

A Novel Airborne Self-organising Architecture for 5G+ Networks

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Abstract—Network Flying Platforms (NFPs) such as unmanned aerial vehicles, unmanned balloons or drones flying at low/medium/high altitude can be employed to enhance network coverage and capacity by deploying a swarm of flying platforms that implement novel radio resource management techniques. In this paper, we propose a novel layered architecture where NFPs, of various types and flying at low/medium/high layers in a swarm of flying platforms, are considered as an integrated part of the future cellular networks to inject additional capacity and expand the coverage for exceptional scenarios (sports events, concerts, etc.) and hard-to-reach areas (rural or sparsely populated areas). Successful roll-out of the proposed architecture depends on several factors including, but are not limited to: network optimisation for NFP placement and association, safety operations of NFP for network/equipment security, and reliability for NFP transport and control/signaling mechanisms. In this work, we formulate the optimum placement of NFP at a Lower Layer (LL) by exploiting the airborne Self-organising Network (SON) features. Our initial simulations show the NFP-LL can serve more User Equipment (UE)s using this placement technique.

Index Terms—Airborne SON; 5G+ wireless networks; radio access network (RAN); networked flying platforms (NFPs); unmanned aerial vehicle (UAV); drones; low altitude platform (LAP); medium altitude platform (MAP); high altitude platform (HAP);

I. INTRODUCTION

The Fifth Generation (5G) networks, which are expected to be rolled out soon after 2020, will support a 1000 times higher average data traffic, 10-100 fold increase in data rate and connected devices [1]. One of the enabling solutions to meet the demand for high data rate is the densification in cellular network by complementing the ultra-dense deployment of low power small base stations (SBSs) with the airborne cellular network and forming a multi-tier heterogeneous network (Het-Net) for 5G+ systems.

One of the biggest challenges in designing such an airborne cellular network communication system, is to optimally position the flying Base Station (BS) or drone-cell and maintain that position so that the network can benefit the most. Extensive work by numerous research groups investigated how the position of the flying BS or drone-cell can affect the performance of the aerial and terrestrial communication systems as well how its position can play a vital role in the operation of the network. For instance, in [2] authors looked at the effect of different generic mobility models that can be used to characterize the pertinent movements of HAPs

and their effect on the communications. Furthermore, system operating parameters such as the flight path, operation location and service duration over a particular service area can be of high significance in terms of optimized communications for the users on the ground if the aim is to provide seamless connectivity during handoff between platforms [3]. [4] introduces a genetic Interference-aware Positioning of Aerial Relays (IPAR) algorithm which is able to find suitable positions for the UAVs that maximize the downlink throughput of the cellular network. Similarly, [5] discusses efficient algorithms developed to compute the optimal position of the drone for maximizing the data rate, which are shown to be highly effective via simulations. In [6], authors presents that the optimal altitude is a function of the maximum allowed pathloss and of the statistical parameters of the urban environment, as defined by the International Telecommunication Union. They also present a closed-form formula for predicting the probability of the geometrical line of sight between a Low Altitude Platform (LAP) and a ground receiver. In [7] authors present a 3-D placement problem with the objective of maximizing the revenue, which is measured by the maximum number of users covered by the drone-cell. To solve this problem, they have formulated an equivalent problem which was solved efficiently to find the location and size of the coverage region, and the altitude of the drone-cell.

An airborne cellular network comprises of Network Flying Platform (NFP)s of various types including Unmanned Aerial Vehicle (UAV)s, drones, balloons, and high-altitude/medium-altitude/low-altitude platforms (HAPs/MAPs/LAPs) to expand the cellular coverage and deliver Internet services to remote and dedicated regions where infrastructure is not available and expensive to deploy. However, a major challenge in such networks is how to design and manage Self-organisation in cellular networks which is mostly seen as a result of distributed decision making [8]. In conventional SON, self-configuration, self-optimization and self-healing are considered as main SON functions. An airborne cellular network has a more dynamic nature compared to a fixed cellular network because the position of its elements may change over the time. This may be due to change in demand, weather conditions, coverage requirements, battery limitations and even due to some real-time traffic changes/abnormalities in the network. In such an airborne cellular network each BS i.e., NFP-LL, must be capable of performing a combination of conventional and emerging SON functionalities for airborne cellular network depending on the role of NFPs in the network.

The rest of the paper is organised as follows: A novel airborne cellular architecture is introduced in Section II. Section III presents optimisation problem of the proposed airborne SON and its implementation. Section IV presents simulation

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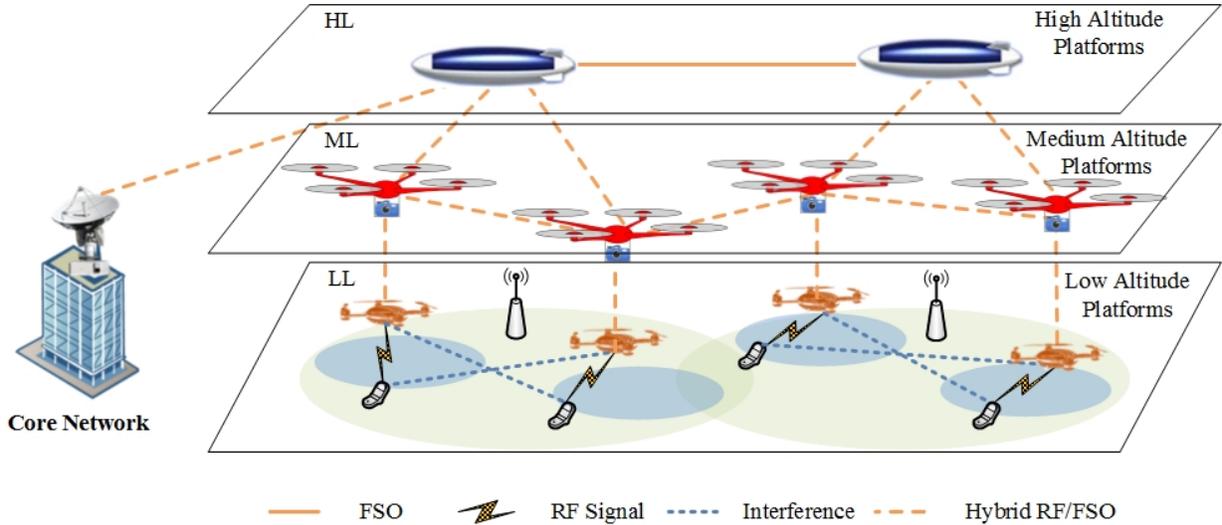


Fig. 1. Graphical illustration of the hierarchical airborne self organizing architecture where variety of NFPs are flying at different altitudes and are offering a complementary wireless network.

results and some discussions on the results. Conclusions are drawn under section V and finally some challenges are summarised in Section VI.

II. AIRBORNE SELF ORGANISING NETWORKS

In an emerging airborne cellular network, the SON functionalities can be realized differently. For example, when a cell outage is detected, neighboring BSs in conventional SON compensate this outage by increasing their transmission power or changing their antenna tilt (self-healing) while in an airborne SON, NFPs can also effectively reorganise their positions to compensate the outage with lower energy consumption. The new placements can be decided centrally or locally at each NFP element – distributed decision making.

A. Proposed Systems Architecture:

Fig. 1 shows our proposed novel layered architecture where NFPs are distributed in a hierarchal manner such that the LL is responsible for access or fronthaul for small cells, Higher Layer (HL) is responsible for transport network and Medium Layer (ML) is serving as a relay between the two layers. NFPs in the LL are typical low altitude platforms (LAPs) flying at relatively lower altitudes and responsible for network optimisation including NFP placement and association based on resource allocation, interference management, etc. On the other side, NFPs such as UAV, unmanned balloons or drones flying at low/high/medium altitude can be used to enhance network coverage and capacity by deploying a swarm of flying platforms that implement novel radio resource management techniques [9]. In this paper, operating in the HL belong to High Altitude Platform (HAP) category and are responsible for optimising the resources in transport networks for lower layers. NFPs in the ML belong to the Medium Altitude Platform (MAP) category and are responsible for relaying the network between the lower and higher layers in our proposed architecture. Safety and security of the proposed NFPs driven cellular network is of significant importance as such network

deployment are more prone to the associated network security risks including their safe operation and security of information. In our architecture, NFPs in the medium layer are dual role playing i.e., in addition to relaying, medium altitude platforms (MAPs) are performing surveillance to ensure safe and secure operation of the architectures. The surveillance operation includes network monitoring, surveillance scheduling, and decisions to further optimise the network and ensure reliable and secure operation by exploiting the collaboration between the participating NFPs in the medium layer. NFPs in the lower layer are optimally distributed to offer capacity and expand coverage via resource and interference management. It is to note that in the proposed architecture HAPs and MAPs are flying with fixed/known locations, however, LAPs are flying with relatively random or optimally distributed locations and offering coverage or capacity in an optimal way.

B. Functionalities of Layers in Proposed Architecture:

The general system architecture of our proposed NFP has been divided into three layers of operation. The HL ranging between 15km-25km, the ML ranging between 5km-15km and the LL which is up to 5km height. For each layer, the operating conditions can vary in terms of wind speed, humidity and temperature. This means that certain type of platforms can be operational at a particular layer, that can cope with the flying conditions as well as provide their services which can range from surveillance, broadband connectivity to backhaul communications as described below.

1) *HAP*: is a stratospheric platform capable of delivering a wide range of services such as mobile cellular communications, broadband wireless access as well as search and rescue services. A HAP is expected to operate at the HL providing Line of Sight (LOS) connectivity over a wide geographical area (30km radius). Such platforms can either be planes or airships, manned or unmanned that can carry a payload of a few kilograms to a few tones and can stay airborne from a few hours to a few years depending on their type, size, power constraints and fuel capacity. A HAP can provide ubiquitous

TABLE I
SUMMARY OF AERIAL PLATFORMS PARTICIPATING IN AIRBONE CELLULAR NETWORK.

Platform Name	AirShip AirPlane AirBalloon AirCopter (S/P/B/C)	Manned Unmanned (M/U)	Max Altitude (approximately) (m)	Platform length (m)	Platform width (Wing Span) (m)	Platform weight (kg)	Range (km)	Max Payload (kg)	Endurance (hrs)
Lower Layer - LAP									
Amazon Drone	C	U	122			25	16	2.26	0.5
Aerovironment Dragon Eye	P	U	150		1.1	2.7		0.5	0.37
SkyHook (Helikites)	B	U	2286	7.31	5.48		Fixed	40	Tethered
Zepellin-NT	S	M	2600	75	19.5	8790	900	1900	24
MD4-1000 (DHL)	C	U	3000	1.03	1.03	2.9	20	1.2	0.8
Skyship 600 (Charly)	S	M	3050	59	15.2	3757	1019	2343	52
Desert Star (Helikites)	B	U	3352	10.05	6.7		Fixed	100	Tethered
MRI P2006T	P	M	4200	8.7	11.4	850	926	380	6
Protonex	P	U	4250		8.2	50	600	25	9
Medium Layer - MAP									
Schiebel Camcopter S-100	P	U	5486	3.11	1.24	110	180	34	6
ScanEagle	P	U	5944	1.6	3.1	16		7.1	15
Airlander 10	S	M	6100	92	43	20000		10000	504
General Atomics Prowler II	P	U	7600	5	10.75	250	2000	270	48
FOTROS	P	U	7600	6.2	17		2000		30
EADS SDE Eagle 1	P	U	7620	9.3	16.6	1000	1000	250	24
Solar Impulse 2	P	M	8534	22.4	72	2300		408	117
MQ-1 Predator	P	U	8839	8.53	17	1233	400	487	24
Anka - A	P	U	9144	8	17.3	1400	4896	200	24
Silver Arrow Sniper	P	U	9145	9.4	18	1250	200	400	26
Higher Layer - HAP									
IAI Heron	P	U	10000	8.5	16.6	900	350	250	52
Predator B (MQ-9B)	P	U	15000	11	20	2223	1852	1700	14
G520 Strto 1	P	M	16000	13.82	33	3300	3670	1400	8
Northrop Grumman Global Hawk	P	U	18000	14.5	39.9	6781	22779	1360	32
Zephyr 6	P	U	18288		18	30		2.27	30
Aurora Flight Sciences Perseus	P	U	19812	7.62	21.79	1936		99.79	24
Stratobus	S	U	20000	100	30			250	5 years
M-55 Geophysica	P	M	21000	22.86	37.46	13995	4965	7000	6.5
ISIS (Integrated Sensor is Structure)	S	U	21500	137.16				2700	10 years

coverage providing backhaul and control/fleet coordination services for other aerial platforms at lower layers. A fleet of HAPs can be used to provide extended communication coverage and redundancy if necessary, while inter-platform communications can be established employing Free Space Optics (FSO).

2) *MAP*: are aerial platforms operating at the ML that can be used as a relay between a HAP and a LAP. Depending on the operation scenario, current available MAP in the market are mostly UAV with long endurance capabilities as well as manned aerial vehicles. UAV platforms can stay airborne for several hours and are usually destined for military missions. MAP coverage area is expected to be of up to 5km radius.

3) *LAP*: such as tethered balloons, drones, operate at the LL. Like HAP and MAP, LAP exhibit common features such as LOS communications with favorable radio conditions, while they have the ability to rapidly deploy a fleet of LAP with modular communication payload capabilities. LAP are currently in high demand for public usage and the current market is driving the drone industry in delivering newer and smarter platforms, with higher endurance and greater range, more agile and efficient aerial vehicles. LAP are optimally distributed to offer capacity and expand coverage via resource and interference management.

Table 1 lists a number of aerial platforms that can be employed to carry out a mission on a particular layer. In LL, LAP are expected to feature a relatively small size, limited payload and endurance capabilities in minutes or hours while offering rapid deployment operating below 5km height. LAP are expected to operate in organised / scheduled shifts in order to ensure continuity of service. MAP are expected to be able

to cope with a heavier payload in order to maintain their role as network relays between LL and ML featuring more functionalities than LAP. They are capable of staying aloft for a greater duration of time (hours / days) in order to support the operation of LAP. MAP are expected to be operational between 5-15km height subject to the local aviation regulations of operation. Finally, HAP operating on HL will be of much bigger size operating at a height around 17-20km height. Such platforms will be carrying a much heavier payload that would support Radio Frequency (RF) and FSO communications. It should be able to stay operational for days/months without require refueling. A possible scenario is to use Protonex as LAP that can stay aloft up to 9 hours while the Airlander10 can operate as MAP providing services at about 10km height. Finally, a HAP such as ISIS can stay aloft for a great duration of time providing connectivity to the MAP.

III. OPTIMISATION OF AIRBONE SON

In our proposed architecture the position of LAPs in the LL is defined centrally and the NFP has the ability to re-organise the LL to achieve its target, which can be capturing as many UEs, maximizing the achievable rate, and/or fairness among UEs. However, optimum placement is an NP-hard problem.

NFP-LL placement to capture maximum UEs can be for-

mulated as:

$$\begin{aligned} & \max \sum_{n=1}^N \sum_{u=1}^U d_{n,u} \\ & \text{subject to } \sum_{u=1}^U d_{n,u} \leq 1, \quad \forall n \in \{1, \dots, N\} \\ & d_{n,u} = \begin{cases} 1 & RSS_{n,u} > RSS_{-n,u} \\ 0 & \text{otherwise} \end{cases} \quad \forall u \in \{1, \dots, U\}, \end{aligned}$$

where N is the number of LAPs in NFP-LL, U is the number of UEs, and $d_{n,u}$ is 1 if the u^{th} UE is served by LAP n , otherwise it will be zero. $RSS_{n,u}$ denotes the received signal strength of UE u from LAP n . $RSS_{-n,u}$ denotes the strengths of received signal from other nodes of NFP and the Macrocells, if exists.

The above mixed integer nonlinear problem can be linearized using the technique presented in [10] and commercial packages like CPLEX can solve the mixed integer linear problem. Problems with limited number of UEs, and LAPs serving as hotspots can be solved with exhaustive search. In this work we use this technique. However, in more complex scenarios even the mixed integer linear problem will be too complex. Therefore, metaheuristic algorithms can be used to find an efficient sub-optimum solution [11]. We introduce some of these metaheuristic methods.

A. Resource allocation using metaheuristics:

Popular metaheuristics in radio resource allocation are Genetic Algorithms (GA), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO).

1) *GA*: code the solution into a chromosome (also known as individual) and evaluates the optimality of the solution with a function called fitness function [12]. In this work the fitness function is the sum captured UEs, and the chromosome consists of the position of UAVs. Crossover and mutation are tools of GA for improving the solutions. Crossover combines fragments of two chromosomes and creates a new chromosome which is another solution in the feasible area. Mutation is the tool which is hired for overcoming the local optimums; mutation changes a gene randomly with the hope of reaching better solutions. The algorithm starts with a randomly generated population of chromosomes and at each iteration it creates a generation of offspring using crossover and mutation. The fittest of parent and offspring generations are kept for the next iteration and the rest are discarded. This way GA keep the population size constant. The algorithm stops after the maximum number of iterations is reached.

2) *ACO*: has been used in radio resource management for network planning and spectrum allocation [13]. The main idea is taken from the way ants find the shortest path to the food using pheromone. The shorter and more popular paths have higher density of pheromone while longer paths will lose pheromone due to the evaporation. In this model each solution will be coded as a path, and at each iteration each ant chooses a path with a probability that is proportional to the amount of pheromone. After a certain number of iterations the most popular will be selected, i.e. the algorithm converges.

3) *PSO*: models the social behavior of a group of birds [14]. It consists of a swarm of candidate solutions called particles, which explore an n-dimensional hyperspace in search

of the global solution. Compared to GA and ACO modeling the mixed integer problems is more straightforward in PSO.

B. Decentralized decision making:

In the proposed architecture we use centralized decision making to define the position of LAP in LL. However, the architecture has the potential to integrate a distributed decision making mechanism for positioning the LAP. Game theory is the most popular techniques used for designing and analyzing distributed decision making approaches [15]. Different classes of game theoretic approaches can be used to model competition, cooperation, and coalition between different players, LAPs. Game theoretic analysis of the system tells that if there exists a path that leads the competition/cooperation of independent decision makers to an equilibrium. In other words, it enables the system designers to avoid objective functions that lead the system to instability.

In an airborne network settings, parameters of the network will change much faster than a terrestrial network. Therefore, learning from past experiences is extremely important in both centralized and decentralized decision making mechanisms for airborne SON [16]. In decentralized systems, learning techniques help reaching an equilibrium in fewer iterations.

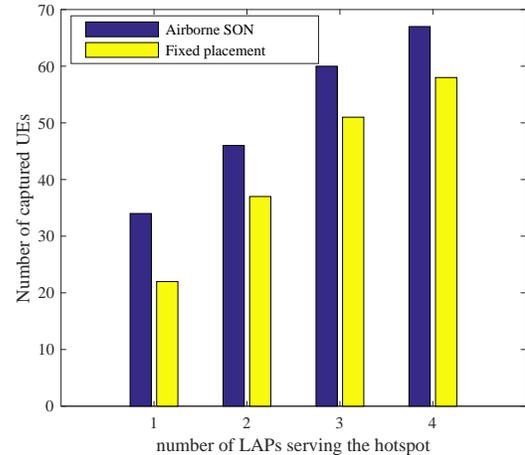


Fig. 2. Number of UEs captured by airborne SON compared to the fixed placement of LAPs in NFP-LL. The network has 150 UEs where a third of them are in the demand hotspot. Demand hotspot has a radius of 250 m (e.g. outdoor concert area).

IV. SIMULATION RESULTS AND DISCUSSIONS

We modeled an NFP where the LL provides service to a demand hotspot. The UEs in the system are served by the macrocell and the NFP-LL assists the macrocell by capturing UEs. The NFP optimizes its LL for a given number of LAPs. Due to weather conditions, battery failure or surveillance duty the system may lose an LAP. In this work, we compared an airborne SON system that reorganizes itself with an NFP with fixed LL placement. Our results in Fig. 2 shows that the airborne SON outperforms the fixed placement. Cross-layer optimisation approaches are required to optimise the placement or positioning of NFPs across the layers in proposed airborne SON.

V. CHALLENGES AND FUTURE DIRECTIONS

Although airborne systems have attracted industry and academia's attention in the last couple of years, there still exists several challenges and open research directions. Following are some of the important challenges for future airborne SON:

A. Standardization

Airborne cellular networks are yet to be standardized. The existing networking standards cannot fully address the challenges of airborne networks and proper standards for airborne communication and networking is required.

B. Surveillance

Airborne cellular network would offer complementary connectivity services to expand the coverage or inject the capacity under some unknown situations, therefore their successful operation would depend on advanced surveillance mechanisms to detect amateur flying platforms and combat to avoid any further disruption in cellular services.

C. Information security

Secure transmission of information over wireless links is still a challenge for future Internet architecture. In our proposed system, NFPs in all layers have the ability to move and complement the existing network, therefore, the dynamic nature of the airborne cellular network could be an additional challenge to ensure secure coverage expansion or capacity enhancement.

D. Ethics and privacy

NFPs and swarm of NFPs may face two-fold challenges in order to comply with regulatory issues related to privacy and ethics. NFPs should be able to protect the privacy of the connected users while following the flying ethics as per regulations and avoiding no-flying zone.

E. Testbed and verification

Various projects in Europe and United States study and test the performance of future Internet and connectivity architecture, resource allocation techniques, waveforms, and integration of future technologies using advanced testbeds [17]. To the best of our knowledge, none of the existing testbed validation and experimentation provide an environment for testing the proposed airborne SON.

VI. CONCLUSIONS

In this paper we have presented a novel layered architecture where NFPs, of various types and flying in low/medium/high layers in a swarm of flying platforms, are considered as an integrated part of the future cellular networks to inject additional capacity and expand the coverage for exceptional scenarios and hard-to-reach areas. In our proposed architecture

the position of LAPs in the LL is defined centrally and the NFP has the ability to re-organise the LL to achieve its target, which can be capturing as many UEs, maximizing the achievable rate, and/or fairness among UEs. To evaluate the proposed architecture, we compared an airborne SON system that reorganizes itself with an NFP with fixed LL placement. Our results show that the airborne SON outperforms the fixed placement.

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