2014 Fifth International Conference on Intelligent Systems, Modelling and Simulation

Algorithmic Approach for Strategic Cell Tower Placement

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***Abstract*— the increasing number of cell phone users and the usage of cell phones in remote areas have demanded the network service providers to increase their coverage and extend it to all places. Cost of placing a cell tower depends on the height and location, and as it can be very expensive, they have to be placed strategically to minimize the cost. The research aims to find a simple implementable algorithm which effectively determines the strategic positions of the cell towers. Given a satellite image and population density, and obtaining topographical information from GIS (Geographic Information Systems), potential tower locations can be determined. Applying the proposed three stage algorithm, out of many potential tower locations only the indispensible and optimal locations can be chosen. In addition, this algorithm helps to find out the optimal height of the tower at a chosen potential tower location. Hence, the proposal will provide cost-effective way for tower placement specifying their optimal position and height to cover any area and population.**

Keywords—Extreme topography;Remote areas;Potenial tower location;Optimal tower locations;Optimal height of tower;Cost-effective.

I. INTRODUCTION

The era of telephones is almost obsolete. In present world situation, all people across the world use cell phones. News by ITU (International Telecommunication Union) announces that the number of cellphones would overtake the world population by 2014[1]. In a similar fashion, the usage of mobile internet has increased. Irrespective of their economic condition everyone, including the ones in rural areas and people living in extreme geographical areas have started using cell phones. So it is high time that cell phone service providers extend their service to rural areas, as well as areas with extreme topography to provide effective connectivity. It is important to provide a cost-effective method to place cell towers to cover all the customers in an area.

The numbers of service providers have increased manifold in the last decade and the competition between them has necessitated in finding an efficient algorithm to place their towers in a strategic way. This way they can ensure the customers of the service provider an excellent connectivity at remote as well as extreme regions at an affordable cost.

Cell Towers being expensive needs to be strategically placed, to reduce cost. Moreover, the optimal height of a tower being placed need to be wisely calculated as the height of the tower not only affects the coverage of the tower but also affects the cost of its placement. In this context, we come across various complications. For instance, signals fail to reach certain areas as range of coverage gets distorted due to geographical constraints. Henceforth, potential tower locations have to be determined in any given area. And only the best and most necessary ones that are needed to cover maximum customers in the area, have to be chosen along with their respective optimal height. These details can help the service provider companies to set up their tower in a cost-efficient manner so that they can cover maximum customers in the area and in turn maximize their profit. This can help in establishing efficient connectivity throughout the area.

A study by Jason, Terry and Loren [2] in 2009, suggest an efficient algorithm to identify the best tower locations amongst a list of potential tower locations by providing a three way solution, first by greedy approach, then by ratio heuristics and finally by genetic algorithm. It compares the three solutions, and demonstrates that the genetic algorithm is the best solution.

The identification of the potential tower locations from any satellite image of an area is an important problem, which has been overlooked by the above paper. Since this is a problem to be implemented on practical grounds, the legitimacy of potential tower locations plays a major role.
Realizing the above need, a study by Prof. Dr. Alaa and Prof.Dr.Soukaena [3] in 2011 uses a spatial data mining and geographical information system to find the potential tower locations. This was accomplished by using DEM (Data Elevation Model) on the satellite image of the area.

The optimal height of the tower at any potential tower location is another important issue ignored by the above studies. This problem needs to be addressed as the height of the tower plays an important role in determining the coverage and the cost of its placement.

Though these papers provide a novel approach to solve problems in similar context, there is a need to consider more parameters. This enables to a practically reliable solution for network service providers to implement while placing

2166-0662/14 $31.00 © 2014 IEEE
DOI 10.1109/ISMS.2014.112

towers in an area. An algorithm is needed, such that it starts from raw satellite image and determines the strategic position and respective optimal height. This enables service providers to have efficient connectivity, covering maximum area and customers while reducing the cost of placement thus increasing their profit.

Taking a satellite image of Agumbe, a place in Karnataka, India, a remote region with extreme topography where cellphone network is not available, this algorithm was simulated. Hence, the best tower placement positions were determined along with their respective heights represented in graphs in the 'Results and Conclusion' section. In a similar way, the algorithm so proposed can help us find the most cost-efficient and maximum-population-covering tower positions.

II. PROBLEM STATEMENT

In todays interconnected world, linking remote areas is of prime importance to network providers. But while it is of great importance, it is also vital that it is achieved in a cost effective manner. Providers are looking at ways to attain coverage of such areas using minimum infrastructure and at a minimal cost. This paper goes through the heuristics to do so.

With the satellite image of the area to be covered, it is possible to ascertain the possible positions to place a tower. Using Geographic Information System (GIS), topographical and spatial modeling and its analysis can be done. This is an important step as cell towers and other wireless solutions are constrained by Line of Sight (LOS) restrictions.

For example, a tower placed on the highest hill (in a rural setting) or building (in a urban setting) need not be the best solution due to other obstacles (such as another smaller hill or building) blocking the LOS of the tower to all areas of the region under consideration. To avoid such situations, the most appropriate locations are ascertained using satellite imagery.

The demographic details of the region, such as the population to be covered and population density are used. This information is essential as it helps to determine the necessity of a tower in a region. For instance, a very small population which is sparsely distributed in a region would require more than one tower, where the cost of tower placement exceeds the amount generated from that population. Such complications occur while trying to solve the problem. Hence, such information helps to ascertain only the most cost-efficient positions.

The intensity of the signal at a particular point is not considered. We assume a particular threshold value of intensity, above which we consider the customer to be covered, and below it as not covered. This makes sense as our aim is to cover all customers with enough intensity to connect them to the wireless network, not determine the intensity of signal or 'strength of the signal' each customer gets.

The towers are considered from a minimum height H_{min} to $H_{max.}$ At a height lower than H_{min}, there will be attenuation of EM waves. Attenuation is the gradual loss in intensity of EM waves as it travels close to the ground [4]. At a height beyond $H_{max,}$ tower heights are impractical. Towers of various heights are considered, as taller the tower, larger the area covered but at the same time its cost will be higher. The goal is to find the optimum height of the tower such that the region covered is large and the cost of its placement is minimum. Hence there will be a trade-off between the height of the tower and cost of the tower.

The cost of the tower is considered from a lifetime cost point of view, as the cost of initial placement and maintenance varies radically depending upon topography and geo-political factors. In rural areas or rocky and mountainous terrains are tough locations to install a tower. Meanwhile in urban settings, a tower on a high-rise building will be more costly taking into account lease costs. Also taller towers will have a higher cost to manufacture, hence the cost of tower linearly depends on it height. These towers will have a higher initial cost but maintenance cost will be approximately the same for all towers, hence can be taken as a constant. Therefore, the cost of the tower can be expressed as

$$Cost = ah + m. \qquad (1)$$

Where a=Initial cost of the tower (constant)
m=Lifetime maintenance cost of the tower (constant)
h= Height of the tower

For any given area, there will be some customers who are heavy users, i.e., who make a lot of call and use a lot of data which generates revenue. At the same time, there are some customers who are not so heavy users of data and do not make a lot of calls. Obtaining such data will be very tough and taking such factors into consideration will complicate the problem. To simplify the process, the average revenue from a customer is assumed to be a fixed value irrespective of locality or economic condition.

Considering the above mentioned constraints, we have designed an algorithm which aims at finding the most appropriate position to locate a tower in the considered area of land. Our study also targets at finding the optimal height taking into account the lifetime costs of placing a tower at a particular location. Thus, our algorithm considers the cost of placing towers at all possible locations on the given map and outputs the most economically viable options.

III. ALGORITHM AND APPROACH

Optimal placement and determination of the heights of the individual towers requires a multistage approach. The given terrain data (satellite images or contour plots) must first be processed and converted into a three dimensional plot. Then suitable tower locations (the potential tower locations) may be found and further filtered to obtain an optimal distribution. The heights of the towers, that maximize coverage and minimize costs, must also be determined in a cost effective and efficient manner.

Since the size of the data handled is very large, inefficient time-consuming algorithms cannot be used. An effort is made to keep the order of growth of the time complexity of the algorithm within bounds. However since it is a one-time calculation priority may be given to accuracy rather than computation time. The approach to solving the problem may be divided into three stages:

A. Identification of potential tower locations

Potential tower locations can be identified using a graphical representation of the surface. Using Geographic Information Systems (GIS) the satellite image/contour plots of the given area is converted into a Surface plot. A curve of the form z = f(x,y) is obtained. This curve is denoted by S.

The next step is to identify the local maxima on the surface plot S. Local maxima are chosen as potential tower locations because local maxima points to regions on a surface that have greater altitude when compared to their immediate surroundings. Naturally such points are more likely to be ideal tower locations, as a tower with a higher base tends to cover a larger area with lesser obstacles to signals emitted by the tower, as there is no taller obstacle in its surroundings.

The surface is processed using the first derivative test [6] and second partial derivative test [7] to enumerate the set L where

$$L = \{(a, b) \mid f_x (a, b) = 0\ f_y (a, b) = 0,\ f_{xx} (a, b) <0,\quad f_{xx} * f_{yy} - f_{xy}^2>0\}$$

Here f_x denotes the partial derivative the curve f with respect to the dimension x, f_y denotes the partial derivative of the curve f with respect to dimension y, f_{xx} denotes the second order partial derivative the curve f with respect to the dimension x, f_{yy} denotes the second order partial derivative the curve f with respect to the dimension y and f_{xy} denotes the partial derivative the curve f with respect to the dimension x further being differentiated with respect to dimension y.

Regions where the surface plot cannot be defined, non-differentiable points and discontinuous points on the surface **S** are discarded, as these points tend to represent regions of hostile terrain where practically towers cannot be set up.

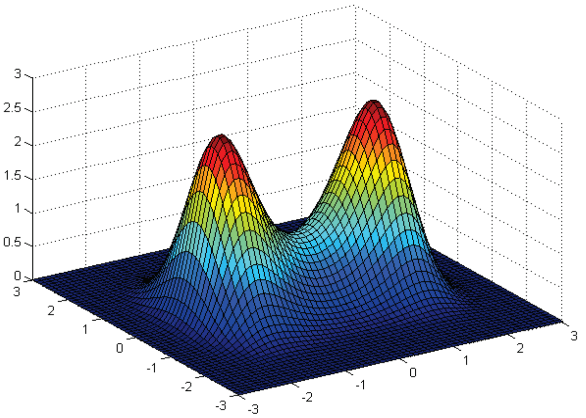

Fig.1: A simple surface plot.

The red peak regions represent local maxima. The plot shows that local maxima are ideal tower locations as they are elevated against their surroundings. The height of the tower location also adds to the suitability of the tower location.

B. Determination of coverage of potential tower locations and appropriate gridding

The given area is first covered with grid lines of width g where g is the maximum possible grid size that can be used. If the grid width becomes comparable to the wavelength of the tower radiations, errors may arise in subsequent calculations.

The total population in each grid is obtained by summating the given dot-distribution. The standard deviation of the population distribution over the grids is calculated and the grid width is reduced so as to minimize the standard deviation. However, the smaller the grid's size the larger the computation time for the algorithm.

A threshold radio-wave intensity ($\mathbf{I}_{min}$) is decided for each grid based on population considerations and other priorities. By using inverse-squared law [5] A grid is said to be "covered" by a tower if:

$$\frac{P}{\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0^{\,2})}} > I_{min} \qquad (2)$$

Equivalently:

$$P/r^2 > I_{min} \qquad (3)$$

Where P is the broadcast intensity of each communication tower, with respect to Eq. 2, (x, y, z) is the center of the grid and (x_0, y0, z0) is the top of the tower. With respect to Eq. 3, r is the distance of the center of a grid from the tower.

Moreover there must not be any interfering terrain between the tower and the center of the grid. This may be verified by ensuring that the line joining the center of the grid and the tower does not intersect the surface **S** at any other point.

For each point in **L** (set of all potential tower locations), we compute the set of grids covered by that point ($\mathbf{G_{cov}}$). This essentially gives the area covered or managed by one particular tower. In order to represent this area as a region $\mathbf{R_{cov}}$, the convex hull of the points in $\mathbf{G_{cov}}$ is found.

The heights of the towers may be varied as the intensity function P/r^2 also varies with height. Therefore the number of grid squares covered by each tower also depends on the heights of the tower in the question. It is assumed that the maximum possible height of the tower (due to structural and construction limits) is h_{max} and the minimum height of the cellular towers to be h_{min}(to avoid attenuation of broadcast waves).

Therefore to determine the optimal height of each tower, the regions covered by it at various heights must be considered. A continuous variation of height will complicate further calculations and increase the time complexity of the computation. So, a discontinuous/descrete height variation is considered. If we are to consider d different heights then:

$H_1 = h_{min} + (h_{max}-h_{min})/d$,
$H_2 = h_{min} +2* (h_{max}-h_{min})/d$
…..
$H_d = h_{min} +d* (h_{max}-h_{min})/d$.

C. Optimization of tower distribution

Now that the region of coverage of all possible towers has been calculated for different heights, we can move on to the optimization of the distribution.

Equally tall towers in close proximity are redundant as they have a large overlapping area. It is necessary remove some of the towers so as to reduce the overlapping regions. Also, there are situations where a taller tower at a position could cover all the customers covered by two smaller towers in the neighboring potential tower location. Hence, while filtering the towers, higher priority must be given to the towers with the taller bases. Therefore the towers are considered in the decreasing order of the heights of their bases. The algorithm has to be applied taking the potential tower locations in decreasing order of their height of the local maxima.

An algorithm that optimizes tower heights by considering all possible height permutations will have an exponential order of growth and cannot be used. A more sophisticated approach is required.

The potential tower locations are marked in a map of the given region. The covered regions (R_{cov}) corresponding to the heights (H_1, H2, H3…H_d) are also plotted on the map. The drawn convex hulls are considered to be ripples and each tower is considered to be the center of a ripple moving radially outward.

For each R_{cov} ripple plotted, the violations (points where ripples collide) are computed. The number of violations for the i^{th} tower is calculated by the formula:

$$V_{norm} = \frac{V}{\frac{z_i}{z_{max}}} \tag{4}$$

Here V_{norm} refers to normalized number of ripple collisions and V refers to the total number of ripple collisions, z_i refers to the height of the i^{th} local maxima, and z_{max} refers to the height of the tallest local maxima i.e. the global maxima.

If the V_{norm} for any tower grows very quickly with the height of the tower, then the tower is discarded. However if there aren’t too many collisions for different tower heights, then the tower may be considered as optimal tower. Its height may be decided by considering the point of discontinuity (point of inflexion) on the V_{norm} vs height graph.

Once the number, heights and position of the towers have been decided, the associated cost of providing cellular coverage to the region is calculated by Eq.1. The lifecycle cost of a tower (cost of fabricating, setting up and maintaining a tower of height h for its entire lifecycle) is assumed to be constant given. The final cost of coverage is the sum of the individual costs of each tower.

IV.RESULTS AND DISCUSSIONS

In order to simulate the above proposed algorithm, we take a satellite image, and try to find the strategic cell tower positions and the respective height of tower to be placed, by following the steps described in the Algorithm and Approach section.

A. Identification of potential tower locations

The satellite image of Agumbe, Karnataka, India was acquired through Google Earth. It was analyzed using GIS and surface plot was developed as discussed in section III part A. The local maxima were found, which are represented by blue points. These are considered to be the potential tower locations.

B. Determination of coverage of potential tower locations and appropriate gridding

This image is overlaid with the population density of the region to get the distribution of customers in the region. This is represented by the red shading on the map. Standard deviation across population density over the grids would be calculated and the image would be gridded appropriately to minimize the standard deviation, i.e. to accommodate approximately equal population in each grid. Doing so would give us an image similar to the one illustrated below as an example.

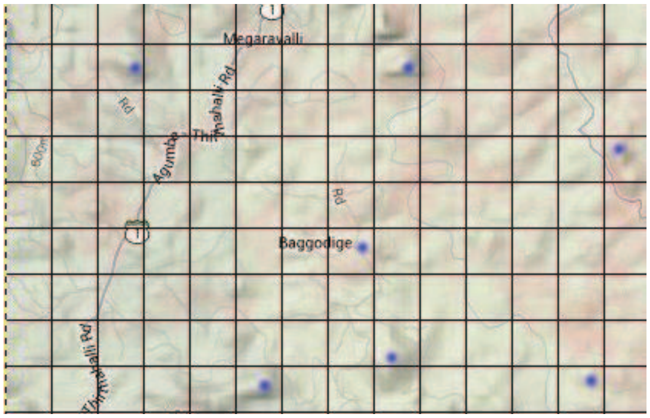

Fig.2: Satellite image with potential tower locations with appropriate grids.

For each potential tower location, the tower is considered to be H_{max} H_{min} and the median height. By identifying the coverable grids as discussed in section III part B, the convex hulls for three different heights of each tower is drawn. (Note that, here due to appropriate gridding, the region with denser population, has a smaller radius of coverage around the tower in consideration).The region outlined in yellow is the convex hull for height $H_{min,}$ in red for towers of median height and in blue for towers oh height H_{max}. This is shown in Fig3. Note that we have taken just three different heights to simulate, but in real life scenario more tower heights can be taken and convex hulls for each of these tower heights for each tower can be drawn to increase accuracy of the solution. Also in order to demonstrate we have assumed arbitrary H_{min} and H_{max}. This is shown in Fig. 3.

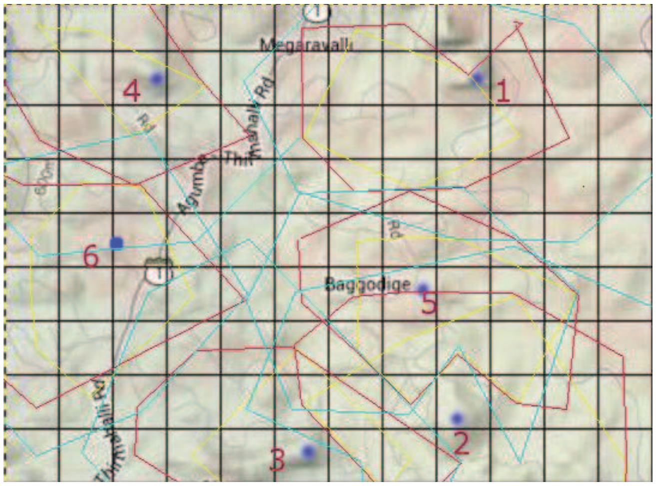

Fig.3: Satellite image with potential tower locations and their convex hull.

C. Optimization of tower distribution

The potential tower locations were numbered in decreasing ordered of their heights (i.e. from global maxima to smaller local maxima to shortest local maxima). In the decreasing order of elevation of potential tower locations, the normalized number of collisions of the range of each tower (V_{norm}) as discussed in Eq. 4 is plotted against the respective height of the tower in consideration.

For tower locations that are not optimal, their graphs will start increasing exponentially at small heights.. This practically represents that overlapping regions of coverage of the tower, in turn the violations are higher at small heights of the tower itself, and also that it increases rapidly with small increase in tower height. Hence this tower is covering the same region as covered by another tower of higher priority (the priority is given on decreasing order of their local maxima as discussed above in section III. Part C). Therefore the tower locations with such graphs can be rejected. The graph for such towers is shown in Fig 4.

For tower locations that are at strategic positions, their graphs give low violations till a particular height and then increase rapidly after that height. This particular height is called the point of inflexion and can be considered as the optimal height of the tower to be placed at this location. Practically this represents that there is no overlaps in the covered regions by a tower in this location and hence violations are less. And as height increases after reaching an particular height, the overlaps in covered regions in turn the violations increase rapidly, so this height is considered as optimal height. Any taller tower would just cover an overlapping region already covered by another tower, so a taller would be necessary. Hence this tower location can be chosen as a strategic location and the tower of the optimal height so obtained, can be placed at this location. The graph for such towers is shown in Fig 5.

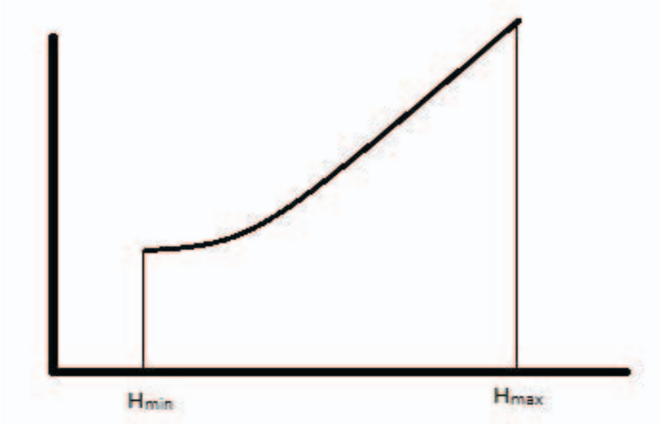

Fig.4: Graph of a tower that is not at an optimal position.

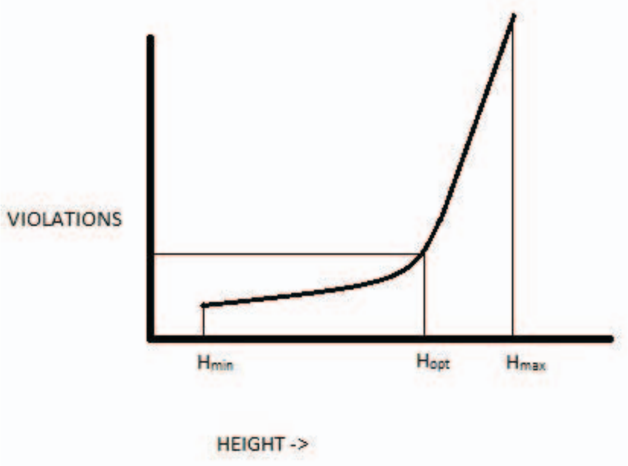

Fig.5: Graph of a tower at an optimal position

In the region under consideration, tower locations 5, 6 and 3 are rejected as they have exponential graphs similar to Fig. 4. And tower locations 1, 2 and 4 have a graph similar to Fig. 5, hence they can be considered, and towers of the height equal to their respective H_{opt} value.

The cost of placement can be calculated using Eq.1 where cost is a function of height. Knowing respective H_{opt} we can get the cost of the towers considered to be places, hence we can get the total cost of placement of all towers in the considered region. Now, after this simulation, we can see that most of the population in this region is covered by the chosen towers. Here arbitrary values have been used, just to simulate our algorithm to illustrate its implementation, but in practical situations, relevant values can be used to get accurate values.

V. ACKNOWLEDGEMENT AND REFERENCE

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