14 Network Planning for IEEE 802.16j Relay Networks

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CONTENTS

In this chapter, a problem formulation for determining the optimal node location for base stations (BSs) and relay stations (RSs) in relay-based 802.16 networks is developed. A number of techniques are proposed to solve the resulting integer programming (IP) problem—these are compared in terms of the time taken to find a solution and the quality of the solution obtained. Finally, there is some analysis of the impact of the ratio of BS/RS costs on the solutions obtained.

Three techniques are studied to solve the IP problem: (1) a standard branch and bound mechanism, (2) an approach in which state space reduction techniques are applied in advance of the branch and bound algorithm, and (3) a clustering approach in which the problem is divided into a number of subproblems which are solved separately, followed by a final overall optimization step.

These different approaches were used to solve the problem. The results show that the more basic approach can be used to solve problems for small metropolitan areas; the state space reduction technique reduces the time taken to find a solution by about 50 percent. Finally, the clustering approach can be used to find solutions of approximately equivalent quality in about 30 percent of the time required in the first case.

After scalability tests were performed, some rudimentary experiments were performed in which the ratio of BS/RS cost was varied. The initial results show that for the scenarios studied, reducing the

RS costs results in more RSs in the solution, while also decreasing the power required to communicate from the mobile device to its closest infrastructure node (BS or RS).

14.1 INTRODUCTION

IEEE 802.16 technologies are advancing rapidly. The base standards have been defined, industry is offering products to the marketplace, and network operators are deploying systems and offering service to subscribers. Mobile variants of the technology are now receiving a lot of attention: the WiBro system in Korea provides coverage for large population centers and has a substantial user base; the WiMax Forum is hosting a number of events designed to solve interoperability problems for 802.16e compliant systems, in advance of providing certification to products.

While all this momentum behind the technology bodes well, there are still significant issues that must be addressed before WiMax sees mass market adoption in many places throughout the world. In many countries, changes in spectrum allocation or regulations are necessary before WiMax systems can be rolled out. In some countries, the low cost of high-speed wired broadband connections make the business case for WiMax solutions less compelling. Subscriber terminals are still evolving, but the form factor of most current WiMax terminals is still quite large for mobility applications. So, while there are many reasons to believe that the future is bright for mobile WiMax technology, it will be some years before it reaches maturity.

One very important issue which is faced by network operators at initial network roll-out is how to provide maximum coverage at minimum cost. One approach which can be very useful in this context is to employ so-called relay network architectures. The essential idea is to use RSs, which are associated with BSs to effectively increase the coverage area of the BS at low cost. If the price point of the RSs is sufficiently low, this can result in a lower cost coverage solution than the traditional BS-based solution.

The 802.16 standards body has been developing standards for 802.16-based relay network architectures. More specifically, it is working on standards for BSs and RSs which enable them to work with legacy 802.16-2004 [1] and 802.16e [2] compatible devices—this will result in the 802.16j [3] standard. The 802.16j task group are focusing on issues associated with how to make minimal modifications to the signaling and frame structure such that operation with legacy systems is possible, while introducing a relay-based network architecture.

While the work of the 802.16j task group is still in the relatively early stages—the standard will most likely not be ratified until 2009 at the earliest—it is interesting to determine how the relay network architecture will impact network design and deployment. Because relays introduce a significant change to the network architecture, traditional network planning approaches are no longer applicable and new approaches are required.

In this chapter, new approaches to planning of 802.16j relay are described. The contributions of this chapter are twofold. First, there is a synthesis of previous proposals to solve this problem—the basic branch and bound approach, the approach using state space reduction and the clustering approach. Second, there is an analysis of the impact of the ratio of BS/RS costs on the resulting solution.

The structure of the chapter is as follows. An overview of the main components of 802.16j is first provided. This is followed by a short discussion of radio propagation models suitable for this context. The main problem formulation is then presented, followed by a discussion of the different solution techniques. These different techniques are then compared in terms of scalability and solution quality and the results are presented. Finally, there is some analysis of the impact of the BS/RS costs.

14.2 OVERVIEW OF IEEE 802.16J

In IEEE 802.16j low cost RSs are introduced to provide enhanced coverage and capacity. Using such stations, an operator could deploy a network with wide coverage at a lower cost than using only (more) expensive BSs to provide good coverage, and increasing significantly the system throughput. As network utilization increases, these RSs could be replaced by BSs as required. The mesh architecture defined in WiMAX is already used to increase the coverage and the throughput of the system. However, this mode is not compatible with the point-to-multipoint (PMP) mode with no support of the OFDMA PHY, fast route change for mobile station (MS), etc. Hence, the standards organization has recognized this as an important area of development, and today a task group is charged with drafting a new standard: the IEEE 802.16j mobile multihop relay design to address these issues. The first draft of the IEEE 802.16j standard has just finished in August 2007.

14.2.1 IEEE 802.16j Scope

The IEEE 802.16j is aiming to develop a relay mode based on IEEE 802.16e by introducing RSs depending on the usage model:

- Coverage extension
- Capacity enhancement

In other words, the relay technology is first expected to improve the coverage reliability in geographic areas that are severely shadowed from the BS or to extend the range of a BS. In both cases, the RS enhances coverage by transmitting from an advantageous location closer to a disadvantaged SS than the BS. Second, it is expected to improve the throughput for users at the edges of an 802.16 cell. It has been recognized in previous 802.16 contributions that subscribers at the edges of a cell may be required to communicate at reduced rates. This is because received signal strength is lower at the cell edge. Finally, it is expected to increase system capacity by deploying RSs in a manner that enables more aggressive frequency reuse. Figure 14.1 illustrates the different scenarios in which relay mode could be used. However, introducing such RSs considerably alters the architecture of the network and raises many issues and questions. It is still unclear what system design is appropriate and can be realized at a low cost while still providing good coverage with an enhancement of the throughput. AQ1

The 802.16j task group's scope is to specify OFDMA PHY and MAC enhancement to the IEEE 802.16 standards for licensed bands. These specifications aim to enable the operation of fixed, nomadic, and mobile RSs by keeping the backward compatibility with SS/MS. In other words, the standard will define a new RS entity and modify the BS to support Mobile Multihop Relay (MMR) links and aggregation of traffic from multiple sources. An MMR link represents a radio link between an MMR-BS and an RS or between a pair of RSs. Such link can support fixed, portable, and mobile RSs and multihop communications between a BS and RSs on the path. An access link is a radio link that originates or terminates at an SS/MS. Figure 14.2 illustrates the main scope of the project.

14.2.2 Relay Station Capabilities

As the standard is still evolving, it is not clear what the final variant will look like. However, at present, it appears that two categories of RS will be defined: low capability RS (simple RS) and high capability RS (full function RS). The simple RS is used for low cost deployment, and operates on one OFDMA channel. It contains no control functionality (i.e., control functions are centralized in the MMR-BS) with one transceiver and optionally supports multiple input multiple output (MIMO). The full function RS can operate on multiple OFDMA channels, implement distributed control functions, and support MIMO. This type of RS has a further two variants: fixed/nomadic full function RS and mobile full function RS. Mobile RSs add support for handover and the ability to deal with a varying channel due to mobility. Table 14.1 summarizes the different RSs capabilities.

At present, it is considered that an MMR network could be composed of multiple usage models [6] including multiple RS types specifically deployed. But at present, there is only a little work about the heterogeneous functionalities of the RSs in different scenarios.

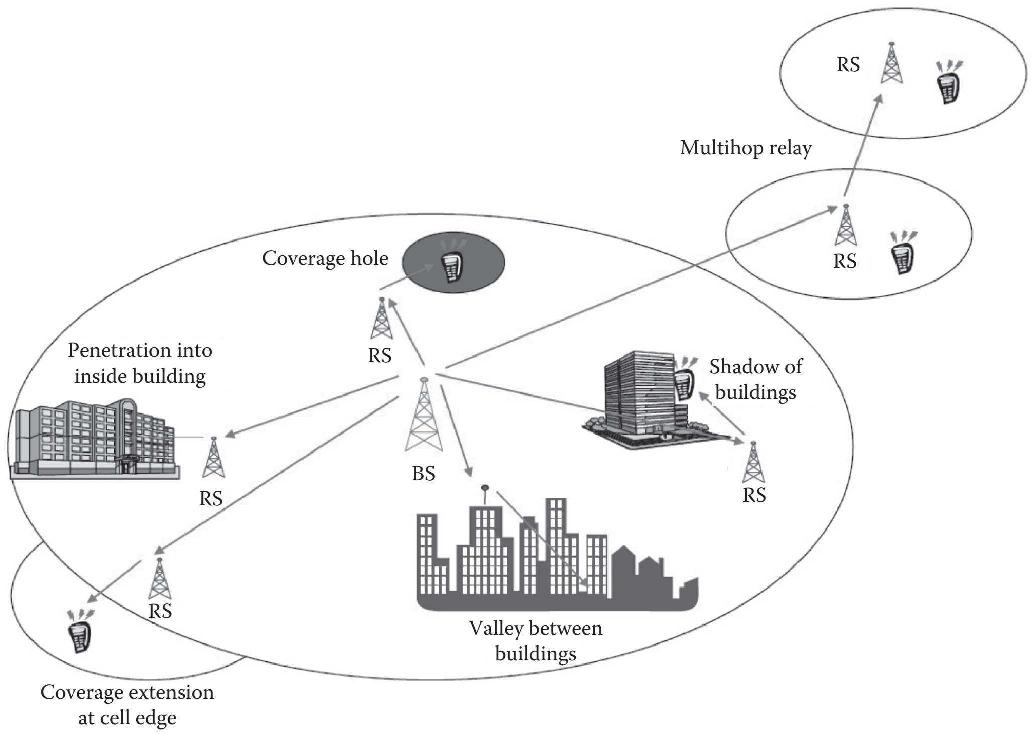

FIGURE 14.1 IEEE 802.16j example use cases. (From Sydir, J., IEEE 802.16 Breadband Wireless Access Working group C Harmonized on 802.16j (Mobile Multihop Relay) usage Models, July 2006.)

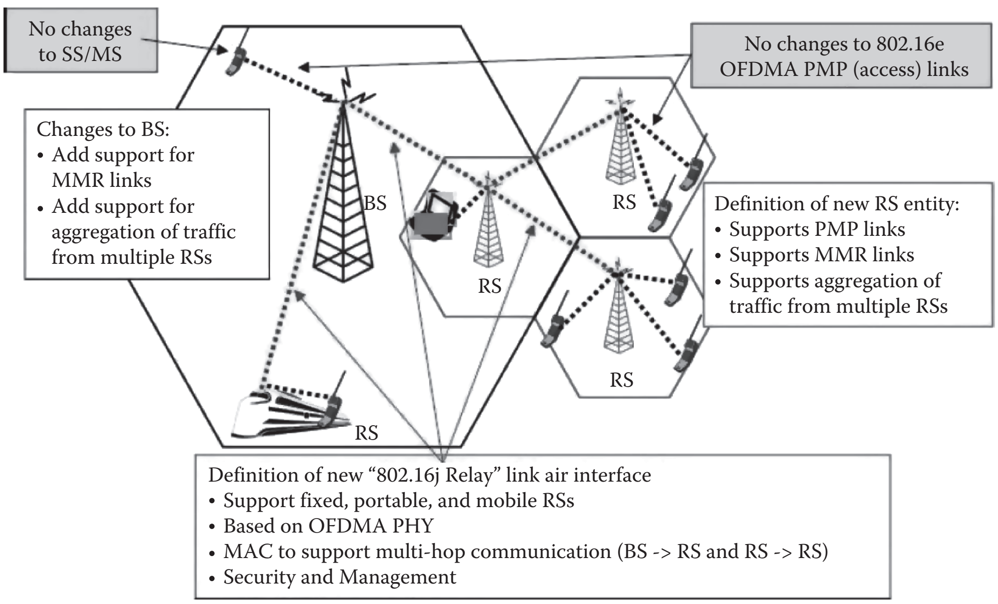

FIGURE 14.2 IEEE 802.16j project scope.

TABLE 14.1
RS Capabilities

	Simple RS	Full Function Fixed/Nomadic RS	Mobile RS
Number of OFDMA channels	1	≥1	≥1
Duplexing on MMR and access links	TDD	TDD or FDD	TDD or FDD
Frequency sharing between access and MMR links	Yes	Yes or No	Yes or No
Mobility	Centralized in MMR-BS	Centralized in MMR-BS or distributed in RSs	Centralized in MMR-BS or distributed in RSs
Antenna support	SISO or MIMO	MIMO	MIMO

For example, an MS can move from the coverage provided inside a building by fixed/nomadic RS to a train where the coverage is provided by a mobile RS. Furthermore, there is no direct mapping between the usage models and the types of RS. An operator may deploy a variety of different RS types depending on traffic, mobility, topology (two hops or more) within the area of each RS location for a specific usage model.

In fact, the future standard will not answer all the issues raised by the RS incorporation to provide vendor differentiation. For instance, intelligent scheduling either at the BS (in a centralized approach) or at the BS and RSs (in a distributed approach) are required to minimize the interference that occurs at the RSs.

14.3 RADIO PROPAGATION MODELS

In any wireless network planning problem, the radio model is a key component. Because of the variety of the propagation environment, there is no universal propagation model. In general, radio models can be almost arbitrarily complex. However, working with such models can be very computationally intensive and it is important to find the model with the right balance of abstraction and complexity for the problem under study. For the WiMax network planning problems, two propagation models can be suitable and are described below.

14.3.1 Free-Space Model

The free-space model [7] (originally published by H.T. Friis in 1946) is the simplest model that can only be applied in open area, i.e., no obstruction on the transmission line. This model is considered as a standard propagation model, a reference and benchmark of all other propagation models.

The path loss of the free-space model is

$$L_{fs}(f,d) = 32.44 + 20\log_{10} f + 20\log_{10} d \tag{14.1}$$

where

L_{fs} is the free space path loss in decibels

d is the distance between the transmitter and the receiver in kilometer

f is the frequency in MHz

In the free space model, many factors, such as reflection/multipath, shadowing, fading, atmosphere factors, etc., that may affect radio on its transmission path are omitted. This model, consequently, does not capture key transmission characteristics of radio, so it is not a very appropriate model for real world scenarios.

14.3.2 SUI Model

The Stanford University Interim (SUI) model was developed for design, development, and testing in the multipoint microwave distribution system frequency band [8] (2–3 GHz). It was recommended by the IEEE 802.16 standard body. The SUI model is valid for radio propagation within the 2–3 GHz range and has different parameter settings for urban, suburban, and rural scenarios. The maximum path loss (type A) is hilly terrain with moderated-to-heavy tree density. The minimum path loss (type C) is mostly flat terrain with light tree densities. The intermediate path loss condition is type B.

The SUI model is used for receiver's antenna height between 2 and 10 m. The path loss model is given by

$$L_{\mathrm{SUI}}(d, f, h_m) = A + 10\delta \log_{10}\left(\frac{d}{d_0}\right) + X_f + X_h + s, \quad \text{for } d > d_0 \tag{14.2}$$

AQ2 with the correction factors for the operating frequency and for the CPE antenna height of the model:

$$X_f = 6 \log_{10}\left(\frac{f}{2000}\right) \tag{14.3}$$

$$X_h = -10.8 \log_{10} \frac{h_m}{2}, \quad \text{for terrain type A and B} \tag{14.4}$$

$$X_h = -20 \log_{10} \frac{h_m}{2}, \quad \text{for terrain type C} \tag{14.5}$$

where

L_{SUI} is the SUI path loss in decibels

d is the distance between the BS and the CPE antennas in meters, d_0 = 100m

h_m is the CPE height above ground

s is a log normally distributed factor that is used to account for the shadow fading owing to trees and other clutter and has a value between 8.2 and 10.6 dB

The other parameters are defined as

$$A = 20 \log_{10} \frac{4\pi d_0}{\lambda} \tag{14.6}$$

$$\delta = a - bh_b - c/h_b \tag{14.7}$$

where

h_b is the base station height above the ground in meters and should be between 10 and 80 m parameters

a, b, c are the constants dependent on the terrain type and are shown in Table 14.2.

The SUI model was chosen to be used in the following network planning models based on the following reasons: (1) the model was accepted by the IEEE 802.16 standard body; (2) it has a good compromise between simplicity and accuracy, i.e., it models the key characteristics of the radio frequency and it is simple, computationally with a relatively small number of parameters.

TABLE 14.2
Constant Values for the SUI Model Parameters

Model Parameters	Terrain Type A	Terrain Type B	Terrain C
a	4.6	4.0	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

14.4 IEEE 802.16J NETWORK PLANNING PROBLEM FORMULATION

Here, a specific problem formulation for planning of multihop 802.16 networks is developed. The following inputs are assumed:

- A set of candidate BS and RS sites
- User demand, modeled by a set of discrete test points (TPs)
- this approach has been widely used in previous work and originally appeared in Ref. [10]
- A suitable propagation model
- A set of costs associated with BS and RS

The objective is to determine the set of BSs and RSs from the total set of candidate BS/RS sites that can accommodate the user demand at lowest cost.

The propagation model used here is the well-known SUI channel model. To use the model, it is necessary to define a number of parameters: terrain type, frequency of operation, antenna height, etc. In the experiments described below, a single set of parameters was used as in Table 14.3.

The height of BSs and RSs is the general height of a building, radio tower, or other constructions that can be mounted as BS/RS. The height of TP is average height of an adult. 2.5 GHz is the frequency recommended by WiMax forum for mobile WiMax systems.

14.4.1 INTEGER PROGRAMMING MODEL

The following problem inputs are defined:

- $S = \{1, \ldots, m\}$: Candidate site for BSs
- $R = \{1, \ldots, n\}$: Candidate site for RSs
- $T = \{1, \ldots, t\}$: TPs
- $c_j^b (j \in S)$: Cost of each BS
- $c_j^r (j \in R)$: Cost of each RS
- $u_i (i \in T)$: Traffic demand for each TP (number of connections)

TABLE 14.3
Parameters Used in SUI Model

Parameter Name	Value
Height of BSs and RSs	Random value between 10 and 80 m
Height of TPs	1.6 m
Frequency	2.5 GHz
Terrain type	C, mostly flat terrain with light tree densities

The set of BS sites differs from those of RS, as a BS is larger than an RS in size and has more functionalities. Also, the multihop concept is limited to nodes which are at most two hops from the BS: hence subscriber stations (SSs) can connect to an RS which is connected to the BS, or they can connect directly to the BS.

The gain matrices are determined based on the SUI model:

- $g^b_{ij}(0 < g^b_{ij} < 1, i \in T, j \in S)$: Propagation factor of the radio link between TP i and candidate site of BS j
- $g^r_{ij}(0 < g^r_{ij} < 1, i \in T, j \in R)$: Propagation factor of the radio link between TP i and candidate site of RS j
- $g_{ij}(0 < g_{ij} < 1, i \in R, j \in S)$: Propagation factor of the radio link between candidate site of RS i and candidate site of BS j

The decision variables of the problem are a set of binary variables as follows:

$$y_j = \begin{cases} 1, \text{if a BS is installed in } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } j \in S \tag{14.8}$$

$$z_j = \begin{cases} 1, \text{if an RS is installed in } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } j \in R \tag{14.9}$$

$$x^b_{ij} = \begin{cases} 1, \text{TP } i \text{ is assigned to BS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in T \text{ and } j \in S \tag{14.10}$$

$$x^r_{ij} = \begin{cases} 1, \text{TP } i \text{ is assigned to RS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in T \text{ and } j \in R \tag{14.11}$$

$$r_{ij} = \begin{cases} 1, \text{RS } i \text{ is assigned to BS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in R \text{ and } j \in S \tag{14.12}$$

It is now possible to write the objective function:

$$\min_{x,y,z,r} \left[\left(\sum_{j=1}^{m} c^b_j y_j + \sum_{j=1}^{m} c^r_j z_j \right) + \lambda_1 \left(\sum_{i=1}^{t} \sum_{j=1}^{m} u_i \frac{1}{g^b_{ij}} x^b_{ij} \right) + \lambda_2 \left(\sum_{i=1}^{t} \sum_{j=1}^{n} u_i \frac{1}{g^r_{ij}} x^r_{ij} \right) + \lambda_3 \left(\sum_{i=1}^{n} \sum_{j=1}^{m} \frac{1}{g_{ij}} r_{ij} \right) \right] \tag{14.13}$$

subject to the following constraints:

$$\sum_{j=1}^{m} x^b_{ij} + \sum_{j=1}^{n} x^r_{ij} = 1, \quad \forall i \in T \tag{14.14}$$

$$\sum_{j=1}^{m} r_{ij} = z_i, \quad \forall i \in R \tag{14.15}$$

$$x^b_{ij} \leqslant y_j, \quad \forall i \in T, \forall j \in S \tag{14.16}$$

$$x^r_{ij} \leqslant z_j, \quad \forall i \in T, \forall j \in R \tag{14.17}$$

$$r_{ij} \leqslant y_j, \quad \forall i \in R, \forall j \in S \tag{14.18}$$

In the objective function (Equation 14.13), the first term constitute the cost of installing the BSs and RSs. The next two terms relate to the transmit power of the mobile stations—it is desirable to limit the required transmit power for the mobile devices since the mobile devices normally have less power and thus, the radio frequency can transmit shorter than that from a BS. The first of these terms relates to the transmit power of those devices that are communicating directly with the BS, while the second relates to devices that are using the relays. The final term ensures that RSs are associated with their closest BSs. The parameters λ_1, λ_2, and λ_3 are weight parameters which determine how much weight is given to each of these terms in the optimization process. Note that this formulation is somewhat independent of node transmit power—it simply tries to find a solution with lowest path loss between nodes.

The set of constraints are quite natural. Constraint 14.14 ensures every TP is assigned to either a BS or an RS. Constraint 14.15 ensures every RS assigned to only one BS; also if the RS is not installed, it cannot be assigned to a BS. Constraints 14.16 through 14.18 ensure that TPs are not assigned to BSs that are not present, TPs are not assigned to RSs that are not present and RSs are not assigned to BSs that are not present.

14.4.2 State Space Reduction

The above problem formulation is a 0-1 IP problem. Standard approaches can be used to solve this problem, such as the branch and bound algorithm. However, since it is an NP-hard problem, it can take huge amount of time to solve when the problem size scales up. To reduce the execution time, some more constraints could be added to reduce the problem state space. These extra constraints derive from understanding of the problem.

As each TP is connected to only a single RS or BS which is close to it, it is possible to add constraints which limit the set of RSs/BSs that any given TP can be associated with. In this way, the problem state space can be reduced considerably. There are two natural choices to determine whether it should be possible to allocate a TP to an RS/BS: the decision could be based on distance or path loss. In this work, the latter was chosen because the path loss reflects naturally the received signal quality. By means of close, a percentage parameter is set during the experiments and the first percentage number of TPs are considered close to the corresponding BS or RS (Refer to Section 14.5.2). The following matrices were then introduced:

$$f_{ij}^{b} = \begin{cases} 1, \text{TP } i \text{ is close to BS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in T \text{ and } j \in S \tag{14.19}$$

$$f_{ij}^{r} = \begin{cases} 1, \text{TP } i \text{ is close to RS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in T \text{ and } j \in R \tag{14.20}$$

$$f_{ij} = \begin{cases} 1, \text{RS } i \text{ is close to BS } j \\ 0, \text{otherwise} \end{cases} \quad \text{for } i \in R \text{ and } j \in S \tag{14.21}$$

And the following constraints are added for this variant of the problem:

$$x_{ij}^{b} \leqslant f_{ij}^{b}, \quad \forall i \in T, \quad \forall j \in S \tag{14.22}$$

$$x_{ij}^{r} \leqslant f_{ij}^{r}, \quad \forall i \in T, \quad \forall j \in R \tag{14.23}$$

$$r_{ij} \leqslant f_{ij}, \quad \forall i \in R, \quad \forall j \in S \tag{14.24}$$

Constraints 14.22 and 14.23 ensure that TPs can only be associated with nearby BSs or RSs, respectively. Constraint 14.24 ensures that RSs will only be associated with nearby BSs.

14.4.3 Clustering Approach

Clustering is a very standard technique for grouping entities together which are somehow related. In this case, these entities are related due to their geographical proximity. The main idea behind the clustering approach described here is to divide the larger problem into a number of smaller problems, each of which can be solved separately using the formulation above. The advantage of this is that the resulting time to find a solution is significantly lower. A clustering approach is used rather than more primitive methods of dividing the state space as it tends to result in fewer problems at the boundaries between the different clusters [11].

The clustering approach employed here comprises of three steps:

1. Use the standard k-means clustering based on a particular metric to divide the state space into k separate clusters.
2. Use the problem formulation described above to solve the problem for each of the clusters independently.
3. Given the resulting set of RS and BS locations, perform a reallocation of TPs to RS/BS and RS to BS using another IP formulation.

The first two steps mentioned above are quite intuitive; the purpose of the third step is to address the problems that arise at the boundary. More specifically, it is possible that TPs or RSs at the boundary of a cluster are associated with an RS/BS within that cluster when there is a much closer RS/BS in a neighboring cluster: the third step above enables such points to be associated with nodes in other clusters.

The first step, generating clusters, was performed by generating clusters of nodes (TP, BS, RS) which have similar path losses to all other nodes (BS, RS) in the system. Note that this is a variant of an approach in which distance to other nodes is used as the metric.

A large gain matrix is first generated as input to the problem. This gain matrix comprises of all path losses between all nodes in the system as shown below:

$$M = \begin{bmatrix} A & B \\ C & D \\ E & F \end{bmatrix} \tag{14.25}$$

In which, A, B, C, D, E, and F are all matrices as follow:

$$A = \begin{bmatrix} l_{1,1} & \cdots & l_{1,m} \\ \vdots & \ddots & \vdots \\ l_{t,1} & \cdots & l_{t,m} \end{bmatrix}; \quad B = \begin{bmatrix} l_{1,m+1} & \cdots & l_{1,m+n} \\ \vdots & \ddots & \vdots \\ l_{t,m+1} & \cdots & l_{t,m+n} \end{bmatrix};$$

$$C = \begin{bmatrix} l_{t+1,1} & \cdots & l_{t+1,m} \\ \vdots & \ddots & \vdots \\ l_{t+n,1} & \cdots & l_{t+n,m} \end{bmatrix}; \quad D = \begin{bmatrix} l_{t+1,m+1} & \cdots & l_{t+1,m+n} \\ \vdots & \ddots & \vdots \\ l_{t+n,m+1} & \cdots & l_{t+n,m+n} \end{bmatrix};$$

$$E = \begin{bmatrix} l_{t+n+1,1} & \cdots & l_{t+n+1,m} \\ \vdots & \ddots & \vdots \\ l_{t+n+m,1} & \cdots & l_{t+n+m,m} \end{bmatrix};$$

$$F = \begin{bmatrix} l_{t+n+1,m+1} & \cdots & l_{t+n+1,m+n} \\ \vdots & \ddots & \vdots \\ l_{t+n+m,m+1} & \cdots & l_{t+n+m,m+n} \end{bmatrix} \tag{14.26}$$

where

matrix A represents the gain matrix between TPs and BSs
matrix B represents the gain matrix between TPs and RSs
matrix C represents the gain matrix between RSs and BSs
matrix D represents the gain matrix between RSs and RSs
matrix E represents the gain matrix between BSs and BSs
matrix F represents the gain matrix between BSs and RSs

Thus, the matrix M has a dimension of $t + n + m$ by $m + n$.

The k-means clustering algorithm is then applied using the above gain matrix to obtain k clusters: the nodes in each cluster are characterised by similar path loss to all RS and BS in the system. This results in k distinct, nonoverlapping clusters, typically of comparable size for realistic node distributions.

In step 2, the standard branch and bound algorithm was used to obtain RS and BS locations for each cluster. This resulted in solutions for each cluster in which the TPs were allocated to RSs/BSs in that specific cluster.

A new problem formulation was developed for the final step to overcome the boundary issues. This problem differs from the original in that the RS and BS locations are now fixed, and the focus is on determining the relationships between TPs, RSs, and BSs: more specifically, which TPs should be allocated to which RS/BS and which BS each RS should be associated with.

The problem can be stated as follows:

$$\min_{x,r}\left[\lambda_1\left(\sum_{i=1}^{t}\sum_{j=1}^{m}u_i\frac{1}{g_{ij}^b}x_{ij}^b\right)+\lambda_2\left(\sum_{i=1}^{t}\sum_{j=1}^{n}u_i\frac{1}{g_{ij}^r}x_{ij}^r\right)+\lambda_3\left(\sum_{i=1}^{n}\sum_{j=1}^{m}\frac{1}{g_{ij}}r_{ij}\right)\right] \quad (14.27)$$

subject to

$$\sum_{j=1}^{m}x_{ij}^b+\sum_{j=1}^{n}x_{ij}^r=1, \quad \forall i\in T \quad (14.28)$$

$$\sum_{j=1}^{m}r_{ij}=z_i, \quad \forall i\in R' \quad (14.29)$$

$$x_{ij}^b\leqslant y_j, \quad \forall i\in T, \quad \forall j\in S' \quad (14.30)$$

$$x_{ij}^r\leqslant z_j, \quad \forall i\in T, \quad \forall j\in R' \quad (14.31)$$

$$r_{ij}\leqslant y_j, \quad \forall i\in R', \quad \forall j\in S' \quad (14.32)$$

where S' and R' are the sets of BS and RS locations, respectively. As the formulation is very similar to that presented earlier, it is reasonably clear what the objective is and what the constraints represent.

14.5 RESULTS AND DISCUSSION

The objective of these tests can be divided into two parts. One is to obtain an understanding of the scalability of the problem formulation—the basic and the state space reduction model. More specifically, the objective was to understand if this problem formulation can be used to solve problems of realistic size. Given that it is, in principle, an NP-hard problem, it is important to understand the range of problems for which standard solution techniques are appropriate and the range of problems which require the development of heuristics which employ domain knowledge.

The second is to determine how the clustering approach compares with the more rudimentary approaches. The comparison was performed based on both the time taken to obtain a solution and the

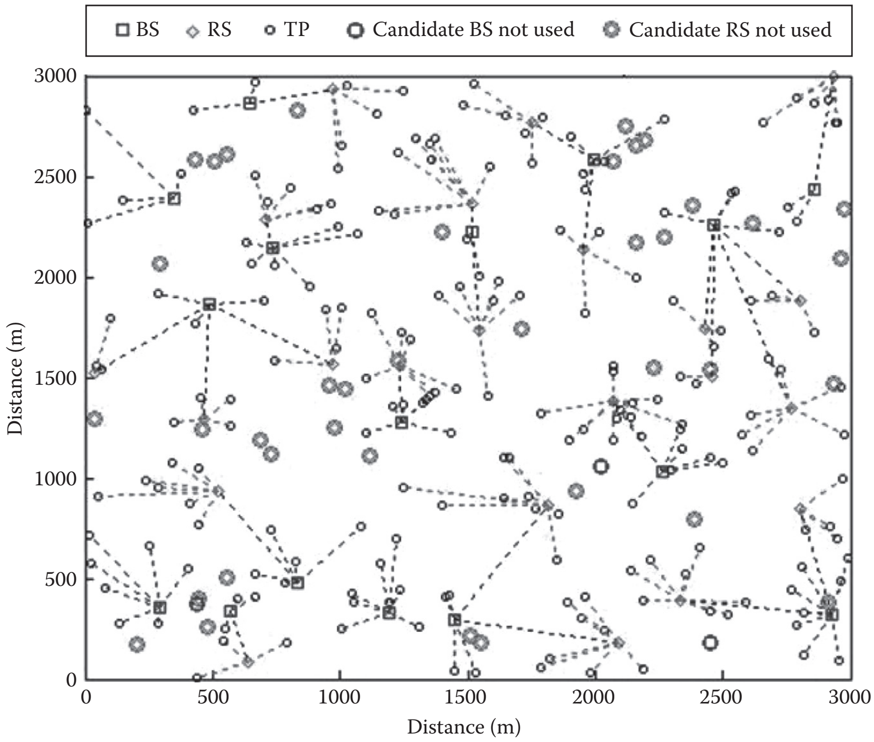

FIGURE 14.3 A typical output of the planning tool.

quality of the resulting solution; naturally, the former relates directly to the scalability characteristics of the approach and its applicability for realistic scenarios.

A number of tests were performed in which the number of BSs, RSs, and TPs were varied. All tests were done using a standard desktop computer—Centrino Duo 2.0 GHz, 1 GB Memory, Windows Vista. Twelve tests were performed each time and the mean execution time taken. As there was some variation in the results, the minimum and maximum execution times were removed and the mean taken over the remaining ten results.

Problems were generated at random. The locations of each of the BSs, RSs, and TPs were chosen randomly from an area of size 3 × 3 km. The (x, y) coordinates of each node were chosen by selecting two random variable from the distribution $U(0, 3000)$. For each of the problems the same set of weight parameters were used: $\lambda_1 = 8$, $\lambda_2 = 8$, and $\lambda_3 = 20$. However, it is worth noting that the values of these parameters have little impact on the time required to find solutions. In each of the problems, the BS cost was chosen at random and was three times the cost of the RS.

In all of the following tests, the branch and bound method found the optimal solution to the given problem. Figure 14.3 shows one possible result for planning a network with 20 candidate BSs, 60 candidate RSs, and 200 TPs. In the solution, 10 BSs are selected with 36 RSs.

14.5.1 Integer Programming Model

Four sets of tests were performed with the basic variant of the problem to determine its sensitivity to different parameters.

In the first experiment, all three parameters were scaled—the number of candidate BSs, candidate RSs, and TPs. The number of BSs was varied and the numbers of RSs and TPs were three times and ten times this figure, respectively. Figure 14.4 shows how the time required finding a solution

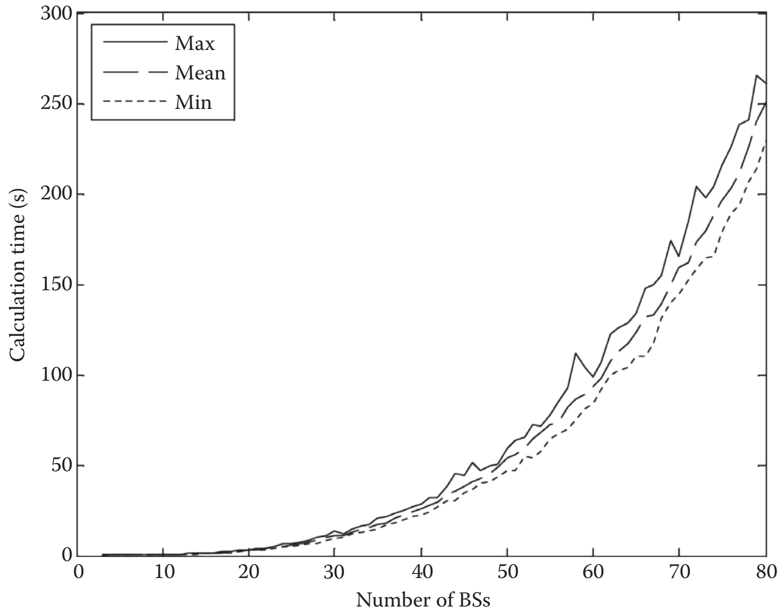

FIGURE 14.4 Calculation time when three parameters are scaled at the same time.

scales up. As it can be seen, the problem can be solved for up to 80 candidate BSs and 240 RSs with ease. Further, the results show that the problem complexity is scaling up quite rapidly. Indeed, further experiments were performed in which the number of candidate BSs was increased to 120 and the resulting execution mean time was under 30 min. The system is exhibiting scaling properties which are quite nonlinear, although some basic curve fitting has shown that for the available data set, the scaling is considerably less than exponential.

Figure 14.5 shows the calculation time when only the number of BSs is scaling. The number of RSs is set to 90 and the number of TPs is set to 300 in all tests.

A similar experiment was performed in which the number of RSs was scaled up and the number of BSs and TPs remained constant. Again it is clear that the system is scaling up linearly in this parameter (Figure 14.6). The number of BSs is set to 30 and the number of TPs is set 300 in all tests.

Finally, in this set of experiments, the sensitivity to the number of TPs was considered. The same characteristic is again observed: the system scales linearly as can be seen from Figure 14.7. The number of BSs is set to 30 and the number of RSs is set to 90 in all tests.

From the figures, it can be seen that this algorithm should suit small size network planning problems since the time cost is very short for small number of BSs. The time varies almost linearly if individual parameter is varying. For the problem sizes studied—which are typical for small metropolitan scenarios—the solution can be found quickly on typical desktop computers, e.g., under two minutes for problems with 50 candidate BS sites, and approximately ten minutes for problems with 100 candidate BS sites. The time cost for the planning could increase to one day long or a few days to plan a larger network, e.g., around 500 candidate sites, but it is still practicable.

14.5.2 Effect of the Constraints Reducing the State Space

Based on the test results, the additional constraints do not affect the planning result obtained but shortened the execution time significantly.

Figure 14.8 shows the effect of the state space reduction in solving different problem sizes. The execution time of applying and not applying the state space reduction constraints are shown in the

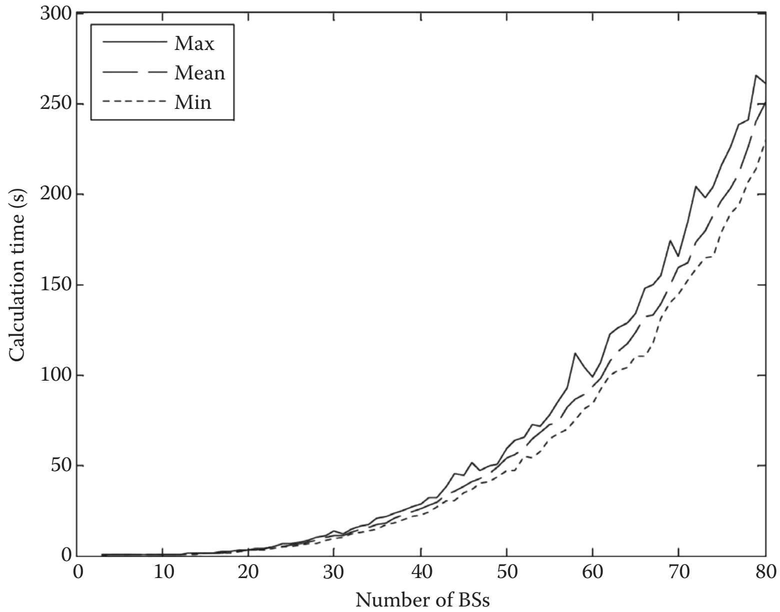

FIGURE 14.5 Calculation time when only the number of BS is scaled.

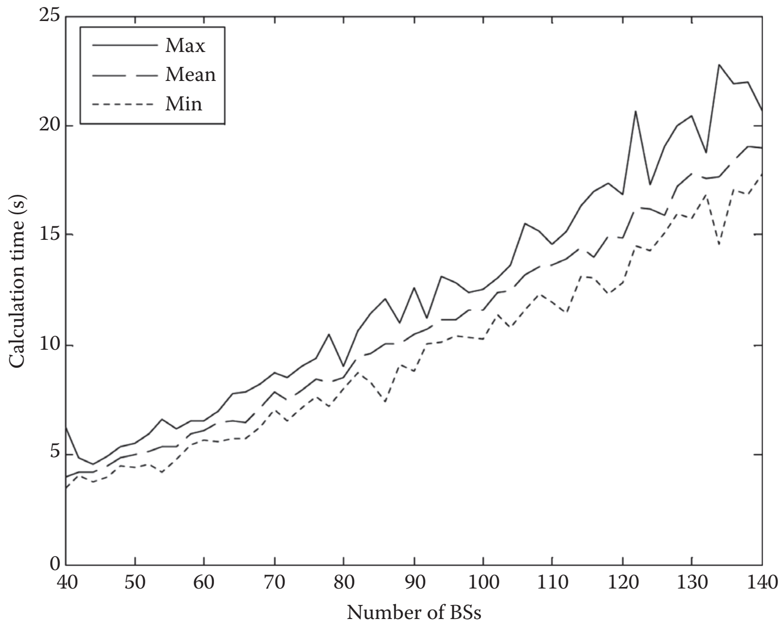

FIGURE 14.6 Calculation time when only the number of RS is scaled.

figure. The problem size varies depending on the number of candidate BS, which scaling between 30 and 75. The three parameters are scaling in the same manner as in Figure 14.4. It can be seen that it reduces half of the execution time.

Figure 14.9 shows the effect of the parameter which defines the term "close to" as in Section 14.4.2. The parameter defines the percentage of the state space is reduced. It vary between 0

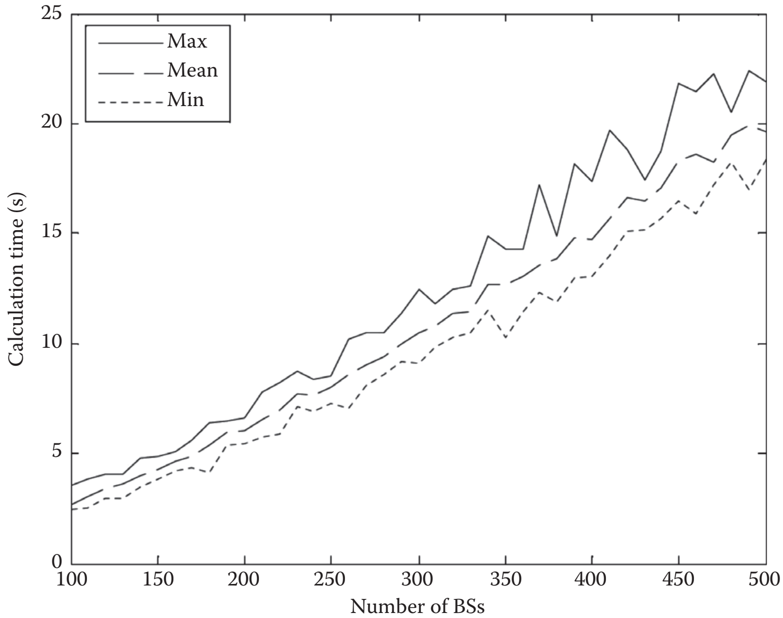

FIGURE 14.7 Calculation time when only the number of TP is scaled.

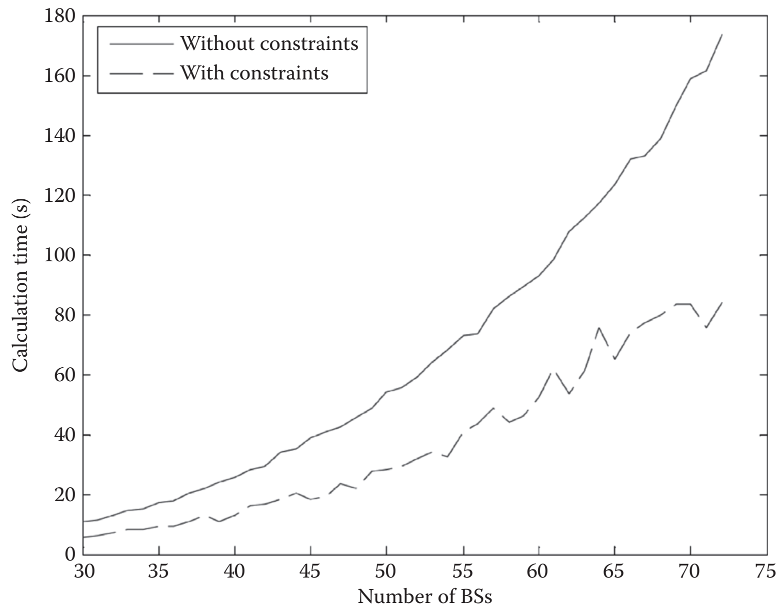

FIGURE 14.8 Comparison of the calculation time, with and without the additional constraints.

and 75 percent which means the rest of the nodes, i.e., 100–25 percent of all the other nodes (TP/RS that can connect to the node itself) are considered close to the node it self. In all tests, the number of candidate BSs is set to 80, the number of candidate RSs is set to 240, and the number of TPs is set to 800. From the figure, it is very obvious that the additional constraints could increase the performance and the more percentage of the state space is reduced, the more time can be saved.

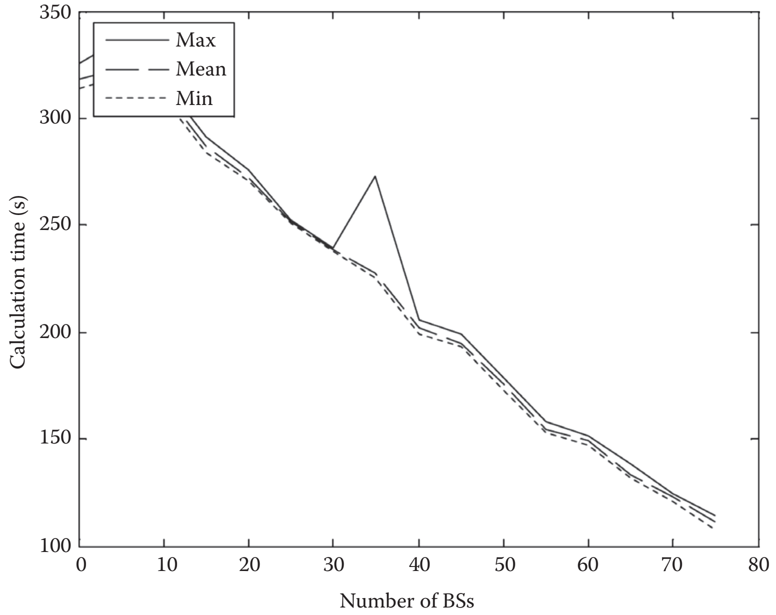

FIGURE 14.9 Trend of the calculation time when different filtered percentage is applied.

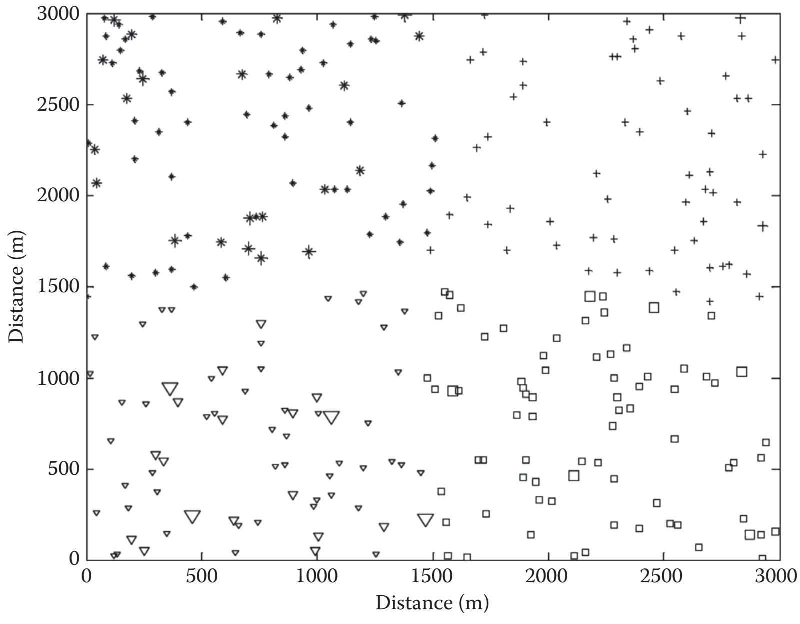

FIGURE 14.10 A clustering output with 4 clusters in which different shapes represent different clusters.

14.5.3 Using the Clustering Approach

Before considering the final output of the clustering approach, it is interesting to consider how well the clustering algorithm works. Figure 14.10 shows a clustering output of a network with 20 candidate BSs, 60 candidate RSs, and 200 TPs. There, it can be seen that the clustering algorithm divides the nodes into four groups of approximately equal size.

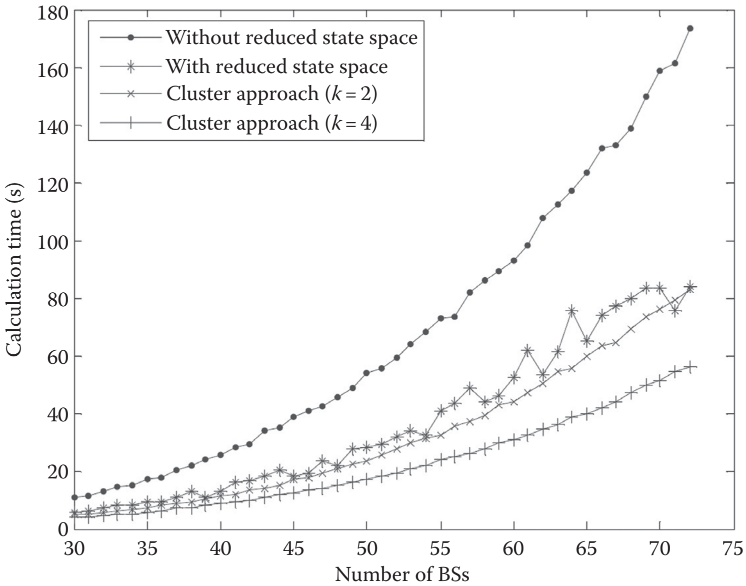

FIGURE 14.11 Comparison of the calculation time, with and without the state space reduction constraints and the clustering approach.

Once the clusters were obtained, the performance of the full approach was considered. Figure 14.11 compares the calculation time of using the clustering algorithm with that of using the basic model. Two variants of the clustering approach were considered: one in which the number of clusters was 2 and one in which 4 clusters were used.

The results show that the clustering approach results in significant improvements—the amount of time required obtaining the solution decreases by up to 60 percent. The results show that the 4-cluster solution operates significantly faster: this is to be expected, as it involves the solution of significantly smaller problems.

It is interesting to consider further the impact of the number of clusters. Figure 14.12 shows the calculation time of the whole clustering model with different k values. All other parameters remain the same: 80 candidate BSs, 240 candidate RSs, and 800 TPs. When $k = 1$, the clustering model is the same as the basic model.

From the Figure 14.12, it can be seen that the calculation time drops as the number of clusters increases. As the number of clusters increases, the execution time drops to 20 percent of the nonclustered approach. It is worth noting, however, that the number of clusters reduces to have much impact above 4–6 clusters, for the problem size studied. This indicates that it is not necessary to have a large number of clusters to obtain significant savings: further, increasing the number of clusters does not result in further savings. It is anticipated, however, that larger problems could benefit from slightly larger numbers of clusters.

It is insufficient to consider execution time alone: it is necessary to consider the quality of the resulting solution. Figure 14.13 shows how the overall cost changes with k. The figure shows the variation normalized to the known optimal solution obtained via branch and bound. The scenarios are the same as those in Figure 14.4. While it is clear that k does have an impact on the resulting overall cost—with increasing k resulting in poorer solutions—the difference is so small as to be considered negligible. Further, there is a small improvement which results from the final step that reduces this difference.

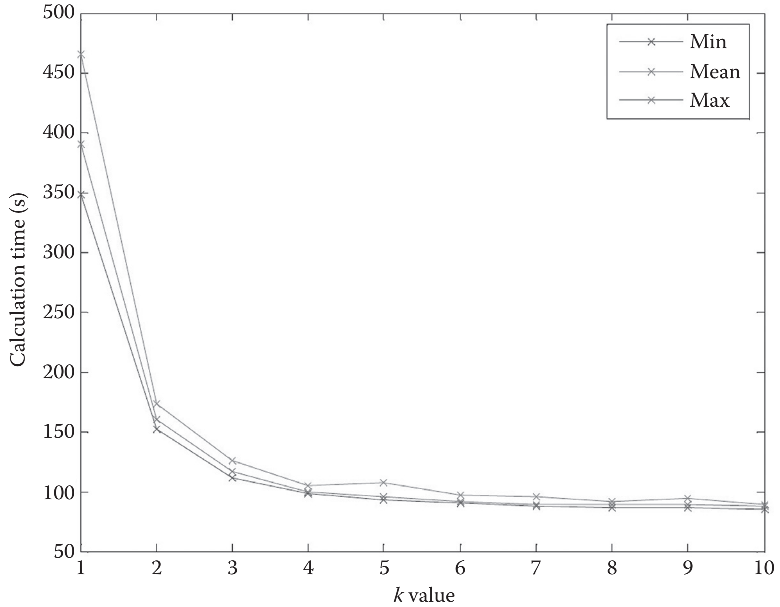

FIGURE 14.12 Calculation time for different k values.

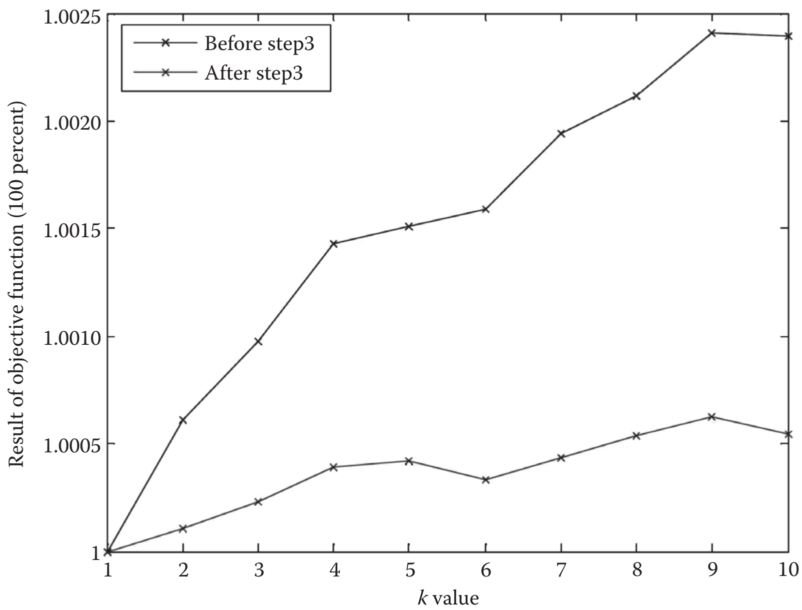

FIGURE 14.13 BS and RS costs for different k values.

14.5.4 Impact of the Ratio of the Cost of BS to RS on Solution

It is also worth to notice how the ratio of the cost of BS and RS affects the site selection. Intuitively, as the ratio raising, the RS becomes relatively cheaper, so it should tend to select more RS compared to the BS and connections from TP to RS should increase. Figure 14.14 shows the trend. It shows number of connections between TP and BS and between TP and RS as the cost ratio varying from

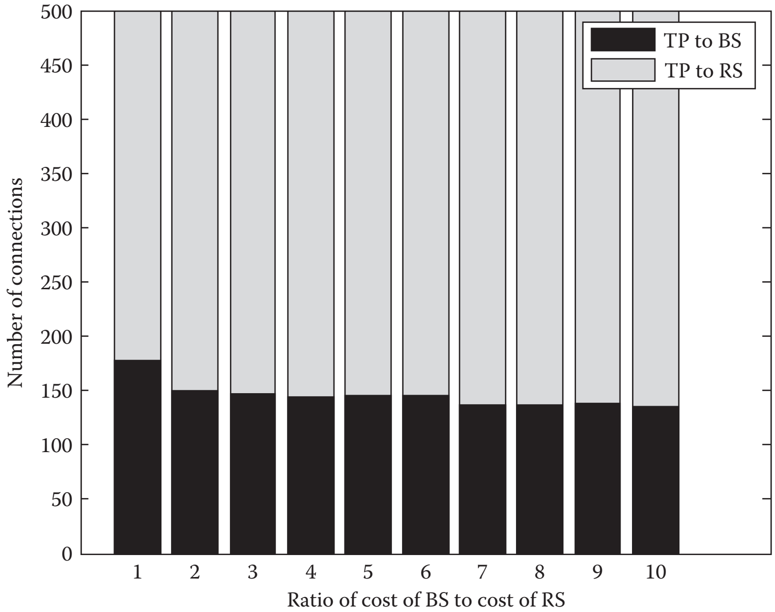

FIGURE 14.14 Number of connections between TP and BS and between TP and RS as the ratio of the cost of BS and RS is varied.

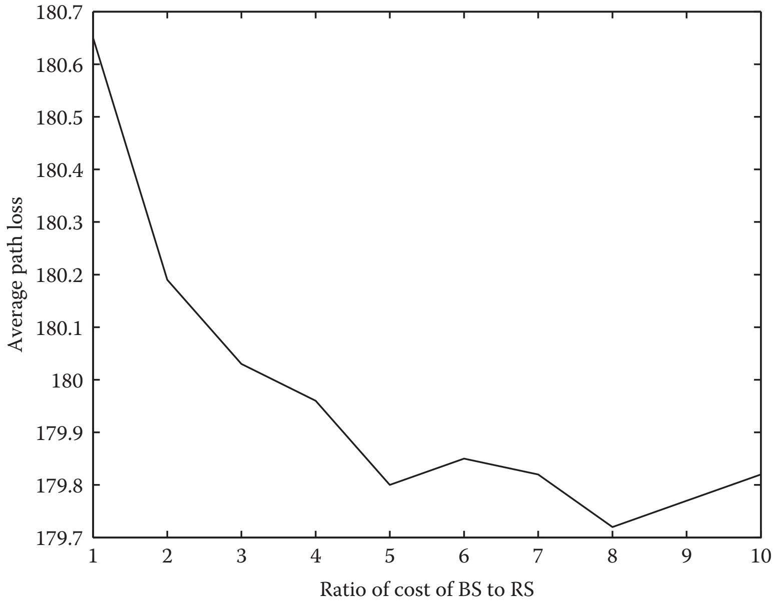

FIGURE 14.15 Average path loss between each TP and its communicating node as the ratio of the cost of BS and RS is varied.

one to ten, i.e., from the cost of BS equals to the cost of RS to the cost of BS ten times the cost of RS. Figure 14.15 shows the corresponding average path loss between each TP and its communicating node. It can be seen that the path loss is decreasing which means the quality of the radio received becomes higher as the cost of RS becoming lower.

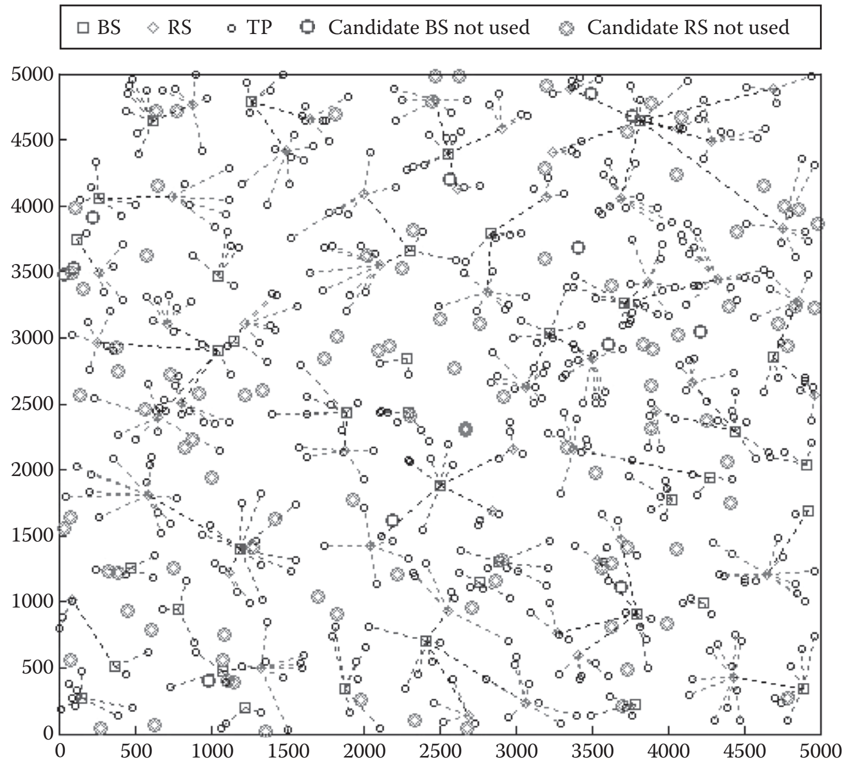

FIGURE 14.16 An output of the planning tool when the ratio of the cost of BS and RS is 1.

Figures 14.16 and 14.17 show two extreme cases. In both cases, the number of candidate BS sites is 50, the number of candidate RS sites is 150, and the number of TP is 500. Figure 14.16 shows the plan of the cost of BS equals to the cost of RS. In this case, there are 38 BSs and 50 RSs being selected; 177 connections between TP and BS; 320 connections between TP and RS. Figure 14.17 shows the plan of the cost of BS ten times to the cost of RS. In this case, there are 28 BSs and 75 RSs being selected; 133 connections between TP and BS; 367 connections between TP and RS.

14.6 CONCLUSION

In this chapter a model for planning 802.16-based relay networks is proposed. An IP formulation was developed and an investigation of the applicability of standard algorithms to this problem was performed. The results show that the standard branch and bound algorithm can find optimal solutions to problems of reasonable size on standard hardware. More specifically, these techniques can be used to solve planning problems for small metropolitan areas or areas of a city. Further, the results show that the time required to obtain solutions scales linearly with each of the individual parameters of the problem. However, when all parameters are scaled, the time complexity increases more quickly.

A simple state space reduction mechanism was also considered. While the performance of this can vary, it was found to reduce the computing time required by 50 percent for realistic cases. A clustering approach was also proposed and it was shown to deliver significant time improvements over the two previous approaches, finding solutions in 30 percent of the time required by the basic model with negligible impact on solution quality. The analysis found that the system has some sensitivity to the number of clusters used: for the size of problems studied, 4–6 clusters are optimal

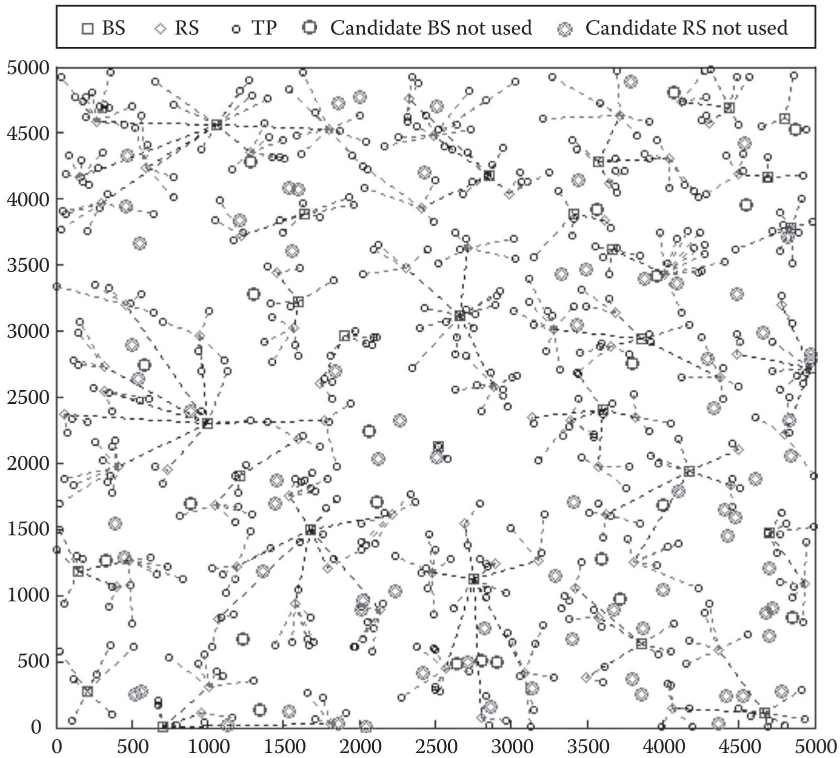

FIGURE 14.17 An output of the planning tool when the ratio of the cost of BS and RS is 10.

in terms of execution speed and quality of resulting solution. This new approach enables larger problems to be solved in realistic time on typical computing hardware.

Some analysis of the impact of the ratio of BS/RS cost was also performed. This analysis showed that as the cost of RS decreases (relative to that of the BS), the solutions comprise of more RSs. Further, the path loss between the mobile node and the infrastructure node is lower in the case that the RS cost is lower.

This initial work clearly leaves many questions unanswered. Future work will involve investigation of frequency reuse in this context, addition of QoS constraints to the model, further study of the impact of power constraints, and some investigation of the impact of the weighting parameters. Also heuristic techniques are necessary to be studied to significantly reduce computation complexity and present corresponding results.

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