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A Dome packing method for UAV positioning using 3D Beamforming in WPCN for water distribution network

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***Abstract*— In the practical implementation of wireless powered communication network (WPCN) project, the energy consumption is an important factor to evaluate the performance and efficiency of the communication. In this project, a UAV enabled WPCN acts as a hybrid access point to handle multiple ground terminals (GT's) in an uneven plane. The ground terminals will harvest radio frequency (RF) energy from the RF signals directed by the UAV and these terminal uses this harvested energy to send information to the uplink. The objective of the paper is to find an optimal position of UAV using a proposed dome packing method to navigate the UAV, thus UAV will be able to charge the GTs within the cluster using 3D beamforming method where the beam will be focusing to a particular terminal rather than broadcasting the signals everywhere and thereby minimize the total energy consumption and mission completion time.**

Keywords*— Wireless powered communication network, Water distribution network, Unmanned aerial vehicle, 3D Beamforming, optimization.

I. INDRODUCTION

The water distribution network (WDN) is an important research area that focus on different issues such as intelligent monitoring for water quality, leakage etc and integrates new technologies for better and easier use. The WDN in the urban terrain covers wider area with pipes, sensors (nodes) and other components. Continuous monitoring requires communication between nodes and pipelines and these nodes send information to the control station and hence the power and its usage during communication is important for continuous monitoring [1-2]. Currently these components are powered by battery, however compared to the traditional battery charging technology, WPCN research is leading to new techniques in energy harvesting and management due to wireless charging. As a result, it does not require battery replacement, resulting in lower operating costs and improved performance. Another use of WPCN is its consistent and controlled power delivery under various application specific demands that makes it best suited for low powered IoT devices. All these makes WPCN a preferable choice in wireless energy transfer (WET) for low operational cost, higher range and small form factor [3].

It is been past few decades that the UAV were developed for different applications such as military and emergency situations like flood [4]. In a UAV enabled WPCN, the UAV can act as an energy provider, data access point or as a hybrid access point depending on its purpose or application. In traditional fixed base station, much cost was involved in the maintenance, networking and resources which lead to use UAV as a flying base station. It is widely used recently because of the advantage in electronics such as high-speed microprocessors, sensors and new type of antennas etc. To increase the coverage, performance and operation, the UAV can act as a flying base station to work effectively that suits the application scenario as in figure 1.

In the past, sensors deployed in the ground needs to be recharged by replacing the battery after a fixed time-period which requires time and labour. This issue could be solved by combining WPCN and UAV which uses energy harvesting methods to harvest radio frequency (RF) energy from the RF waves directed by the UAV and the sensors uses this energy to transmit information to the uplink. Hence, the development of research in UAV enabled WPCN and its energy consumption is of great importance. There are huge benefits of using UAV as aerial base station such as the flexibility to move around and deployment helps rapid communication and a better line of sight (LoS) [5]. Even though the UAV creates huge benefits, there are some technical challenges which require some serious concerns such as battery life, energy consumption, 3D placement of UAV, trajectory planning which evaluates the performance of the communication.

The UAV helps to provide a constant LoS communication and different methods and architectures were recommended to increase the energy efficiency during communication by optimizing the trajectory path while acting as a flying base station [6]. A trajectory based on time discretized approach with an assumed mission completion time to maximize the minimum harvested energy were used in one of the researches whereas another approach is used to maximize the average performance and minimum throughput to all devices [6]. A framework to optimize the trajectory in two-dimensional space has been introduced with single ground user and a UAV with constant speed is studied [7]. However, the ground users were considered uniformly in a two-dimensional plane for simplicity, but it may affect the applicability during implementation if it is considered in an uneven plane. The placement of the sensors is based on the work of [8]

The limited capacity and availability using a single UAV leads to its enhancement to use of multi UAV enabled communication system to handle different groups of ground terminal in large area. It helps to achieve higher throughput and lower delay. The research on improving the energy by focussing on throughput gained much attention.

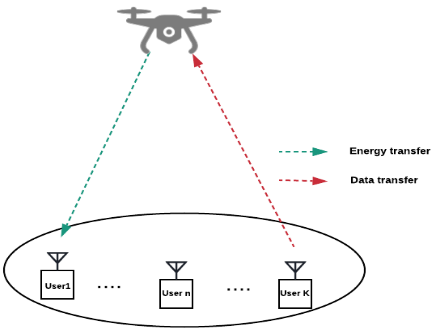


Fig 1: UAV as a flying base station

The deployment of UAV's in 2D space, the optimal altitude to achieve better coverage, finding the minimum number of drones also were studied in [9]. The energy efficiency is still a major factor during practical implementation in wireless powered networks. Some research assumed that the UAV would have surplus energy for its operation and some used methods like successive convex approximation for solving non-convex optimization problems, scheduling to manage the energy used by UAV [10].

The innovation in the field of antenna design by developing Beamforming method attracted more researchers to integrate it and implement in different scenarios such as mobile communication, energy harvesting etc. It is a method which uses multiple antennas to focus the waveform to a specific direction and alleviate the coverage issues as well as interference issues. For example, when moving a laptop from one place to another using a beamforming router, it recalculates the energy and the beam moves along with the movement of the laptop. A review of the implementation of beamforming in energy harvesting wireless networks summarize the concepts, architectures and different approaches [11]. This method has also been applied in full-duplex wireless powered communication to curtail self-interference and improve the throughput among the users [12]. In [13] and [14], a review of the beamforming methods and the factors which affects beamforming were discussed. The first factor which affects beamforming is the array design which focus on the array configuration used in the design of the antenna as its ability to scan the main beam in three-dimensional space based on the elevation and azimuth angle. The second factor is the beaming period which depends on the network throughput and delay, and throughput drops and delay increases with increasing beaming time. Finally, the third factor is the range and it is used in wireless networks at medium and small ranges to provide a better signal to noise ratio. So, all these factors need to be considered while designing a beam. This paper focus on optimizing of the third factor which is the optimal position of the UAV which is required to minimize the energy during the communication by assuming some of the beaming factors as constant. In the practical application, the energy consumption affects the efficiency of wireless communication and the energy consumption of network which depends on the UAV's optimal position and time for moving and hovering. Hence this paper develops a algorithm for optimal position of the UAV to reduce the energy consumption and communication time for its operation.

To extend UAV enabled WPCN into water distribution network (WDN) application, the major factor that require a serious concern is minimizing the usage of energy during communication due to large scale of WDN. The optimization of unmanned aerial vehicle (UAV) positioning, height, throughput and time are the factors that should considered carefully while the minimizing the energy usage [15]. This case study is to apply on a water distribution system where a terrain is considered, which consists of surface with various elevations and hence a three-dimensional perspective of the ground nodes and the UAV is essential for delivering energy and communication services to the ground nodes. Therefore, a dome could be the perfect geometrical shape that could be applied to the considered model. As mentioned above, the altitude or height of the UAV is one of the aspects influencing the energy and time of the flight and this paper targets to optimize the position to efficiently use the power for UAV communication later in the research. Hence, a dome packing method with 3-dimensional beamforming method will be used to implement this work. The three-dimensional beamforming method is used to direct the energy signals to a destined ground terminal for an efficient communication compared to the traditional broadcasting method. The antenna arrays will be integrated with the UAV in this model to implement beamforming which will improve the coverage and efficiency of energy during communication.

In this paper, the remaining sections are organised as follows. Section 2 explains the related works and motivation for the project and section 3 specifies the model of the system, section 4 provides the proposed dome packing method and section 5 explains the simulation results and concluding with section 6.

II. Related work and Motivation

Beamforming uses multiple radiating elements integrated into the antenna and phase shift them by adjusting the magnitude to point at different directions to reach the ground sensors. The main advantage is to gain more energy at the destination compared to the traditional antennas. The direction of arrival is calculated using adaptive algorithms processed by the digital signal processor. For example, in order to change the direction of the active main lobe of the beam, an n-element phased array with variable delays can be used.

A. Beamforming using UAV

The Beamforming used in UAV for wireless communication to direct a signal/beam to an intended receiver. Beamforming is applied in some research where uplink has higher throughput for on board UAV [11][14]. The benefits of implementing beamforming include increased coverage since the beam is directed to a destination, higher data rate and quality of service, high security since the beams are not broadcasted in all the directions and less interference.

A two-dimensional (2-D) beamforming is mostly applicable in cellular communication or networks where the nodes to be accessed are placed in the horizontal axis of the antenna and it uses beamforming to control the beam pattern. Each of the sectors in cellular communication used a one- dimensional array of antenna elements to provide a circular shaped radiation pattern [16]. In [17], a 2-dimensional beaming algorithm is used in imaging using microwaves to detect the target behind the wall by reconstructing the images whereas [18] used for millimetre wave communication to attain high throughput in mobile communication. Even though 2D beamforming is widely used in different mobile communication network, it will not be an ideal fit in this paper as the scenario is considered on a three- dimensional perspective and hence a 2d approach will not be applicable.

A 3-D beamforming design with mm wave is used to identify beam coverage of the target area with fixed height in a plane whereas 3-D beamforming design for 5G cellular communication with fixed base station is used to study the impact of beaming [19][20]. Most of the previous literature focus on the coverage radius with less focus on the height of the UAV[19][21] whereas a 2-D (two-dimensional) trajectory planning, energy optimization and throughput maximization were investigated assuming it in an even plane[18][22]. One of the main attributes to optimize is the height of the UAV in a downlink communication while considering an uneven plane from a three- dimensional perspective of the UAV and ground node.

The tangential line method is used to find the trajectory of the UAV while collecting the energy or data. The research work in [23] uses tangential line method for path designing and broadcast energy to the ground nodes to achieve minimum throughput maximization. Whereas, [24] uses it for trajectory planning and trajectory optimization. The UAV requires much energy to fly higher to collect data and then lower the height to be available near the sensors to transfer energy. This time and energy loss can be reduced by using 3-dimensional beamforming.

The optimization is often performed in UAV to manage the time, energy, performance and throughput during the communication. In [25], the UAV acts as a flying base station and the performance optimization of the UAV to ground communication under time constraints using a cell partitioning approach is implemented. In [26] and [27], energy efficiency is optimized by considering the hardware components such as landing gear, blades etc that constitute the weight of the UAV. Whereas [28],[29] used an iterative algorithm for optimizing the energy transfer and power and thereby increasing the energy efficiency in relay assisted WPCN and UAV enabled sensor network. In [30] where UAV acts as an aerial base station, energy efficiency is maximized by optimizing power allocation, trajectory, user scheduling and bandwidth in wireless mobile communication. The optimization of trajectory, routing or path are common in most of the UAV communication design for improving energy efficiency, performance and throughput. The authors of [9] proposed a model and a design for energy efficiency by considering the trajectory path, speed and time of a fixed wing UAV. Whereas, [31] used 3d trajectory and resource allocation for sum throughput maximization in solar powered UAV communication. Most of the research work focus n energy optimization in an even plane and the height of the UAV is assumed to be a constant. Based on the literature [25]-[31] there are no relevant research in minimizing the total energy of the UAV in a terrain. The authors in [32] proposed a multiantenna beamforming to maximize the minimum throughput performance on an even plane, but this work will focus on optimizing the altitude on a terrain by considering the maximum coverage of the GT's and planning to extend later towards increasing the energy efficiency by considering trajectory and time constraints.

This research focus to find the 3D position of the UAV to achieve the optimal altitude using beamforming in the wireless powered communication network in application of WDS. A beamforming model of UAV is proposed in this work, where the algorithm named dome packing to group and pack the sensors based on the beamforming range/ coverage will find the optimal height of the UAV to charge the sensors on the ground. This paper also proposes a theoretical model to optimize the energy used in UAV enabled WPCN by optimizing the position of the UAV in the terrain.

III. System Model

A system model is proposed to optimize the position of the UAV and thereby reducing the time and energy of the flight shown in figure 2. In this model, a WPCN system with rotary wing-based UAVs which will be in line of sight (LoS) communication with the ground terminal nodes (GT's) connected to a rechargeable battery will be used. The GT's are positioned with x,y,h values to get a 3D perspective of the GT points. The UAV collects energy from an RF energy charging point and broadcast energy to GTs through WET using beamforming on board. The elliptical shape in the figure 2 represents the area where the ground sensors are placed with in the radius of Rc. Since a three-dimensional perspective of both the UAV and the ground nodes are considered, dome will be the ideal shape to represent clustering of the GT's in the terrain area. The radius of the clusters is represented using r. The initial position of the UAV will be calculated by using a 3D K-means clustering algorithm using the GT points (x_n,y_n,h_n) to calculate the clusters and its centroids. It is also considered that the energy will also be received by the nodes during beamforming which is on the same line of sight as that of the nodes while charging.

This work will be using rotary wing UAV with Beamforming on board as it requires up, down motions and hovering positions. It will be using a three-dimensional perspective of the ground users which is assumed to be on an uneven plane with a downlink channel model.

Let the GT's be k Є {1,2…,N} will be on the ground and the UAV at position P at precalculated height H with a line of sight (LOS) communication path. The height is calculated after the initial clustering by using the mean progression of the different heights of the GT's in a cluster. A Uniform rectangular array (URA) with MxN antenna array elements with half wavelength spacing which will be integrated in the UAV to implement 3D beamforming and the GT's with a single receiving antenna.

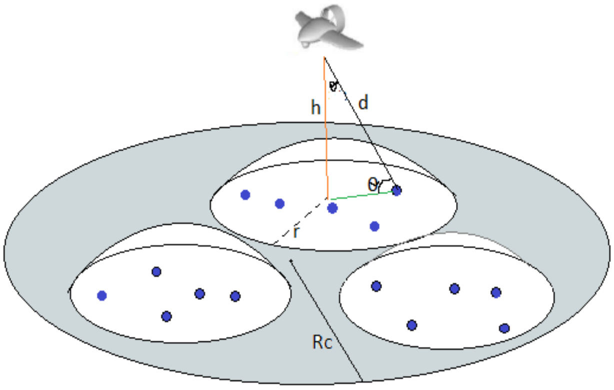


Figure 2: Representation of UAV enabled WPCN with 3d beaming

The beam receiving area is assumed to be an ellipse of area 'Rc'. The channel vector can be represented as (M, N, $\theta, \emptyset$) where θ and $\emptyset$ are the azimuth and elevation angles. The antenna radiation pattern in GT's direction is formulated by

$$A(\theta, \emptyset) = A_H(\theta) + A_V(\emptyset) \quad (1)$$

And the antenna gains in horizontal and vertical planes (A_H, A_V) is calculated as

$$A_H(\theta) = \min[12(\frac{\theta}{\theta_{3dB}})^2, A_m] \quad (2)$$

$$A_V(\emptyset) = \min[12(\frac{\emptyset - \emptyset_{tilt}}{\emptyset_{3dB}})^2, A_m] \quad (3)$$

where θ_{3dB} and $\emptyset_{3dB}$ represents the 3dB beamwidth of the horizontal and vertical patterns, and A_m is the side lobe level attenuation, and $\emptyset_{tilt}$ represents the beam tilting angle[13][33]. The angles to steer the beam towards the GT direction is calculated by $\tan^{-1}(H/d)$ where d is the distance (horizontal and vertical) from the cluster center to the ground terminal k. The half power beamwidth is also calculated to find the range of the beam created using dsin(∝) where ∝ is the beamwidth.

IV. Proposed Dome Packing Method

In the proposed dome packing method, the ground terminal devices are randomly distributed at an area represented by radius Rc, which can be partitioned into K master clusters c={c1…cK} by 3D clustering using K-means [34] and a cluster center 'τ' for each cluster is calculated. The UAV is positioned at c and 3D beamforming is applied at the precalculated height H. A heuristic approach will be used so that the UAV will not perform any height calculation operations at child nodes to save energy during recalculations. If any of the GT's are not reachable or the strength of the beam is less than -30 dB power (stronger the beam, less charging time), then the UAV should be adjusted to calculate the optimal position. The new position (Δx, Δy, Δh) of the UAV will be calculated where Δx, Δy, Δh are the change in x, y and H. It is calculated on the basis of the position of the GT and the coverage of the beam. If the GT is not in the coverage, a re-clustering with child clusters will be performed followed using 3D beamforming.

Algorithm: Proposed Dome packing Method
Finding the Optimal position of UAV for a single dome

```
Initialize target network and the UAV;
Initialize UAVs' initial position P and IoT ground
terminal (GT)' positions
for GT k = 1, ···, N, do
        Perform initial clustering of the IoT devices.
end for
As a result c1,.,cK master clusters will be formed
Calculate centroid of each master cluster τ
        for c=c1…cK
        do
        Position the UAV to the cluster c's centroid at a
        precalculated position (x,y,H);
        Apply 3D Beamforming at the current UAV's
        location
        if any GT's in the cluster is not reachable and
        strength of beams is less than -30db power
            then a delta value will be calculated for a new
            position of UAV with Δx, Δy, Δh
                if the new position is within the coverage
                then, apply 3D Beamforming at the new
                position
                else, based on optimal position, perform
                re-clustering (child cluster) at h value to
                cover the GT's
         Apply 3D Beamforming at the new position
        else the precalculated position (x,y,H) will be the
        same
        end for
```

V. Simulation Results

Based on the model and simulation, the numerical results are used to validate the effectiveness of the proposed approach in optimizing the position of the UAV for energy minimization.

In the simulation, its assumed that 8 ground terminal nodes were placed at predefined positions at varying height from the ground and the UAV is positioned at an altitude of H metres from the ground. The transmission power of the UAV to communicate with the GT's is 25dBm, frequency f= $1x10^{6}$, c=$3x10^{8}$ and the pathloss in the channel is µ. The UAV and the GT's have a line of sight (LOS) communication. Initially, a 3D clustering is applied to all the GTs and the clusters with their centroids are fed to the UAV.

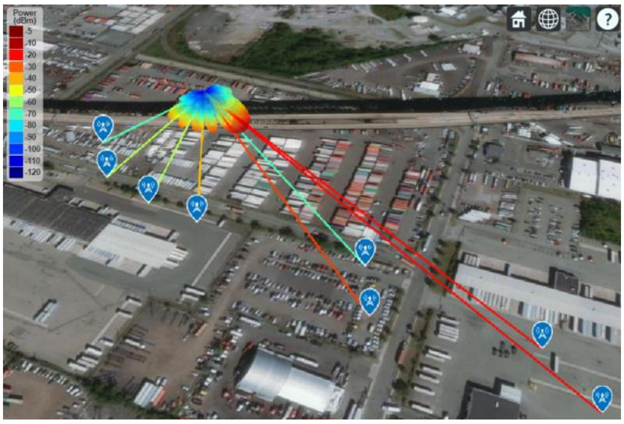


Figure 3: 3D Beamforming in UAV enabled WPCN

At the next step the optimal position of the UAV (x, y, H) is calculated using the proposed algorithm and 3D beamforming is performed with vertical and horizontal angles with the GT nodes as represented in Figure 3. After calculating the optimal position, the beam will be steered towards each GT's to charge it effectively. Based on the model, the results are represented as in Figure 4, 5 and 6.

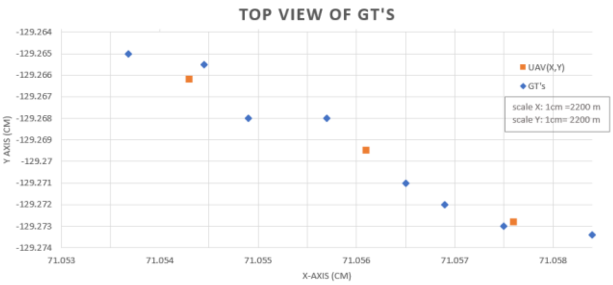


Figure 4: Position of GT's vs UAV position

The figure 4 represents a top view of the model with the position of the UAV and the GT's in the coordinates of the x, y axis. A side view of the GT's is represented as in figure 5, since it depicts a 3D view of the model and the x,y,H axis were scaled down to 1:20. From the simulation results on Figure 5, the optimal position of the UAV for charging of the GT's is calculated and a comparison of the model with an existing model [27] (represented as UAV charging) is performed to compare its rate of change. In the figure 6, a mathematical calculation of the energy used by the UAV (moving, hovering and beaming) is computed [35-36] after energizing each GT's and a comparison of the total energy consumed by the UAV against the GT's with and without using DOM packing is represented.

To calculate the energy consumption of the UAV the model proposed in [36] is used for this work. From the simulation results on figure 6, it is evident that the proposed dome packing method provides better energy consumption than the compared method.

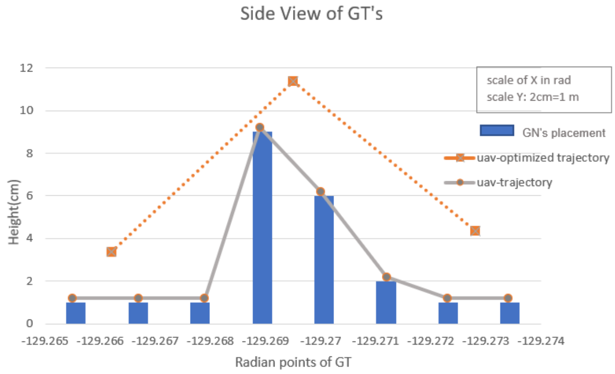
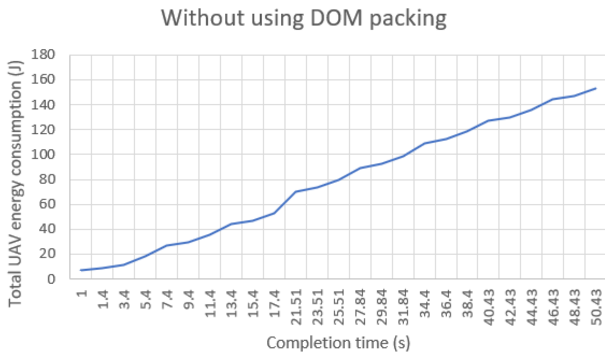
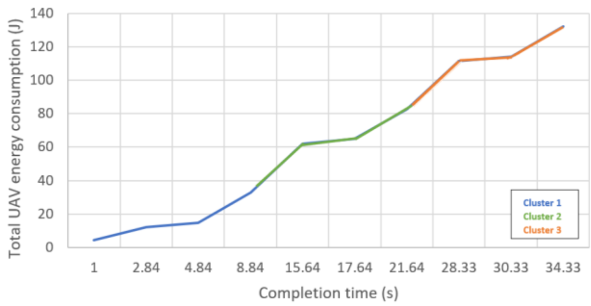


Figure 5: The optimal positions of UAV for charging the GT's using DOM packing and without DOM packing method



(a) Without using DOM packing method



(b) Using DOM packing method

Figure 6: Total energy consumption of the UAV vs completion time with and without DOM packing method

VI. CONCLUSION AND FUTURE WORK

The research in WPCN is fast growing, combining with computing, beamforming and energy harvesting could lead new way of communication. In this work, a UAV enabled wireless powered communication network is used as a flying base station to provide energy to the ground sensor nodes in an uneven plane using 3D beamforming technique and this energy will be used to send information to the uplink. The total energy consumed by the UAV could be reduced by optimizing different factors and in this work, the position of the UAV is optimized by applying a dome packing algorithm. The future work is planned to extent the scenario to multi-UAV deployment and energy efficient trajectory design of UAV by considering the time factor. Later, the total combined energy consumption for the communication is calculated against the energy received using artificial intelligent methods to reach a constant value to achieve energy efficiency in the wireless powered communication network.

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