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Abstract

In this report, the survivable wireless communications network design problem is considered, where smart antennas may be adopted for sectorization. An optimization-based algorithm is then proposed to provide wireless network planners and managers with both decision and operation support, so that the total network deployment and operation cost can be minimized under QoS (Quality-of-Service) and survivability constraints. In the integrated model presented in this paper, the following five major problems are jointly considered: (i) the MTSO (Mobile Telephone Switching Office) configuration and capacity assignment problem; (ii) the wired backbone network design problem; (iii) the base station allocation, sectorization and power control problem; (iv) the channel assignment problem; and (v) the system survivability problem. These five problems are inherently coupled. The joint problem is formulated as a combinatorial optimization problem and the basic approach to the algorithm development is Lagrangean relaxation. In computational experiments the proposed algorithm achieves up to 23% and 21% cost reduction, respectively, over two sensible heuristics.

I. Introduction

The advantages of convenience and mobility have resulted in the rapid growth of demand for mobile communication services. Nevertheless, the availability of spectrum is rather limited [1], [2], [10], [12], [15]. To meet the increasing demand, we need to increase the capacity of base stations or to maximize the utilization of spectrum. In recent years, there are numerous papers providing recommendations on how to improve the utilization of spectrum. These techniques include modulation, coding, multiple access and sectorization (the adoption of smart antennas).

In the different cells of FDMA/TDMA systems, one can use the same frequency channel to provide services, as long as it satisfies the engineering constraint, which requires that the CIR (carrier to interference ratio) be under certain level of threshold. The co-channel interference is a key effect of the CIR in FDMA/TDMA systems. Smart antenna did well in improving efficiency of spectrum. If omni-direction antennas were replaced with smart antennas, then co-channel interference can be reduced and thus spectrum efficiency can be enhanced.

We intend to consider this technique when designing a wireless communication network. In this stage, we find the minimum construction cost of a wireless communication network that can provide enough quality of services to each user in it. This paper addresses on wireless communication network design which consists of the following five problems: (i) MTSOs configuration and capacity assignment problem; (ii) the wired backbone circuit-switching network topology design problem; (iii) base station allocation, antenna configuration of each base station and power control problem; (iv) channel assignment problem; and (v) high reliability of system problem. These five problems are inherently entangled together and each has positive and negative effects on one another. It is rather complex to consider all of them at a time.

The wireless communication network model discussed in this paper includes the following components: Mobile Telephone Switching Offices (MTSOs), base stations (BSs), clusters of mobile terminals (MTs), and the links of wired backbone network topology. In [3], Gavish describes clearly the functionality of cellular networks. However, the model described by Gavish is different from the model discussed herein. A cluster of mobile terminals mean many phones carried by many subscribers. Each mobile terminal requests a channel to connect with the antenna of the base station. In our model, a channel means a pair of frequencies, including a forward-link frequency and an up-link frequency. Its QoS requirement means the call-blocking rate. A base station refers to a tower that serves the mobile terminals in its vicinity. A cell denotes an area covered by the base station. The coverage depends on the strength of its signal. In our model, there are three fixed sectorizations provided by smart antennas in a cell. The antenna has its capacity constraint that each type of antenna has limited number of channel assigned to. MTSO is the central switch, which monitors all cellular calls, assigns frequency channels, and performs administrative function such as billing and arranging handoffs. We should build a wired circuit-switching network to connect each MTSO. Additionally, we also provide high reliability for important locations. We try to construct a reliable network to satisfy the QoS requirements in case base station failures.

The demand for mobile communication services has increased tremendously in recent years. There is an urgent need for new techniques to improve spectrum utilization so as to allow more users with the same available spectrum [10]. Sectorizing a cell can produce two effects. First, it reduces co-channel interferences. Second, it divides the cell into smaller sectors [2]. As has been recognized by [1], [2], [10] and [12], sectorization can improve spectrum utilization. The mathematical model given later expresses the influence of sectorization on design and planning of wireless networks, where it is anticipated that sectorization will increase frequency reuse efficiency.

Most papers are based on regular cell system. They only have one system parameter - base station effective radius. All base stations are of the same size and with the same transmission power. In this paper, we provide a generic model that fulfills the real-world situation.

In addition to the above, we also aim to solve the routing problem at network design stage. Since backbone topology is a key effect on routing problem, we determine the routing path for each OD pair and the backbone topology of network at the same time. For the sake of reliability, we try to allocate more resources. In case of any base station failure, we can automatically re-allocate resources to provide equally good services. In this model, non-uniform traffic distribution and non-regular cells system are taken into consideration to better simulate the real-world situation.

A number of different approaches are mentioned above to solve those complex problems. In this paper, we adopted Lagrangean relaxation as the basic approach.

In this paper, Section 2 describes the problem formulation. Section 3 presents the Lagrangean relaxation approach. Section 4 discusses procedures to calculate primal feasible solutions. Section 5 provides computational experiments to evaluate the solution quality. Finally, Section 6 summarizes this paper.

II. Problem Formulation

In this Section, a model is established to address the integrated wireless communication network design problem. With this model, we seek to solve the problem of sectorization and the location of components and backbone topology design at once. Prior to this, we build a robust wireless communication network to deal with the situation of any base station failure. The following are the given inputs: (i) candidate BS location; (ii) candidate MTSO location; (iii) traffic demand of each OD pair; (iv) system parameter - coverage ratio, CIR, and call blocking rate; (v) cost function of channel license; (vi) capacity and type of antennas; (vii) capacity of MTSO; and (viii) capacity of each link. Our objective is to minimize the total cost of wireless communication network required under various constraints, such as capacity constraint of each component in the wireless network and QoS constraints. The decision variables include the total number of channels required, effective coverage of each cell, channel assignment, configuration of operation parameters of each base station, backbone circuit-switching network topology design, and capacity of each link. To better describe this problem, the following notation is defined:

E:	The set of network states (in this paper, we consider only the normal state where all the network components are functional, and the failure states where exactly one base station is dysfunctional in each failure state)
B:	The set of candidate locations for a base station
F:	The set of available channels
S:	The set of antenna types, which contains 4 elements: s_0, s_1, s_2, and s_3, where s_0 represents an omni-directional antenna, s_1 represents the first sector, s_2 represents the second sector and s_3 represents the third sector
T:	The set of mobile terminals
W:	The set of OD pairs
P_w:	The set of paths which can support requirement of OD pair w
$¥$:	Threshold of acceptable CIR (in dB)
D_{jt}:	Distance between base station j and mobile terminal t
M:	Upper bound on total number of channels
N_{js}:	Upper bound on number of channels that can be assigned to antenna s in base station j
R_{js}:	Upper bound of radius of antenna s in base station j
$\Phi_{jsj's'}$:	Indicator function which is 0 if antenna s' of base station j' never effects antenna s of base station j and $D'_{jj'}{}^{-\sim}$ otherwise (details of this function is introduced in the next section)
G_{js}:	An arbitrarily large number
$D'_{jj'}$:	Distance between base stations j and j'
$¢_{wt}$:	Indicator function which is 1 if mobile terminal t belongs to OD pair w and 0 otherwise
$«_{jst}$:	Indicator function which is 1 if mobile terminal t can be served by antenna s in base station j and 0 otherwise
$\sim$:	Attenuation factor (2< ~ <6)
P_w:	The set of paths which can support requirement of OD pair w
L_1:	The set of links which is between two MTSOs
L_2:	The set of links which is between an MTSO and other systems
L_3:	The set of links which are between MTSOs and ISPs
L_4:	The set of links between a base station and an MTSO
L_5:	The set of radio links between a mobile terminal and a base station through an antenna
${}^{e}_{js}$:	Call blocking probability of antenna s in base station j required by users at network state e
${}^{-}\left(g^e_{js},\ {}^{e}_{js}\right)$:	Minimum number of channels required for traffic demand g^e_{js} such that the call blocking probability shall not exceed ${}^{e}_{js}$
$£\left(c_l, ±^e_l\right)$:	Maximum traffic (in Erlangs) that can be supported by c_l trunks such that the call blocking probability shall not exceed $±^e_l$
$±^e_l$:	Call blocking probability of link l required by users at network state e
A^e:	Acceptable coverage ratio at network state e
$¢_{pl}$:	Indicator function which is 1 if link l is on path p and 0 otherwise
$°_{lt}$:	Indicator function which is 1 if mobile terminal t is one end of link l, and 0 otherwise
${}^{a}_{ljs}$:	Indicator function which is 1 if base station j is one end of link l and through antenna s, and 0 otherwise
$\Delta^L_l(c_l)$:	Cost function of link l with capacity c_l
$\Delta^B_{js}(n)$:	Cost function of antenna s in base station j with capacity n
Δ^F_i:	Channel i licensing cost
$\Delta^A_j(a_j)$:	Cost function of antenna type in base station j
h_i:	Decision variable which is 1 if channel i is installed and 0 otherwise
n_{js}:	Number of channels required by antenna s in base station j
y^e_{jsi}:	Decision variable which is 1 if channel i is assigned to antenna s in base station j at network state e and 0 otherwise
a_j:	Decision variable which is 1 if base station j uses smart antennas and is 0 if base station j uses an omni-directional antenna
r^e_{js}:	Transmission radius of antenna s in base station j at network state e
g^e_{js}:	Aggregate flow on antenna s in base station j at network state e (in Erlangs)
z^e_{jst}:	Decision variable which is 1 if mobile terminal t is serviced by antenna s of base station j at network state e and 0 otherwise
x^e_p:	Routing decision variable which is 1 if path p is selected at network state e and 0 otherwise
c_l:	Capacity assigned for link l

We model the integrated wireless communication network design problem considering sectorization as the following mathematical formulation:

$$Z_{IP2} = \min \sum_{j\in B}\sum_{s\in S}\Delta^B_{js}(n_{js}) + \sum_{j\in B}\Delta^A_j(a_j) + \sum_{l\in L}\Delta^L_l(c_l) + \sum_{i\in F}\Delta^F_i h_i \quad \text{(IP2)}$$

subject to:

$$\sum_{l\in L_5}\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p ¢_{pl}\, {}^{a}_{ljs} \le g^e_{js} \qquad \forall j\in B, s\in S, e\in E \qquad (1)$$

$${}^{-}(g_{js},\ {}^{e}_{js}) \le \sum_{i\in F} y^e_{jsi} \qquad \forall j\in B, s\in S. e\in E \qquad (2)$$

$$A^e \le \frac{\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p}{\sum_{w\in W} k_w} \qquad \forall e\in E \qquad (3)$$

$$\sum_{i\in F} y^e_{jsi} \le n_{js} \qquad \forall j\in B, s\in S, e\in E \qquad (4)$$

$$n_{js} \le N_{js} \qquad \forall j\in B, s\in S \qquad (5)$$

$$\sum_{\substack{j'\in B\\ j'\ne j}}\sum_{s'=S} (r^e_{j's'})^{\sim}\Phi_{jsj's'} y^e_{j's'i} \le G_{js} + (\frac{1}{¥} - G_{js}) y^e_{jsi}$$

$$\forall j\in B, s\in S, i\in F, e\in E \qquad (6)$$

$$D_{jt} z^e_{jst} \le r^e_{js} «_{jst} \qquad \forall j\in B, s\in S, t\in T, e\in E \qquad (7)$$

$$0 \le r^e_{js} \le R_{js} \qquad \forall j\in B, s\in S, e\in E \qquad (8)$$

$$z^e_{jst} \le «_{jst}\sum_{i\in F} y^e_{jsi} \qquad \forall j\in B, s\in S, t\in T, e\in E \qquad (9)$$

$$\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p ¢_{pl} \le £(c_l, ±^e_l) \qquad \forall l\in L-\{L_5\}, e\in E \qquad (10)$$

$$\sum_{w\in W}\sum_{p\in P_w} x^e_p ¢_{pl}\, {}^{a}_{ljs}\, °_{lt} \le z^e_{jst} \qquad \forall j\in B, s\in S, t\in T, l\in L_5, e\in E \,(11)$$

$$\sum_{p\in P_w} x^e_p \le 1 \qquad \forall w\in W, e\in E \qquad (12)$$

$$0 \le \sum_{j\in B}\sum_{s\in S} z^e_{jst} \le 1 \qquad \forall t\in T, e\in E \qquad (13)$$

$$\sum_{s\in S} z^e_{jst} \le 1 \qquad \forall j\in B, t\in T, e\in E \qquad (14)$$

$$y^e_{jsi} \le h_i \qquad \forall j\in B, s\in S, i\in F \qquad (15)$$

$$y^e_{jsi} \le a_j \qquad \forall j\in B, s\in S-\{s_0\}, i\in F, e\in E \,(16)$$

$$y^e_{js_0 i} \le 1 - a_j \qquad \forall j\in B, i\in F, e\in E \qquad (17)$$

$$\sum_{s\in S} y^e_{jsi} \le 1 \qquad \forall j\in B, i\in F, e\in E \tag{18}$$

$$\sum_{i\in F} h_i \le M \tag{19}$$

$$h_i = 0 \text{ or } 1 \qquad \forall i\in F \tag{20}$$

$$y^e_{jsi} = 0 \text{ or } 1 \qquad \forall j\in B, s\in S, i\in F, e\in E \tag{21}$$

$$a_j = 0 \text{ or } 1 \qquad \forall j\in B \tag{22}$$

$$z^e_{jst} = 0 \text{ or } 1 \qquad \forall j\in B, s\in S, t\in T, e\in E \tag{23}$$

$$x^e_p = 0 \text{ or } 1 \qquad \forall w\in W, p\in P_w, e\in E \tag{24}$$

$$c_l \in Q_1 \qquad \forall l\in L_1 \tag{25}$$

$$c_l \in Q_2 \qquad \forall l\in L_2 \tag{26}$$

$$c_l \in Q_3 \qquad \forall l\in L_3 \tag{27}$$

$$c_l \in Q_4 \qquad \forall l\in L_4\,. \tag{28}$$

The objective function is to minimize the total deployment cost of the wireless communication network, including cost of base stations, links, MTSOs, channels' license, etc. Constraints (1)-(2) are designed to ensure that the number of channels assigned to each antenna in the base station is large enough to serve its slave mobile terminals under certain call blocking rate. Constraint (3) is required to ensure that the coverage constrain is satisfied. Constraints (4)-(5) are to ensure that the number of channels assigned to each antenna in the base station is under its capacity. Constraint (6) is to ensure that for each channel, the sum of the interference introduced by other co-channel users is less than the threshold. Constraint (7) is to ensure that an antenna in the base station only can serve those mobile terminals that are in its coverage area of effective radius. Constraint (8) is to ensure that the transmission radius of each antenna in the base station range between 0 and R_{js}. Constraint (9) is to ensure that an antenna in the base station not provide any service if it is not assigned any channel. Constraint (10) requires that the aggregate flow of like l not exceed the capacity of link l at failure state e. Constraint (11) is to ensure that if an antenna does not provide service to a mobile terminal, the link between them not be selected as a part of routing path. Constraint (12) is to ensure that each OD pair would be transmitted at most on one path, because system would not have enough capacity to provide services on failure state e. Constraint (13) is to ensure that at most one base station could provide service to one mobile terminal. Constraint (14) is to ensure that the antennas in the same base station cannot provide service to the same mobile terminal. Constraint (15) is to ensure that a channel is installed before assigning the channel to a base station. Constraints (16)-(17) are required to ensure that each base station uses either omni-directional antenna or smart antennas. Constraint (18) is to ensure that the antennas in the same base station cannot be assigned the same channel. Constraint (19) is to ensure that the total number of channels required be no greater than the number of available channels. Constraints (20)-(24) are to ensure the integer property of the decision variables. Constraints (25)-(28) are to ensure that the capacity of each link be chose from a given set.

III. Lagrangean Relaxation

By using the Lagrangean relaxation method, we can transform the primal problem (IP2) into the following Lagrangean relaxation problem (LR2) where Constraints (1)-(4), (6)-(7), (9)-(11), and (15)-(18) are relaxed. For a vector of non-negative Lagrangean multipliers, a Lagrangean relaxation problem of IP2 is given below:

$$Z_{D2}\left(v^1_{jse}, v^2_{jse}, v^3_e, v^4_{jse}, v^5_{jsie}, v^6_{jste}, v^7_{jste}, v^8_{le}, v^9_{jstle}, v^{10}_{jsie}, v^{11}_{jsie}, v^{12}_{jie}, v^{13}_{jie}\right)$$

$$= \min \sum_{j\in B}\sum_{s\in S} \Delta^B_{js}(n_{js}) + \sum_{j\in B} \Delta^A_j(a_j) + \sum_{l\in L} \Delta^L_l(c_l) + \sum_{i\in F} \Delta^F_i h_i$$

$$+ \sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^1_{jse}\Big(\sum_{l\in L_5}\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p \text{¢}_{pl}\, {}^{a}{}_{ljs} - g^e_{js}\Big)$$

$$+ \sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^2_{jse}\Big(\text{¯}(g^e_{js},\ {}^{e}_{js}) - \sum_{i\in F} y^e_{jsi}\Big)$$

$$+ \sum_{e\in E} v^3_e\left(A^e - \frac{\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p}{\sum_{w\in W} k_w}\right) + \sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^4_{jse}\Big(\sum_{i\in F} y^e_{jsi} - n_{js}\Big)$$

$$+ \sum_{i\in F}\sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^5_{jsie}\Big(\sum_{\substack{j'\in B\\ j'\neq j}}\sum_{s'=S} (r^e_{j's'})^{\sim}\Phi_{jsj's'}\, y^e_{j's'i} - G_{js} - \Big(\frac{1}{\text{¥}} - G_{js}\Big) y^e_{jsi}\Big)$$

$$+ \sum_{t\in T}\sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^6_{jste}\big(D_{jt} z^e_{jst} - \text{«}_{jst} r^e_{js}\big)$$

$$+ \sum_{t\in T}\sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^7_{jste}\Big(z^e_{jst} - \text{«}_{jst}\sum_{i\in F} y^e_{jsi}\Big)$$

$$+ \sum_{l\in L-L_5}\sum_{e\in E} v^8_{le}\Big(\sum_{w\in W}\sum_{p\in P_w} k_w x^e_p \text{¢}_{pl} - \text{£}(c_l, \pm^e_l)\Big)$$

$$+ \sum_{l\in L_5}\sum_{t\in T}\sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^9_{jstle}\Big(\sum_{w\in W}\sum_{p\in P_w} x^e_p \text{¢}_{pl}\, {}^{a}{}_{ljs}\, {}^{\circ}{}_{lt} - z^e_{jst}\Big)$$

$$+ \sum_{i\in F}\sum_{j\in B}\sum_{s\in S}\sum_{e\in E} v^{10}_{jsie}\big(y^e_{jsi} - h_i\big) + \sum_{i\in F}\sum_{j\in B}\sum_{e\in E} v^{12}_{jie}\big(y^e_{js_0 i} - 1 + a_j\big)$$

$$+ \sum_{i\in F}\sum_{j\in B}\sum_{s\in\{s_1,s_2,s_3\}}\sum_{e\in E} v^{11}_{jsie}\big(y^e_{jsi} - a_j\big) + \sum_{i\in F}\sum_{j\in B}\sum_{e\in E} v^{13}_{jie}\Big(\sum_{s\in S} y^e_{jsi} - 1\Big)$$

subject to: (5), (6), (12)-(14) and (19)-(28). To solve (LR2), we can decompose (LR2) into the following eight independent and easily solvable optimization subproblems. According to the weak Lagrangean duality theorem [4], for any $v^1_{jse}, v^2_{jse}, v^3_e, v^4_{jse}, v^5_{jsie}$, $v^6_{jste}, v^7_{jste}, v^8_{le},\ v^9_{jstle}, v^{10}_{jsie}, v^{11}_{jsie}, v^{12}_{jie}, v^{13}_{jie} \ge 0$, Z_{D2} is a lower bound on Z_{IP2}. There are several methods for solving the dual problem, of which the subgradient method [5] is the most popular and is employed here. In iteration k of the subgradient optimization procedure, the multiplier vector ® is updated by ®^{k+1} = $\text{®}^k + t^k g^k$. The step size t^k is determined by $t^k = \text{¢}\left(Z^h_{IP2} - Z_{D2}(\text{®}_k)\right)/\left\|g^k\right\|^2$.

IV. Getting Primal Feasible Solutions

Using Lagrangean relaxation and the subgradient method as the basic approach to attack these problems, we can calculate theoretical lower bounds on the optimal objective function value of the primal problem and to utilize solutions to the Lagrangean relaxation problems and/or the corresponding Lagrangean multipliers to calculate primal feasible solutions [8], [9], [14]. Owing to the complexity of the primal problem, a divide-and-conquer strategy is adopted to obtain primal feasible solutions.

We divide this problem into three parts: (i) mobile terminals homing subproblem and base station configuration subproblem, including antenna type and power control; (ii) channel assignment subproblem; (iii) backbone network topology design subproblem and capacity assignment subproblem. In each subproblem, we provide some heuristics to get the primal feasible solution. The heuristics of the first and second subproblems are described in the accompanying paper. Detailed descriptions are omitted due to the length of the paper.

While solving the primal problem, we sought to find out some heuristics to improve our feasible solutions. In this part, we consider the value of each terminal z_{jst}, which is calculated when getting dual solutions. We use these values to determine the base station allocation subproblem and the mobile terminal homing subproblem. In this subproblem, we take "Difficulty Degree" [13] as our heuristics. According to our experiments, the "Difficulty Degree" calculated from dual problem is better than that calculated from primal problem.

In the third part, we take $\sum_{e\in E} v^8_{le}$ and its length for each link as its weight. Then, we use minimum cost spanning tree algorithm to select enough L_1 links to build a tree for routing. For each base station j, we chose the L_4 link, which has the minimum cost, as its candidate link. Then, we can calculate each routing path for each OD pairs on each scenario. According to the aggregate traffic of each link, we assign proper capacity to it under call blocking rate constraint. Repeat the above process to consider each network state to get several values of each link. We choose the maximum volume of capacity of each link, which is calculated on each network state, as our primal solution.

V. Computational Experiments

Owing to the complexity of this problem, it is unlikely to obtain tighter lower bound by solving dual problem. However, during the course of solving the dual problem, we could gain many hints to get the primal heuristics. To show that the proposed algorithm calculates good primal feasible solutions, we implement two simple algorithms for a comparison with the proposed one. In Section 4, we use some heuristics to determine the mobile terminals' homing subproblem. Contrarily, we use an intuitive thought to determine it in these simple algorithms. We assign each mobile terminal to be served by the base station that has the shortest distance between them. Additionally, we assume that omni-directional antenna will result in the lowest system cost. We then can easily determine z_{jst}. According to the slave mobile terminals in each base station, we can determine the radius of each base station. Then, we apply corresponding "Difficulty Degree" to solve channel assignment subproblem. In the topology design subproblem and capacity assignment subproblem, because we do not have any multiplier as our reference to determine the weight of each link, we merely adopt its length of each link as its weight. For convenience, we call this algorithm as SA1. Except the type of antenna in each base station, this algorithm almost looks like SA1. Here, we assume that smart antenna will result in the lowest system cost. In other parts of decision variables, we apply the same process in the SA1. For convenience, we call this algorithm as SA2.

We provide an algorithm related with Lagrangean relaxation based heuristics to solve this problem. The procedures are shown below:

Step 1. Read configuration file to construct MTSOs, BSs and MTs.
Step 2. Calculate constant parameters, like $c_{jsj's'}$, $«_{jst}$, $¯(n,B)$ and assign Lagrangean relaxation improve counter to equal 20.
Step 3. Initialize multipliers.
Step 4. According to given multipliers, optimally solve these problems of SUB3.1, SUB3.2, SUB3.3, SUB3.4, SUB3.5, SUB3.6, SUB3.7 and SUB3.8 to get the value of Z_{dual}.
Step 5. According to heuristics of Section 4, get the total cost of the wireless network design, the value of Z_{IP2} for all network states.
Step 6. If Z_{IP2} is smaller than Z_{IP2}*, we assign Z_{IP2}* to equal Z_{IP}. Otherwise, we minus 1 from improve counter.
Step 7. Calculate the step size and adjust the Lagrangean multipliers.
Step 8. Increase the iteration counter by 1. If the interaction counter is over the prespecified threshold, stop. And, Z_{IP2}* is returned as the best found primal objective function value. Otherwise, go to Step 4.

Algorithm LR2

In the computational experiments, the input parameters are set as follows: call blocking probability requirement of links = 1%; call blocking probability requirement of base stations = 3%; maximum number of channels that can be assigned to a base station = 120; fixed cost of an MTSO = 30,000,000 NT dollars; fixed cost of a base station = 5,000,000 NT dollars; fixed cost of a base station = 200,000 NT dollars; cost of a transponder (each can serve 8 channels) = 400,000 NT dollars; cost of licensing a channel = 200,000 NT dollars; unit wire connection cost = 300,000 NT dollars/km. In Case 1 3 MTSOs, 5 BSs, 40 MTs and 20 OD pairs are considered. The traffic demand for each OD pair is 1.5 Erlangs. The selections of transmission radius are 0.5 km, 1.5 km, 2 km, 3 km, 3.5 km and 4 km. In Case 2 3 MTSOs, 20 BSs, 40 MTs and 20 OD pairs are considered. The traffic demand for each OD pair is 1.5 Erlangs. The selections of transmission radius are 0.5 km, 1.5 km, 2 km, 3 km, 3.5 km and 4 km.

The first set of computational experiments is performed on Case 1. At the runs of 0 to 9, we randomly generate a pair of coordinates as the location of each mobile terminal. Each run is performed 500 iterations and the best calculated solution is reported. The solution of run 0 is shown in Figure 1 and comparison of each run is shown in Table 1. LR2 is the minimum value among the results of each iteration of LR2 algorithm by using *DDjs*(12). "Improvement over S1" is a measuring indicator, used to evaluate the quality of the proposed algorithm compared with SA1. The value is calculated to equal (S1-LR2)/LR2. "Improvement over S2" is also a measuring indicator, used to evaluate the quality of the propose algorithm compared with SA2. The value is calculated to equal (S2-LR2)/LR2. The fourth experiment is performed on Case 2. It is performed 500 iterations to get the best solution. The solution is shown in Figure 2. We can divide base stations into three groups. The first group is the major base station group. On non-failure scenarios, we only use these to serve each user. The second group is the backup group. When any base station of the major group fails, we need to use this group to meet our QoS requirement of each user by re-assigning channels and re-sizing radius. The last group contains those base stations that are not allocated. With these experiments, it is observed that the proposed algorithm can effectively and efficiently solve the BS allocation subproblem. In addition, the respective numbers of base stations installed in both sets of computational experiments are close.

VI. Summary and Conclusion

The model given in this report is hereby concluded in terms of formulation, reliability and performance. In terms of formulation, we model a mathematical expression to describe the fixed sectorization problem. At the same time, we consider not only non-uniform size cell but also non-uniform traffic demand. In this point, our model is more generic. Because of the complexity of this problem, we use Lagrangean relaxation and the subgradient method as the main methodology. When using these mathematical tools, they can provide us some hints to improve our heuristics. In terms of reliability, we try to allocate more resources. When any base station fails, we can dynamically re-allocate resources to provide equally good services. In terms of performance, the Lagrangean relaxation based approach is computationally shown to be significantly superior to a number of intuitional algorithms.

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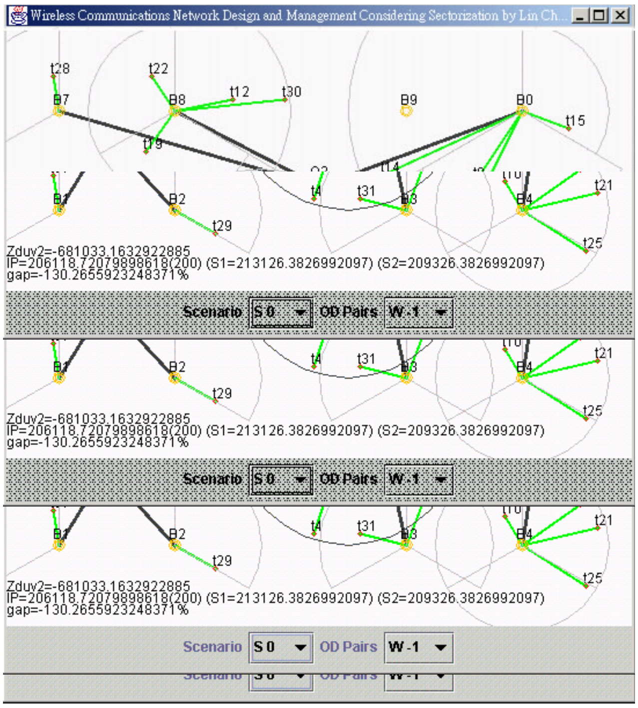
Run #	**0**	**1**	**2**	**3**	**4**
S1	212,726	184,283	208,526	183,958	204,068
S2	208,326	183,083	208,726	181,958	202,068
LR2	206,119	156,457	182,694	164,813	183,630
Impro. over S1 (%)	3.21	17.79	14.14	11.62	11.13
Impro. over S2 (%)	1.07	17.02	14.25	10.40	10.04
Run #	**5**	**6**	**7**	**8**	**9**
S1	190,288	189,088	158,289	181,283	178,235
S2	187,688	187,288	157,089	178,683	175,835
LR2	166,668	158,136	149,203	147,709	156,458
Impro. over S1 (%)	14.17	19.57	6.09	22.73	13.92
Impro. over S2 (%)	12.61	18.44	5.29	20.97	12.38

Table 1: The Result of Case 1

BS #	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
s_0	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a
s_1	U	U	U	U	B	U	B	U	U	B
s_2	U	U	U	U	B	U	B	U	U	B
s_3	U	U	U	U	B	U	U	U	U	U
BS	U	U	U	U	B	U	B	U	U	B
BS #	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
s_0	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a
s_1	B	P	U	U	P	B	P	P	P	P
s_2	P	P	U	U	P	B	P	P	P	B
s_3	P	P	U	U	U	B	P	P	P	P
BS	P	P	U	U	P	B	P	P	P	P

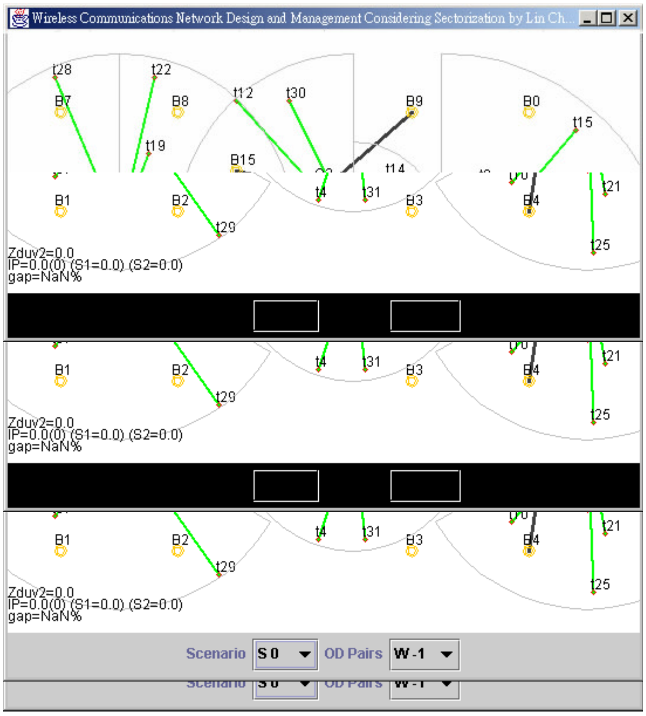
P: primary **B**: backup **U**: unused

Table 2: The Result of Base Station Allocation for Case 2



```
Wireless Communications Network Design and Management Considering Sectorization by Lin Ch...
Zduv2=-681033.1632922885
IP=206118.72079898618(200) (S1=213126.3826992097) (S2=209326.3826992097)
gap=-130.2655923248371%
```

Figure 1: Solution for Case 1 at Run 0



```
Wireless Communications Network Design and Management Considering Sectorization by Lin Ch...
Zduv2=0.0
IP=0.0(0) (S1=0.0) (S2=0.0)
gap=NaN%
```

Figure 2: Solution for Case 2