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3D Placement of Drone-Mounted Remote Radio Head for Minimum Transmission Power Under Connectivity Constraints

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ABSTRACT Dense small cell deployment in a cloud radio access network (C-RAN) is an effective approach to satisfy the increasing requirements of the emerging fifth generation (5G) mobile networks. Nevertheless, the optimal deployment of small cells is not always possible due to certain limitations, such as the existence of backbone infrastructure and appropriate power supply. In addition, the increased throughput requirements in a certain area may be temporal, such as in the case of an event such as a sports match or a concert. To this end, the leverage of multiple drone-mounted remote radio heads (D-RRHs), coupled with advanced user scheduling and multiplexing schemes, can be a promising asset in provisioning an on-demand and dynamic C-RAN. Nevertheless, finding the optimal placement of the D-RRHs, under certain quality of service (QoS) constraints can be challenging. In this work, we propose a D-RRH placement approach that minimizes the transmission power by optimally placing the D-RRH. We formulate the placement optimization problem and decouple it into two separate sub-problems, namely the horizontal placement and the vertical placement problems. An implementation of the Weiszfeld algorithm is utilized in order to solve the horizontal placement problem by finding the point that minimizes the sum distances. The vertical placement problem is calculated as a function of the optimal elevation angle and the radius of the coverage area. In order to evaluate the performance of the proposed approach, we carried out extensive evaluations and compare our proposed approach against two similar approaches. The evaluation results show the feasibility of the proposed approach in minimizing the required transmission power and maintaining fairly good performance in terms of user connectivity.

INDEX TERMS Cloud radio access network (C-RAN), base station (BS), drone, fifth generation (5G), placement optimization, remote radio head (RRH), unmanned aerial vehicle (UAV).

I. INTRODUCTION

Providing ubiquitous connectivity to users with varying service requirements is one of the main challenges of the 5th generation (5G) mobile networks. It is estimated that there will be more than 9 billion devices connected to mobile networks worldwide, while mobile data traffic is expected to increase by five times [1], [2]. The first commercial 5G network, expected to launch in 2020, features up to 90% less energy consumption and over 1000x the network capacity of the current 4G networks [3].

The satisfaction of the ever-increasing and diverging requirements of mobile communications requires a significant expansion in terms of network capacity and spectrum

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efficiency. The current mobile network architecture is unable to support the ever-increasing and diverging requirements of the next generation of mobile networks. In order to realize the 5G vision, many radical changes should be carried out regarding the underlying infrastructure and utilized communication technologies [4]. Cloud-radio access network (C-RAN) [5], [6] is a novel concept, which enables fast, scalable, and cost-efficient deployment of mobile networks. The C-RAN architecture consists of baseband units (BBUs), remote radio heads (RRHs), and the fronthaul infrastructure. The BBUs are virtualized and concentrated into one entity called BBU pool, which is often located at a data center, while RRHs are deployed in remote sites. The BBUs perform complex processing, such as fast modulation/demodulation, encoding/decoding, radio resource scheduling, and link management.

Nevertheless, the RRHs cannot always be deployed in an optimal location, where they will provide the best network performance, due to the nonexistence of underlying infrastructure, such as a backbone connection to the core network, or a power supply [7]. The increasing requirements in terms of higher capacity and lower latency of the envisioned 5G applications make the deployment of conventional RRHs inefficient. To this end, the use of drone-mounted remote radio heads (D-RRHs) can prove a promising asset in enhancing the flexibility of the RAN. D-RRHs can be deployed in areas where a conventional small cell cannot be deployed [8]. In addition, multiple D-RRHs can be deployed in a particular area, with each D-RRH providing connectivity to a specific part of the users located in that area. As the D-RRHs will be placed closer to the users, service providers can deliver higher quality of service (QoS) to their subscribers.

The optimal placement of D-RRHs in a 3-dimensional (3D) area is challenging, as certain factors have to be considered, such as the required network capacity and user connectivity. Several research works have been proposed aiming to tackle this challenge. Dhenke *et al.* [9] demonstrated the D-RRH capability to improve the coverage by increasing the signal strength in areas coverage holes. Zhang *et al.* [10] studied the spectrum sharing of D-RRHs using the 3D Poisson point process and calculated the optimal density of drone-BSs to maximize the network throughput. The authors in [11] investigated the performance of an unmanned aerial vehicle base station (UAV-BS) in an area where there are two types of users, namely the downlink users served by the UAV-BS, and the D2D users that communicate directly with each other. Mozaffari *et al.* [12] designed a clustering method to find the optimal trajectories and locations of drone-cells. In [13], the authors formulated the 3D placement problem for a single D-RRHs as a mixed-integer nonlinear programming (MINLP) problem and solved it through the bisection search algorithm. Kalantari *et al.* [14] investigated how different types of backhauls, offering various data rates, affect the number of served users and proposed two approaches, namely network-centric and user-centric, for finding the optimal position of a drone-BS. The authors in [15] decoupled the UAV-BS deployment problem into the vertical and horizontal placement problems and modeled them as a circle placement problem and a smallest enclosing circle problem, respectively. The authors in [16] considered the drone-BS placement problem with in-band full-duplex communication. The placement problem was formulated as a non-linear non-convex combinatorial optimization problem and was decomposed into the drone-BS placement problem and the joint bandwidth and power allocation problem. Wang *et al.* [17] proposed an optimal D-RRH placement method to serve a set of ground users, using the minimum required transmit power, by formulating the optimal drone position problem by decoupling the horizontal dimension from the vertical dimension. The authors in [18] designed a greedy algorithm in order to determine the optimal hovering point over a service area. The algorithm also aims to provide a guaranteed user data rate in that particular area. A macro hotspot scenario, involving moving drone-BSs and users, is explored in [19]. The drone-BSs serve as many users as possible, depending on the received signal strength. The authors showed that a significantly large network throughput can be achieved by incorporating an intelligent mobility algorithm and a user association scheme. The utility maximization problem of a UAV-enabled cellular network is investigated in [20]. The optimization problem is decoupled into three sub-problems that are solved using the successive convex optimization technique and a modified alternating direction method of multipliers. Wang *et al.* [21] investigated the UAV deployment problem in two scenarios. In the first scenario, the UAVs assist the existing ground BSs, while in the second scenario, the UAVs are deployed alone. A hybrid algorithm is proposed to heuristically determine the minimum number of UAVs and find the optimal position of each one. The authors in [22] proposed a framework for determining the optimal number and positions of the drone-BSs, by leveraging a genetic algorithm and a simulated annealing algorithm. Wang and Yang [23] investigated the UAV deployment in the 3D space. In addition to the air-space pathloss, the proposed model also considers ground obstacle constraints. To solve the non-convex fractional optimization problem, the authors reformulate it to a simpler form and utilize two approximation approaches, namely the eigenvector and random sampling approaches. Kim *et al.* [24] considered a UAV-assisted decode-and-forward relay network employing Simultaneous Wireless Information and Power Transmission. The optimum power splitting and time allocation factors were derived in order to minimize the outage probability. Finally, the authors in [25] proposed a method to jointly optimize the trajectory of a UAV and the pre-coding vectors of a BS. The joint optimization problem is divided into two subproblems. In the first subproblem, the UAV trajectory and transmission scheduling were optimized, while in the second subproblem two schemes were utilized to optimize the pre-coding vectors of the BS.

In this paper, we propose an approach to find the optimal location of a D-RRH in the 3D space that minimizes the D-RRH transmission power, under the constraint of providing coverage to a minimum number of users. As stated in [26], power has a significant impact on network performance, as well as the user experience. By optimally placing the D-RRH so as to minimize the required transmission power, any extra power will lead to the increase of user QoS (i.e., in terms of datarate). The charging of the D-RRH is another important factor to consider. To this end, several methods have been proposed, such as having the D-RRH charge or replace its battery at specific ground stations ([27], [28]), leverage solar cells [29], [30], or utilize simultaneous wireless information and power transmission (SWIPT) schemes [31], [32].

The contributions of this paper are summarized as follows:

- We formulate the D-RRH placement problem that aims to minimize the required transmission power. The formulated problem is decoupled into two separate problems, namely horizontal and vertical placement problems.
- We propose an optimization approach that involves three steps. In the first step, we determine a temporary horizontal position, while in the second step we determine the coverage radius and the vertical position. In the third and final step, we determine the optimal horizontal position.
- We implement a Weiszfeld-based algorithm in order to solve the horizontal placement problems, which are considered a particular form of the Weber-Fermat problem.
- We solve the vertical placement problem by calculating the minimum coverage radius that provides connectivity to a required number of users.
- We carry out extensive performance evaluation and compare our proposed approach to the ones proposed in [15] and [17] in terms of connectivity and power loss for various connectivity requirements and user deployments in different propagation environments.

The remainder of this paper is organized as follows: The system overview is provided in Section II, along with the problem formulation and the proposed optimization approach. Section III presents the evaluation of the proposed approach, while Section IV concludes this work.

II. SYSTEM OVERVIEW

A. PATHLOSS MODEL

The conventional pathloss models, that are used to model the links between the RRHs and the users, are not suitable for links between D-RRHs and users, due to the flying height and high mobility of D-RRHs. The probability of line of site (LoS) of an air to ground (AtG) link is calculated as [33]:

$$P(h, d_i) = \frac{1}{1 + \alpha \exp(-\beta(\frac{180}{\pi} \arctan(\frac{h}{d_i}) - \alpha))} \tag{1}$$

where α, and β are coefficients based on the environment (e.g., urban, rural, etc.). The set of users is denoted $U = \{1, 2, \cdots, |U|\}$, where $|U|$ is the number of users. Additionally, the altitude of the D-RRH is denoted by h, while the horizontal distance between the D-RRH and user i, $i \in U$ is denoted by $d_i = \sqrt{(x_i - x_D)^2 + (y_i - y_D)^2}$, where (x_i, y_i) and (x_D, y_D) are the locations horizontal locations of the user and the D-RRH, respectively. Therefore, the pathloss model for LoS and non-LoS (NLoS) links can be written as:

TABLE 1. Propagation Parameters in Different Environments.

Environment	α	β	η_{LoS}	η_{NLoS}	θ^*
Suburban	4.88	0.43	0.1	21	20.34°
Urban	9.61	0.16	1	20	42.44°
Dense Urban	12.08	0.11	1.6	23	54.62°
High-rise Urban	27.23	0.08	2.3	34	75.52°

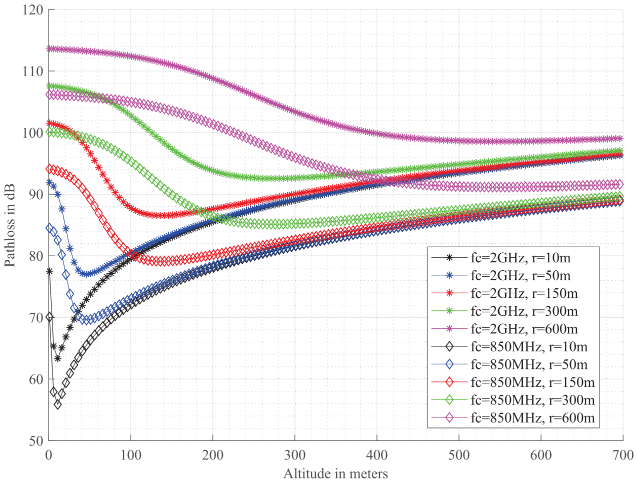


FIGURE 1. Pathloss as a function of altitude.

$$L(h, d_i) = 20\log(\sqrt{h^2 + d_i^2}) + AP(h, d_i) + B \tag{2}$$

where $A = \eta_{LoS} - \eta_{NLoS}$ and $B = 20\log(\frac{4\pi f_c}{c}) + \eta_{NLoS}$, f_c is the carrier frequency (in Hz), c is the speed of light, and η_{LoS} and η_{NLoS} are the mean additional losses (as shown in TABLE 1).

Fig. 1 shows the pathloss (in dB) between a user and a D-RRH as a function of the altitude, for various carrier frequencies (denoted as F_c in the figure) and horizontal distances (denoted as r in the figure), while the horizontal distance is fixed. It is apparent that, in all cases, the pathloss is decreased up to a certain altitude, and then is increased as the altitude increases. This happens because, in low altitudes, the probability of η_{NLoS} is much higher, due to reflections of various objects (e.g., buildings). As the altitude is increased the η_{LoS} probability increases, resulting in the decrease of pathloss.

The received signal power P_r at a user depends on the pathloss experienced by the communication link and can be calculated as:

$$P_r^i = P_t^i - L(h, d_i) - P_n \tag{3}$$

where P_t^i is the D-RRH transmission power to user i, $L(h, d_i)$ is the experienced pathloss, and P_n the power of the additive white gaussian noise (AWGN). The AWGN power will essentially be the same for all the users located in a particular area. Therefore, the impact of the noise to the determination of the optimal D-RRH location will be nominal. Without loss of generality, we assume that $P_n = 0$.

In general, both large-scale and small-scale fading should be taken into account in the channel model. However, perfect knowledge of channel state information (CSI) is difficult to obtain prior to the drone flight [34]. Therefore, the optimization approach presented in this work only considers large-scale fading.

B. PATHLOSS MINIMIZATION

According to Shannon's channel capacity formula, the user datarate is considerably affected by the received power. In order to ensure a high QoS in terms of datarate, the user received power P_r^i must exceed a certain power threshold, denoted by P_{min}. This can be translated as the transmission power P_t^i plus the minimum power threshold P_{min} being greater than the pathloss $L(h, d_i)$.

$$P_t^i + P_{min} \geq L(h, d_i) \tag{4}$$

Consequently, the minimization of the pathloss will result in the minimization of the required P_t^i. However, as the transmission power is reduced, the coverage area of the D-RRH will decrease. We introduce the binary variable u_i that denotes whether a user is covered as:

$$u_i = \begin{cases} 1, & \text{if user is covered} \\ 0, & \text{if user is not covered} \end{cases} \tag{5}$$

Therefore, the optimization problem can be written as follows:

$$\begin{aligned} \underset{\{x_D, y_D, h\}}{\text{minimize}} \quad & \sum_{i=1}^{|U|} u_i \cdot P_t^i \\ \text{subject to:} \quad & 0 \leq P_t^i \leq P_{max}, \forall i \in U && \text{(6a)} \\ & x_{min} \leq x_D \leq x_{max} && \text{(6b)} \\ & y_{min} \leq y_D \leq y_{max} && \text{(6c)} \\ & h_{min} \leq h \leq h_{max} && \text{(6d)} \\ & \sum_{i=1}^{|U|} u_i \geq \Pi \cdot |U|, \quad \forall i \in U && \text{(6e)} \\ & u_i = \{0, 1\}, \quad \forall i \in U && \text{(6f)} \end{aligned}$$

Constraint (6a) is used to maintain the transmission power in the range $[0, P_{max}]$, while constraints (6b), (6c), and (6d) enforce the D-RRH position within the area limits. Constraint (6e) requires that the number of covered users is greater than the required threshold, denoted by Π, while constraint (6f) enforces equation (5). Finally, $|U|$ is the cardinality of U which denotes the set of the deployed users.

Due to the nonlinear equations (1)-(3), the sum in constraint (6e) and the binary value u_i, the aforementioned optimization problem is a non-convex MINLP, which is an NP-hard problem [35]. In order to solve this optimization problem, we decouple the horizontal from the vertical placement and propose a three-step approach to solve it. Algorithm 1 provides a summary of the proposed approach.

Algorithm 1 Proposed Approach

```
Input: user positions: $(x_i, y_i)$, $i \in U$
Output: optimal D-RRH position: $(x_D^*, y_D^*, h^*)$
    STEP 1:
    find the temporary horizontal position $(x_D^T, y_D^T)$ that minimizes the sum distances of all users using the Weiszfeld-based algorithm (Algorithm 2)
    STEP 2:
    find the optimal elevation angle by numerically solving equation (10)
    find the radius $r^*$ of the coverage area and the subset of covered users $U_{cov}$, so that a required number of users is covered using Algorithm 3
    calculate the optimal altitude as $h^* = r^* \cdot \tan\theta^*$
    STEP 3:
    find the optimal horizontal position $(x_D^*, y_D^*)$ that minimizes the sum distances of the users in $U_{cov}$, using the Weiszfeld-based algorithm (Algorithm 2)
    return $(x_D^*, y_D^*, h^*)$
```

C. STEP 1: TEMPORARY HORIZONTAL PLACEMENT

In the first step, the horizontal placement problem can be solved by finding the temporary (x_D^T, y_D^T) horizontal point that minimizes the sum of all distances between the drone and the users. Therefore, the horizontal placement problem can be written as:

$$\begin{aligned} \underset{\{x_D, y_D\}}{\text{minimize}} \quad & \sum_{i=1}^{U} d_i \\ \text{subject to:} \quad & x_{min} \leq x_D \leq x_{max} && \text{(7a)} \\ & y_{min} \leq y_D \leq y_{max} && \text{(7b)} \end{aligned}$$

This horizontal placement problem is a particular format of the Fermat–Weber problem [36], where all sum-weighs are set to one, and can be solved using Algorithm 2, which is a Weiszfeld algorithm implementation [37]. The algorithm uses as input the users positions and outputs the optimal (x_D^*, y_D^*) location of the D-RRH.

D. STEP 2: VERTICAL PLACEMENT

After the temporary horizontal placement of the D-RRH at (x_D^T, y_D^T), the optimal vertical placement is calculated in this step. Fig. 2 shows a D-RRH at h altitude that provides coverage to an area of radius r. The term d denotes the distance between the D-RRH and the edge of the coverage area, while the term θ denotes the elevation angle. By referring to Fig. 2, the following equations are obtained:

$$\begin{aligned} \theta &= \arctan(\frac{h}{r}) \\ d &= \frac{r}{\cos\theta} \\ h^2 + r^2 &= d^2 = (\frac{r}{\cos\theta})^2 \end{aligned} \tag{8}$$

Algorithm 2 Weiszfeld Implementation

```
Input: user positions: $(x_i, y_i)$, $i \in U$
Output: optimal D-RRH position: $(x_D^*, y_D^*)$
    Initialization:
    calculate starting position as:
        $x^0 = \frac{\sum_{i=1}^{|U|} x_i}{|U|}, y^0 = \frac{\sum_{i=1}^{|U|} y_i}{|U|}, t = 0$
    Main loop:
    while $\sqrt{(x^t - x^{t-1})^2 + (y^t - y^{t-1})^2} > 10^{-6}$ do
        $t = t + 1$
        calculate $x^t$ and $y^t$ as:
            $x^t = \frac{\sum_{j=1}^{|U|} \frac{x_j^{t-1}}{\sqrt{(x_j^{t-1} - x_i)^2 + (y_j^{t-1} - y_i)^2}}}{\sum_{j=1}^{|U|} \frac{1}{\sqrt{(x_j^{t-1} - x_i)^2 + (y_j^{t-1} - y_i)^2}}}$
            $y^t = \frac{\sum_{j=1}^{|U|} \frac{y_j^{t-1}}{\sqrt{(x_j^{t-1} - x_i)^2 + (y_j^{t-1} - y_i)^2}}}{\sum_{j=1}^{|U|} \frac{1}{\sqrt{(x_j^{t-1} - x_i)^2 + (y_j^{t-1} - y_i)^2}}}$
    end while
    assign the D-RRH coordinates as the final $x^t$ and $y^t$:
        $x_D^* = x^t$, $y_D^* = y^t$
    return $(x_D^*, y_D^*)$
```

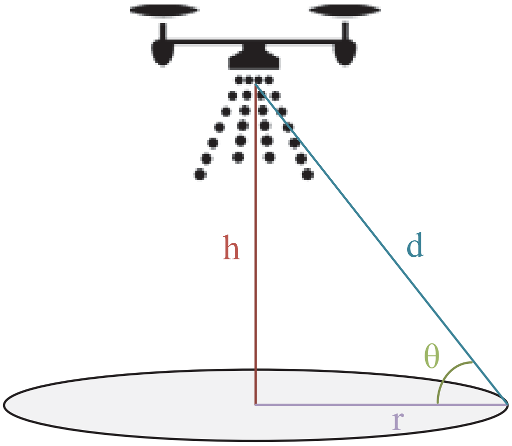


FIGURE 2. Drone coverage area.

Based on these equations, equation (2) is re-written as:

$$L(h, r) = 20 \log(\frac{r}{cos\theta}) + \frac{A}{1 + \alpha \exp(-\beta(\frac{180}{\pi}\theta - \alpha))} + B \tag{9}$$

The optimal elevation angle (θ^*) can be found by differentiating equation (9) and setting it equal to 0 as:

$$\frac{\pi}{9ln(10)} \tan\theta^* + \frac{\alpha\beta A \exp(-\beta(\frac{180}{\pi}\theta^* - \alpha))}{[\alpha \exp(-\beta(\frac{180}{\pi}\theta^* - \alpha)) + 1]^2} = 0 \tag{10}$$

Algorithm 3 Proposed Approach

```
Input: user positions: $(x_i, y_i)$, $i \in U$, optimal x-y D-RRH
    coordinates: $(x_D^*, y_D^*)$, required percentage of covered
    users: $\Pi$
Output: optimal radius: $r^*$, subset of covered users: $U_{cov}$
    sort the distances of all users from the drone:
        sorted_D=sort($d_i$)
    select the first $\Pi \cdot |U|$ users that will be connected to the
        D-RRH and add them to the subset $U_{cov}$
    set the optimal radius equal to the distance of the $\Pi \cdot |U|$th
        user:
        $r^*$ =sorted_D( $\Pi \cdot |U|$)
    return $r^*$, $U_{cov}$
```

The results, by numerically solving equation (10), for different environments are (also summarized in TABLE 1): a) $\theta = 20.34°$ for the suburban environment, b) $\theta = 42.44°$ for the urban environment, c) $\theta = 54.62°$ for the dense urban environment, and d) $\theta = 75.52°$ for the high-rise urban environment.

The optimal radius r^* will be the minimum radius that will provide coverage to the required number of users. The proposed approach of finding r^* is shown in Algorithm 3.

After obtaining the radius r^* that covers the required number of users, the optimal D-RRH altitude h^* can be calculated by substituting θ^* with the solutions of equation (10) for different environments:

$$h^* = max(r^* \cdot \tan\theta^*, h_{min}) \tag{11}$$

E. STEP 3: FINAL PLACEMENT

In the final step, the optimal horizontal position (x_D^*, y_D^*) can be determined by solving the following problem:

$$\underset{x_D, y_D}{\text{minimize}} \quad \sum_{i=1}^{U_{cov}} d_i$$

$$\text{subject to:} \quad x_{min} \leq x_D \leq x_{max} \tag{12a}$$

$$y_{min} \leq y_D \leq y_{max} \tag{12b}$$

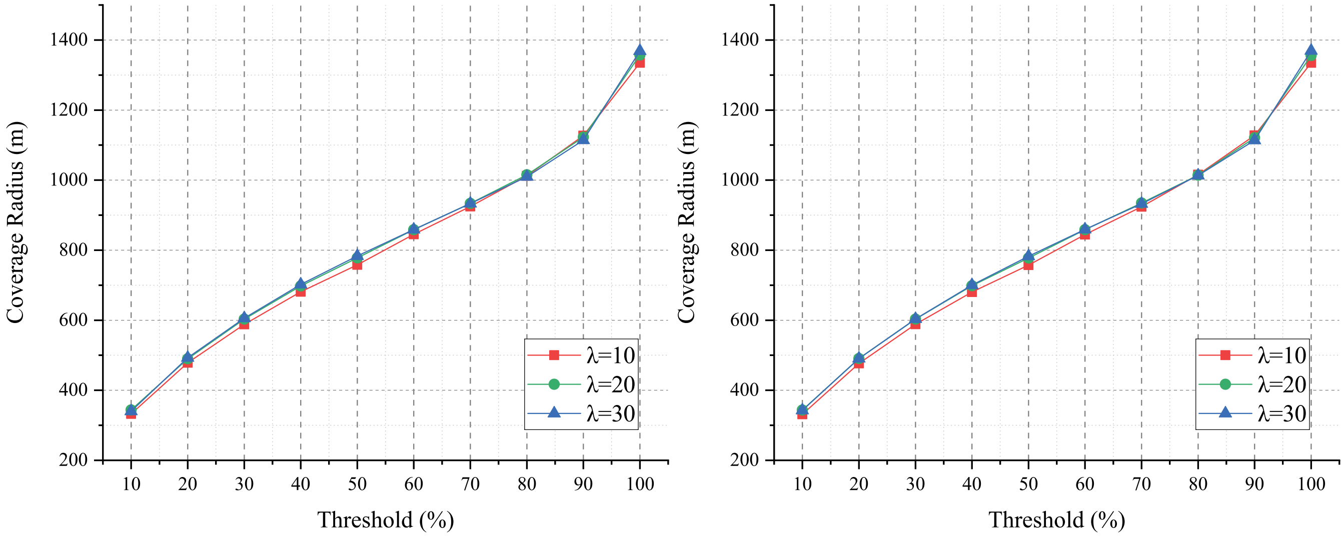
where U_{cov} denotes the subset of users that are covered by the D-RRH.

Therefore, the optimal D-RRH position in the 3D space is denoted by (x_D^*, y_D^*, h^*). The maximum pathloss will be experienced by the users that are located at the edge of the coverage area (i.e., $d_i = r^*$) and will be equal to $L(h^*, r^*)$ (eq. (2)). The transmission power for the users inside the coverage can be calculated through equations (2) and (4) as:

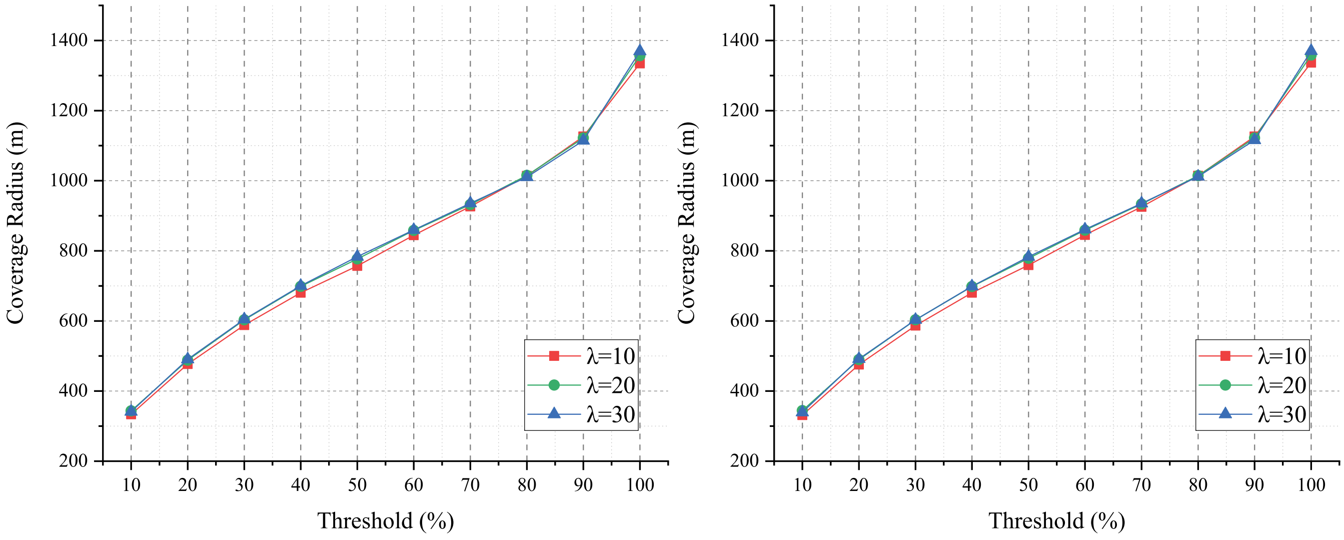
$$P_t^{i*} = L(h^*, r_i) + P_{min}, \text{ for } r_i < r^* \tag{13}$$

III. EVALUATION

A simulation environment in Matlab was developed, where the proposed approach is evaluated through Monte Carlo simulations [38]. Specifically, the final results were derived by taking the average values from running 1000 simulations.



(a) Suburban Environment (b) Urban Environment



(c) Dense Urban Environment (d) High-rise Urban Environment

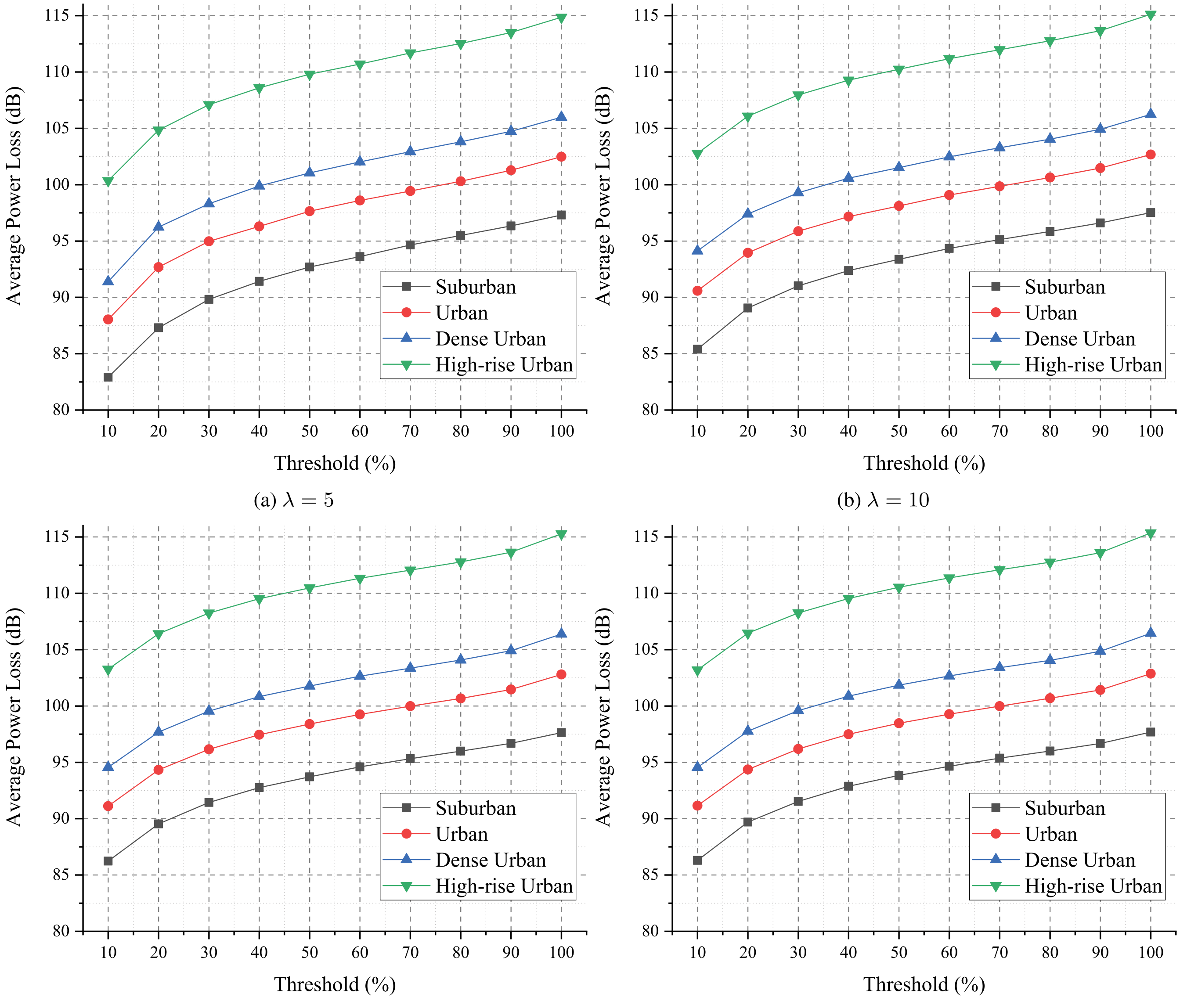
FIGURE 3. **Coverage radius as a function of the threshold Π for various deployment rates and propagation environments.**

An area of $2km \times 2km$ is considered, where the users are uniformly deployed with a density of λ that ranges from 5 to 30 users/km^2, while the percentage threshold Π ranges from 10% to 100%. For safety reasons, the minimum altitude of the D-RRH is set to 100m. Finally, the carrier frequency is $f_c = 2$ GHz. A summary of the simulation parameters is provided in TABLE 2.

FIGURE 3 shows the coverage radius as a function of the threshold in the considered propagation environments. The deployment rates are $\lambda = 10$, $\lambda = 20$, and $\lambda = 30$ users/km^2, while the threshold Π ranges from 10% to 100%. Specifically, the coverage radius in case of $\lambda = 10$ (i.e., red line) ranges from 350m to 1310m, when $\Pi = 10\%$ and $\Pi = 100\%$, respectively. Similarly, the coverage radius in case of $\lambda = 20$ (i.e., green line) ranges from 360m to 1350m, while the coverage radius in case of $\lambda = 30\%$ (i.e., blue line) ranges from 360m to 1380m. As expected, in order to provide connectivity to more users, the coverage radius has to be increased. According to the results, the coverage radius is slightly increased with the increase of deployment rate.

TABLE 2. **Simulation Parameters.**

Parameter	Value
x_{min}, y_{min}	0 m
x_{max}, y_{max}	2000 m
h_{min}	100m
λ	5–30 users/km^2
Π Threshold	10–100 %
Carrier Frequency (f_c)	2.0 GHz



(a) $\lambda = 5$

(b) $\lambda = 10$

(c) $\lambda = 20$

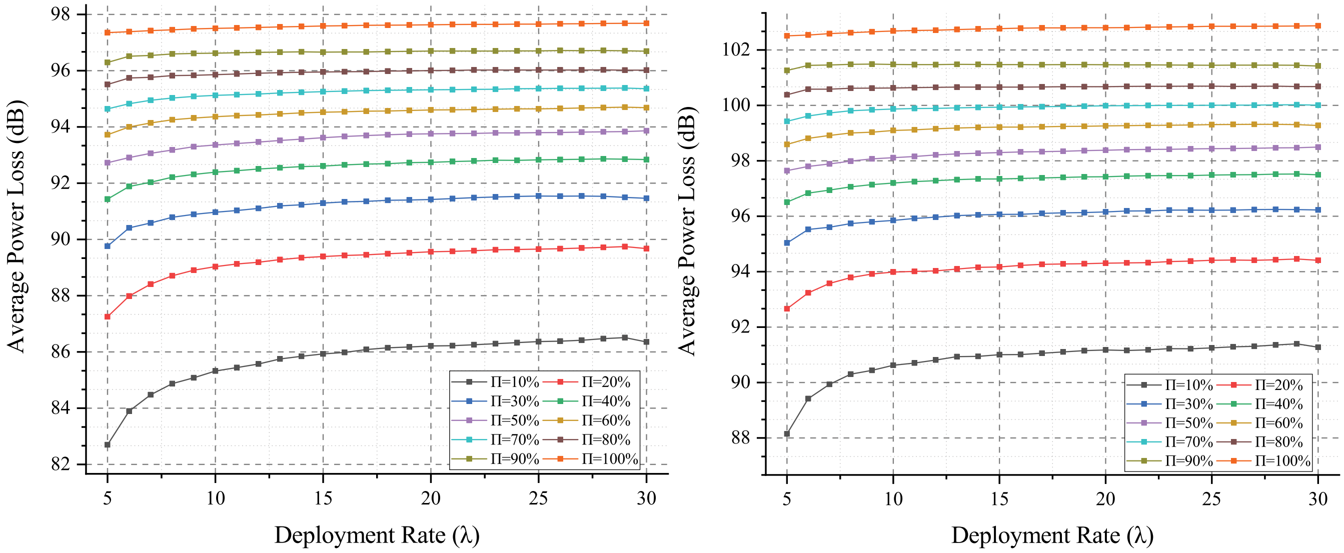
(d) $\lambda = 30$

FIGURE 4. **Average power loss as a function of the threshold for environments and user deployment rates.**

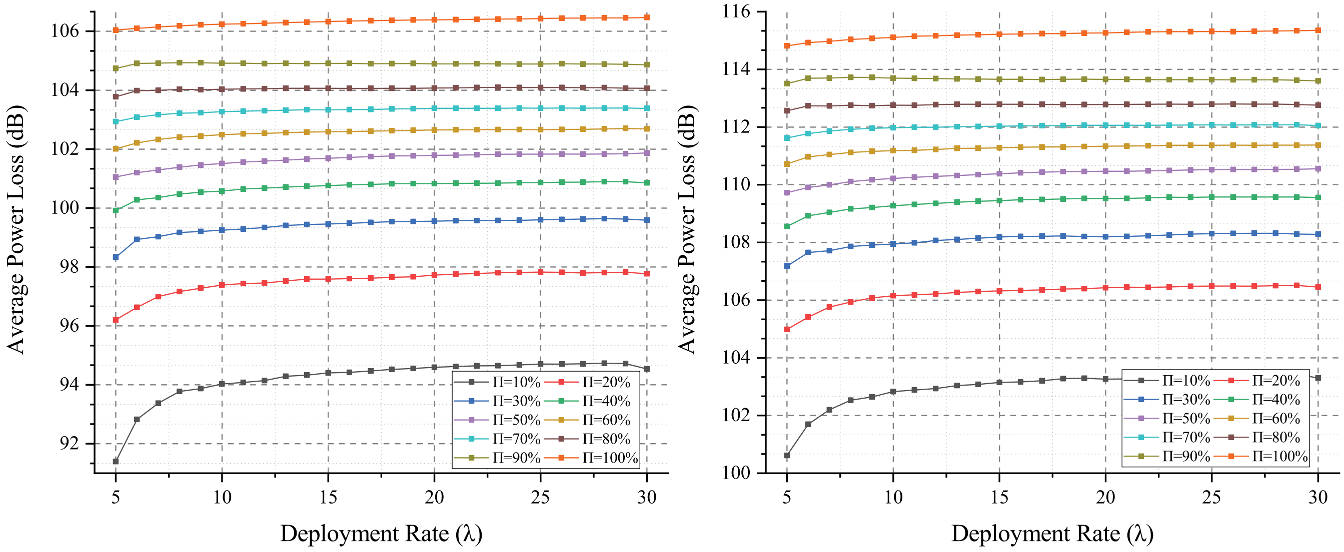
Furthermore, the coverage radius is the same in all considered propagation environments. Therefore, the propagation environment does not have an impact on the coverage radius, as the coverage radius only depends on the position of the users on the horizontal plane.

FIGURE 4 depicts the average power loss as a function of the threshold for the considered propagation environments, when deployment rates are $\lambda = 5$, $\lambda = 10$, $\lambda = 20$, and $\lambda = 30$ users/km^2 and the threshold ranges from $\Pi = 10\%$ to $\Pi = 100\%$. The results indicate that the deployment rate does not have an impact on the average power loss. Therefore, for all cases of λ, the values of average power loss are as follows: in the suburban and urban environments, the average power loss ranges from 83 dB to 97 dB and from 88 dB to 103 dB, respectively. Similarly, the average power loss ranges from 92 dB to 106 dB for the dense urban environment and from 100 dB to 115 dB for the high-rise urban environment. This increase in the average power loss is expected, as the D-RRH has to transmit in larger distances in order to provide connectivity to a larger number of users. Furthermore, the propagation environment has a considerable impact on the average power loss, due to the higher number of obstacles and reflections.

The average power loss as a function of the user deployment rate for various thresholds and propagation environments is shown in FIGURE 5. The deployment rate ranges from $\lambda = 5$ to $\lambda = 30$ users/km^2, while the threshold ranges from $\Pi = 10\%$ to $\Pi = 100\%$. According to the results, in all propagation environments, the threshold significantly affects the average power loss, while the deployment rate has



(a) Suburban Environment (b) Urban Environment

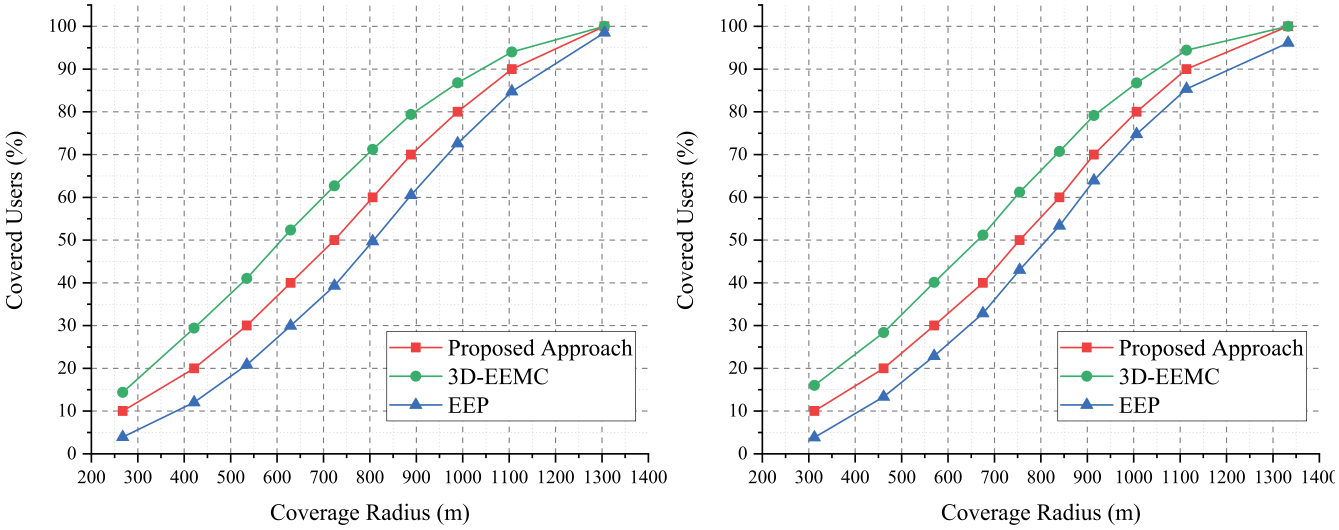


(c) Dense Urban Environment (d) High-rise Urban Environment

FIGURE 5. **Average power loss as a function of the user deployment rate for various thresholds and propagation environments.**

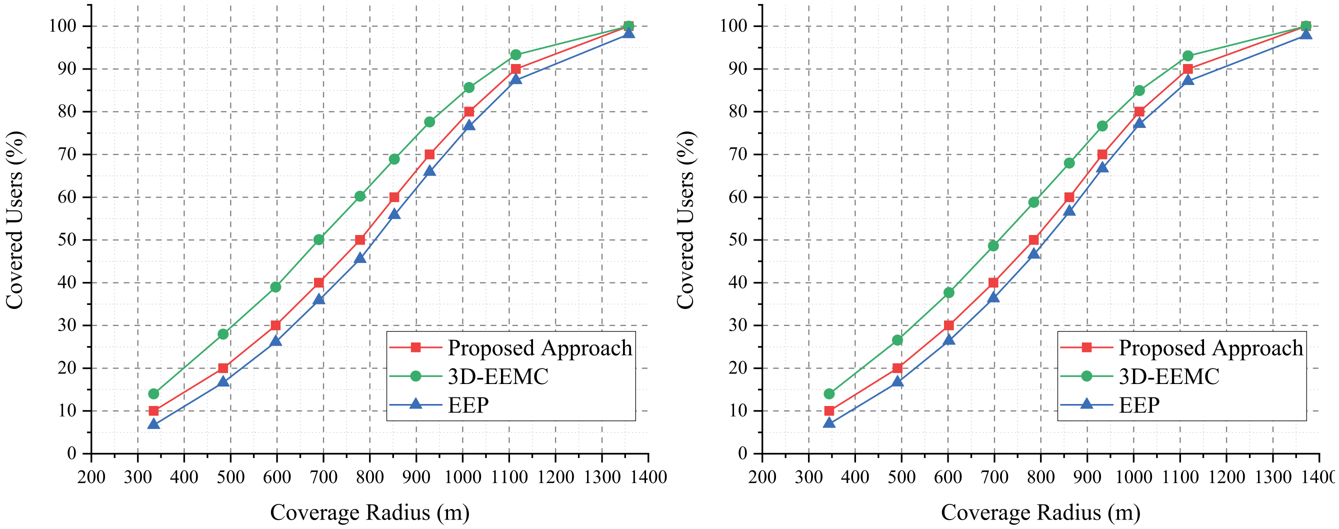
a slight impact. Furthermore, as the threshold is increased, the impact of the deployment rate on the average power loss decreases. This is expected, because when there are less deployed users and a low threshold, the D-RRH can be placed closer to those users, thus reducing the power loss. Regarding the effect of the propagation environment, it can be noticed that the suburban environment has the lowest overall power loss, while the high-rise urban environment has the highest one.

To further evaluate our proposed approach, we compared it, to the ones that were proposed in [15] and [17], namely 3D-EEMC and EEP, respectively. In FIGURE 6, we evaluate our proposed approach against 3D-EEMC and EEP in terms of user connectivity as a function of coverage radius in the considered propagation environments. It is apparent that in all of the approaches and environments, the percentage of covered users linearly increases as the coverage radius is increased. Additionally, the propagation environment has a very limited effect on user coverage. According to the results, 3D-EEMC has the highest overall performance, while EEP has the lowest. Compared to 3D-EEMC, our proposed approach has lower performance, as the aim of the approach is to minimize the transmission power, whereas the aim of 3D-EEMC is to increased connectivity. Nevertheless, our proposed approach has a better performance compared to EEP, as it can cover more users with the same coverage radius. This is due to our approach minimizing the sum-distances between the D-RRH and the covered users.



(a) Suburban Environment

(b) Urban Environment



(c) Dense Urban Environment

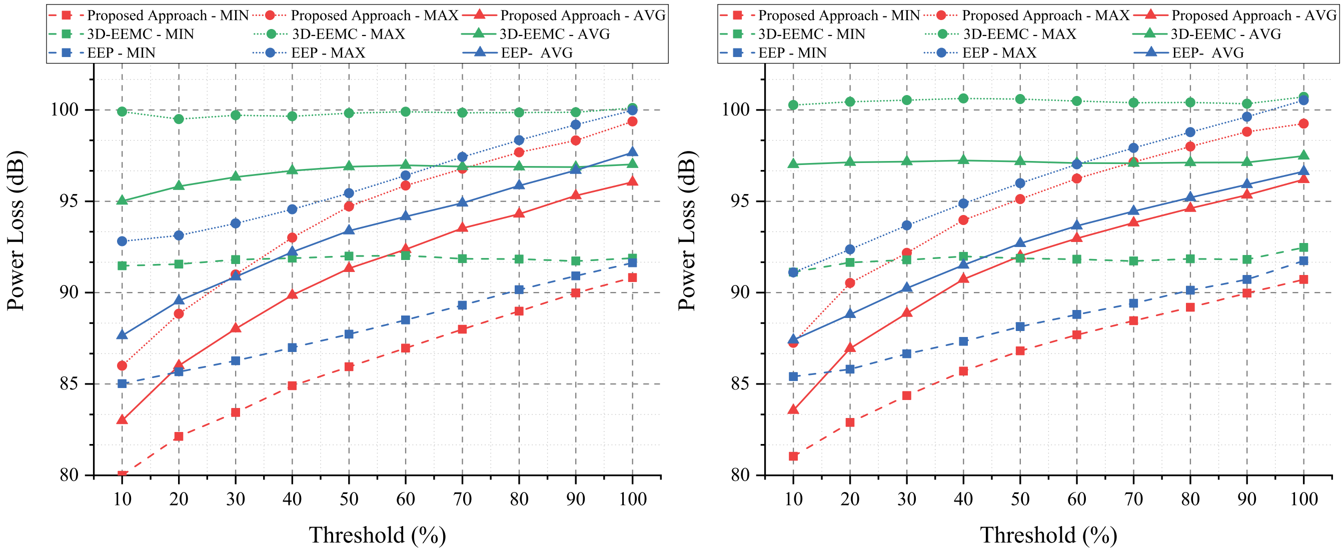
(d) High-rise Urban Environment

FIGURE 6. **User coverage as a function of the radius in various propagation environments.**

FIGURE 7 compares the minimum, maximum, and average power loss of the aforementioned approaches, as functions of the threshold in the considered propagation environments. In the suburban environment, as the threshold is increased from $\Pi = 10\%$ to $\Pi = 100\%$, the minimum, maximum, and average power loss of 3D-EEMC remain almost steady at 91 dB, 96 dB, and 100 dB, respectively. In EEP, the minimum power loss ranges from 85 dB to 91 dB, the maximum power loss ranges from 93 dB to 100 dB, and the average power loss ranges from 87 dB to 96 dB. In our proposed approach, the minimum power loss ranges from 80 dB to 91 dB, the maximum power loss ranges from 86 dB to 98 dB, and the average power loss ranges from 84 dB to 96 dB.

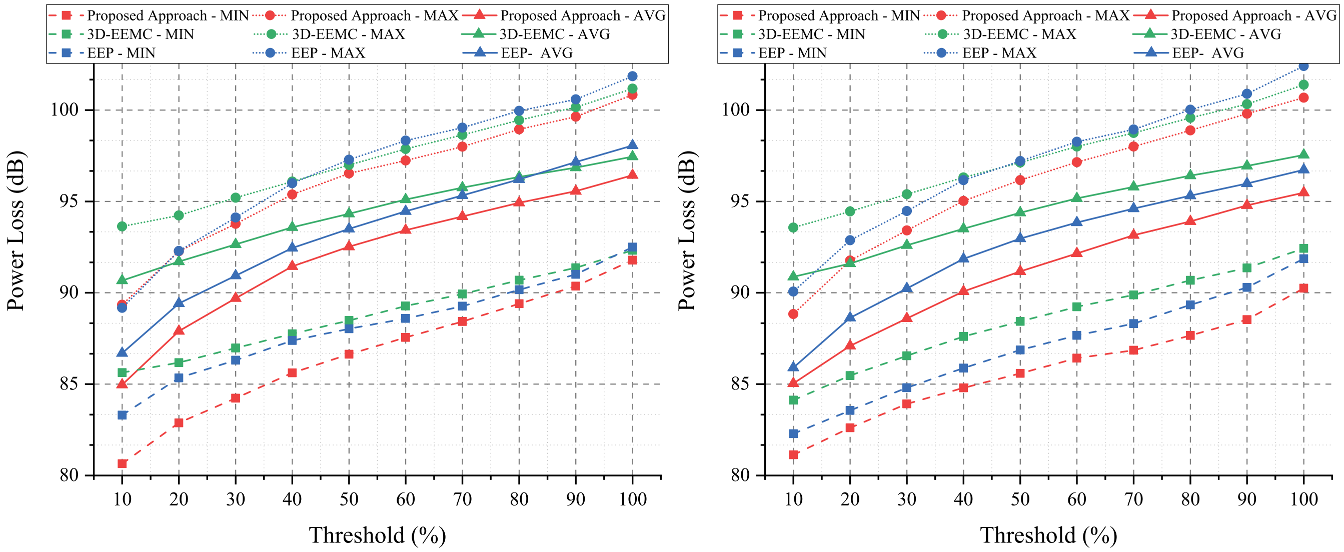
In the urban environment, as the threshold is increased from $\Pi = 10\%$ to $\Pi = 100\%$, the minimum, maximum, and average power loss of 3D-EEMC remain almost steady at 91 dB, 97 dB, and 101 dB, respectively. In EEP, the minimum power loss ranges from 85 dB to 92 dB, the maximum power loss ranges from 91 dB to 101 dB, and the average power loss ranges from 87 dB to 96 dB. Moreover, in our proposed approach, the minimum power loss ranges from 81 dB to 91 dB, the maximum power loss ranges from 86 dB to 98 dB, and the average power loss ranges from 84 dB to 96 dB.

In the dense urban environment, the minimum power loss of 3D-EEMC ranges from 86 dB to 91 dB, while the maximum and average power losses range from 94 dB to 101 dB and from 91 dB to 96 dB, respectively, as the threshold is increased from $\Pi = 10\%$ to $\Pi = 100\%$. In EEP, the minimum power loss ranges from 83 dB to 92 dB, the maximum power loss ranges from 89 dB to 103 dB, and the average power loss ranges from 81 dB to 95 dB. Additionally, in our



(a) Suburban Environment

(b) Urban Environment



(c) Dense Urban Environment

(d) High-rise Urban Environment

FIGURE 7. **Power loss as a function of the coverage threshold in various propagation environments.**

proposed approach, the minimum power loss ranges from 84 dB to 91 dB, the maximum power loss ranges from 89 dB to 101 dB, and the average power loss ranges from 84 dB to 96 dB.

Finally, in the high-rise urban environment, the minimum power loss of 3D-EEMC ranges from 84 dB to 91 dB, while the maximum and average power losses range from 94 dB to 102 dB and from 91 dB to 97 dB, respectively, as the threshold is increased from $\Pi = 10\%$ to $\Pi = 100\%$. In EEP, the minimum power loss ranges from 83 dB to 92 dB, the maximum power loss ranges from 90 dB to 104 dB, and the average power loss ranges from 81 dB to 97 dB. Moreover, in our proposed approach, the minimum power loss ranges from 84 dB to 91 dB, the maximum power loss ranges from 89 dB to 101 dB, and the average power loss ranges from 85 dB to 96 dB.

Among the three approaches, 3D-EEMC features the lowest between performance in terms of minimum, maximum, and average power loss, respectively, while our proposed approach features the best performance in the aforementioned terms. EEP features and overall in-between performance.

IV. CONCLUSION

In this work, we proposed an approach for finding the optimal D-RRH location in the 3D space, that minimizes the transmission power under a constraint, in which a required number of users is covered. The energy-efficient D-RRH placement problem was formulated and decoupled into two sub-problems, namely the horizontal placement and the vertical placement problems. The horizontal placement problem is efficiently solved using an implementation of a Weiszfeld-based algorithm, and hence, the optimal horizontal location is determined. Consequently, the vertical placement is calculated as a function of the coverage area and the optimal elevation angle for different propagation environments.

To evaluate the proposed approach, we carried out extensive evaluations in terms of coverage radius and average power loss, as well as comparisons against three similar approaches, in terms of connectivity and power loss. According to the results, our proposed approach is able to provide the minimum required transmission power and maintain a fairly good performance in terms of user connectivity. Furthermore, the evaluation results indicate that the coverage radius is not affected by the user deployment rate, but it is heavily affected by the connectivity threshold, and as a result, the coverage radius increases as the connectivity threshold is increased. Moreover, the propagation environment affects the average power loss, due to the signal distortion.

A further extension of this work involves the placement of multiple D-RRHs in order to provide maximum and efficient area coverage. Moreover, multiple user deployment scenarios, involving user hotspots, will be considered. Another extension that will be considered is the real-time micro-adjustment of the D-RRH position based on the current CSI. To this end, the increased energy consumption due to the micro-adjustments will be taken into account. Finally, the presence of multiple users in a particular area will lead to increased interference. Therefore, after the optimal placement of the D-RRH, user scheduling and power allocation schemes should be utilized to mitigate interference and increase the overall throughput of the network. To this end, we aim to integrate this work with our previous works in [39] and [40].

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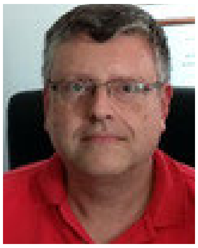

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