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Antennae Location Methodology for a Telecom Operator in India

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Antennae Location Methodology for a Telecom Operator in India

Abstract

This paper proposes a methodology for location of Base Stations of cellular radio networks in India with the objective of optimizing and automating the process of network planning. Operations of a large telecom operator in rural parts of India are studied. The Operator's network planning team currently uses a manual approach to identify locations for the Base Stations. In this study the Base Station location problem is modelled as a discrete facility location problem and methodology that would help deal with conflicting network planning objectives i.e. cost, signal quality and coverage is presented and the best strategy under budget uncertainty is also explored. The model is run on data pertaining to one of the large States in India using CPLEX 10.0 [25] and OpenSolver [1]. Results indicate that, using the optimal approach, cost savings to the extent of 26% can be achieved. This is equivalent to a saving of INR 1 billion in the single State that is studied. Considering that the model can be replicated throughout the country, adoption of the proposed methodology can bring about substantial savings in the Operator's Base Station infrastructure costs.

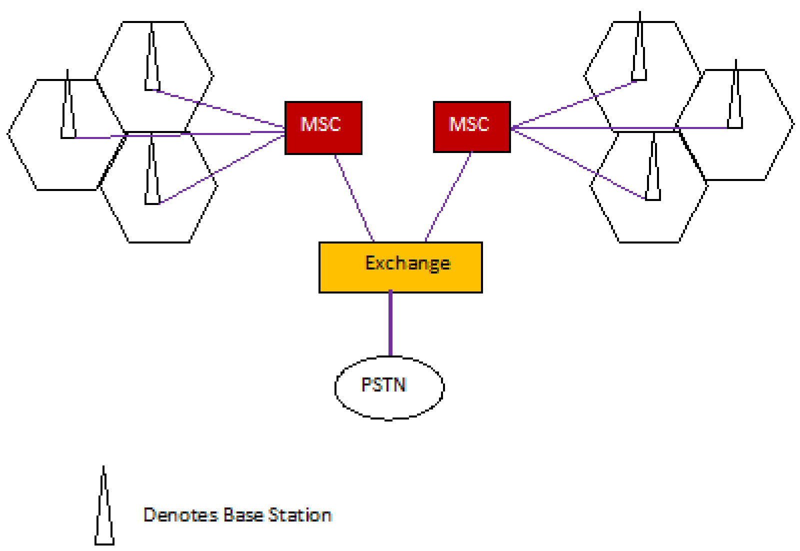
Keywords: Antennae Placement, Base Station Location, Network Planning, Facility Location

Introduction

The Figure 1 below provides a brief introduction to GSM cellular access network. The geographical area to be supplied with a radio signal is typically divided into regular shaped cells. Each cell has a corresponding Base Station that provides radio coverage to the cell. Each Base Station supports multiple Mobile Stations in its cell.

Figure 1

GSM Cellular Access Network



The Base Stations are connected with land wires to the Switches (MSC) and the switches are physically connected with land wires to the Local Exchange. The locations of the Local Exchanges are typically fixed and a single exchange caters to several Base Stations and MSCs.

One of the network design problems discussed widely in the literature deals with finding the optimal number, location and capacities of the MSCs and the problem of how the MSCs are to be connected to the Base Stations and to the Local Exchange [2, 3]. Such literature assumes that the Base Station locations and configurations are known. The other category of literature discusses the configuration and location of the Base Stations [4, 5] themselves. In this paper we focus on the problem of deciding the location of Base Stations for GSM network planning and take conflicting objectives into consideration.

Operations in rural areas of one of the largest mobile telephony providers in India are studied and data pertaining to one of the large States is used for illustrative purposes, hereafter referred to as the “Operator” and “Sample State”, respectively.

Currently, the Operator follows a manual procedure for determining the Base Stations locations as and when the need arises. Base Stations are hosted at a ground based steel tower which contains a battery and a diesel generator engine at the ground level and an antenna at the top. Throughout this paper the terms Base Station placement problem and Antenna placement problem are used interchangeably. We also use the term tower to represent the whole unit that comprises of Base Station, ground based steel structure, battery and generator engine.

The operator uses a planning tool which has the village latitude and longitude information and can model the terrain to understand signal propagation. The tool can take the Base Station locations, their height, transmission power and direction of antennae as inputs and give the list of villages that will and will not receive GSM coverage, along with the signal strength available at the villages, as an output. The Operator thus identifies the locations for telecom towers manually by varying the inputs with the objective of minimizing cost and maximizing coverage. It is felt that the current trial and error manual approach, though effective, is not optimal in terms of coverage and cost.

As of now, the Operator provides GSM coverage to approximately 18000 villages in the Sample State while around 7000 villages are not covered. There are approximately 800 GSM Base Stations constructed by the operator to provide this coverage and each Base Station, along with the supporting infrastructure, costs INR 4.5 million approximately. The cost details of a typical Base Station are given in Appendix A. Given that the costs associated with the Base Station equipment and the supporting infrastructure are significant, a procedure for determining the locations of Base Stations that can optimize the costs and coverage is desirable.

Our work proposes a methodology for determining the optimal number and locations of Base Stations such that a given number of villages can be provided GSM coverage. The costs associated with locating Base Stations in the 18000 villages covered in the Sample State using the manual method are compared with that of the optimal method and the savings are analysed.

Providing 100% coverage for all the villages in the Sample State, though desirable, is likely to be prohibitively expensive and more so as some of the villages are bound to be far flung. It is, therefore, desirable to understand the extent to which coverage needs to be reduced to meet cost constraints. Hence another objective of this paper is to propose a method to understand the non-linear relationship between cost and coverage. This would help the Operator choose the most desirable combination of cost and coverage.

We assume that a typical GSM Base Station in rural parts of India provides coverage to areas within 5 Kilometres (KM) radial distance. We also assume that villages within 2KM radial distance of the Base Stations would receive a stronger signal strength thereby enjoying higher quality of service. It is, therefore, desirable for the Operator to maximize the population covered within 2KM radial distance using a minimum number of Base Stations. The telecom operator thus faces three conflicting objectives, namely cost, coverage and high quality of coverage. To address these we propose a model whereby the operator can specify both the parameters simultaneously, i.e. the proportion of population to be covered within 5KM radial distance from the Base Stations and the proportion of population to be covered within 2KM radial distance from the Base Stations and optimize the cost. For instance, the operator may specify that 80% of the population is to be covered within 5KM radial distance from the Base Stations and that 50% of the population is to be covered within 2KM radial distance from Base Stations and then use the model to optimize costs of providing this coverage.

Section 2 of the paper elaborates the context of the problem and assumptions that can be made in the Indian rural scenario. Section 3 describes the models and the various scenarios considered. Section 4 gives the results and analysis and Section 5 presents the conclusions.

Indian Rural Context

The Antennae placement problem is usually combined with Antennae configuration problem in the literature. For example Mathar and Niessen choose the optimal location and configuration of Base Stations in a single model [5]. Antenna height, beam direction and transmission power are determined along with the location of towers. In the context of rural areas in India the terrain can be largely assumed to be flat due to the absence of tall buildings. Such an assumption is true in most cases with exceptions being obstructions to the signal due to the presence of a hillock. It is, therefore, desirable for the operator to erect GSM towers with height and transmission power being as high as permitted so that a single tower can cover a large area reducing overall infrastructure requirements. In the Indian scenario the height varies between 40m-60m, with a large number of operators choosing to place the antennae in the 40m segment. The transmission power of the Base Station is fixed at 20W, the maximum permitted by the licensor. The antennae height and power are, therefore, taken to be fixed in the given context.

Minimizing interference and multi-coverage are important issues when there is dense ordering of cells in a given area and these are treated as additional objectives in some instances as done by Mather and Niessen [5]. However, given the sparse ordering of cells in the rural areas, interference and multi-coverage is minimal and, therefore, not relevant for our model.

In our approach the objectives are cost, coverage and quality of coverage. One of the objectives is taken to be the objective function for the model and the other two objectives are treated as constraints. It is also possible to model these conflicting objectives simultaneously as a multiple objective problem (MOP) such as done by Reasinen [7]. [8,9] for reviews on algorithms for MOP.

A range of algorithms for solving the cell planning problem have been tried in the literature, primarily due to the complexity involved. Deterministic heuristic algorithms have been proposed by several authors [10,11,12]. Meta-heuristic algorithms based on simulated annealing [13,15,16,17], tabu search and genetic algorithms [14,18,19,20,21] have been adopted as well and have become increasingly popular.

In the given rural context since the height of the tower and transmission power of the Base Station can be taken as fixed, and interference and multiple paths do not play a role, the complexity of the problem reduces significantly. We are able to obtain results with reasonable accuracy using CPLEX 10.0.

The Model: Optimal Approach

Daskin [22] presents a taxonomy of location problems based on the underlying space in which the problem is embedded and discusses discrete and continuous facility location models. In discrete models the potential facility locations are taken to be discrete and finite in number whereas in continuous models the facility can be located anywhere in the plane and can have an infinite number of combinations, such as the model described by Murray et al. [23]**.** In the given context the demand points, i.e. the villages, are discrete and finite in number. The potential facility location points, where a Base Station can be erected, can only be in places of habitation for ease of maintenance and are, therefore, discrete and finite in number. Moreover, a village has to be within 5KM radius from the nearest GSM Base Station for it to be considered to be "covered" or "served adequately". The location of Base Stations is, therefore, modelled as a discrete set covering facility location problem as follows:

Let Y_j be a binary decision variable which takes a value of 1 if Base Station is located in village j and 0 otherwise, C_j be the set of villages that would get signal coverage if a Base Station is placed in village j and let N be the total number of villages.

Minimize $\sum_{j=1}^{N} Y_j$

Subject to

$$\sum_{\{j \mid i \,\varepsilon\, C_j\}} Y_j \geq 1 \qquad \forall\, i, \quad \text{(Each village is covered)}$$

$$Y_j \in \{0,1\} \qquad \forall\, j.$$

The latitude and longitude information is used to calculate the distance between villages and this information is obtained from the Survey of India maps. Village population details are obtained from the census data for the Sample State and locations of existing towers and cost were obtained from the Operator.

There are approximately 26,000 villages in the Sample state. Assuming that each village is a potential Base Station location, 26,000 binary decision variables are required to decide if a given village is chosen for locating a Base Station and 26,000 constraints are needed to ensure that each village is covered.

The basic model assumes that the Operator's only objective is to minimize the number of towers such that all villages are covered. In addition other practical scenarios considered are as follows:

a. Covering all villages can be prohibitively expensive and, therefore, a proportion of the population to be covered (i.e. within 5KM) is specified by the Operator based on budget considerations. The formulation is explained through Excel in Appendix B.2
b. Assuming that the Operator has sufficient budget to extend coverage (within 5KM) to all villages in the State, the proportion of population that gets a higher quality signal (i.e. within 2KM radius) is specified based on cost considerations.

c. Both the proportion of population within 5KM radial distance and the proportion within 2KM radial distance are specified by the Operator based on cost considerations.

The model is modified to take each of these scenarios into consideration. In the case where partial coverage is provided, an additional binary variable and a constraint need to be introduced for each village to identify the villages that are covered. Hence for the first scenario the number of variables and constraints required are double of those required for the basic model. This is explained in greater detail in Appendix B. For the second scenario an additional binary variable and a constraint need to be introduced for each village to identify whether it has higher quality coverage and therefore the number of variables and constraints are doubled in this case as well. For the third scenario, additional binary variables and constraints need to be introduced for each village for both purposes and, therefore, the number of variables and constraints are tripled.

Results

4.1 Current approach Vs Proposed optimal approach:

The Sample State has 25071 villages. Information pertaining to around 1000 of these villages were removed from consideration due to errors in the data. Among the 25071 villages, the Operator currently provides GSM coverage to 17900 villages and the remaining 7171 do not have GSM coverage. On analysis of the data, it was observed that some of the villages have existing GSM coverage due to the presence of a tower in a nearby rural area and some due to the presence of a tower in a nearby urban area. Modelling coverage due to an urban tower is outside the scope of this work and hence the villages covered by nearby urban towers were removed from the data set. The analysis was focussed on the remaining 15362 villages covered by rural towers alone in order to compare the number of towers currently used with the numbers obtained using the optimization model.

Table 1 Village Coverage Status

S. No.	Description	Number of villages
1	Villages without any GSM Coverage	7171
2	Villages with existing GSM Coverage due to towers present in an Urban Area	2538
3	Villages with existing GSM Coverage due to a towers present in a Rural Area	15362
4	All Villages	25071

A set covering model was set up using CPLEX 10.0 for these 15362 villages. The results indicate that no more than 700 Base Stations are required for covering the 15362 villages while the Operator has deployed 811 Base Stations using the planning tool. This indicates a cost saving of 14%. However, it is observed that the 811 towers deployed currently will not only cover the 15362 villages but also other villages lying along the boundaries. This holds true for the 700 towers proposed by the optimal approach as well. For purposes of comparison a reverse exercise was carried out to find the number of villages that are covered, i.e. lie within 5KM of the existing 811 towers and a similar exercise was carried out for the 700 towers proposed by the optimal approach. It is found that a total of 16,388 villages can be covered by the existing 811 towers while the 700 proposed towers can cover 19,081 villages. This translates to the current tower density, defined as number of villages covered per tower, being 20.2 and the optimal tower density being 27.3. Thus in terms of tower density, the optimal approach is better than the Operator's current approach by 26%, implying that cost could have been reduced by 26% had an optimal approach been followed.

Solving the model for the 7171 villages that do not have existing GSM coverage, it is found that the tower density, as given by the optimal solution, is 10.3 which is significantly lower than that obtained for villages with existing GSM coverage. The latitude and longitude information reveals that these villages are in far flung areas, which explains the relatively lower tower density.

For the sake of completeness, the model is also solved for all 25071 villages in the Sample State. The gap between the best integer solution and the best lower bound as reported by CPLEX in this case is observed to be higher. Table 2 below summarizes the results obtained for the Sample State.

Table 2 State Level Results

S. No.	Description	Number of villages	Existing number of Towers	Optimal Number of Towers	Gap
1	Villages with existing GSM Coverage	15362	811 Rural Towers	700	6.9%
2	Villages without any GSM Coverage	7171	None	696	0
3	All Villages	25071		1124	15%

4.2 Cost Vs Coverage

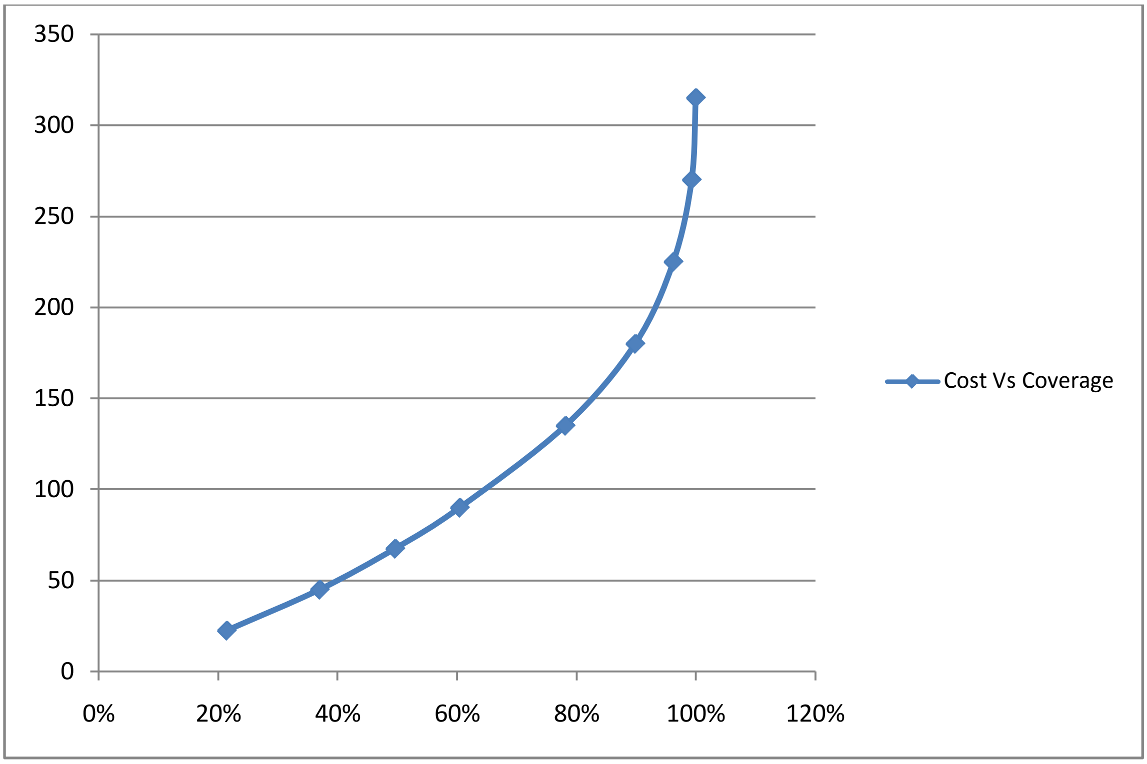
It is desirable to understand the trade-off between the conflicting objectives of cost and coverage. If the proportion of population covered for any given budget could be determined, the Operator can choose the most appropriate levels of coverage and cost. This analysis is carried out for the aforementioned 15362 villages within the Sample State. The population of 15.99 million in these villages is considered to be the total population for the purpose of this analysis. The budget, i.e. the number of Base Stations to be installed, is varied and the corresponding proportion of population that can be covered is obtained by taking the number of Base Stations as a constraint and maximizing the proportion of population covered in the linear program. This resulted in a maximal set covering model which was solved using CPLEX 10.0. The results obtained are given in Table 3 and Figure 2 below:

Table 3 Cost Vs Coverage

Cost (millions INR)	Base Stations	Population Covered (millions)	Proportion of population Covered
3150	700	15.99	100%
2700	600	15.88	99%
2250	500	15.39	96%
1800	400	14.37	90%
1350	300	12.5	78%
900	200	9.67	60%
675	150	7.94	50%
450	100	5.92	37%
225	50	3.43	21%

Figure 2

Cost vs Coverage



X Axis: Percentage of Population within 5KM of Base Stations
Y Axis: Millions INR
(follow the given guidelines for the axes and legend etc)

As the proportion of population covered is increased, the optimal number of Base Stations needed to provide the required coverage increases and as a result the cost increases. It is clear from the graph that the relationship between Cost and Coverage is not linear. For example a reduction of only 10% in coverage from the level of 100% results in nearly a 43% reduction in cost. Using this analysis the operator can decide where he wants to lie along the cost and coverage curve based on his coverage requirements and budget constraints.

4.2.1 Optimal level of coverage without budget constraints:

In section 4.2 we presented the non-linear relationship between cost and coverage. In this section we analyse how a point on the Cost Vs Coverage can be chosen by the Operator in a situation where though there is no budget constraint, the Operator would not want to spend money on coverage unless it is profitable. In this scenario it would be useful for the Operator to have information on the marginal cost of providing coverage and the marginal revenue that can be expected.

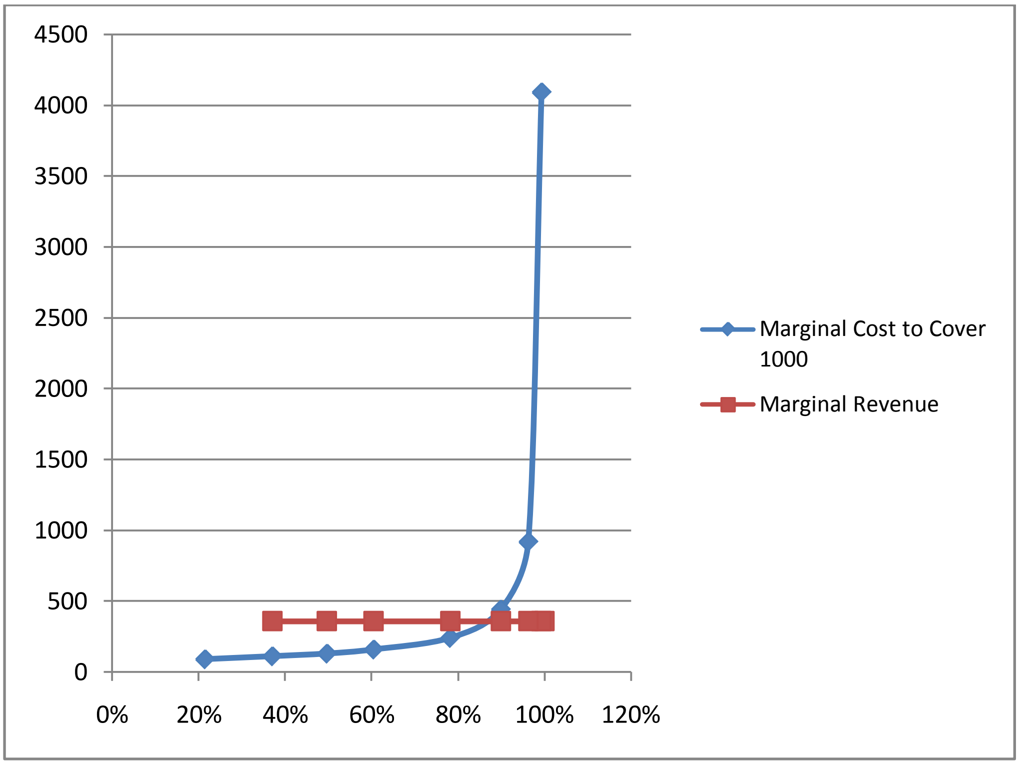
The expected marginal revenue is estimated as:

$$(1000) * (Rural\ tele - density) * (Operator\ Market\ Share) * (ARPU) * (Life\ cycle)$$

Where the Rural tele-density is estimated to be 25% and the estimated Operator market share is 15%. Average Revenue Per User Per Month (ARPU) is estimated to be INR 100, discounted over the revenue generation period of 10 years. Taking operational costs to be approximately 20% of the total revenue, the expected marginal revenue is estimated to be INR 360,000. For the purpose of this analysis it is assumed that the marginal revenue does not change with proportion of population covered. The marginal cost of providing coverage is the slope of the Cost Vs Coverage graph where the population is scaled to 1000's. The marginal cost of providing coverage and the expected marginal revenue are plotted and presented in Figure 3.

Figure 3

Choosing Desirable Coverage (State)



Y Axis : The marginal cost to cover additional 1000 people and willingness to spend in units of INR 1000
X Axis: Proportion of Population Covered

As can be observed from the graph, the point of intersection of marginal cost and marginal revenue is at about 86% of coverage implying that it is not profitable for the Operator to provide coverage beyond 86% of the population for the Sample State.

4.2.2 Optimal strategy for phased budget availability

It is common for the Operator to plan on providing coverage in a phased manner as the budget may be available in different phases or time periods. The Operator has the option of a) independently determining the optimal locations of Base Stations to be deployed in each phase based on the budget availability. The optimal locations though determined without long term objective in mind is the best option in the short run. b) Determining the optimal locations of Base Stations keeping the long term objective in mind and, based on budget availability in each phase, choosing a subset to be deployed in a phased manner. The two options are analysed for the aforementioned 15362 villages and the associated costs are compared to quantify the level of inefficiency involved when the budget is available in two phases.

For option-a a maximal set covering problem is solved to find the proportion of population that can be optimally covered with the number of Base Stations that can be deployed given the budget in the first phase. Subsequently, a set covering facility location problem is solved to cover the remaining population in the second phase. In the case of option-b, as seen in section 4.1, the optimal number of Base Stations required to provide coverage for the 15362 villages is 700. The results obtained for different levels of budget availability in phase 1 are presented in Table 4 below. It can be observed that option-a is always inefficient in the long run (i.e at the end of phase 2) with inefficiency varying from 9% to 17% for the different scenarios considered.

Table 4 Inefficiency of Phased Optimization

Scenario	Phase	No of Base Stations	Proportion of Population Covered	Inefficiency
1	Phase 1	300	78%	13%
	Phase 2	500	22%	
2	Phase 1	400	90%	17%
	Phase 2	440	10%	
3	Phase 1	200	60%	9%
	Phase 2	570	40%	

It follows that the best strategy for the Operator is to solve the optimization problem at once for the entire state or region by keeping the long term objective in mind. However, he can build towers chosen from this optimal solution in multiple phases as and when budget becomes available.

4.2.3 Optimal strategy with Budget Uncertainty

In reality the Operator may not be certain of the long term plan due to uncertainty of budget availability, technology becoming obsolete or change in market conditions. For example let us consider that the budget for phase 1 is available but is uncertain for phase 2. Under such uncertainty option-b will continue to be more efficient if budget becomes available, as seen earlier. However, if the budget fails to become available in phase 2, option-a will be more efficient. Thus under uncertainty the choice of option for planning Base Stations locations for phase 1 is not clear. As seen earlier option-a is efficient in the short run while option-b is efficient in the long run if budget becomes available.

We explore the extent to which option-b might be suboptimal compared to option-a when the budget for phase 2 fails to become available. In other words, we explore how suboptimal option-b might be in the short run.

Two possible scenarios, differing in the long term goal set by the Operator, are considered for the purpose of illustration. In the first scenario (Case-1), the Operator's long term goal is to provide 100% coverage and in the second (Case-2), the Operator's long term goal is to provide only 86% coverage, which in practice might be a more realistic goal as discussed in section 4.2.1. The optimal solution obtained by setting up set covering model for 100% coverage is called FinalOptimalSolution_1 and the optimal solution obtained for 86% coverage is called FinalOptimalSolution_2.

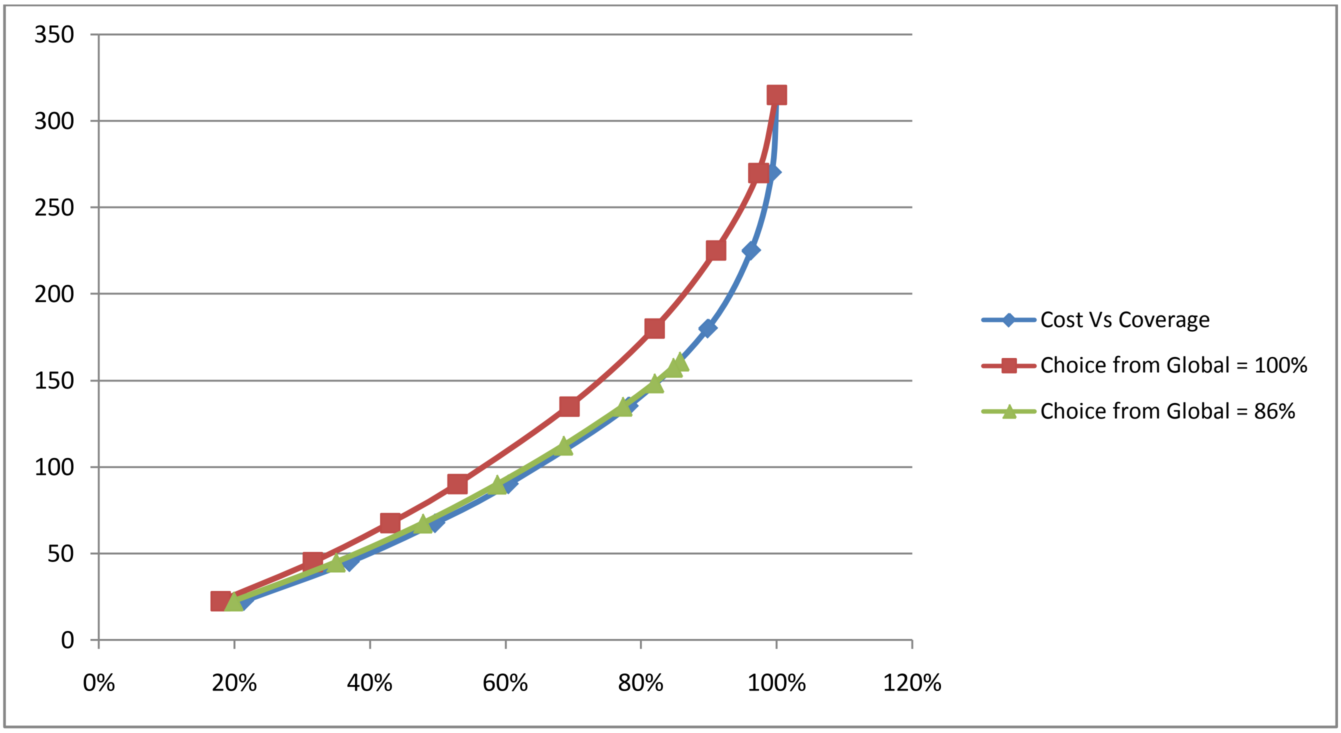
Figure 5 below illustrates the sub-optimality of option-b in the short run. The “Cost Vs Coverage” curve, is same as in Figure 2. The “Choice from Global : Case 1” curve is obtained by setting up a maximal set covering model for each available budget but the potential or candidate facility locations are chosen only from FinalOptimalSolution_1, and the “Choice from Global: Case 2” curve is obtained by setting up maximal set covering model for each available budget but the potential or candidate facility locations are chosen only from FinalOptimalSolution_2.

In case 1, where the final objective of the Operator is to provide 100% coverage, the cost of providing this coverage is INR 3150 million. Let us consider that the budget is available in two phases, INR 1350 million being available in Phase 1 and the rest in Phase 2. Using Option-a for Phase 1 results in 78% coverage (Cost Vs Coverage curve) while using Option-b results in 69% coverage (Choice from Global : Case 1 curve). Thus in the short run, option-b is less efficient than option-a by about 9% in terms of coverage. In case the budget is unavailable in phase-2, the Operator is forced to live with this sub-optimal solution in the long run as well.

In case 2, where the final objective of the Operator is to provide 86% coverage, the cost is INR 1611 million. Let us consider that the budget is available in two phases, INR 1350 million being available in Phase 1 and the rest in Phase 2. Using Option-a for Phase 1 results in 78% coverage (Cost Vs Coverage Graph) while using Option-b results in 77% coverage (Choice from Global : Case 2). Thus in the short run, option-b is less efficient than option-a by about 1% in terms of coverage. In case the budget is unavailable in phase-2, Operator is forced to live with this sub-optimal solution in the long run as well. However, the level of sub-optimality is very insignificant.

Figure 4

Optimal Vs Choosing from global



It is interesting to observe that if the final goal is to provide 86% coverage, which is a realistic goal for the Operator, the "Choice from Global : Case 2" is very close to the "Cost Vs Coverage graph". The average inefficiency, in terms of cost, of option-b is only around 1% to 2% in the short run, implying that even if the budget does not become available in phase-2, the inefficiency of option-b is very minimal.

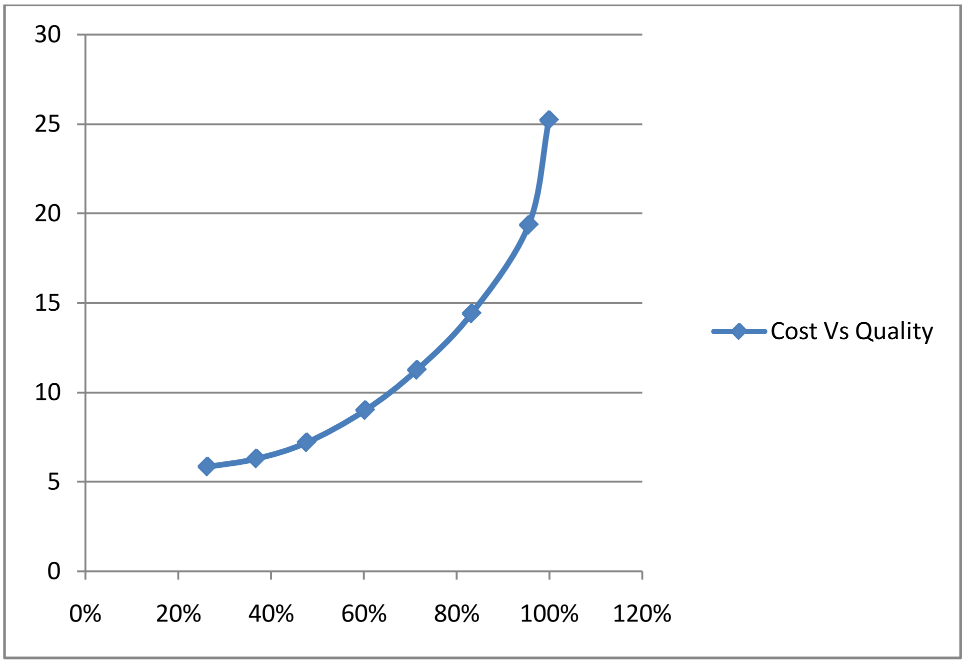
Thus it follows that, even under uncertainty, the best strategy for the Operator is to plan for the long term and build a subset of Base Stations from the global optimal solution in the short term, especially if the final goal is to provide less than or equal to 86% coverage. As discussed in section 4.2.1, providing less than or equal to 86% coverage is a practical and realistic goal set by the Operator.

4.3 Cost Vs Quality of Coverage

It is desirable to understand the trade-off between the two conflicting objectives of cost and high quality of coverage. If the information on the budget requirement for desired level of high quality of coverage is known, the Operator can choose the appropriate trade-off between high quality coverage and cost. This analysis is carried out for around 400 villages within the Sample State. The population of 0.42 Million in these villages is considered to be the total population for the purpose of analysis. The number of Base Stations made available is varied and the proportion of population that can be covered with high quality signal is obtained. The number of Base Stations is taken to be a constraint for the various scenarios. The proportion of population to be covered (i.e within 5KM) is 100% in each scenario and is taken as a constraint. The proportion of population covered with high quality signal (i.e. < 2KM) is maximized under these constraints, resulting in a maximal set covering model which is solved using CPLEX 10.0.

Figure 5

Cost Vs Quality of Coverage (District)



X Axis: Percentage of Population with in 2KM from nearby tower
Y Axis: Cost in Crores INR

As the proportion of population with high quality coverage is increased, the optimal number of Base Stations needed increases and hence the cost increases. From the graph it is observed that it costs INR 58.5 million to provide high quality coverage to 26% of the population. To provide high quality coverage for 60% of population it costs INR 90 million**,** implying that in this case by increasing the expenditure on Base Stations by only 53%, the proportion of villages with high quality coverage increases by 129%. The relationship between cost and quality of coverage is clearly non-linear. The operator can decide where he wants to lie along the curve based on the budget and the desired level of quality of coverage. In the case of cost versus coverage, the nonlinear relationship is observed to be similar for district and state level analysis. The same is expected to hold in this case as well.

Conclusions

As seen from the results for the Sample State, the optimal approach can lead to significant cost savings of up to 26% compared to the current manual approach. This translates to around INR 1 billion given that currently 811 Base Stations are being used each costing INR 4.5 million.

When the conflicting objectives of cost and coverage are considered it is seen that a compromise of 10% on coverage results in cost savings of about 42%. Hence the 26% savings obtained in cost by using the optimal approach over the manual approach can be further enhanced by judiciously compromising on coverage.

The planning tool can be used to accurately obtain the information on villages covered by a Base Station and given as an input to the optimization model rather than assuming that all villages within a 5KM radial distance are covered and all villages with in 2KM radial distance have high quality coverage. Once the Operator decides on the proportion of population to be covered and the proportion of population to be provided high quality coverage the optimization model can be used to determine the optimal Base Station locations instead of the trial and error method using the planning tool as done currently.

Under scenarios where budget may be available in phases or when budget availability may be uncertain, the best strategy is to solve the optimization problem for the entire region and choose a subset of Base Stations based on budget considerations. This approach is beneficial for extending GSM coverage in cases of new rollouts as well as for covering regions where partial coverage has already been provided.

Appendix A: Cost of GSM Base Station

A GSM Base station along and the supporting infrastructure includes the following:

1) A 40 Meter Ground Based Steel tower.
2) Battery/Power Plant and Civil Works.
3) Diesel Generator Engine.
4) Base Transceiver Station (BTS).

Table 5 gives the cost estimates for a Base Station obtained from the Operator.

Table 5 Cost of Base Station

	Capital Expenditure (INR)	**Present Value of Other costs (INR)**
Cost of 40 Meter Ground Based Steel Tower	1000000	
Cost of Battery/Power Plant & Civil works	400000	
Cost of Diesel Generator Engine	300000	
Cost of BTS	1000000	
Operating cost per month (Rs 25000)		1564000
Rent (Rs 3000 per month)		187000

Thus the total cost of a Base Station and the supporting infrastructure is INR 4.5 Million approximately.

Appendix B: The Formulation

B.1 Set Covering Formulation: Example

Let us consider that there are 5 villages and the objective is to cover all these villages with minimum number of towers.

Table 6 Set Covering Method

S.No of Village Column A	Decision Variable Column B	Constraint Column C
1	Y_1	$Y_1 + Y_2 >= 1$
2	Y_2	$Y_2 + Y_1 + Y_3 >= 1$
3	Y_3	$Y_3 + Y_2 + Y_5 >= 1$
4	Y_4	$Y_4 >= 1$
5	Y_5	$Y_5 + Y_3 >= 1$

Objective: Minimize $(Y_1 + Y_2 + Y_3 + Y_4 + Y_5)$

To prepare Column C described above an Excel Macro was used. This macro finds the distance of a particular village from all other villages and finds out all the villages that are within 5KM radius from a given village. In this document we reference this column as Coverage Column.

B.2 Formulation for Partial Coverage: Example

Let us consider that there are 5 villages with a total population of 4100 and the objective is to cover 80% of the population (i.e. 3280) with minimum number of towers.

Table 7 Model Formulation for Partial Coverage

S.No Col A	Decision Variable Col B	Population Col C	Coverage Col Col D	Col E	Col E * Population Covered
1	Y_1	500	$Y_1 + Y_2$	If{$(Y_1 + Y_2) >= 1$} = 1, Else 0	500*E[1]
2	Y_2	1000	$Y_2 + Y_1 + Y_3$	If{$(Y_1 + Y_2 + Y_3) >= 1$} = 1, Else 0	1000*E[2]
3	Y_3	1200	$Y_3 + Y_2 + Y_5$	If{$(Y_3 + Y_2 + Y_5) >= 1$} = 1, Else 0	1200*E[3]
4	Y_4	700	Y_4	If{$Y_4 >= 1$} = 1, Else 0	700*E[4]
5	Y_5	700	$Y_5 + Y_3$	If{$(Y_5 + Y_3) >= 1$} = 1, Else 0	700*E[5]
	Total	4100			**Total**

Objective: Minimize $(Y_1 + Y_2 + Y_3 + Y_4 + Y_5)$

The constraint is
Total >= 3280

Here we are not interested in to ensuring coverage for the entire population of 4100 and instead ensure that at least 3280 people are covered. To handle the "If" statement in column E, new binary variables are introduced and hence the number of variables are doubled.

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