Abstract—Unmanned aerial vehicles mounted base stations (UAV-BSs) are expected to become one of the significant components of the Next Generation Wireless Networks (NGWNs). Rapid deployment, mobility, higher chances of unobstructed propagation path, and flexibility features of UAV-BSs have attracted significant attention. Despite, potentially, high gains brought by UAV-BSs in NGWNs, many challenges are also introduced by them. Optimal location assignment to UAV-BSs, arguably, is the most widely investigated problem in the literature on UAV-BSs in NGWNs. This paper presents a comprehensive survey of the literature on the location optimization of UAV-BSs in NGWNs. A generic optimization framework through a universal Mixed Integer Non-Linear Programming (MINLP) formulation is constructed and the specifications of its constituents are elaborated. The generic problem is classified into a novel taxonomy. Due to the highly challenging nature of the optimization problem a range of solutions are adopted in the literature which are also covered under the aforementioned classification. Furthermore, future research directions on UAV-BS location optimization in 5G and beyond non-terrestrial aerial communication systems are discussed.

Index Terms—unmanned aerial vehicles, beyond 5G, non-terrestrial networks, optimization, UAV base station, survey

I. INTRODUCTION

Aerial base stations, which are also known as Unmanned Aerial Vehicle Base Stations (UAV-BSs) or drone-BSs have attracted significant interest in the past few years. Their rapid deployment, flexible relocation, and higher chances of experiencing Line-of-Sight (LoS) propagation path features have been perceived as promising opportunities to provide service in currently difficult to address service provisioning scenarios like short duration extremely crowded gatherings. Dynamically and selectively increasing the capacity of the network and improving the agility are also considered among the essential capabilities of beyond 5G cellular networks [1]. Moreover, the coverage advantage of UAV-BSs over the terrestrial BSs’ due to their higher operational altitudes highly likely to improve the performance of heterogeneous networks served by both the legacy terrestrial BSs and UAV-BSs collectively [2]. We use Flying Base Station (FBS) as the notation to denote all types of base stations that are either mounted on drones/UVVs or on platforms that have the ability to fly or float while serving as a wireless base station.

Figure 1 illustrates a number of these that includes improving the Quality of Service (QoS) in sites where unexpected demand occurs (e.g., crowded sports events) [3]. As the deployments of terrestrial wireless networks are generally planned based on long-term traffic behaviour, matching the capacity with the demand at all times is not possible. This behaviour causes to either under-utilization of the resources or excess of capacity in the network. Therefore, a significant amount of resources are left idle in certain sites while fluctuating demand cannot be satisfied in other sites. To avoid such shortcomings of the existing wireless networks, FBSs are expected to help moving the excess capacity in the network towards where the demand occurs so that the network resources are utilized efficiently and the QoS improves significantly [4]. For example, it is proposed to offer limited incentives such as price reduction or high data rate to users with unsatisfactory coverage to move towards the better coverage regions served by FBSs [5].

The number of academic studies on the utilization of FBSs...
in NGWNs is increasing rapidly as well as the number of citations they receive as illustrated in Figure 2. The data is compiled from the SCOPUS database by using search phrases “aerial base station,” “UAV base station,” “drone base station,” and “flying base station.” Total number of papers that we encountered is 124 (earliest of which was published in 2012).

Despite the rapid built-up of the literature on FBSs for NGWNs in recent years, location optimization problem for FBSs have not been systematically surveyed to the best of our knowledge. It is worth mentioning that there are several survey/overview papers on FBSs [6]–[8], however these studies do not cover the FBS location optimization problems in detail. The FBS location optimization problems often include non-convexity in nature together with binary and continuous variables and are difficult to solve by either using existing solution methods or commercial solvers. Therefore, significant efforts have been put into devising novel approaches to address such complex problems. In this study, we create a novel and a detailed taxonomy of FBS location optimization problems and associated solution approaches. Within this taxonomy we surveyed and analyzed the literature to provide a concise digest of the current state-of-the-art which we believe will foster future research on FBS location optimization.

II. BASIC PROBLEM DEFINITION

FBSLP aims to determine the 3D locations of FBSs to improve certain sets of QoS objectives while satisfying predetermined sets of Service Level Requirements (SLRs) of the users and capacity restrictions of the FBSs. Note that the term “user” refers to any device that requests a certain amount of data transmitted through a communication channel. Let \( J = \{1, \ldots, n\} \) be the set of the FBSs, \( I = \{1, \ldots, m\} \) be the set of users, and \( T = \{1, \ldots, r\} \) be the set of periods. Let \( X \in \mathbb{R}^{n \times 3} \) and \( Y \in \mathbb{R}^{m \times 3} \) be the matrices that represent the coordinates of the FBSs (decision variables) and the users (parameters), respectively. It is obvious that the third column value of each row of \( Y \) is equal to 0, since the users are usually assumed to be located on the ground level. Let \( f_{it} : \mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R} \) be the function that defines the utility incurred when user \( i \) is served, \( g_{jt}^k : \mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R} \) be the actual SLR level of user \( i \) related to \( k^{th} \) SLR, and \( h_{jt}^k : \mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R} \) be the \( l^{th} \) actual capacity level of FBS \( j \) in period \( t \). Note that, these functions are, typically, non-convex. Moreover, let \( w_{j,t,t-1} \in \mathbb{R}^3 \times \mathbb{R}^3 \to \mathbb{R} \) be the function that governs the trajectory of the FBS \( j \) in consecutive periods.

Assume that there exist \( p \) different SLR levels for the users and \( q \) different capacity levels for the FBSs. Let \( v = \{1, \ldots, \eta\} \) be SLR-capacity pairs that directly associate with each other and \( \eta \leq \min\{p, q\} \). FBSLP can be formulated as a Mixed Integer Non-Linear Programming (MINLP) formulation, which is presented in (P):

\[
\begin{align*}
\text{(P):} \quad & \max \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{r} u_{ijt} f_{it}(y_{ijt}, x_{ijt}) \\
\text{subject to} \quad & \sum_{j=1}^{n} u_{ijt} \leq 1, \forall i \in I, \forall t \in T \\
& \sum_{v=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{r} g_{jt}^v(y_{ijt}, x_{ijt}) u_{ijt} \leq h_{jt}^v(x_{ijt}) z_{jt}, \forall j \in J, \forall t \in T \\
& w_{j,t,t-1}(x_{jt}, x_{jt-1}) \leq C_{jt}, \forall j \in J, t = 2, \ldots, r \\
& u_{ijt} \in \{0, 1\}, \forall i \in I, \forall j \in J, \forall t \in T \\
& z_{jt} \in \{0, 1\}, \forall j \in J, \forall t \in T \\
& D_{lo} \leq X \leq D_{up}.
\end{align*}
\]

In this formulation, \( s_{ijt}^k \) is the \( k^{th} \) SLR level requested by user \( i \) in period \( t \). \( C_{jt} \) is the regulation parameter for FBS \( j \) in period \( t \) which is, typically, considered as the maximum allowed distance or velocity for an FBS in consecutive periods, since extreme changes in the distance or the velocity can deteriorate the performance of the FBSs in terms of Energy Consumption (EC) or movement capability. \( u_{ijt} \) is the binary variable that is equal to 1 if the actual SLR level provided by FBS \( j \) is included in the left-hand side of the inequalities. Constraint set (1) ensures that only the users whose demands are satisfied can be served. Constraint set (2) states that the users can be served by only one FBS. Constraint set (3) guarantees that capacities of the FBSs cannot be exceeded. Here, only the SLRs in \( v \) is included in the left-hand side of the inequalities. Constraint set (4) prevents the FBSs to change their location in consecutive periods in a way that violates their movement.
Utility, SLR, and capacity definitions in the FBSLP vary for different problem environments. The utility is usually defined as profit, sum-rate, or coverage. The SLR is defined as minimum threshold value of QoS examined (i.e., data rate). The capacity is related to backhaul capacity, Transmit Power (TP), or EC. In some cases, the objective may be minsum type such as minimizing the total EC or the total mission completion time. This conversion can easily be realized by changing the objective function to \( \min \sum_{j \in J} \sum_{t \in T} e_{jt} z_{jt} \), where \( e_{jt} : \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R} \) is the cost function of FBS \( j \) in period \( t \).

One of the main differences of FBSLP from the existing optimization problems in NGWNs is the air-to-ground (A2G) channel model that is generally used in optimization problems in NGWNs. The air-to-ground (A2G) approach, we use the following notation to determine the SNR where the Signal-to-Noise Ratio (SNR) is above a certain threshold. Adopting this approach, we use the following notation to determine the SNR between user \( i \) and FBS \( j \) in period \( t \), \( \text{SNR}_{ijt} \):

- \( G_{jt} \): TP of FBS \( j \) in period \( t \) in dBm,
- \( f_c \): carrier frequency in Hz,
- \( c \): speed of light in m/s,
- \( d_{ijt} \): distance between user \( i \) and FBS \( j \) in period \( t \) in meter,
- \( b_{ijt} \): bandwidth allocated to user \( i \) by FBS \( j \) in period \( t \) in Hz,
- \( \theta_{ijt} \): elevation angle between user \( i \) and FBS \( j \) in period \( t \) in degrees,
- \( \eta, \alpha, \beta, \varphi_{\text{LoS}}, \varphi_{\text{NLoS}} \): parameters varying according to the environment.

Then, \( \text{SNR}_{ijt} \) can be found by (6):

\[
\text{SNR}_{ijt} = A - 10\eta \log_{10}(d_{ijt}) + \frac{B}{1 + \alpha e^{-\beta(d_{ijt}-\alpha)}} - 10\log_{10}(b_{ijt}) \tag{6}
\]

where \( A = G_{jt} - 10\eta \log_{10}(\frac{4\pi f_c}{c}) - \varphi_{\text{NLoS}} \) and \( B = \varphi_{\text{LoS}} - \varphi_{\text{NLoS}} \). It has been shown that when \( b_{ijt} \) is fixed, if a local maxima exists in (6), then it is the only local maxima for a given SNR value [10]. Although this is a strong property to use, manipulating (6) is still complicated since it is neither a convex nor a concave function. In fact, SNR increases with respect to the increasing altitude of the FBS due to the LoS advantage. However, impact of the altitude has a negative effect on the SNR as the distance dominates (6) after this threshold.

### III. Classification

Problem (P) includes a non-convex objective function and constraints with binary and continuous variables which renders finding an unambiguous solution a challenging task. In fact, the FBSLP belongs to the NP-hard problem class as, with a number of assumptions, it can be reduced to the well-studied set covering or maximal covering location problems which are shown to be NP-hard [11]. Therefore, various approaches such as decomposition and heuristic algorithms have been proposed to solve the FBS LP instances in reasonable time. The solution approaches have been commonly focused on two major sets of the problems, \( X \) (coordinates of the FBSs) and \( Y \) (coordinates of the users). The solution approaches differentiate from each other by the assumptions of mobile FBSs only, mobile users only, or both mobile users and FBSs.

We classified literature on FBS location optimization under three major categories based on how \( X \) and \( Y \) sets are treated. The first category, namely static FBSLP (SFBSLP), has focused on solving the problem for a snapshot of the time where both users and the FBSs are assumed to be not moving. The second category, namely semi-dynamic FBSLP (SMFBSLP), relaxes this assumption in \( J \) and allows the FBSs to move to improve the performance of the network in a finite time horizon. The last group, namely dynamic FBSLP (DFBSLP), relaxes the stationary assumption in \( I \) as well, where both the users and the FBSs are allowed to move. Note that the set \( T \) becomes redundant in SFBSLP and can be removed from (P) together with constraints (4) and all subscripts in other parameters and variables. In SMFBSLP and DFBSLP, users are generally assumed to move following a predefined random pattern in periods, hence, \( Y \) is explicitly provided for each period. Moreover, all problems can be divided into two more cases depending on locating a single FBS (\( n = 1 \)) or multiple FBSs. The latter one is more complex since one more dimension is added to the search space.

One of the main components of the FBSLP is the utility function. Recall that \( f_{it} \) defines the amount of utility gained when user \( i \) is served in period \( t \). In maxsum problems, the utility may refer to an indicator that represents whether the user is covered/served or not (alternatively utility can be the level of the service like the rate provided to the user). Other utility functions refer to the Spectral Efficiency (SE) or the SNR of the user. SE and SNR can also be considered as SLR levels, since the value under a minimum threshold of the SE or the SNR implies an unreliable service. In minsum problems, the utility is replaced with a cost function and is associated with the FBSs rather than the users. The costs refer to TP, EC, or latency. In a limited number of problems, in which the FBSs are used to dispatch the data packages, the cost refers to the service time (ST).

Other components of the FBSLP are the SLR and capacity functions. Most of the studies discussed in this paper do not consider the SLR and the capacity in the same problem. Instead, the problems are subject to either up to two SLR requirements for the users or up to three capacity restrictions
| Paper | FBS | Utility | Cost | SLR | Capacity | Solution |
|-------|-----|---------|------|-----|----------|----------|
| SFBSLP |     |         |      |     |          |          |
| [1]    | S   | User number | -    | SNR | Backhaul capacity | Exact    |
| [3]    | S   | User number | -    | SNR | Backhaul capacity | ENUM     |
| [4]    | M   | Sum-rate    | -    | -   | Backhaul capacity, Cover all users, No overlap among the FBSs | PSH      |
| [5]    | S   | Combined function* | -    | Pathloss | - | Exact, PSH |
| [10]   | S   | User number | -    | SNR | - | Exact |
| [12]   | S   | Profit      | -    | Rate | Backhaul capacity | PSH |
| [13]   | S   | User number | -    | SNR | - | Exact (MOSEK) |
| [14]   | M   | Coverage    | TP   | SNR | - | PSH |
| [15]   | M   | Coverage    | -    | SNR | - | PSH |
| [16]   | M   | SE          | -    | SE  | - | ENUM |
| [17]   | M   | FBS number  | -    | -   | Cover all users | PSH |
| [18]   | M   | SE          | -    | -   | - | GA** |
| [19]   | S   | Sum-rate    | TP   | Rate | Maximum rate | Exact (single user case) |
| [20]   | M   | -          | Latency | - | Discrete locations | LA |
| [21]   | S   | -          | TP   | Rate | Cover all users | PSO |
| [22]   | S   | -          | TP   | Rate | Cover all users | GDA |
| [23]   | M   | SNR        | -    | Interference | - | PSH |
| [24]   | M   | FBS number | -    | SNR | - | Exact |
| [25]   | S   | User number | -    | SNR | - | ENUM, PSH |
| [26]   | M   | -          | TP   | Rate | - | Exact** |
| [27]   | S   | SE         | -    | -   | - | PSH |
| [28]   | M   | -          | Spatial irregularity | - | Exact number of the FBSs to be selected | PSH |
| SMFBSLP |     |         |      |     |          |          |
| [29]   | S   | Sum-rate   | TP   | -   | Maximum time per period, Maximum velocity per period | PSH** |
| [30]   | M   | -          | TP   | Rate | - | PSH |
| [31]   | M   | -          | TP   | SNR | Minimum number of users | PSH |
| [32]   | M   | -          | TP   | SNR | - | PSH |
| [33]   | M   | Minimum rate | -    | One-on-one assignment | - | PSH |
| [34]   | S   | Secrecy     | -    | Rate | Maximum distance per period | PSH |
| [35]   | S   | Minimum rate | -    | Energy neutrality | Maximum TP | PSH |
| [36]   | M   | ST          | SNR  | -   | Maximum velocity per period | PSH |
| [37]   | M   | Minimum rate | -    | Outage | Maximum velocity per period | PSH |
| [38]   | S   | Sum-rate    | -    | Rate | - | PSH** |
| [39]   | M   | -          | EC   | -   | Maximum consumed energy per period, Maximum stored energy per period | Exact (CPLEX) |
| [40]   | S   | -          | EC   | Rate | - | PSO, PSH |
| [41]   | S   | Latency     | -    | -   | Capacity on energy | PSH |
| [42]   | S   | Average rate | -    | -   | Maximum velocity per period, Maximum average TP | PSH |
| [43]   | S   | Sum-rate    | EC   | Rate | Maximum time to fly per period, Maximum EC per period | Exact** |
| [44]   | M   | -          | Combined cost function*** | Demand | Capacity on TP, Receive from at least one ground BS, Cover all users | LA |
| [45]   | S   | Minimum rate | -    | -   | Maximum distance per period | PSH** |
| [46]   | M   | -          | ST   | -   | Maximum velocity per period, Minimum distance between two adjacent FBS in the array | PSH |
| [47]   | M   | -          | ST   | -   | Maximum disconnectivity time | DP** |
| DFBSLP |     |         |      |     |          |          |
| [48]   | M   | -          | TP   | Combined QoE | - | LA |
| [49]   | M   | Coverage   | -    | SNR | Backhaul capacity | PSH** |
| [50]   | S   | SE         | -    | -   | Maximum velocity per period, At most 1 user is served by FBS per period | PSH** |
| [51]   | M   | -          | TP   | Rate | Maximum movement per period | Exact |
| [52]   | S   | Sum-rate   | -    | -   | Cover all users | LA |

S: Single, M: Multiple
* Utility function includes two components: User number + Profit
** The altitude of the FBSs are assumed to be fixed.
*** Cost function includes three components: Total interference + time to complete the tasks + latency.
for the FBSs. The SLR functions may refer to SE, rate, SNR, or demand for data packets, while the capacity functions may refer to the number of active FBSs, the total time that the FBSs can hover, and a number of QoS constraints such as the backhaul capacity, total TP, or the minimum utilization ratio. For the dynamic problems, there are usually additional constraints that require the FBSs to return back to their starting locations, which may be the charging station or to another location to be dispatched.

Table II presents the FBS location optimization literature categorized according to the classification methodology we created and explained in this section. Due to the space limitations, we cannot include all the papers in the literature on FBSs for NGWNs; however, we compiled a large subset of the literature with the highest relevance and highest number of citations. The features we employed to classify the solution approaches are as follows:

- **Exact**: The approach guarantees to find the global optimum or is able to provide the worst case deviation from the optimal if stopped early,
- **Given heuristic names**: The approaches are well-known Dynamic Programming (DP) or meta-heuristics such as Particle Swarm Optimization algorithm (PSO), Genetic Algorithm (GA), or Gradient Algorithm (GDA),
- **Learning algorithm (LA)**: The approach benefits a learning procedure such as reinforcement learning,
- **Enumeration algorithm (ENUM)**: The approach uses an exhaustive search technique to find the best solution,
- **Problem specific heuristic (PSH)**: An ad hoc approach tailored according to the problem properties.

One of the important trends in FBS literature is the shift of the focus from static problems to the dynamic ones. For example, 74% of the papers in 2018 were on dynamic problems which was only 25% in 2015. Note that, the assumption of static users do not reflect the real-world accurately. However, SFBSLP is still likely to receive further attention in future because of the convenience of analyzing static environments.

Solving the optimization problems on FBSLP is a challenging task. Generally, it is not possible to adopt off-the-shelf approaches, therefore, most of the researchers created problem specific solution approaches. For example, 56% of the studies proposed a new heuristic (PSH) and additional 10% have adopted a meta-heuristic with specific adjustment to parameters of the algorithms.

SLR is usually considered as the data rate requested by the users or SNR value. The most adopted capacity constraints in the literature are the distance that the FBSs move or the velocity that the FBSs can hover in a period and the coverage threshold. Sum-rate and coverage are the most frequently employed objectives to be maximized, while energy related objectives such as the total TP and the total EC are the most used cost functions.

### IV. Conclusion and Future Research

In this paper, we present a concise overview of the optimization approaches to solve the location problem of FBSs for NGWNs which are envisioned to be the integral constituents of the future networks (i.e., 5G and beyond). Not only do we overview the solution methodologies in the literature, but also we give the general form of the mathematical formulation of the FBS location problems. Literature on FBSs has substantially grown in recent years due to their unique capabilities like rapid deployment and flexibility. However, FBSs have brought significant challenges to be addressed to take complete advantage of the opportunities that arise.

One of the important future research avenues is to ensure reliability of the services provided by FBSs. The users expect ubiquitous and reliable connections while moving on the ground, therefore, reliable backhaul links should be integrated to the heterogeneous networks where the FBSs are utilized. Another important research area is to address the problem of limited battery-dependent operational service span of the FBSs. Indeed, many studies have shown that the service time of the FBSs is limited and novel techniques should be adopted to boost the energy efficiency. Otherwise, it is unlikely that the envisioned application scenarios of FBSs will ever receive widespread adoption. Developing versatile and faster solution algorithms for the FBS location problems is also a promising future research topic. For example, learning based optimization algorithms have a potential to handle unexpected changes in the problem environment in comparison to specific algorithms developed to solve predefined problem structures.

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