key words: UAV, FANET, nanosatellite

1.1 Introduction

The use of Unmanned Aerial Vehicles (UAVs) and nanosatellites (nSATs) is increasingly common. They provide low-cost support for a large class of applications, making their use appealing for research and market operators. Both of them can be used individually, or in the form of a swarm; when dealing with nSATs, also constellation topologies are possible. While their use as single objects is sufficient in several application fields, it may represent a limitation in others. Using multiple UAVs or nSATs needs coordination and data exchange services among them and with one or more Ground Control Stations (GCSs), thus requiring more complex network architectures. In the last few years, the use of UAVs swarms, referred to as Flying Ad-Hoc Networks (FANETs) in the literature [1], is becoming increasingly of interest. Anyway, their diffusion is limited by the complexity of Command and Control (C2) operations. A FANET is characterized by distinctive features, typically absent in other networks: a high mobility degree, an average and peak movement speed that can challenge the effectiveness of the communication. Nowadays, those peculiarities still present some challenging research issues to be faced.

Moving to applications, the concept of *servgoods* is described in [2]. Autonomous vehicles, such as UAVs, can be *enveloped* with a service-oriented layer, in order to make the vehicles (more generally, any goods) smarter and more adaptable to particular uses: those entities are defined as servgoods. Technologies like nSATs and UAVs can be considered as the servgoods of the future, being able to sense the environment, to process collected data, to react to events, and to learn from past experiences. Therefore, an overall framework is needed in order to properly deal with such a complex ecosystem, starting from technological and architectural considerations, and then considering privacy, security and liability, as well. In this work, we analyze network architectures and applications in the literature, providing a survey on these topics. Furthermore, we present a preliminary investigation on opportunities and challenges when jointly using nSATs and UAVs.

The rest of this paper is organized as follows: Section 1.2 provides an overview of the state of the art. Section 1.3 deepens the investigation, by providing technical details on the network architectures and on the applications for FANETs and for nSATs. Particular attention to joint solutions is payed in Section 1.3.3. The conclusions are in Section 1.4, opening to the future work still needed for a joint use of UAVs and nSATs.

1.2 Related works

The use of UAVs is becoming very common in several civilian application fields. From time to time, UAVs are used jointly with satellites, in order to exploit the advantages that they can provide. A typical use case is related to disaster scenarios, where satellites can provide services of damage assessment, and UAVs can be used for a closer assessment and for relief actions. For instance, the works in [1, 3] show how the use of a FANET or a nSAT constellation can provide communication and remote sensing services, respectively, in a low-cost and fast deploying way, with acceptable accuracy. Apart from disaster scenarios, a wide range of applications can also benefit from using UAVs, and several ones are described in [4, 5, 6], such as power lines inspection, monitoring of cultural heritage sites, environmental monitoring, fire and gas detection, as well as precision agriculture. Those scenarios have in common Machine-to-Machine (M2M) traffic profiles in the large majority of the use cases under consideration, and the use of satellites [7] is quite mature when dealing with such a traffic, thus opening to joint uses. In particular, precision agriculture is largely benefiting of the use of UAVs [8], due to low operational costs, high operational flexibility, and high spatial resolution of imagery. The authors show that adopting UAVs is advantageous for small areas, and that a break-even point exists at approximately five hectares; above such a threshold, airborne and then satellite technologies have lower imagery costs. Anyway, the use of nSATs is not investigated in [8], and a system architecture including both UAVs and nSATs, as preliminary discussed in this work, may represent a real breakthrough for the investments in this fast rising field. If C2 is considered, a GCS can be used to control one or more UAVs via Non Line of Sight (NLoS) and Beyond Line of Sight (BLoS) nSAT links [9]. In fact, if UAVs can be employed to aid communications and extend coverage, by providing relaying, data dissemination and collection services, the covered area can be extended from single-hop scenarios to multi-hop scenarios by using nSATs. In the former case, one or more UAVs are controlled from a GCS, while, in the latter, the use of nSATs can largely extend the coverage by providing intermediate hops.

The use of nSATs can provide several advantages, from low cost and lower delivery delays to fast deploying operations w.r.t. to the use of satellites, thus opening to the possibility of having up-to-date orbiting technology at any time and making this market segment more and more attractive.

1.3 Network architectures and Application fields

Sections 1.3.1 and 1.3.2 present networks architectures for nSATs and for FANETs, respectively, highlighting the most relevant features of both. In Section 1.3.3, we identify the most common application scenarios and also discuss how a joint architecture can be profitable in the upcoming future.

1.3.1 Nanosatellites

About sixty years ago, the first satellite launches took place. Since then, the number of launches has exploded, thanks to the several mission goals that can be accomplished by satellites, such as weather monitoring, disaster prevention, space and Earth observation, and telecommunications [10]. However, the build and launch process of a satellite is extremely expensive (about \$150-\$200 million for a Low Earth Orbit (LEO) satellite and \$300 million for a Geostationary Earth Orbit (GEO) satellite). Such high costs have prevented the access to space to small and medium-sized businesses for a long time. Nowadays, thanks to Micro-Electronics (MEs) and Micro-Systems Technologies (MSTs), the satellite hardware components are decreasing in size, both primary and payload ones [11]. MSTs can provide smaller objects, power savings, and increased robustness. Currently, it is possible to embed all the necessary systems in a single object that weights just a few kilograms (instead of a few tons), which is called *nanosatellite*.

Since 2000, more than 80 universities and several emerging nations have developed programs that provide the realization and launch of nSATs for different purposes [12]. These programs may involve a single or a group of nSATs which can be launched at the same time as secondary payloads of bigger satellite launches. They can constitute a swarm (see Figure 1.1a) or a constellation (see Figure 1.1b), depending on the deployment strategy. In a *swarm*, all satellites are quite close to each other [13] since they are rapidly deployed one after the other. In a *constellation*, nSATs are equally spaced in the chosen orbital plane (or planes in case of multi-orbit constellations) [14]. Their deployment is sequential and highly synchronized. In both cases, the use of a set of nSATs leads to some advantages: for instance, in [15] the data gathering, processing and transmission functions towards Ground Stations (GSs) are distributed throughout

(a) nSAT swarm (b) nSAT constellation

Fig. 1.1: Logical representations of common nSAT topologies.

the whole swarm. The limited resources can be better exploited by sharing the computing power and employing data exchange through Inter-Satellite Links (ISLs). Communication latency decreases thanks to the higher amount of contacts between GSs and nSATs, especially in constellations where these contacts are spread during all the day, which also leads to a considerable improvement in throughput. The employment of more than one nSAT allows achieving a larger *footprint* (area on the Earth's surface covered by nSATs) and providing a higher fault tolerance. Nowadays, there are hundreds of on-going projects which involve nSATs. Thousands of these objects are in orbit and still active, as reported in the online *Nanosatellite Database* at `www.nanosats.eu`. The most relevant features of possible nSAT network configurations under consideration in this work, i.e., single, swarm, and constellation, are summarized in Table 1.1.

	Single	**Swarm**	**Constellation**
Communication Latency	**high**: data exchange when nSAT is in the communication range of GSs	**high**: data exchange when nSATs are in the communication range of GSs, and among close nSATs	**low**: data exchange when nSATs are in the communication range of GSs, and among spread nSATs
Fault Tolerance	**low**: single nSAT (no backup)	**high**: multiple close nSATs, thus redundant services	**moderate**: widely spread nSATs with redundant services
Throughput	**low**: few contacts between an SAT and each GS per day	**moderate**: few contacts between each nSAT and each GS per day, but high number of overall contacts between nSATs and GSs per day	**high**: high number of overall contacts between nSATs and GSs per day
Available resources	**low**: limitations on on-board HW/SW components: size and weight, computational power, available energy, storage capacity	**high**: each nSAT shares its available resources with close members	**moderate**: each nSAT shares its available resources with other members, but with larger delays than those in swarms
Energy Consumption (per nSAT)	**moderate**: a nSAT performs both data collection and data exchange operations with GSs	**low**: several nSATs perform data collection and data exchange within the swarm, while others perform data exchange with GSs	**high**: all nSATs perform data collection and data exchange within the constellation and with GSs
Coverage	**low**: single footprint	**moderate**: several footprints widely overlapping in a small area	**high**: several footprints slightly overlapping in a vast area
Cost	**low**: unitary production and single launch costs	**moderate**: multiple nSATs production and single launch costs	**high**: multiple nSATs production and multiple launch costs

Table 1.1: Most relevant features of different nSAT network configurations.

1.3.2 Flying Ad-Hoc Networks

In a FANET, the nodes cooperate exchanging data among them, and this can present some challenges: in fact, UAVs can move at high speeds, thus introducing Doppler effects when communicating with GSs. Furthermore, an UAV swarm is generally scattered in space, so that the distance among them can limit the effectiveness of communications. A FANET is controlled from the ground by using a GCS. For the sake of simplicity, we assume that the GCS is also the entity collecting user data[1] The connectivity among UAVs and GCS is of primary importance, especially in the case of C2 links, and should guide in the design of network architectures.

We now describe the most common architectures for FANETs in the literature, which can be seen in Figure 1.2. Figure 1.2a shows one of the simplest architectures for a FANET: each node communicates directly with the GCS. Nodes can move within GCS radio coverage (Line of Sight (LoS) communications). UAV-to-UAV communications suffer a potentially large delay because data need to be routed through GCS. An alternative network architecture relies on the use of fixed terrestrial infrastructure, such as scenarios involving cellular networks [**?**], shown in Figure 1.2c. Base stations (BSs) can be used to support both UAV-to-UAV and UAV-to-GCS communications. This architecture has some drawbacks: the installation of new BSs for a larger coverage is expensive, and the already existing infrastructure is not designed for air-to-ground communications: thus, high-altitude UAVs may experience a really poor link quality. In addition, each UAV must be within the communication range of at least one BS, which is unlikely to happen in rural areas, thus limiting the use of such an architecture.

In order to overcome the limitations due to LoS communications, NLoS scenarios may be taken into account by relying on satellites [17] or on nSATs. In terms of coverage, both the centralized and the cellular-like architecture may benefit from the use of satellites (see Figures 1.2b and 1.2d). In the former case, UAV-to-UAV communications are affected by an even larger propagation delay, especially in the presence of GEO satellites. Despite the larger coverage, a satellite-based architecture introduces different design challenges. Propagation delay, fading attenuation and error-prone wireless links must be taken into account, especially in the case of C2. The last solution relies on the definition of a UAV ad-hoc network [18, 19]. Each UAV participates in the data forwarding, removing the need for any infrastructure. Within the swarm, one node acts as Cluster Head (CH) and is in charge of forwarding data between nodes and GCS via satellite (see Figure 1.2e), while the other members act as slave members. We assume that the CH is able to carry a larger payload and has more available energy than the slave members. The CH needs at least two radio interfaces: one for local transmissions and one for remote transmissions via satellite. Within the swarm, IEEE 802.11-based communications are typically assumed in the literature [20]. In Figure 1.2e, a star topology is proposed, namely *simple hierarchical*

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[1] C2 and data links should be different physical links for safety reasons.

architecture, thus each UAV is connected only to the CH, which is connected to the GCS via satellite. The main weakness of the last architecture is the lack of robustness: if the CH fails, the entire network is compromised, thus backup CHs are required to improve the robustness. In order to overcome such limitations, a possible alternative, namely *complex hierarchical architecture*, consists in relying on a hierarchical network architecture [21], as proposed in Figure 1.2f. In the latter, three entities can be recognized: the CH, the routers (Rs) and the end-devices (EDs), corresponding to three different classes[2] of UAVs. EDs (small class) are connected to the closest router (medium/large class), which in turns is connected to one or more close routers. Each router stores the list of connected EDs and acts as a forwarder for the messages of connected EDs. Each router is equipped with a satellite communication module. The CH acts as *primary router*, with exclusive access to the satellite channel, while the other ones (*secondary routers*) cannot access it: in case of failure of the CH, a secondary router is elected as new CH, thus providing fault-tolerance. The presence of multiple routers also improves the spatial coverage, allowing for multi-hop communications. Several issues must be taken into account with such a hierarchical architecture: UAVs must be able to detect the CH failure, and a CH election algorithm must be designed and implemented, as well as a data synchronization protocol among CH and secondary routers (backup CHs).

Table 1.2 summarizes some of the most relevant features characterizing the aforementioned network architectures. In particular, we compare the hierarchical architectures with the centralized and cellular-like ones.

	Centralized	**Cellular-like**	**Hierarchical (simple)**	**Hierarchical (complex)**
Communication latency	**Low/medium** propagation delay (typically LoS)		**High** propagation delay (BLoS, NLoS)	
Fault Tolerance	**Very limited**: centralized solution	Roughly **proportional** to the number of BSs	**Very limited**: centralized solution	**Proportional** to the number of routers
Scalability and performance issues	**Limited** by the number of UAVs contemporarily controllable by GCS via a single LoS link	**Moderate** scalability due to the infrastructure; larger delay w.r.t. the centralized solution	**High** scalability due to the hierarchical architecture, but a single CH may represent a bottleneck in case of high traffic rates	
Coverage	**Very limited**: UAVs must move within radio coverage of GCS	**Roughly proportional** to the number of BSs	**Limited**: each UAV must fly within radio coverage of the CH	**Scalable**: the larger the number of Rs, the wider the covered area
Cost	**Roughly proportional** to the number and class of UAVs to be deployed: small and low-cost UAVs carry more limited payloads than larger UAVs			
	Low: single LoS link	**Low**: use of existing BSs	**High** cost due to the additional HW/SW modules to be installed on each router	
Energy consumption	**Limited/moderate** power consumption: UAVs directly communicate with a GCS and operate independently, thus energy-saving mechanisms can be adopted		**High** power consumption: routers always active for traffic forwarding	

Table 1.2: Comparison among network architectures for FANETs.

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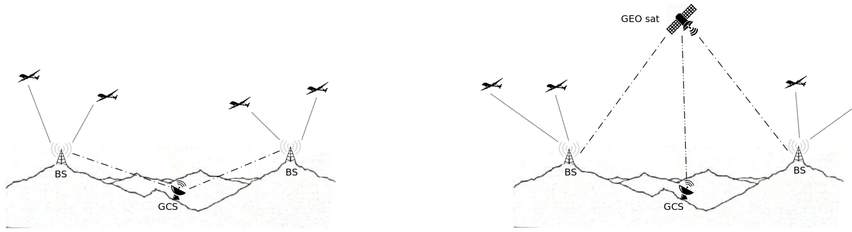
[2] In this work, the class of an UAV describes the amount of available resources on it, such as energy or computational power: larger classes have more available resources than smaller classes.

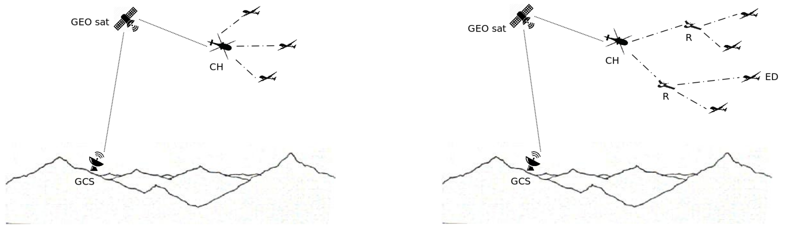
(a) the simplest centralized architecture with a GCS

(b) centralized architecture with the use of satellites



(c) distributed architecture relying on terrestrial repeaters

(d) distributed architecture relying on terrestrial repeaters and satellites



(e) simple hierarchical architecture with satellites and a CH

(f) more complex hierarchical architecture with satellites and a CH

Fig. 1.2: Network architectures for FANETs.

1.3.3 Joint architectures and Application fields

As we summarize in Table 1.3, the combined use of a FANET and of nSATs can enrich the available services in different application scenarios. We consider three reference scenarios: search and rescue, surveillance and monitoring, and goods delivery. For instance, in a Search And Rescue (SAR) scenario in case of large wildfires, the use of both solutions can provide, at the same time, an overview of the whole situation from nSATs and a closer look from UAVs. The latter can be also used to follow operators or civilians in danger, and to timely deliver medical supplies, for instance, while the former help in assessing the whole situation in order to support real-time rescue operations and the decision process. UAVs can be seen as a *mobile extension* of the footprint of a nSAT, a sort of *additional logical beam*. One of the most relevant advantages of multi-UAV systems is the coverage: the larger is the number of UAVs, the wider is the

	Safety	**Target identification**	**UAV preservation**	**Integration between UAVs and nSATs**
Search and rescue	Strong safety requirements, for instance in urban scenarios where buildings, trees and other obstacles can block the operations or the swarm can itself be a danger	nSATs can provide information on the target and UAVs can confirm the identification through on-board equipment	nSATs can provide information on buildings, trees, and obstacles in order to avoid collisions with UAVs	nSATs can extend the capabilities of UAV swarms by helping to identify targets in vast areas and by providing map information
Surveillance and monitoring	nSATs can quickly notify any events of interest, while UAVs can provide close details when deployed	nSATs can search a vast area for target(s). UAVs can provide actual identification and *follow me* services	Need of a continuous estimation of the residual energy of UAVs	nSATs can strongly extend the capabilities of UAV swarms in vast areas, while UAVs can provide on-demand services closer to ground
Goods delivery	nSATs can provide (quasi) real-time information on the delivery area/target to assist an UAV during a safe items delivery	nSATs continuously track the position of a (mobile) target avoiding failed UAV-assisted deliveries	nSATs can confirm the operativeness of deployed UAVs and the position of goods	nSATs and UAV swarms can cooperate in perform challenging deliveries, for instance to mobile/maritime destinations

Table 1.3: Assessment of the benefits of an integrated platform composed of nSATs and UAVs in three reference scenarios.

covered area, especially in case of a hierarchical network architecture. According to the application domain, additional components can be installed on-board of UAVs: satellite/radio communication modules, high-resolution cameras, and chemical detectors are just some examples.

Mission requirements and typical performance indicators [22] for the three reference scenarios under consideration are reported in Table 1.4.

	Mission requirements	**Performance indicators**
Search and rescue	*Time-critical*: hazards and/or victims must be timely identified	*Response time* (time between target identification and rescue operations)
Surveillance and monitoring	*Target identification and tracking*: the target must be correctly identified and tracked	*Identification delay and reaction time*: rapid target identification and prompt reaction
Goods delivery	*Goods tracking and safety*: goods position and integrity must be known	*Delivery time and reliability*: goods should arrive as soon as possible in a consistent state

Table 1.4: Mission requirements and performance indicators in three reference scenarios.

A key issue for both nSATs and UAVs is the energy consumption: while the former ones are equipped with solar panels for battery recharging in order to ensure proper functioning of on-board systems at all time, the latter ones land when the mission is completed or the available energy is almost depleted. Joint scenarios require a policy for the overall energy management, in order to ensure a working system at each time. Strategies and policies to deal with the latter are left to future studies.

1.4 Conclusions

In this work, we describe feasible network architectures for nanosatellites and FANETs, pointing out the potential strengths and weaknesses of each considered solution. We identified some plausible application scenarios involving the combined use of UAVs and nSATs, thus preliminarily discussing the advantages of a hybrid FANET-nSAT architecture. Low cost and reduced propagation delay are some of the advantages that make a nSAT-based solution appealing w.r.t to the use of LEO/GEO satellites. For instance, C2 links require reliability, and low propagation delays: the latter can be fulfilled by using nSATs in place of LEO/GEO satellites when BLoS/NLoS scenarios are considered. Several limitations, such as limited bandwidth, absence of fault-tolerance, unreliability, lack of coverage, and energy issues must be taken into account, thus requiring further investigations on both architectural and performance aspects of a joint architecture.

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