Survey: Aerial Base Stations and Their Placement in Future Cellular Networks

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Abstract—**Due to the ever-expending usage of unmanned aerial vehicles, between terrestrial and aerial terminals a highly reliable and ever-present connection is required. This in turn serves as a way of controlling such devices safely and allows them to be used to exchange data between terminals. The equipment of unmanned aerial vehicles can function as a collection of services provided to the users on the ground through the use of a wireless infrastructure or it can be a user equipment of aerial nature, functioning in conjunction with terrestrial users, depending on its usage. To give an example, for the purposes of surveillance and broadcasting and any streaming service that functions in real time, the usage of aerial user equipment and aerial base stations can be considered in ordered provide greater capacity, efficiency of energy and coverage where wireless networks are involved. Solutions that include unmanned aerial base stations prove to be both faster and easier to use in terms of deployment time and accessibility to certain areas compared to their non-aerial counterparts respectively, and mobility is an obvious benefit in all of the aforementioned cases. That being said, such an approach comes with its own set of challenges of both an academic and technical nature, and in order to ensure their wide usage, these challenges have to be addressed properly. For those purposes, this paper aims to serve as both a survey study and literature search with the aim of giving an overview of the use of unmanned aerial vehicles, their main scenarios of usage, certain research areas that include their optimal placement and the optimization of their trajectory including open research issues, directions and future work in this domain. The survey shows that the work undertaken regarding aerial base stations has increased exponentially in the recent years with significant developments in the optimization of their placement and trajectory, as well as progress in overcoming energy limitations, however despite this, the domain can be considered in its infancy as there are still many obstacles to be overcome if it is to have widespread use one day.**

Keywords—Unmanned aerial vehicle, wireless networks, communication, aerial networks, cooperative unmanned aerial vehicles

I. INTRODUCTION

Where tasks of surveillance and missions of critical observation and monitoring are needed, many military and government institutions have employed the usage of unmanned aerial vehicles conventionally. While that has been the initial rather limiting case for the usage of unmanned aerial vehicles, it has become an option to employ them for a wide variety of application scenarios in the real world because of the advancement in wireless communication technologies and embedded systems from both an academic and technological standpoint. To give an example, used together with their terrestrial peers, unmanned aerial vehicles have to ability to act as aerial users of a special nature, and are generally given the name cellular connected unmanned aerial vehicles. Furthermore, in order to supply certain geographical locations with on demand wireless communications that can be deemed both reliable and economical, unmanned aerial vehicles are able to be used as aerial base stations (also called aerial communication platforms). Their usage in such a way has prompted various use case scenarios which include but are not limited to the relaying of mobile communications, proper recovery of services in case of emergency situations such as terrorist attacks or natural disasters, the dissemination of information and collection of data where sensor networks are involved, and ever present coverage [1]-[3].

For all intends and purposes, including academic and research ones, unmanned aerial vehicles are categorized into two, which are high altitude platforms and low altitude platforms, and they can be recognized by these categorizations. As their name suggests the ones which generally operate in higher altitudes which is generally considered to be above 10km, provide greater coverage with a larger mass and a longer time of flight are called high altitude platforms, although naturally their deployment is more complicated and more expensive, as they have to be more advanced and physically resilient than their low altitude counterparts. In contrast, their smaller relatives, called low altitude platforms, operate in lower altitudes and are smaller, quicker and cheaper, not to mention that they can be used flexibly, as they are designed to be more agile and responsive for short term use. But despite their agility, due to the difficulties in providing the necessary energy for them, their flight times are significantly shorter than their high-altitude counterparts [1]. Low altitude platforms are therefore more suitable to be used in temporary events such as festivals or sports, as well as in situations where time is of the essence like emergency operations and response. They are good candidates for serving as hotspots with a high rate of wireless data access, offloading of traffic and on demand connectivity delivery. Of course, as with everything this comes with its own unique set of design challenges in order to operate efficiently. The question is, of course, with what combination of movement, positioning and energy optimization principles is it possible to achieve effective use of unmanned aerial base stations, and it seems unlikely that there is a single answer for the question as the possible use cases and variables including environmental ones that factor into their usage is seemingly numerous. How to place unmanned aerial base stations and considering their fight time and energy limitations while planning their trajectory in spaces, their complexity, expense and the demands of the users regarding the quality of the service they provide can be considered some of the infinitely many challenges where wireless networks with unmanned aerial vehicles are involved, on which there is an ever increasing amount of work, as networks comprised entirely or partially of unmanned aerial base stations seem to show promising future prospects.

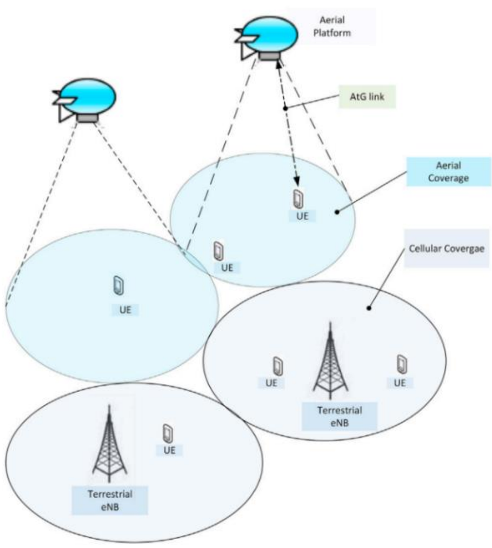

Figure 1: Terrestrial cellular coverage with aerial network support [20]

This paper serves as a survey and literature search study where research on unmanned aerial vehicles is involved. It starts with a short description of the general classification of problems employed, moves on to giving an overview of currently existing work based on unmanned aerial vehicles, including optimal placement and trajectory optimization, an overall comparison of works in the same domain and finishes with open research issues, directions and future work that can be beneficial to focus on.

II. Classification of Related Works

As the works that concern themselves with aerial base stations are extensive and cover a very diverse range of issues, some of which also overlap with each other, it is beneficial to classify them for a more precise analysis. It should be noted that some of the more general classifications include both aerial base stations and unmanned aerial vehicles in general. Therefore, the works included in the following chapter that were analyzed have been classified into certain subtopics for an easier analysis. First and one of the foremost of the domains is energy optimization of unmanned aerial vehicles. This can be further divided into two subcategories, one where the vehicle is in active operation and one where it is not, and therefore in a sleep or standby mode. Solutions include closely analyzing the power consumed during propulsion and coming up with methods to decrease the power that is being consumed, while other approaches include deployment strategies for vehicles that consume less resources. Another very important problem is related to the placement of unmanned aerial base stations. Coming up with efficient algorithms to provide maximal coverage while factoring in environmental occurrences as well as energy and cost limitations makes this an extensively studied domain, where most of the recent work taking place is either directly or indirectly related to it. As the paper mainly concerns itself with this particular problem, it was seen beneficial to sub-categorize the surveyed work in this domain as past and most recent. Optimal path planning and calculation of trajectory is also yet another problem, and researches in this domain also make up a category on their own. This problem can be further categorized into two sub domains, one where only one unmanned aerial base station is considered at a time and one where more than one vehicle is included in the trajectory optimization.

III. Related Works

A. Works Related to the Energy Optimization Problem

a) Works Where the Vehicle is in Active Operation: Since the application and usage of unmanned aerial vehicles have been recognized to have a wide range, researchers have made it a priority to focus on them in the recent years. In order to introduce a more efficient way of energy use where aerial base stations are concerned, there have been brand new works in the past few years, and the focus of some of the research about aerial platforms have been testing their performance as relays, tracking systems for multiple targets and channel modeling from the air to the ground, among others [8]-[10]. One such research considered the consumption of energy for propulsion in unmanned aerial vehicles and created a new approach for unmanned aerial vehicle communication through the optimization of its trajectory, which returned more energy efficient results [11]. By coming up with a new energy consumption during propulsion model, they were able to figure out how efficient the unmanned aerial vehicle communication is in terms of energy consumption. In yet another research, two theories were created and proposed [12]. These solutions both employ a formulation that includes the programming of linear integers. The first solution has the intention of decreasing the amount of energy the unmanned aerial vehicle consumes whereas the second solution introduces an aim of preferring unmanned aerial vehicles which have more capacities in terms of resources in order to reduce the time it takes for their response. Yet another research guarantees the proposed rate of success of itself which introduces a scheme of relaying that improves how long the network can last which happens to be both cooperative and energy efficient [13]. In order to reduce how complicated, the scheduling process is, a suboptimal algorithm was created by them, which uses an alternative and recursive approach in decoupling the balancing of the energy and the rate adaptation, all the while maintaining computational efficiency. There is a work that concerns itself with the problem of how to maximize the energy efficiency [14]. A closed-form solution that is suboptimal was obtained, which was based on a metric of energy efficiency, the description of which is the ratio belonging to the capacity of the network to the both communication and maneuvering consumption of power. In order to achieve this, two variables which are namely load and speed factor of the unmanned aerial vehicle-based relay were considered. With the aim of gathering information from Internet of Things devices on the ground, a different investigation was made regarding the best trajectory through the use of Aerial Base Stations [15]. In order to achieve optimal mobility parameters of unmanned aerial vehicles to allow suitable uplink communications for Internet of Things devices with consumption of energy in minimal values, a brand-new proposal was created through this investigation. What took place was minimizing the power if transmit belonging to the devices through accurately creating a cluster of Internet of Things devices, where an unmanned aerial vehicle was used for every individual cluster, all of which created the first step. As the step following that, through the exploitation of the framework belonging to the theory of optimal transportation to have communications that are energy efficient in Internet of Things networks which are time varying, the most suitable paths of the unmanned aerial vehicles were determined. Another optimal framework of deployment for unmanned aerial vehicles that are operational as aerial base stations was also proposed by the same group of researchers [16]. In order to gather information regarding the association of optimal cells, and from that coming up with the most suitable unmanned aerial base station locations by employing the framework for the location of facilities, theory of optimal transport was applied by them. A cloud computing system of a mobile nature based on unmanned aerial vehicles was investigated in yet another research, where with the intention of offering mobile users who have only limited local processing opportunities, an unmanned aerial vehicle which is mobile is granted capabilities of computing. Minimization of the overall consumption of mobile energy and abiding by the requirements of Quality of Service belonging to the offloaded mobile application is the goal of their approach. Via Frequency Division Duplex and through the use of either orthogonal or Non-Orthogonal Multiple Access schemes, the previously mentioned offloading is made possible by the communications of uplink and downlink taking place between the mobile devices and the unmanned aerial vehicle. In order to figure out how effective exactly the implementation of a relay that is cooperative, another research was made [17]. The aim was to make better the terminals on the ground in terms of energy efficiency and exchanging information with the platforms in place for recovery operations during emergencies. A strategy of adaptive transmitting in real time was also proposed, with the main intention being the selection of links both direct and cooperative depending on the conditions of the channel in order to achieve greater efficiency in energy [18]. It was proven that based on the temporal disposition belonging to uplink channels both in the air and on the ground, cooperation between moving terminals that are terrestrial has the ability to enhance the efficiency of the energy usage in the uplink. A cooperative scheme and how to create and evaluate it has also been proposed [19]. The goal in that research has been to make the aerial-terrestrial links of communication that are operated by batteries survive for a longer amount of time and also make them more efficient in terms of energy consumption. Differently from all the works so far mentioned, there is another research that introduces an algorithm for sleep mode which is based on reinforced learning in order to have more energy efficient aerial base stations [20].

b) Works Where the Vehicle is not in Active Operation: Creating various algorithms in order to come up with a sleep mode to improve energy efficiency in base stations has also been the focus of some research papers. In one instance, through the implementation of transmissions on the side of the base station an approach to increase the energy efficiency in mobile networks was proposed [21]. Markov decision process has been used as a tool of approach in an effective manner to come up with a sleep mode for what is called green communications in certain recent works. Including an activation mechanism that can maximize more than one function that is objective belonging to the quality of service and resulting in better energy efficiency, an optimal controller based on Markov decision process was also proposed [22]. It was proven that the algorithm that was developed makes the energy requirement for a typical network day 25% less. Various different works have the intention of investigating the savings of energy in a user terminal for single users through the use of a sleep mode. These works therefore assume a single user and employ Markov chains [23][24]. Arriving packets that are correlated were in relation with each other were considered in order to come up with a sleep mode mechanism based on Markov decision process in one of these previously mentioned works [23]. Likewise, a scenario of a single user and station was assumed in order to come up with a policy for optimal sleep in a numerical manner through the handling of the problem as a semi Markov decision process [25]. Based on a Markov decision process that is observable only in part, a brand-new scheme for the scheduling of sleep was the topic of another research [26]. The works that have been mentioned so far have all came up with ways for a base station sleep mode where the traffic is low and for the remaining time period the base station is assumed to be in active mode. Since the base station has only two states to which it can change, this is called a “2-state model”. What was shown through these works is that the entire amount of energy that is being consumed can be lessened significantly through the use of this said model. It must be noted however that there remains a certain possibility of calls to drop where the users are novel, as the time required for the base station to get out of sleep mode and turn to active mode requires a great amount of time. In the case of small cells how much time it requires can be anywhere from some seconds to a couple of minutes and if the cell is what is called a macro cell, the wake-up time can take up to 10-15 minutes [27]. Where the efficiency of energy belonging to the system is concerned, this obviously proves to be a significant limitation. Therefore, through the usage of less power in return for a better wake up time, what can be called a low consumption mode was also proposed [21]. This bears some resemblance to a standby mode that was conceived by a different research [20]. What sets that apart from the previously existing works in the domain is the existence of an algorithm that is dependent on a Markov decision process that allows changing between three modes, which is turn has little bearing on the Quality of Service requirements while saving more energy.

As the main focus of this particular survey paper, from this point forward the focus will be on selected existing works in literature that is about the placement of aerial base stations and the optimization of their trajectory with the aim of achieving maximal coverage.

There is extensive work on the application use cases of unmanned aerial vehicles, which can be divided into various categories including the collection of data and the dissemination of information, the intensity with which the network operates and the maximizing the coverage of unmanned aerial vehicles, how safe they are to use in a public domain, internet of things communications and intelligent systems of transport, all of which will be briefly touched upon [29].

The opportunities of line of sight in short range and the versatility in movement of unmanned aerial vehicles can be taken advantage of in order to make them gather and distribute information to and from a very large number of wireless devices that are distributed. One such example can be the previously cited work on the usage of such vehicles in agricultural applications [2].

In order to get a high degree of coverage based on the intensity of the network that is being employed, there has been an ever increasing request for faster wireless access, in no small part due to the increase in number of smart phones and tablets in modern day society. While the existing infrastructure of communication that is based on ground services has been used for some time, adding the usage of unmanned aerial vehicles in order to boost both the coverage and capacity of networks seems to have beneficial results [2].

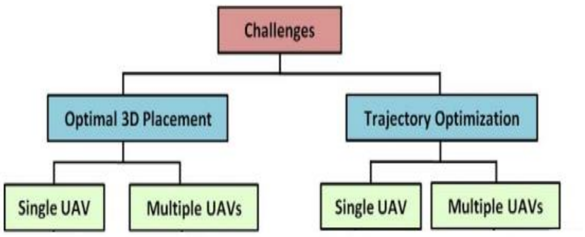

Figure 3: Taxonomy of domains and challenges, where both the placement and optimization problems are separately handled for single and multiple UAVs [29]

Another such domain is that of public safety, as this is a critical requirement for efficient aerial base station usage and has been the focus of some works. Terrestrial communication infrastructures are in general highly sensitive to disruptions caused by certain accidents or natural disasters. Therefore in order to accomplish missions of public safety in a fast, efficient and reliable manner, the usage of unmanned aerial vehicles have been considered extensively as a reliable way of providing all these requirements as they are cheap, have high mobility and therefore capable of covering a large amount of ground where access is otherwise infeasible [28].

In order to achieve the most general internet of things applications such as smart grid handling, public transport and healthcare, a solid connection between various internet of things devices is a must. Usage of aerial base stations is a favorable method therefore, since they have been shown to aid overcoming certain internet of things related issues like the limit of energy and geographical factors like areas with high altitude and deserts as they prove to be hard to handle through the use of ground based methods.

This also brings intelligent transport systems into attention, as the newer systems planned involve a complex network of communications of unmanned self-operating vehicles. Therefore, adding unmanned aerial vehicles into the equation in order to have greater connectivity and coverage is the focus of multiple ongoing works. It should be noted however, that while there are many advantages in employing unmanned aerial vehicles for these goals, the main challenge and domain of research remains to be the optimal 3D deployment and the trajectory with which they operate.

B. Works Related to the Optimal Placement Problem

This, in turn, makes us pay closer attention to the research going on related to these aforementioned issues, first and foremost of which is how to place the unmanned aerial vehicles in an optimal manner for them to effectively serve as base stations. The need to focus on the placement problem with such intensity stems from the fact that there is a relation between the line of sight connection creation and the problem of path loss, as unmanned aerial vehicles are both highly mobile and the altitude at which they operate is not fixed to a standard. Many different things factor into this, including the attributes of the air to ground channel, where the users are, energy usage issues which were explained in the previous chapters, and the interference caused by other elements in the network which can also be other unmanned aerial vehicles among others. All of this makes the deployment issue all the more complex and challenging, and there has been many different works focusing on this exact problem.

a) Past Works on Unmanned Aerial Base Station Placement: In one research, with the aim of increasing the coverage to of the ground, a new unmanned aerial vehicle placement strategy was proposed, in which the researchers looked into the deployment altitude of the unmanned aerial vehicle, namely high and low altitudes, and focused on the tradeoff between path loss and the line of sight [30]. Again, in a previously mentioned work, offloading the user when a base station on the ground was overburdened was looked into [2]. As a result of this work it was possible to come up with a new 3D unmanned aerial vehicle base station placement strategy with a great amount of ground coverage all the while maintaining a certain quality of service for the users, which was in no small part due to taking advantage of what they called a bisection search algorithm. The research that took place in [3] can be considered an expansion of the research done in [2] through assuming every user can have different requirements for the quality of service. Through the usage of stochastic geometry, the effect of an unmanned aerial vehicles operating altitude and their amount in the sky was analyzed in the case of a public safety application situation [28].

More than one unmanned aerial base station can be used to cooperate in the sky with the aim of establishing communications with users on the ground in real time. There is a certain number of base station deployments required for this, and through the use of a greedy algorithm, an approach is proposed to figure out the least amount of unmanned aerial vehicle base stations needed as well as how to place them in 3D space in order to allow users that are not covered inside a service area [31]. Yet another work looked into this optimal placement problem where more than one unmanned aerial vehicle base stations are involved with the aim of overcoming the delay occurring in the network in an efficient manner [32]. They have approached the issue as a minimax problem and solved it through the employment of entropy nets to come up with an optimal placement algorithm the effectiveness of which they later show. In order to gather information from internet of things units based on the ground, another method of efficient placement and employment of more than one unmanned aerial vehicle base station was investigated in [1]. For the coverage issue and how to increase it in a most efficient manner, one such work focused on the employment of unmanned aerial vehicle base stations that have directional antennas on them [33]. In a given geographical area, they were able to come up with the minimum number of unmanned aerial vehicles that need to be employed and numerically evaluated the various tradeoffs in different cases of unmanned aerial vehicle base station employment. Yet a different work exists where again the least number of unmanned aerial vehicle base stations that need to be used and how to place them in a most efficient manner is investigated [34]. What is done in this work is a technique to come up with the coordinates of the unmanned aerial vehicle base stations through the usage of a heuristic algorithm that employs particle swarm optimization.

b) Recent Works on Unmanned Aerial Base Station Placement: The problem of placement is arguably the domain with the highest amount of focus and related work; therefore, it is beneficial to specifically focus on some of the most recent work on this domain as well. A recent study [44] concerns itself with the problem of queuing delay, as in cases where the size of the buffer has a certain limit in Internet of things scenarios this is an exceedingly important issue. They point out that the existing work regarding queuing delay management revolves mostly around controlling the power that is being transmitted or through the use of dynamic allocation of the spectrum. They take advantage of the great mobility and agility of unmanned aerial vehicle base stations and use these qualities in order to adjust the placement of the unmanned aerial vehicle base stations according to the changing wireless tele-traffic. Pointing out the constraints on the unmanned aerial vehicles battery life and the speed with which it can move, they come up with an unmanned aerial vehicle placement problem that minimizes the delay, which they base on three different assumptions. First case is where the details about the wireless tele-traffic and its dynamics are known, the second case is where the knowledge is only limited to statistics and the third case is where neither statistical knowledge nor knowledge about the number of arriving packets exist, in which case they employ an approach with reinforcement learning. They point out that their methods show promising results in terms of both the availability of the buffer overflowing and the average delay that occurs. Another recent research aims to magnify the area of coverage with a new placement approach that uses deep reinforcement learning [45]. They point out the issues and challenges regarding the placement of unmanned aerial base stations and their further complication caused by blockages specific to the aera such as buildings. This paper uses a deep reinforcement learning method in order to cope with this issue, where they offer a design with two levels, one of which is a design of a preliminary nature that bases itself on the most prominent line of sight model of channel, and the other one is a more advanced approach to improve the unmanned aerial vehicle base station positions on channel states specific to the area. They compare their algorithm with the benchmark K-means and DQN algorithms and show that this method can provide a coverage with a much higher rate in a given area. Of course, the recent work is not limited to just this, and one research concerns itself with wireless networks that employs unmanned aerial vehicle base stations that are cache enabled and limited with backhaul [46]. They work on the problem on how to jointly come up with a three dimensional unmanned aerial base station placement, relation between user and unmanned aerial base stations as well as the limitations and employment of resources related to the bandwidth, all the while trying to use as little power as possible during downlink transmit. Their algorithm is of an iterative nature and uses a method called decomposition in which firstly the coordinates of unmanned aerial base stations are discerned and then the association between the user and the base stations as well as the employments related to the bandwidth are optimized. Their results show an effective algorithm that can give an idea about the effect of how the traffic is distributed and the power of transmit as well as the employment of backhaul of unmanned aerial base stations. As mentioned before, deep reinforcement learning is a very popular area of research when it comes to recent placement studies regarding unmanned aerial base station placement and one such research intends to increase the efficiency of the spectrum as much as possible through the use of a mathematical optimization model for the planning of location regarding unmanned aerial base stations, while also considering the possible effects of both line of sight and non-line of sight path loss in 5G networks [47]. The timeliness belonging to the training process is improved through the creation of deep Q-learning for the training process, and through the large-scale pre-learning experience of different user layouts. They point out that the results of their simulation can come up with more than nine tenths of the greatest possible efficiency while also providing a decent quality of service. Deployment of each and every unmanned aerial base station can create a substantial increase in the overall cost for the network operation, and most recent placement studies therefore also focus on algorithms that minimize the required number of these vehicles while providing acceptable coverage within a given area. In [48], researchers develop a method that is based on a sparse recovery approach. They take advantage of the sparsity that resides in the differences among any two mobile base stations and approach the placement issue as a constrained optimization problem, which in the end results in getting rid of the redundant mobile base stations as much as possible. Their simulations make sure that the computational complexity of the developed algorithm stays within acceptable parameters and show that the number of deployed unmanned aerial vehicle base stations is almost optimal. Coming up with methods that include the usage of traditional ground base stations alongside their aerial counterparts is also a domain that has recently attracted attention, as it helps with overcoming certain constraints other approaches generally face. One study develops a social spider optimization as a placement algorithm that factors in the association of the aerial unmanned vehicle base stations with both user equipment's and terrestrial base stations [49]. They undertake extensive measurements in order to investigate and tune the parameter values to the most optimal results. The efficiency is compared to two other schemes and shows an average gain of 18% and 31% in comparison to them respectively.

C. Works Related to the Trajectory Optimization Problem

Coming up with suitable trajectories while employing unmanned aerial vehicles while accounting for many different factors including the duration of the flight, preventing collisions, the needs of all the users on the ground and the limitations caused by energy is yet another aspect while working on unmanned aerial vehicle base stations. Therefore, many different works, most of which are recent, exist about the optimal path planning in wireless networks that employ the usage of unmanned aerial vehicle base stations.

a) Works Involving a Single Unmanned Aerial Base Station: An investigation is undertaken in [35] that focuses on coming up with an ideal way of calculating the unmanned aerial vehicle's path and power of transmit. The result is an algorithm that includes both path and energy requirement constraints that allows a preferable value of least average throughput for a certain amount of time, however the algorithm is deemed to be suboptimal. One research in this domain focuses on increasing the sum rate belonging to the communications of uplink where an unmanned aerial base station with multiple antennae is employed [36]. In [37], with the intention of photogrammetric detection, which is the detection of information about physical objects through observing and measuring photographic images of a given area, a new strategy of planning for unmanned aerial vehicle trajectories that are energy aware is introduced.

b) Works Involving Multiple Unmanned Aerial Base Stations: The so far mentioned research concerns itself only with optimization of trajectory methods where only one unmanned aerial vehicle is employed. There are, however, certain works related to the employment of multiple unmanned aerial vehicles such as [38], where a swarm of them is used in order to increase the coverage of the network significantly and establish a connection between previously separated heterogeneous networks on the ground. Following this, in order to achieve better latency values and a greater throughput within the network, an algorithm was employed at the main station of control, which plans the path planning of the static positions dynamically in a centralized manner. Just like the previously mentioned works focusing on the uplink throughput, one research was undertaken by researchers with the aim of having a greater minimum throughput for the downlink for the users on the ground by investigating the trajectory of the unmanned aerial vehicles plus the association and scheduling of the users [39]. One more work that is worth mentioning as well looks into more than one unmanned aerial vehicle base stations which can come up with an efficient way of using up fuel, adding into the equation the zones in which they are not allowed to fly and tactics to avoid collisions through the use of mixed integer linear programming [40].

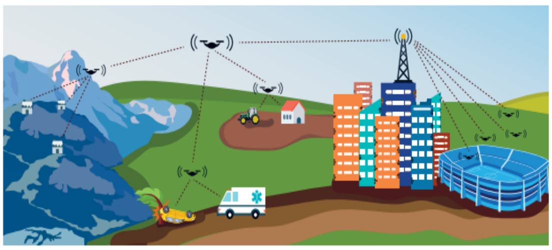

Figure 4: Depiction of an aerial base station network for cellular coverage in overloaded areas [41]

As far as the placement problem is concerned, recent work in that domain is extensive and remains to expand. Many algorithms have been proposed; however, they are not without their shortcomings. To overcome the constraints the current algorithms create, since they need the connection between multiple unmanned aerial vehicle base stations or between multiple unmanned aerial vehicle base stations and a main controller, one work focused on employing both machine learning and stochastic optimization techniques in order to come up with a brand new algorithm [41]. This algorithm, which is to be employed in unmanned aerial vehicle base station placement in the future, does not require information and data exchange between the currently operational unmanned aerial vehicle base stations in the air. The utility function of the network and an iteration of ascent which allows it to be analyzed with the current amount of knowledge that can be employed in real life scenarios is the main reliance of this method. The results are shown to be promising, as in the end a framework that allows for the usage and deployment of unmanned aerial vehicle base stations in a decentralized and highly adaptive manner has been developed. The utility of the network is increased at every individual step the unmanned aerial vehicle base stations take in terms of movement. Through the usage of a certain channel of control by mobile users, messages that are not long are sent and the gradient of the overall network utility is stored in these messages. In addition, a simulation of the case is undertaken in order to confirm the efficiency and the previously available analysis into the convergence also remains available for future steps. The researchers point out that there remains work to be done for cases where there are not enough unmanned aerial vehicle base stations compared to the ground that needs to be covered.

The research work undertaken in order to come up with a maximal coverage placement strategy that is energy efficient is certainly extensive. Since the usage of unmanned aerial vehicle base stations prove to be exceedingly versatile as described before, one research tries to come up with a very small amount of transmit power requirement while serving a great deal of users by developing a brand-new placement strategy [42]. Without any damage in terms of how optimal it is, they divide this problem into two different pieces, namely horizontal and vertical dimensions where the unmanned aerial vehicle base station usage in the direction that is horizontal is modeled as a placement of circle issue. They test the performance metrics through the usage of a simulation where various distribution cases for users exist. Through the separation of dimensions in a vertical and horizontal manner, which means separate evaluations for the x and y axes, their simulations show significant gains in terms of the required power for the transmit and in terms of users that can be served.

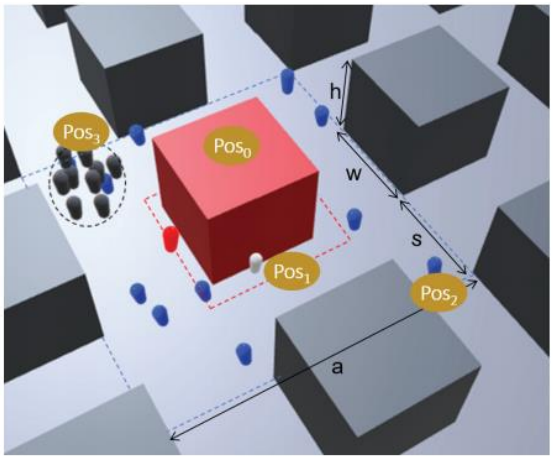

Figure 5: A scenario for aerial base station placement with mobile users in an urban setting, simulated in Unity [43]

One research uses scenario simulations developed in Unity in order to carry out testing for three different placement algorithm methods and the results indicate that while the number of users is great compared to a regular city setting and they move in an unorganized manner the algorithms do not differ greatly in their performance, however when the user number is less or they seem to move more in unison in a general direction, performances of the introduced algorithms differ which warrants future work in this domain to be able to better understand the ideal functionality situations for each of these individual algorithms [43].

IV. COMPARISON AND SUMMARY OF ANALYZED RELATED WORKS

While existing work was already broadly classified prior to their in detail description, this section aims to serves as a summary of all the so far mentioned work in the form of a comparison table, with the reference number of works, the general classification category in which they fall and a brief comparison description of that specific group of works.

Works	Domain of Challenge	Comparison and Summary
[11]-[20]	Energy optimization where the vehicle is in active operation	[11]-[12] concerns itself mainly with propulsion, whereas [13] mainly focuses on simplifying the scheduling process. [15]-[16] seem to show promising results through their inclusion of internet of things devices. [17]-[19] included the employment of ground relays, and not only aerial communications unlike previous works.
[21]-[27]	Energy optimization where the vehicle employs a sleep/standby mode	Works [21]-[26] all employ a Markov decision process in order to come up with a sleep mode approach, however they all also assume there is a single user. What sets [20]-[21] apart is the fact that they employ an additional low power and standby mode.
[2]-[3], [28]-[34], [44]-[49]	Optimal Placement Problem	The general aim of works related to this problem is to maximize the ground coverage while minimizing the number of vehicles involved. Many of the works point out a tradeoff between pathloss and line of sight. [28] strongly emphasizes on the public safety qualities of itself. [33] uniquely comes up with an approach to install antennas on the vehicles while [34] employs a heuristic swarm algorithm. What sets newer work in this domain apart from the previous ones is the employment of deep reinforcement learning, mainly in [45] and [47], and [47] also consider both kinds of path loss. In addition, a brand-new sparse recovery method is introduced in [48] that shows very promising future prospects.
[35]-[37]	Trajectory optimization where a single unmanned aerial base station is employed	[35] considers both path and energy limitations in its trajectory optimization algorithm, however it proves to be suboptimal. In contrast, [36] and [37] use antennas and photogrammetric projection respectively to achieve their goals, however they are not as considerate when it comes to energy limitations.
[38]-[43]	Trajectory optimization where multiple unmanned aerial base stations are employed	[38]-[40] mainly concerns themselves with approaches to reduce latency and increase the minimum throughput, however they rely on heavy information exchange between unmanned aerial vehicles in the swarm. [41] overcomes this issue through a decentralized approach. [42] aims to minimize the transmit power requirements through separate evaluation of dimensions, however unlike [43], it does not expand upon cases like city settings where there are a large number of obstacles and irregularly moving users on the ground.

V. OPEN RESEARCH ISSUES AND CHALLENGES IN AERIAL BASE STATION PLACEMENT

What makes the placement issue a much greater problem in unmanned aerial vehicle base stations compared to their counterparts on the ground is that aerial base stations are deployed and used at various different altitudes. This, in turn effects the uplink and downlink channels based on the height of operation of the aerial base stations. There have been many different research works undertaken in order to overcome this issue of placement, some of which has so far been touched upon. While an approach is to include the altitude of operation belonging to the unmanned aerial vehicle base stations as a factor in the equation and thus treat the problem in three dimensional space, others looked into scenarios in a two dimensional space where the altitude of operation did not change. Other variables also factored into the equation such as whether base stations on the ground exist or how much interference is caused by other unmanned aerial vehicle base stations in close vicinity. The approaches to handle the overall problem ranged from using as many aerial base stations possible to use as little energy as possible in a complete system of aerial vehicles.

Of course, while focusing on the placement issues regarding unmanned aerial vehicle base stations one must not neglect the mobility issues that factor into the formulation of the problems. What makes mobility so essential in this formulation is the fact that this attribute of unmanned aerial vehicle base stations make it possible for changing the coordinates of aerial base stations dynamically and in real time if based on how terrestrial users act and move. Great mobility brings a great deal of flexibility to many placement issues, but currently the capabilities of unmanned aerial base stations in terms of mobility is limited by their hardware specifications. Therefore, many works look into the limitations of their acceleration and movement speed capabilities and various experiments are undertaken, and literature tends to divide the mobility of unmanned aerial vehicle base stations into two types. One such type is a case where the unmanned aerial vehicle part is used only to move the base station from one location to the other, and the base station cannot function during the time it is moving, however it will resume its normal operation as soon as it reaches the intended destination of service. The other type, as can be guessed is where the base station is one with the unmanned aerial vehicle and it continuously provides service as it is changing location in the air. Therefore, a combination of placement and mobility methods are required for efficient usage of unmanned aerial base stations.

As with every wireless device, aerial base stations have the issue of having a rather short time of operation caused by the battery problem, which remains a very critical and crippling problem. Many operations that are intended to be efficient in their power consumption are being undertaken, and this remains a necessity to be able to efficiently use this technology in the future. Both the electronics part of the base station that is responsible for communications and the mechanical part which provides it mobility consumes a considerable amount of energy and therefore the energy saving protocols focused thus far on two different approaches the first of which is a tactic the reduce the energy consumed while communicating, while the second focuses instead on reducing the mechanical energy consumption. It must be noted that activities of a mechanical nature tend to demand considerably more resources than their electronic counterparts and this is affected directly by the mobility of the unmanned aerial vehicle base stations. One solution to this battery issue therefore is to come up with a robust recharging mechanism which involves replacing the aerial base stations with low batteries with new ones in an efficient manner. In comparison with approaches that favor reducing the amount of resources the aerial base stations consume, this solution is both more complex and expensive, as certain location for both replacing and recharging must be defined in populated areas. This also brings the issue of following the battery power of unmanned aerial vehicle base stations in real time.

Usage of unmanned aerial vehicles clearly pose many advantages in different use cases for assistance in creating communication networks that are wireless, however the technology can still be considered in its early stages and there are many problems related to the design and deployment of unmanned aerial vehicles that need to be overcome. The route the unmanned aerial vehicle takes and the placement strategy that needs to be used in a three-dimensional space remain as the foremost design problems since they are directly responsible for the overall quality of the wireless network.

Future work includes the employment of unmanned aerial base stations in 6G cellular networks as they show great promise to increase both the capacity and the coverage of it. Of course, as mentioned, the energy constraints limit the flight time significantly. One recent work proposes an idea of using a tether that provides the aerial base station with both energy and data while it is in operation [50]. The researchers point out to a trade-off between mobility and endurance as well, and extensively describe the challenges and design considerations related to this approach. Nonetheless, this tethered approach has the potential to be a viable alternative to charging on the ground and can make the employment of aerial base stations in future cellular networks as well.

VI. LESSONS LEARNED

Usage of unmanned aerial vehicles clearly pose many advantages in different use cases for assistance in creating communication networks that are wireless, however the technology can still be considered in its early stages and there are many problems related to the design and deployment of unmanned aerial vehicles that need to be overcome. The route the unmanned aerial vehicle takes and the placement strategy that needs to be used in a three-dimensional space remain as the foremost design problems since they are directly responsible for the overall quality of the wireless network.

There are many external factors that contribute into the formulation and planning of algorithms and methods, including the environmental situation, the amount of unmanned aerial vehicles that are being used and the use cases. The height of operation and the flight path of the unmanned aerial vehicles are heavily dependent on these factors.

Currently undertaken researches and projects regarding the placement of unmanned aerial vehicle base stations seem to show a high potential for widespread future use, however, their deployment in three-dimensional space still needs to be investigated extensively before this potential becomes a reality. It should be noted that most of the initial research undertaken seem to consider the unmanned aerial base stations to be stable and unmoving, which is not a very feasible usage of these vehicles. Dynamic methods for using unmanned aerial base stations to assist wireless communications, therefore, is an obvious research domain and problem, considering there are many limitations that enter into the picture when the said unmanned aerial vehicles are mobile.

There is also the issue of coming up with viable paths for unmanned aerial vehicle base stations, and this is heavily dependent on the mobility of users on the ground, which makes the optimization of their movement path an issue to address as well. Current research in this domain includes coming up with a trajectory that can detect and overcome obstacles, jointly coming up with paths and maintaining communication and control whilst in movement.

One must know the unmanned aerial vehicle types and characteristics before anything in order to move forward in this domain. There are already many different models of unmanned aerial vehicles ranging from cheap drones with not a low flight period and payload which are most likely good for scenarios with only one link to a terrestrial point of access to drones employed by both civilian and military applications that can operate for a lengthy amount of time and can have bigger payloads which can be used in mission critical undertakings including providing communications for a large area and surveillance operations. These latter undertakings generally involve expensive wireless communication equipment and data throughput needs that are quite extensive. There are already many unmanned aerial vehicles developed for many different scenarios, that being said, all of these options are not equally sound from an economical perspective. Therefore, a major problem involving today's unmanned aerial vehicles is the problem of costs increasing exponentially as the time of flight and the weight of payload increases. What is needed in the future is to come up with a way that can balance these three factors in a viable manner. While many different works are already being undertaken in this domain at this moment, a viable solution seems to be some time away.

Not having base station coverage in different areas has been a problem for a considerable amount of time, and therefore the usage of unmanned aerial vehicles to provide this service is an idea that has garnered significant interest. There are many theoretical beneficial outcomes of such an undertaking, but realistically speaking, in their current shape and form the usage of aerial base stations in comparison to their terrestrial counterparts is an extremely costly alternative, and this problem needs to be addressed if there is to be the widespread adoption of unmanned aerial vehicle base stations sometime in the future. This is why the previously analyzed work mainly focuses on the placement, power consumption, mobility and recharging of unmanned aerial vehicle base stations to reduce their cost and make them more efficient in terms of operational capabilities as well.

The real-world conditions also factor greatly into these previously mentioned problems, and therefore many different researches included simulations and real-world verifications of aerial base station usage. These solutions range from solar powered aerial vehicles to balloons, among others and while their usage is certainly inventive, there is not enough data on their benefit when used in wireless communication networks that is a mixture of terrestrial and aerial base stations, not to mention the previous cost problem the aerial base station technology suffers from is valid for them as well.

Overall, unmanned aerial base stations is a domain that can be considered in its infancy and most developments are in their early stages as well, however provided that the many challenges previously mentioned can be overcome through the great number of research works that are currently being undertaken, this approach is bound the change the nature of cellular networking technology drastically in the future.

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