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- **Workshop:** Computer Networks
- **Title of this paper:** Reliable Wireless Communication Network Design Considering Customized Multiple-Connectivity
- **Short abstract:** In this paper, we identify reliability issue for channelized wireless communication networks. Due to the time variance and unstable properties of wireless communications, customized multiple-connectivity wireless networks are necessary for many kinds of high-reliability communications. By introducing generic communication QoS assurance and concurrent multiple connectivity routing mechanism, we can design a realistic and reliable wireless network. We formulate a combinatorial optimization algorithm to develop a generic wireless system, which is a multiple-sectorization, power controllable, customized multiple-connectivity, and communication QoS assurance network. We integrate long-term channel assignment and sequential routing mechanisms to en-sure communication grade of service (GoS) and improve spectrum utilization. The objective function of this formulation is to minimize the total cost of network system subject to configuration, capacity, k-connectivity, sequential homing, QoS and GoS constraints. The solution approach is Lagrangean relaxation. We also develop a Lagrangean-based heuristic to get primal feasible solutions.
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Reliable Wireless Communication Network Design Considering Customized Multiple-Connectivity

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Abstract

In this paper, we identify reliability issue for channelized wireless communication networks. Due to the time variance and unstable properties of wireless communications, customized multiple-connectivity wireless networks are necessary for many kinds of high-reliability communications. By introducing generic communication quality of service (QoS) assurance and concurrent multiple connectivity routing mechanism, we can design a realistic and reliable wireless network.

We formulate a combinatorial optimization algorithm to develop a generic wireless system, which is a multiple-sectorization, power controllable, customized multiple-connectivity, and communication QoS assurance network. We integrate long-term channel assignment and sequential routing mechanisms to ensure communication grade of service (GoS) and improve spectrum utilization. The objective function of this formulation is to minimize the total cost of network system subject to configuration, capacity, k-connectivity, sequential homing, QoS and GoS constraints. The solution approach is Lagrangean relaxation with divide-and-conquer algorithms.

I. INTRODUCTION

Due to the rapid growth of wireless applications in the world, the reliability property is become a critical issue for any uninterrupted communication system. One promising technique to overcome spectrum unstable property is multiple-connectivity. By specifying location-based customized multiple-connectivity requirement, network designer must well deploy base stations (BSs) and arrange spectrum resource to ensure individual connectivity requirement concurrently [8].

Cellular systems are generally recognized as spectrum-efficient by increasing the frequency allocation, sectorizing the cells, and resizing the cells [4]. In this paper, we adopt several resource allocation mechanisms, consist of channel assignment, power control and cell configuration design issues, to optimize spectrum utilization of wireless systems. For modeling generic architecture of realistic networks, we allow each base station can be constructed by any number of smart antennas, whose radians and transmission powers can be adjusted as needed.

Efficient spectrum utilization is one of paramount importance when designing high capacity cellular radio systems. The main idea behind channel assignment is to make use of radio propagation path loss characteristics and IF filter in order to minimize the carrier-to-interference ratio (CIR) and hence increase the radio spectrum reuse efficiency. In this paper, we integrate base stations (BSs) allocation, sectorization planning, channel assignment, and power control mechanisms to optimize frequency resource allocation problems. Efficient interference management aims at achieving acceptable carrier-to-interference ratio (CIR) in all active communication links and optimizing the system capacity. We accumulate co-channel interference (CCI), adjacent channel interference (ACI) and near channel interference (NCI) as total interference to evaluate communication QoS [2][7].

Furthermore, in order to ensure grade-of-service (GoS) and support real-time admission control, we pre-route each mobile terminal (MT) by location-based sequential homing mechanism. Sequential homing policies can cooperate with fixed channel assignment mechanism to arrange channel resource more efficiency and provide multiple-connectivity requirement [5][6].

We formulate the wireless network design and resource allocation problem as a combinatorial optimization problem, where the objective function is to minimize total cost of system subject to configuration, capacity, k-connectivity, sequential homing, QoS and GoS constraints. To the best of our knowledge, the proposed algorithm is the first attempt to consider the problem with whole factors jointly and formulate it rigorously. This kind of problems is by nature highly complicated and NP-complete. Thus, we apply the Lagrange relaxation approach and the subgradient method to solve this problem.

The remainder of this paper is organized as follows. Section II provides the problem description, the notation definitions and problem formulation. In Section III, we adopt Lagrangean relaxation as our solution approach to deal with this problem. We also develop several algorithms to optimally solve dual problem. Finally, the summary of this paper is in Section IV.

II. RELIABLE WIRELESS NETWORK DESIGN PROBLEM

A. Problem Description

In this chapter, we intend to establish a model to discuss an integrated wireless communication network design and resource allocation problem. We study how multi-configuration sectorization antennas, generic channel interference, and natural terrain-based radio propagation, will influence the performance of cellular system. Furthermore, we consider the effects of multiple-connectivity and sequential routing properties to enhance reliability of cellular networks. We develop a network design model to deal with BS installation, capacity allocation, channel assignment, power control, and sequential route problems. In order to satisfy the QoS level of requirement for each user in the network, we can adjust the configuration/sectorization of each BS, channel assignment policy, power level of each sector, and sequential homing policy of each MT to increase resource efficiency.

The system parameters are divided into six parts: (1) BS information (e.g. candidate base station (BS) locations, available configuration types, capacity limitations, and downlink power levels), (2) MT information (e.g. traffic demand, connectivity requirement and location), (3) system parameters (e.g. carrier-to-interference ratio (CIR) requirement, receiver sensibility, voice activity and call blocking rate), (4) resource properties (e.g. number of available channels and NFD ratio), (5) cost functions (e.g. channel license, antenna capacity and BS sectorization cost) and (6) propagation environments (e.g. topographical and morphographical data).

The objective of this formulation is to minimize the total cost of wireless communication network subject to: (1) capacity and configuration constraints of each BS, (2) generic channel interference and QoS constraints, (3) k-connectivity and sequential homing constraints, and (4) call blocking probability and receiver sensibility constraints for each MT. We develop several algorithms to determine total number of channels required, configuration/sectorization of each base station, transmission power of each sector, channel assignment plan of system, candidate homes of each MT, sequential homing policy, and average call blocking probability under k-connectivity constraints.

B. Notations

Table 1. Notations for given parameters.

Given Parameters	
Notation	**Descriptions**
A	The set of sector number $A \subset \{A_0, A_1, A_2, A_3, A_4, A_5\}$
T	The set of mobile terminals
C	The set of BSs in the system
M	The set of all kinds of sectorization and deployment types
S_t	The set of permutation for MT *t* which is integer value and $S_t = \{1,2,...,K_t\}$
W	Maximum number of available channels
G_{ja_m}	An arbitrarily large number for Sector a_m of BS *j*
K_t	Connectivity requirement of MT *t* to connect with K_t candidate homes
L_{tj}	Path loss ratio of radio propagation between BS *j* and MT *t*
α	Voice activity
δ	Receiver sensitivity of each MT (in Watt)
γ	Required CIR constraint

λ_t	The mean traffic arrival rate of MT $t \in T$ (in Erlang)
$\overline{\beta}_t$	Required grade of service (GoS) of MT t
$\overline{g_j}$	Upper bound of aggregate traffic for Sector a_m of BS j
$\overline{n}_{ja_m}$	Upper bound of channel number for Sector a_m of BS j
$\overline{p_j}$	Upper bound of transmission power of Sector a_m of BS j
$\overline{B}_{ts}$	Upper bound of call blocking probability for MT t on permutation s
$\underline{B}_{ts}$	Lower bound of call blocking probability for MT t on permutation s
$\overline{F}$	Upper bound of total number of required channels for system
$\underline{F}$	Lower bound of total number of required channels for system
$d(n_{ja_m}, g_{ja_m})$	Blocking probability function for Sector a_m of BS j, which is a Erlang-B formula of traffic demand and available number of channels.
$\theta(\Delta i)$	NFD ratio which is formed as a function of the channel separation normalized to the bit-rate
Δ_m	Configuration cost of BS sectorization type m
$\Delta_C\left(n_{ja_m}\right)$	Capacity cost function of equipments to assign n_{ja_m} number of channels
Δ_F	Spectrum frequency license fee

Table 2. Notations descriptions for decision variables.

Decision Variables	
Notation	**Descriptions**
c_{jm}	Decision variable of Sectorization type m for BS j
n_{ja_m}	Number of channels assigned to Sector a_m of BS j
p_{ja_m}	Effective isotropic radiated power (EIRP) of Sector a_m on BS j (in Watt)
g_{ja_m}	Aggregate flow on Sector a_m on BS $j \in C$ (in Erlangs)
k_{tja_m}	Decision function which is 1 if MT t can be served by Sector a_m of BS j and 0 otherwise
$x_{tja_m s}$	Homing decision variable which is 1 if Sector a_m of BS j is selected as the s^{th} candidate

	path of MT t and 0 otherwise
y_{ija_m}	Decision variable for channel assignment for Sector a_m of BS j about Channel i
f_i	Licensed channel
B_{ts}	Call blocking probability for the s^{th} candidate homing policy for t which belongs to discrete set $B_{ts} \in K_{ts} = \{0, 0.01, 0.02, ..., \overline{B}_{ts}\}$
b_{tja_m}	Blocking probability of Sector a_m on BS j which is referenced by MT t

C. Problem Formulation

Objective function (IP1):

$$Z_{IP1} = \min \sum_{j \in C} \sum_{a_m \in A} \Delta_C(n_{ja_m}) + \sum_{j \in C} \sum_{m \in M} \Delta_m c_{jm} + \sum_{i \in F} \Delta_F f_i \qquad \text{(IP1)}$$

subject to:

$$\prod_{s \in S} B_{ts} \le \overline{\beta}_t \qquad \forall t \in T \qquad (1)$$

$$\sum_{j \in C} \sum_{a_m \in A} x_{tja_m s} b_{tja_m} = B_{ts} \qquad \forall t \in T, s \in S_t \qquad (2)$$

$$d(n_{ja_m}, g_{ja_m}) = b_{tja_m} \qquad \forall t \in T, j \in C, a_m \in A \qquad (3)$$

$$\sum_{t \in T} \lambda_t \sum_{s \in S_t} \left(x_{tja_m s} \prod_{k=1}^{s-1} B_{tk} \right) = g_{ja_m} \qquad \forall j \in C, a_m \in A \qquad (4)$$

$$\gamma \le \frac{\frac{p_{ja_m}}{2L_{tj}} \left(y_{ija_m} + k_{tja_m} \right) + \left(2 - y_{ija_m} - k_{tja_m} \right) G_{ja_m}}{\sum_{j' \in C - \{j\}} \sum_{a'_m \in A} \left(\frac{p_{j'a'_m}}{L_{tj'}} \sum_{i' \in F} y_{i'j'a'_m} \theta(|i - i'|) \right)} \qquad \forall t \in T, i \in F, j \in C, a_m \in A \qquad (5)$$

$$k_{tja_m} \delta \le \frac{p_{ja_m}}{L_{tj}} \qquad \forall t \in T, j \in C, a_m \in A \qquad (6)$$

$$\sum_{j \in C} \sum_{a_m \in A} x_{tja_m s} = 1 \qquad \forall t \in T, s \in S_t \qquad (7)$$

$$\sum_{s \in S} x_{tja_m s} = k_{tja_m} \qquad \forall t \in T, j \in C, a_m \in A \qquad (8)$$

$$\sum_{j\in C}\sum_{a_m\in A} k_{tja_m} \geq K_t \qquad \forall t\in T \qquad (9)$$

$$\sum_{i\in F} y_{ija_m} = n_{ja_m} \qquad \forall j\in C, a_m\in A \qquad (10)$$

$$\sum_{a_m\in A}\left(y_{ija_m} + y_{(i+1)ja_m}\right) \leq 1 \qquad \forall i\in F, j\in C \qquad (11)$$

$$\sum_{i\in F} f_i \leq W \qquad (12)$$

$$y_{ija_m} \leq f_i \qquad \forall i\in F, j\in C, a_m\in A \qquad (13)$$

$$y_{ija_m} \leq c_{jm} \qquad \forall i\in F, j\in C, a_m\in A, m\in M \qquad (14)$$

$$p_{ja_m} \leq \overline{p}_{ja_m} \times \sum_{i\in F} y_{ija_m} \qquad \forall j\in C, a_m\in A \qquad (15)$$

$$\sum_{m\in M} c_{jm} = 1 \qquad \forall j\in C \qquad (16)$$

$$c_{jm} = 0 \text{ or } 1 \qquad \forall j\in C, m\in M \qquad (17)$$

$$y_{ija_m} = 0 \text{ or } 1 \qquad \forall i\in F, j\in C, a_m\in A \qquad (18)$$

$$x_{tja_ms} = 0 \text{ or } 1 \qquad \forall t\in T, j\in C, a_m\in A, s\in S_t \qquad (19)$$

$$k_{tja_m} = 0 \text{ or } 1 \qquad \forall t\in T, j\in C, a_m\in A \qquad (20)$$

$$f_i = 0 \text{ or } 1 \qquad \forall i\in F \qquad (21)$$

$$y_{(|F|+1)ja_m} = 0 \qquad \forall i\in F, j\in C, a_m\in A \qquad (22)$$

$$0 \leq p_{ja_m} \leq \overline{p}_{ja_m} \qquad \forall j\in C, a_m\in A \qquad (23)$$

$$0 \leq n_{ja_m} \leq \overline{n}_{ja_m} \qquad \forall j\in C, a_m\in A. \qquad (24)$$

The objective function is to minimize the total cost of wireless communication networks, such as costs of (1) fixed installation cost of base station *j*, (2) capacity equipment cost, and (3) the spectrum-licensing fee. These items are the major costs in involved in configuring a cellular network. Constraint (1) is the acceptable upper bound of call blocking probability requirement of each MT. Constraint (2) is for calculating the call blocking probability of MT t on the permutation *s*. Constraint (3) decomposes the call blocking probability of Sector j by introducing one additional notation b_{tja_m}. Constraint (4) calculates the aggregate traffic for Sector $j \in C$ under sequential routing effect. Constraint (5) ensures the CIR constraint for received radio QoS of every MT. Constraint (6) ensures receiver sensitivity of each MT *t* must be guarantee. Constraint (7) ensures at most one candidate homes of MT *t* can be select on permutation *s*. Constraint (8) enforces each candidate home must be selected on a permutation. Constraint (9) enforces the k-connectivity constraint of MT *t*. Constraint (10) calculates the total capacity of channels for each sector. Constraint (11) enforce adjacent channel must not be assigned to the same BS. Constraints (12) and (13) ensure the number of assigned channels is less than the total available channels. Constraint (14) ensures channel can be assigned only if this sector is deployed on BS *j*. Constraint (15) ensures transmission power can larger than zero only if we have assigned some channels on this sector. Constraint (16) enforces that only one sectorization type can be selected for each BS. Constraints (17) to (21) enforce the integer property of the decision variables c_{jm}, y_{ija_m}, x_{tja_ms}, k_{tja_m}, and f_i respectively. Constraint (22) limits boundary variable is not used. Constraints (23) and (24) enforce the feasible regions of decision variables p_{ja_m} and n_{ja_m}.

III. SOLUTION APPROACH

By using the Lagrangean Relaxation method [1], we can transform the primal problem (IP) into the following Lagrangean relaxation problem (LR) where Constraints (3), (4), (5), (8), (9), (10), (11), and (13) are relaxed:

A. Lagrangean Relaxation

For a vector of Lagrangean multipliers, a Lagrangean relaxation problem of IP1 is given by optimization problem (LR1):

$$Z_{LR1}\left(\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}\right)=$$

$$\min \sum_{j\in C}\sum_{a_m\in A}\Delta_C(n_{ja_m}) + \sum_{j\in C}\sum_{m\in M}\Delta_m c_{jm} + \sum_{i\in F}\Delta_F f_i$$

$$+\sum_{j\in C}\sum_{a_m\in A}\sum_{t\in T}\mu^1_{tja_m}\left(d(n_{ja_m}, g_{ja_m}) - b_{tja_m}\right) + \sum_{j\in C}\sum_{a_m\in A}\mu^2_{ja_m}\left(\sum_{t\in T}\lambda_t\sum_{s\in S_t}(x_{tja_m s}\prod_{k=1}^{s-1}B_{tk}) - g_{ja_m}\right)$$

$$+\sum_{j\in C}\sum_{a_m\in A}\sum_{i\in F}\sum_{t\in T}\mu^3_{tija_m}\left(\sum_{j'\in C-\{j\}}\sum_{a'_m\in A}(\frac{p_{j'a'_m}}{L_{tj'}}\sum_{i'\in F}y_{i'j'a'_m}\theta(|i-i'|)) - \frac{1}{\gamma}(\frac{p_{ja_m}}{2L_{tj}} - G_{ja_m})(y_{ija_m} + k_{tja_m}) - \frac{2G_{ja_m}}{\gamma}\right)$$

$$+\sum_{j\in C}\sum_{a_m\in A}\sum_{t\in T}\mu^4_{tja_m}\left(\sum_{s\in S}x_{tja_m s} - k_{tja_m}\right) + \sum_{t\in T}\mu^5_t\left(K_t - \sum_{j\in C}\sum_{a_m\in A}k_{tja_m}\right) + \sum_{j\in C}\sum_{a_m\in A}\mu^6_{ja_m}\left(\sum_{i\in F}y_{ija_m} - n_{ja_m}\right)$$

$$+\sum_{j\in C}\sum_{i\in F}\mu^7_{ij}\left(\sum_{a_m\in A}\left(y_{ija_m} + y_{(i+1)ja_m}\right) - 1\right) + \sum_{j\in C}\sum_{a_m\in A}\sum_{i\in F}\mu^8_{ija_m}\left(y_{ija_m} - f_i\right) \quad \text{(LR1)}$$

subject to: (1), (2), (6), (7), (12), (14), (15), (16), (17), (18), (19), (20), (21), (22), (23) and (24).

In this formulation, $\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}$ are Lagrange multipliers and $\mu^3_{tija_m}, \mu^5_t, \mu^7_{ij}, \mu^8_{ija_m} \geq 0$ are non-negative integers. To solve (LR1), we can decompose it into the following four independent optimization sub-problems.

Subproblem (SUB1): (related with decision variables B_{ts}, b_{tja_m}, and $x_{tja_m s}$)

$$Z_{SUB1} = \min \sum_{j\in C}\sum_{a_m\in A}\sum_{t\in T}\sum_{s\in S_t} x_{tja_m s}\left(\mu^2_{ja_m}\lambda_t \prod_{k=1}^{s-1} B_{tk} + \mu^4_{tja_m}\right) - \sum_{j\in C}\sum_{a_m\in A}\sum_{t\in T}\mu^1_{tja_m} b_{tja_m} \quad \text{(SUB1)}$$

subject to: (1), (2), (7), (19), and

$$\sum_{s\in S} x_{tja_m s} \le 1 \qquad \forall t\in T, j\in C, a_m \in A \quad (25)$$

$$\underline{B}_{ts} \le B_{ts} \le \overline{B}_{ts} \qquad \forall t\in T, s\in S_t, B_{ts}\in K_{ts} \quad (26)$$

$$0 \le b_{tja_m} \le 1 \qquad \forall t\in T, j\in C, a_m\in A. \quad (27)$$

Because multiplier $\mu^2_{ja_m}$ is not required to be positive, this formulation is a signomial geometric programming problem, which is more complexity and difficult than polynomial programming one. For dealing with this problem more efficiency, we constrain decision variable B_{ts} to a discrete limited set $K_{ts} = \{\underline{B}_{ts}, \underline{B}_{ts}+0.01, \underline{B}_{ts}+0.02, ..., \overline{B}_{ts}-0.01, \overline{B}_{ts}\}$ by introducing an additional Constraint (26) where notations $\underline{B}_{ts}$ and $\overline{B}_{ts}$ are a sensible lower bound and upper bound. According to experience, the upper bound $\overline{B}_{ts}$ is determined by (1) a artificial threshold: limit the blocking probability to a sensible upper bound of blocking probability (i.e. 20%) or (2) a worst case value: calculate the worst-case blocking probability by duplicate all of traffic from all of users and route to all of candidate homes. The lower bound $\underline{B}_{ts}$ can be determined by only routing the traffic of this MT to candidate home and than calculate the blocking probability.

With loss generality, we introduce Constraint (25) that is implied from Constraints (8) and (20) to keep physical meaning of decision variable $x_{tja_m s}$. As the discrete property of $x_{tja_m s}$ and B_{ts}, we can exhaustively search for all possible values of $x_{tja_m s}$ and B_{ts}. For improving dual solution quality, we introduce an additional Constraint (27) to limit decision variable b_{tja_m} in feasible region. Therefore, decision variable b_{tja_m} can be determined by the following statements,

$$b_{tja_m} = \begin{cases} 1, & \text{if } \sum_{s \in S_t} x_{tja_m s} = 0 \text{ and } \mu^1_{tja_m} \geq 0 \\ 0, & \text{if } \sum_{s \in S_t} x_{tja_m s} = 0 \text{ and } \mu^1_{tja_m} < 0 \\ B_{ts}, & \text{if } \sum_{s \in S_t} x_{tja_m s} = 1 \end{cases}$$

where the assignment purpose is to minimize the objective value under a given combinatorial situation of $x_{tja_m s}$ and B_{ts}. We can decompose this problem into $|T|$ independent sub-problems. Each subproblem solves the following problem (SUB1*t*),

$$Z_{SUB\,1t} = \min \sum_{j \in C} \sum_{a_m \in A} \sum_{s \in S_t} x_{tja_m s} \left(\mu^2_{ja_m} \lambda_t \prod_{k=1}^{s-1} B_{tk} + \mu^4_{tja_m} \right) - \sum_{j \in C} \sum_{a_m \in A} \mu^1_{tja_m} b_{tja_m}$$

subject to: (1), (2), (7), (19), (25), (26), and (27).

We can solve each subproblem by the following steps.

Step 1. Initial variable *minValue*=MAX_VALUE.

Step 2. Select one feasible set of blocking probability values, which satisfy the feasible region defined by Constraints (1) and (26), and assign to temporary set *tempSetB* for each permutation $s \in S_t = \{1,2,...,K_t\}$. Let $passedSector = \{\}$, and $remainingSector =$ $remainingSector = \{\text{all pairs of } (BSId, SectorId) \text{ in the system}\}$.

Step 3. Under a certain call blocking probability set, we arrange the homing decision variable $tempX_{tja_m s}$ in ascending order of its coefficient $\text{Coef}(x_{tja_m s})$ by fixing permutation, where

$$\text{Coef}\ (x_{tja_m s}) = \mu^2_{ja_m} \lambda_t \prod_{k=1}^{s-1} tempB_{tk} + \mu^4_{tja_m}.$$

Step 4. For each permutation $s \in S_t = \{1,2,...,K_t\}$, we assign the smallest $tempX_{tja_m s}$ to equal 1 if Sector (j, a_m) belongs to set $remainingSector$. To satisfy Constraints (7) and (25), we remove this sector (j, a_m) from set $remainingSector$ and insert it into the other set $passedSector$.

Step 5. For each sector (j, a_m), we assign $temp\_b_{tja_m}$ to equal $tempB_{ts}$ if Sector (j, a_m) belongs to set $passedSector$. We assign $temp\_b_{tja_m}$ to equal 1 if $\mu^2_{tja_m} \ge 0$ and 0 otherwise.

Step 6. Under this certain $tempSetB$, calculate the objective value by $tempMin = \sum_{j\in C}\sum_{a_m\in A}\sum_{s\in S_t} tempX_{tja_m s} \times \text{Coef}(x_{tja_m s}) - \sum_{j\in C}\sum_{a_m\in A}\mu^1_{tja_m} temp\_b_{tja_m}$. If $tempMin$ smaller than *minValue*, we assign $x_{tja_m s}$, b_{tja_m}, B_{ts}, and *minValue* to equal $tempX_{tja_m s}$, $temp\_b_{tja_m}$, $tempB_{ts}$, and $tempMin$, respectively.

Step 7. Go to Step 2 to exhaustively search other possible power set $tempSetB$.

Subproblem (SUB2): (related with decision variables g_{ja_m} and n_{ja_m})

$$Z_{SUB2} = \min \sum_{j\in C}\sum_{a_m\in A}\left(\Delta_C(n_{ja_m}) - \mu^2_{ja_m} g_{ja_m} - \mu^6_{ja_m} n_{ja_m} + \sum_{t\in T}\mu^1_{tja_m} d(n_{ja_m}, g_{ja_m}) \right) \quad \text{(SUB2)}$$

subject to: (24) and

$$0 \le g_{ja_m} \le \overline{g}_{ja_m} \qquad \forall j \in C, a_m \in A. \quad (28)$$

We add a redundant Constraint (28) to improve dual solution quality. We decompose this problem into $|C|\times|A|$ independent sub-problems. Each subproblem solves the following problem (SUB2ja_m),

$$Z_{SUB2\,ja_m} = \min \Delta_C(n_{ja_m}) - \mu^2_{ja_m} g_{ja_m} - \mu^6_{ja_m} n_{ja_m} + \sum_{t\in T} \mu^1_{tja_m} d(n_{ja_m}, g_{ja_m})$$

subject to: (24) and (28).

Because decision variable n_{ja_m} is a positive and limited integer, we can exhaustive search n_{ja_m} from zero to $\bar{n}_{ja_m}$. When give a certain value of n_{ja_m}, the call blocking probability term $d\left(n_{ja_m}, g_{ja_m}\right)$ is a convex function of decision variable g_{ja_m}. If multiple $\mu^1_{tja_m} \geq 0$, problem $Z_{SUB2\,ja_m}$ becomes a convex function. To minimize objective value, the optimal g_{ja_m} can be found by using line search technique (e.g. golden section method). Otherwise, if multiple $\mu^1_{tja_m} < 0$, problem $Z_{SUB2\,ja_m}$ becomes a concave function and the optimal solution will occurs either $g_{ja_m} = 0$ or $g_{ja_m} = \bar{g}_{ja_m}$. The upper bound $\bar{g}_{ja_m}$ can be determined by function $d\left(\bar{n}_{ja_m}, g_{ja_m}\right) = \bar{b}_{tja_m}$ where $\bar{b}_{tja_m}$ is an artificial probability threshold for MT *t* being blocked by its candidate home ja_m.

Subproblem (SUB3): (related with decision variables c_{jm}, k_{tja_m}, p_{ja_m}, and y_{ija_m})

$$Z_{SUB\,3} = \min \sum_{j\in C}\sum_{m\in M} \Delta_m c_{jm} - \sum_{j\in C}\sum_{a_m\in A}\sum_{t\in T} k_{tja_m}\left(\mu^4_{tja_m} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja_m}}{2L_{tj}} - G_{ja_m}\right)\sum_{i\in F}\mu^3_{tija_m}\right)$$

$$+ \sum_{j\in C}\sum_{a_m\in A}\sum_{i\in F} y_{ija_m} \sum_{t\in T}\left(\frac{\mu^3_{tija_m} G_{ja_m}}{\gamma} - \frac{p_{ja_m}}{L_{tj}}\frac{\mu^3_{tija_m}}{2\gamma} + \frac{p_{ja_m}}{L_{tj}} \sum_{j'\in C-\{j\}}\sum_{a'_m\in A}\sum_{i'\in F} \mu^3_{ti'j'a'_m}\theta(|i'-i|)\right)$$

$$+ \sum_{j\in C}\sum_{a_m\in A}\sum_{i\in F} y_{ija_m}\left(\mu^6_{ja_m} + \mu^7_{(i-1)j} + \mu^7_{ij} + \mu^8_{ija_m}\right) \quad \text{(SUB3)}$$

subject to: (6), (14), (15), (16), (17), (18), (20), (23), and

$$\sum_{i\in F} y_{ija_m} \leq \bar{n}_{ja_m} \qquad \forall j \in C, a_m \in A \qquad (29)$$

$$\mu^7_{0j} = 0 \qquad \forall j \in C, a_m \in A. \qquad (30)$$

Without loss generality, we add an additional constraint (29) to improve quality of solutions. To aggregate decision variable y_{ija_m}, we reformulate this subproblem by removing Constraint (22) and introducing an additional constraint (30).

Constraints (16) and (17) ensure that there is only one kind of sectorization can be deployed for each BS. Furthermore, Constraints (14) and (15) enforce that only the sectors belong to selected configuration type can be assigned channels and transmission power. Therefore, we decompose this problem into |*C*| independent subproblems (SUB3*j*) and exhaustive search any kind of configuration c_{jm} for each BS. After a temporary configuration $tempC_{jm}$ is determined, we can exhaustive search transmission power p_{ja_m} from zero to $\overline{p}_{ja_m}$.

Under this certain configuration combined with c_{jm} and p_{ja_m}, the remaining decision variables are y_{ija_m} and k_{tja_m}. We can decompose the remaining problem into |*A*| subproblems (SUB3*ja_m*) as follows.

$$Z_{SUB\,3\,ja_m} = \min\ -\sum_{t\in T} k_{tja_m}\left(\mu^4_{tja_m} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja_m}}{2L_{tj}} - G_{ja_m}\right)\sum_{i\in F}\mu^3_{tija_m}\right) + \sum_{i\in F} y_{ija_m}\left(\mu^6_{ja_m} + \mu^7_{(i-1)j} + \mu^7_{ij} + \mu^8_{ija_m}\right)$$

$$+\sum_{i\in F} y_{ija_m}\sum_{t\in T}\left(\frac{\mu^3_{tija_m}G_{ja_m}}{\gamma} - \frac{p_{ja_m}}{L_{tj}}\frac{\mu^3_{tija_m}}{2\gamma} + \frac{p_{ja_m}}{L_{tj}}\sum_{j'\in C-\{j\}}\sum_{a'_m\in A}\sum_{i'\in F}\mu^3_{ti'j'a'_m}\theta(|i'-i|)\right) \qquad \text{(SUB3}ja_m\text{)}$$

subject to: (6), (14), (15), (18), (20), (29) and (30).

For simplicity purpose, we denote the coefficients of k_{tja_m} and y_{ija_m} as $\mathrm{Coef}(k_{tja_m})$ and $\mathrm{Coef}(y_{ija_m})$ respectively. That is $\mathrm{Coef}(k_{tja_m}) = \mu^4_{tja_m} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja_m}}{2L_{tj}} - G_{ja_m}\right)\sum_{i\in F}\mu^3_{tija_m}$ and

$$\text{Coef}(y_{ija_m}) = \sum_{t \in T} \left(\frac{\mu^3_{tija_m} G_{ja_m}}{\gamma} - \frac{p_{ja_m}}{L_{tj}} \left(\frac{\mu^3_{tija_m}}{2\gamma} + \sum_{j' \in C - \{j\}} \sum_{a'_m \in A} \sum_{i' \in F} \mu^3_{ti'j'a'_m} \theta(|i' - i|) \right) \right) + \mu^6_{ja_m} + \mu^7_{(i-1)j} + \mu^7_{ij} + \mu^8_{ija_m} .$$

Therefore, we can arrange the contribution of each decision variable to minimize Subproblem (SUB3ja_m).

We can solve this subproblem (SUB3ja_m) by the following steps.

Step 1. Initial minValue=MAX_VALUE

Step 2. For solving (SUB3), we select one type of sectorization configuration for each BS and assign the correspond variable $tempC_{jm}$ to equal one.

Step 3. To solve (SUB3ja_m), we exhaust search any feasible transmission power level and assign to temporary variable $tempP_{ja_m}$ for each Sector (j, a_m).

Step 4. For homing purpose, we calculate $\text{Coef}(k_{tja_m})$ for each Sector (j, a_m) and sort $tempK_{tja_m}$ in descending order of $\text{Coef}(k_{tja_m})$.

Step 5. For minimizing objective value purpose, we assign $tempK_{tja_m}$ to equal one if $\text{Coef}(k_{tja_m}) \geq 0$ and Constraints (6) is feasible. Otherwise, we assign $tempK_{tja_m}$ to become zero.

Step 6. For channel assignment purpose, we calculate $\text{Coef}(y_{ija_m})$ for each channel i and arrange the channels in ascending order of $\text{Coef}(y_{ija_m})$.

Step 7. For minimizing objective value purpose, we assign $tempY_{ija_m}$ to one if $\text{Coef}(y_{ija_m}) < 0$ and $\sum_{i \in F} tempY_{ija_m} \leq \bar{n}_{ja_m}$. Otherwise, we assign $tempY_{ija_m}$ to zero.

Step 8. Calculate the temporary objective value under the power set *tempSetP* by

$tempMin = \sum_{i\in F}\left(tempY_{ija_m} \times \mathrm{Coef}(y_{ija_m})\right) - \sum_{t\in T}\left(tempK_{tja_m} \times \mathrm{Coef}(k_{tja_m})\right)$. If $tempMin$ smaller than $minValue$, we assign c_{jm}, k_{tja_m}, p_{ja_m}, y_{ija_m}, and $minValue$ to equal $tempC_{jm}$, $tempP_{ja_m}$, $tempY_{ija_m}$, $tempK_{tja_m}$, and $tempMin$, respectively.

Step 9. If there is any possible power level has not been tried, go to Step 3 to exhaustively search other possible power $tempP_{ja_m}$. Otherwise, go to Step 2 to try other configuration types.

Subproblem (SUB4): (related with decision variables f_i)

$$Z_{SUB\,4} = \min \sum_{i\in F} f_i\left(\Delta_F - \sum_{j\in C}\sum_{a_m\in A}\mu^8_{ija_m}\right) \quad \text{(SUB4)}$$

subject to: (12), (21), and

$$\underline{F} \le \sum_{i\in F} f_i \le \overline{F}. \quad (31)$$

According to experience, we intend to find the lower bound $\underline{F}$ and upper bound $\overline{F}$ of $\sum_{i\in F} f_i$ to improve efficiency and quality of both dual and primal solutions for this subproblem. Therefore, we enhance the effect of Constraint (12) by introducing additional Constraint (31). Upper bound $\overline{F}$ can be the smaller one between the capacity upper bound summation of every BS or the total available channels in the system. However, it is difficult to find tighter lower bound $\underline{F}$ in this subproblem. We develop a lemma for finding lower bound of required channels.

We can solve this problem by the following algorithm.

Step 1. Arrange the channels in ascending order of $\mathrm{Coef}(f_i) = \Delta_F - \sum_{j\in C}\sum_{a_m\in A}\mu^8_{ija_m}$.

Step 2. According to Constraint (31), if $\sum_{i \in F} f_i \le \underline{F}$, we assign f_i to equal one. If $\underline{F} < \sum_{i \in F} f_i \le \overline{F}$ and $\text{Coef}(f_i) \le 0$, we assign f_i to equal one. Otherwise, we assign f_i to equal zero.

B. The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem [GEOF 1974], for any $\mu^3_{tija_m}, \mu^5_t, \mu^7_{ij}, \mu^8_{ija_m} \ge 0$, $Z_{D1} = \max Z_{LR1}\left(\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}\right)$ is a lower bound on Z_{IP1}. The following dual problem (D1) is then constructed to calculate the tightest lower bound.

Dual Problem (D1):

$$Z_{D1} = \max Z_{LR1}\left(\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}\right)$$

subject to:

$$\mu^3_{tija_m}, \mu^5_t, \mu^7_{ij}, \mu^8_{ija_m} \ge 0$$

In this dual problem, let a ($|C| \times \{|A| \times [|T| \times (|F| + 2) + |F| + 2] + |F|\} + |T|$)-tuple vector g be a subgradient of problem $Z_{LR1}\left(\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}\right)$. In iteration k of the subgradient method [3], the multiplier vector $\pi = \left(\mu^1_{tja_m}, \mu^2_{ja_m}, \mu^3_{tija_m}, \mu^4_{tja_m}, \mu^5_t, \mu^6_{ja_m}, \mu^7_{ij}, \mu^8_{ija_m}\right)$ is updated by $\pi^{k+1} = \pi^k + t^k g^k$. The step size t^k is determined by $t^k = \delta \frac{Z^h_{IP1} - Z_{D1}(\pi_k)}{\left\|g^k\right\|^2}$, where Z^h_{IP1} is the primal objective function value from a heuristic solution (an upper bound on Z_{IP1}) and δ is a constant between zero and two.

IV. CONCLUSION

The proposed algorithm is the first attempt to consider the network design problem with whole factors jointly and formulate it rigorously. In this paper, we identify reliability issue of channelized wireless communications by introducing customized multiple-connectivity effect. The proposed algorithm not only designs a multiple-connectivity network but also guides to route MT among its candidate homes sequentially. Sequential routing mechanism can cooperate with fixed channel assignment to guide real-time admission control to improve GoS and maximize long-term revenues. Therefore, we integrate consider all of these problems together.

By introducing generic interference and propagation model, we can adopt any kind of propagation prediction models or practical radio measurements to evaluate cell coverage and ensure communication QoS [9]. That is the other critical part for this system to assign channels more efficient and design a realistic wireless network, which is multiple-sectorization, power controllable, customized multiple-connectivity, and communication QoS/GoS assurance.

We formulate a combinatorial optimization algorithm to deal with this problem by integrating long-term channel assignment and sequential routing mechanisms to ensure communication grade of service (GoS) and improve spectrum utilization. The objective function of this formulation is to minimize the total cost of network system subject to configuration, capacity, k-connectivity, sequential homing, QoS and GoS constraints. Because this problem is NP-complete, the solution approach we adopt is Lagrangean relaxation. Due to the time variance and unstable properties of wireless communications, the proposed algorithm is helpful to design high-reliability wireless communication networks.

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