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A Discrete Optimization Model for Designing Cellular Networks Considering Electromagnetic Radiation

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*Abstract***—** *The boom in demand for mobile phone throughout the world is causing a constant increase in the BTS (Base Transceiver Station) number, particularly in Medan city. Such increase aims at achieve a better spatial frequency utilization to accomplish the growing number of users and services. However, the electromagnetic radiation (EMR) emitted from BTS are hazardous to human health. In this paper we address a linear mixed-integer programming model that combine the base station location problem, the frequency channel assignment problem and the base station connection to the fixed network considering the EMR. We solve the model using a feasible neighborhood search approach.*

Keywords— *Cellular network; base station location; frequency channel assignment; network design; EMR; feasible search*

I. Introduction

Mobile phone has become an icon for modern life of people around the world. It is not surprising that nowadays almost more than half of population of Indonesia own a mobile phone. The cellular system of mobile phone involves Base Transceiver Station (BTS) antenna ([33]). The main purpose of such antenna is to provide good connection between mobile users and telephone network through radio waves in the coverage area. Therefore the boom in demand for this kind of modern communication systems led to the increase the number of BTS. In Medan city, the capital of North Sumatra Province of Indonesia, for example, we can find more than 5000 BTS antennas. Consequently the locations of these antenna could be anywhere, such as, roof of houses and hospitals, residential complex, shopping mall, etc.

As there are many BTS involved in the cellular system, it is necessarily to design a topology of network configuration of such system. Accordingly there are three problems can be emerged [4] for designing the topology, i.e. BTS location (BTSL) problem, Frequency Channel Assignment (FCA) problem, and Topology Network Design (TND) problem.

Let $N = \{1, \ldots, n\}$ be a set of locations and $F \subseteq N$ be a set of candidate locations at which we may install BTS. Each location *j* in *N* has a particular call traffic demand. The problem in BTSL is to find *F* in such a way these BTS would be able to cover the entire system area with minimum cost. Choosing the best location site could reduce the number of BTS while still ensure a good quality of service to users. The problem for selecting particular locations comes under the heading of combinatorial optimization. In ([18], [4], [5], [6], and [22], used a mixed integer programming model to solve BTSL problem. In [12] proposed a mathematical programming model for the BTSL problem, and then they used genetic algorithm for solving the result model. In [29] used Invasive Weed Optimization to find the best location of BTS. While [14] used stochastic programming, in which they dealt with the expected user distributions for BTSL optimization.

As mentioned before that the demand for cellular communication is booming, particularly in Medan city. The rate of increase in the mobile phone usage has a serious consequence, the availability of the usable frequencies which are necessary for the communication between mobile users and the base stations of cellular radio networks has become outpaced. Careful design of a network is necessary to ensure efficient use of the limited frequency resources. One of the most important issues on the design of a cellular radio network is to determine a spectrum-efficient and conflict-free allocation of channels among the cells while satisfying both the traffic demand and the electromagnetic compatibility (EMC) constraints. This is usually referred to as channel assignment or frequency assignment problem (FAP)

FAPs first appeared in the 1960s ([34]). The development of new wireless services such as the first cellular phone networks led to scarcity of usable frequencies in the radio spectrum. Frequencies were licensed by the government who charged operators for the usage of each single frequency separately. This introduced the need for operators to develop frequency plans that not only avoided high interference levels, but also minimized the licensing costs.

As this is an assignment problem, it can be solved using combinatorial optimization model. Therefore the problem can be formulated as the problem of assigning frequency channels to the selected BTS subject to demand and frequency channel interference constraints. The objective function can vary according to the problem context. When the assignment is based on variable-size frequency spectrum, the objective usually intends to minimize the number of frequency channels used ([30], [36]). As demand for cellular communications is increasing, inference-free channel assignment may not exist for a given set of available frequencies. In this case, the objective is to minimize inference while satisfying demand within a fixed frequency spectrum ([1], [35]). Due to the structure of the problem, several heuristic approaches have been proposed for solving various version of the FAP, such as, Neural Networks ([8], [30], [26]), Genetic and Evolutionary Algorithms ([31], [13], [2], [3], [9]), Local Search techniques [15], Particle Swarm Optimization ([32], [27]), Ant Colony Optimization [28]. A good survey for FAP can be found in [1].

We already mentioned about where to locate BTS and then to design of a network which is necessary to ensure efficient use of the limited frequency resources. In order to make the mobile phone function as expected we need to design topology configuration to connect the candidate base stations to the fixed telephone network. This designing problem has been addressed in the literature as the topological network design (TND) problem ([11], [17]). As this is a problem to design a topology of configuration, then generally it belongs to the combinatorial optimization as well. This problem can be formulated as designing the network topology which is able to connect the candidate base stations to the fixed telephone network such that minimizing cost. Some of the features that can be considered in the problem formulation are the use of hubs, different kinds of media, and link capacities. The topological network design problem is a classical one that has already been explored in other network contexts, and generally it is an NP-hard problem.

Signal of electromagnetic field (EMF) emitted from BTS antenna could create Electromagnetic Radiation (EMR). These signal can cover up to 9 km distance from the BTS, depending to the power illuminated from the BTS. The number of BTS is heavily depend on the number of cellular users [7]. In Medan city, for example, there are seven mobile phone operators. As a consequence there are more and more people get electromagnetic radiated, particularly from the selected BTS location. [37], [38], [39] had made reports about the health effects for the people living near the BTS antenna. Therefore this paper concerns with more than just to design a topology of network configuration of cellular system, but also to include reducing the EMR impact. We aim to model what is called Cellular Topological Network Design (CTND) environmental friendly. We use power density factor to measure the EMR.

The cellular topological network design (CTND) is a very large scale combinatorial optimization problem which consists of the BTSL problem, the FCA problem and the TND problem. Therefore, the CTND is an NP-hard problem since the BTSL, FCA and TND problems are all NP-hard. It is easy to notice that the CTND problem can be solved separately or integratedly. Numerous mathematical programming formulations have been proposed to solve separately each one of these problems, as well as corresponding solution techniques. However, it seems intuitive that both the FCA and the TND problems depend on the BTSL problem solution, as well as their solutions. Previous computational analyses reported in [22] showed that there is a tradeoff between the BSL and FCA and between the BTSL and TND problems. In order to show these relations, the authors solved the CND problem for a small instance. The problem was solved both separately and integratedly.

This paper presents a linear mixed integer programming model to solve the cellular network design problem for second generation networks. We extend the model addressed by [24] by imposing a restriction distance between BTS at the selected location due to the effect of EMR to the people surrounding.

II. MATHEMATICAL MODELLING

The basic framework of the model to be formulated for cellular topological network design considering power density (CTND-PD). Model formulated in this paper is based on [24]. Nevertheless, they only integrated BTS location, The frequency channel assignment (FCA) and the network design in their model. They did not put into consideration about the effect of radiation caused by these BTS.

A. Power Density

This paper will also investigate the limiting exposures to harmful EMR levels around the BTS locations. There are, three numerical models can be used to find exclusion zones around the BTS of Global System of Mobiles (GSM), i.e., Far Field model, Cylindrical model, and Non-vanishing model [7]. These models calculate the power densities. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) the radiation emitted from BTS should be below the threshold of power densities in such a way the radiation is not harmful.

Using the far field model the power density ρ can be expressed as

$$\rho = \frac{PG}{4\pi R^2} \tag{1}$$

Where R is the distance of BTS, P is the power and G is the antenna gain. From the model we can say that the radiation illuminated from antenna is within a sphere with R as its radii. This model is valid only for the far field region defined by a distance greater than $2D^2/\lambda$ where D is the maximum dimension of the antenna and λ is the operating wavelength of the BTS. Minimum threshold value of the power density defines the limiting distance, which constitutes the exclusion zone where the power density is higher than the threshold value and there may exist risk of health hazard.

At the distance less than $2D^2/\lambda$ from the antenna point, which is very close to the BTS, the BTS cannot be assumed to be a point source and the illuminated area cannot be considered to be spherical. For a vertical collinear dipole antenna commonly used in cellular communication, this model considers a cylindrical area close to the antenna for estimating the power density. With this model, spatially averaged power density parallel to the antenna can be estimated by dividing the net antenna input power by the surface area of an imaginary cylinder surrounding the length of the radiating antenna. Then, the average value of the power density near the antenna array can be calculated as

$$\rho = \frac{P}{2\pi LR} \qquad (2)$$

where L is the length of the antenna length. For the GSM sector type antenna, the power density is given by

$$\rho = \frac{180P}{\theta_{BW}\pi LR} \qquad (3)$$

Where θ_{BW} is the azimuthal 3-dB beam width in degrees and has an azimuth angle φ with OX-direction. As the distance from the antenna increases, this model over predicts the exposure level due to the fact that the percentage of the total power radiated through the lateral surface of the cylinder decreases.

For the far field model, as R becomes smaller the spherical area of illumination becomes smaller and tends to be zero as R approaches zero, but in reality this behavior is not true since the physical dimension of the antenna is finite and nonvanishing. Such error can be eliminated by the following formulation.

$$\rho = \frac{PG}{4\pi(R^2 + \frac{G}{4\pi}wh)} \qquad (4)$$

where h and w are the height and width of the antenna respectively. And, the model is called Non-Vanishing model [7].

We can calculate the peak power density ([16], [25], [10]) using the expression

$$\rho^{Peak}(R,\varphi) = \frac{W_{rad}\, 2^{-(\varphi/\varphi_{3dB})^2}}{\varphi_{3dB} RL \sqrt{1 + 2(\frac{R}{\tau_0})^2}} \qquad (5)$$

Where $W_{rad} = \eta P_{in}$; with η is the efficiency of the antenna and P_{in} is the input power in the connector of the antenna.

$$\tau_0 = \frac{\varphi_{3dB}}{6} D_A L \qquad (6)$$

where D_A the direction of antenna.

The distance from BTS as a function of power density can be obtained from the expression ([16], [25], [10])

$$R^{Peak} = R(\rho^{Peak}) \approx \tau_0 \frac{2q}{\sqrt[4]{1 + (4q)^2}} \qquad (7)$$

The value of q can be calculated as follows.

$$q = \frac{3W_{Rad}\, 2^{-(\varphi/\varphi_{3dB})^2}}{\varphi_{3dB}^2 L^2 D_A \rho^{Peak}} \qquad (8)$$

In order to preserve healthy condition to the people who live nearby the BTS caused by the EMR of the BTS, it is necessarily to refine the selected BTS in such a way that the distance between BTS_i and BTS_j greater than R^{Peak}. From the expression of Eq. (7), it is easy to see that R^{Peak} is a function of power density ρ^{Peak}. Therefore we need the next definition.

Definition. In BTS location problem, forbidden location of BTS is defined as locations where BTS_j within the peak distance R^{Peak} of BTS_i ($i \neq j$).

B. The Model

Firstly we define the notation used.

Set

I : set of candidate base transceiver stations (BTSs)

J : set of hubs

K : set of switches

L : set of points of demand

M : set of frequency channels (FCs)

N^i : set of interfering BTSs to BTS i

F : Set of BTS in the forbidden location

Parameters

cost

α_i cost of installing the BTS i $\forall i \in I$

β_{ij} cost to connect the BTS i to the hub j $\forall i \in I, \forall j \in J$

γ_{ik} cost to connect the BTS i to the switch k

$\forall i \in I, \forall k \in K$

δ_{jk} cost to connect the hub j to the switch k

$\forall j \in J, \forall k \in K$

$\eta_{ii'}$ cost for removing BTS i to i'

$\forall i \in I, \forall i' \in I \; \& i' \notin F$

Other parameters

κ_i the maximum number of points that can be served by BTS i $\forall i \in I$

λ_i the maximum number of FCs that can be assigned to BTS i $\forall i \in I$

ρ_j the demand in number of communication channels of point l $\forall l \subset L$

σ the number of communication channels carried by a FC

d the minimum orthogonal frequency distance between adjacent FCs

ρ power density

$$\mu_{ij} = \begin{cases} 1 & \text{if BTS } i \text{ covers point } j \\ 0 & \text{otherwise} \end{cases}$$

$\forall i \in I, \forall l \in L$

and the binary variables are defined as:

$$y_i = \begin{cases} 1 & \text{if the BTS } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

$\forall i \in I$

$$q_{ij} = \begin{cases} 1 & \text{if the BTS } i \text{ is connected to the hub j} \\ 0 & \text{otherwise} \end{cases}$$

$\forall i \in I, i \notin F, \forall j \in J$

$$r_{ik} = \begin{cases} 1 & \text{if the BTS } i \text{ is connected to the switch k} \\ 0 & \text{otherwise} \end{cases}$$

$\forall i \in I, i \notin F, \forall k \in K$

$$u_{jk} = \begin{cases} 1 & \text{if the hub j is connected to the switch k} \\ 0 & \text{otherwise} \end{cases}$$

$\forall j \in J, \forall k \in K$

$$v_{im} = \begin{cases} 1 & \text{if the FC m is assigned to BTS } i \\ 0 & \text{otherwise} \end{cases}$$

$\forall i \in I, i \notin F, \forall m \in M$

Continuous variables

x_{il} the rate of covering for demand l served by BTS i

$\forall i \in I, \forall l \in L$

The values of x_{il} are between 0 and 1. $\forall i \in I, \forall k \in K$

Now we formulate the objective function .

In general, the objective of a network distribution problem is to minimize cost. Therefore, it would be the same for the case of the cellular topology network design considering power density (CTND-PD). The objective consists of the costs of installing BTS, the costs to connect the located BTS to the fixed telephone network and the costs for changing location of BTS due to the unfulfillment of power density threshold.

The costs of locating BTS can be formulated as : $C_1 = \sum_{i \in I} \alpha_i y_i$

Connection costs for each BTS selected to the hub can be written as : $C_2 = \sum_{i \in I} \sum_{j \in J} \beta_{ij} q_{ij}$ Connection costs for each BTS selected to the switch : $C_3 = \sum_{i \in I} \sum_{k \in K} \gamma_{ik} r_{ik}$

Connection costs from hub to the switch:

$C_4 = \sum_{j \in J} \sum_{k \in K} \delta_{jk} u_{jk}$

Removing cost of BTS from i to i':

$C_5 = \sum_{i \in I} \sum_{i' \in I, i' \notin F} \eta_{ii'} y_{ii'}$

The objective of the problem can be expressed as to minimize costs

$$Min\ z = C_1 + C_2 + C_3 + C_4 + C_5 \qquad (9)$$

C. Constraints

There are several constraints needed to be imposed in order to guarantee the feasibility of the BTSL, FCA and power density based cellular network design (PD-CND).

Firstly, we formulate the BTSL problem. As in the usual location problem it is necessary to guarantee that every point of demand is served by the antenna of BTS. In other words, we need to make sure that for the selected BTS is totally covered the demand, as long as the BTS is not in the forbidden location. The expression for this requirement can be formulated as follows.

$$\sum_{i \in I, i \notin F} \mu_{il} x_{il} \geq 1, \qquad \forall l \in L \qquad (10)$$

Furthermore, in the model we should guarantee that a candidate base station which is not selected must not serve any point of demand, and there must be an upper bound for the number of points to be served by a selected BTS. This condition is presented in (11)

$$\sum_{l \in L} \mu_{il} x_{il} \leq \kappa_i y_i, \ \forall i \in I \qquad (11)$$

The set L of points of demand represents the service area of the cellular network. The parameters μ_{il} represent the coverage area of each BTS. The variables x_{il} is defined as the rate of covering demand a point *l* which is served by a BTS *i*. If x_{il} = 1, the BTS *i* serves completely (100%) the demand of the the point *l*. If x_{il} varies between 0 and 1, the BTS *i* $(i \notin F)$ serves only part of the demand of the point *l*. For this case, Eq. (10) guarantees that another or other BTSs serve the remaining demand not served by *i*, noting that $i \notin F$. If x_{il} = 0, the point *l* is not served by the BTS *i*.

Secondly for the CTND problem. First we must guarantee the feasibility of the CTND problem. To fulfil this requirement in the model it is necessarily to make sure that all selected BTSs and the fixed network are well connected. Constraint (12) guarantees for all base stations that if a BTS i is selected $(i \notin F)$, it must be connected at least to a hub or switch, while the Eq. (13) guarantees for all hubs that if there is any selected BTS, which is not in the forbidden location, connected to a hub *j*, it must be connected at least to a switch.

$$\sum_{j \in J} q_{ij} + \sum_{k \in K} r_{ik} \geq y_i, \ \forall i \in I, i \notin F$$

(12)

$$\sum_{k \in K} u_{jk} \geq q_{ij}, \ \forall i \in I, i \notin F, \forall j \in J$$

(13)

Now for the Channel Assignment problem. The expressions (14) through (17) is to guarantee the feasibility of the problem which depends on channel interference, demand and capacity constraints. Eq. (14) states that adjacent frequency channels assigned to the same BTS are separated from each other by at least *d* orthogonal frequency channels. Expression (15) is to make sure that if a frequency channel *m* is assigned to a BTS *i*, it must not be assigned to any one of the BTSs belonging to the interfering set N^i. The interfering sets N^i define for each BTS i ($i \notin F$) the other BTSs that cause interference to its frequency channels. The Eq. (16) imposes that the number of frequency channels assigned to a BTS *i* is enough to serve the demand of the points served by that base station. We introduce parameter σ to define how many communication channels can be carried by a frequency channel. For FDMA technologies it is set to 1, while it can be set to 3 in case of some TDMA technologies. Finally, expression (17) guarantees that a frequency channel can be assigned to a BTS *i* $(i \notin F)$ only if the BTS is selected, and it still imposes a bound on the maximum number of frequency channels assigned to a BTS *i*.

$$\sum_{m=1}^{g+d} v_{im} \leq 1, \ \forall i \in I, i \notin F, \forall g \in \{1, \ldots, |M| - d\}$$

(14)

$$v_{im} + \sum_{g \in N^i} v_{gm} \leq 1, \ \forall i \in I, \ \forall m \in M$$

(15)

$$\sigma \sum_{m \in M} v_{im} \geq \sum_{l \in L} \rho_l x_{ij}, \ \forall i \in I$$

(16)

$$\sum_{m \in M} v_{im} \leq \lambda_i y_i, \ \forall i \in I \qquad (17)$$

Constraints (18) and (19) express the binary and continuous variables, respectively.

$$y_i, v_{im}, q_{ij}, r_{ik}, u_{jk} \in \{0, 1\}, \forall i \in I, \forall m \in M, \forall j \in J, \forall k \in K \qquad (18)$$

$$0 \leq x_{il} \leq 1, \qquad \forall i \in I, i \notin F, \forall l \in L,$$

(19)

III. The Algorithm

We adopt the approach of examining a reduced problem in which most of the integer variables are held constant and only a small subset allowed varying in discrete steps. (4)

The steps of the procedure can be summarized as follows.

Step 1. Solve the problem ignoring integrality requirements.

Step 2. Obtain a (sub-optimal) integer-feasible solution, using heuristic rounding of the continuous solution.

Step 3. Divide the set I of integer variables into the set I_1, at their bounds that were nonbasic at the continuous solution, and the set I_2, $I = I_1 + I_2$.

Step 4. Perform a search on the objective function, maintaining the variables in I_1 nonbasic and allowing only discrete changes in the values of the variables in I_2.

Step 5. At the solution in step 4, examine the reduced costs of the variables in I_1. If any should be released from their bounds, add them to the set I_2 and repeat from step 4, otherwise terminate.

It should be noted that the above procedure provides a framework for the development of specific strategies for particular classes of problems.

The integer results are kept in super basic variables set. Then we conduct an integer line search to improve the integer feasible solution [20].

(6)

IV. CONCLUSIONS

In this article, a solution approach to the NP-hard large scale cellular topological network design considering power density (CTND-PD) problem is proposed. The problem is formulated as a comprehensive linear mixed integer programming model including the base transceiver station location, the frequency channel assignment and the topological network design problems. We discard the locations of BTS which belong to the forbidden location.

We propose a feasible neighbourhood search approach for solving the model.

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