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Cost optimization of integrated network planning based on adaptive sectorization in hybrid F/CDMA telecommunications system via Lagrangean relaxation

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ABSTRACT

In this paper, we investigate the integrated network planning for telecommunications system, which considers adaptive sectorization and a hybrid F/CDMA scheme jointly under quality of service (QoS) constraints. The problem is formulated as a combinatorial optimization formulation in terms of minimizing the cost. We also investigate the viability of using Lagrangean relaxation (LR) to solve the problem. With regard to the computational results, the cost of considering network error states in the planning stage is 45% more than that of non-error. The proposed LR approach outperforms a simple algorithm with a cost improvement of 60%. In addition, the link constraint is more important to the total cost than the node constraint. Given a link constraint, the cost is affected more significantly by a decreasing threshold than by an increasing threshold. The proposed model is not only a valuable reference for network planning in a new field (e.g., a desert scenario), but also fits the planning requirements when some equipment pre-exists (an embedded scenario). We assign constant values to several decision variables, so the model is adaptable to various scenarios.

1. Introduction

1.1. Challenges of integrated network planning

The use of wireless communications continues to experience dramatic growth. While voice services are now almost ubiquitous, wireless data applications have only recently gained momentum. The ongoing migration of voice services from wired to wireless systems, as well as the ever-increasing number of data applications, figure prominently in the drive toward fulfillment of code division multiple access (CDMA)-based 3G systems and beyond. Generally, wireless cellular network planning involves both wireline and wireless (radio) elements. Fig. 1 shows the system architecture of an integrated wireline/wireless network. In wireline networks, planning issues include mobile switching center (MSC) allocation, MSC interconnection, base station (BS) allocation or cell placement, BS configuration (cell sectorization), backbone topology, and traffic routing. The MSC serves as the access point for the wireless network to connect to the wireline backbone network. A number of wireless networks, i.e., radio access networks (RANs), are connected to the MSC. The coverage of a RAN consists of several cells, each of which is served by a BS. Since the backbone topology is a key factor in the routing problem, the backbone topology and the routing path for each origin–destination (OD) pair must be considered jointly. Meanwhile, in a wireless system, channel (spectrum) assignment, BS power control, and mobile station/mobile user (MS/MU, the two terms are used interchangeably hereafter) homing must be considered. For each MU, the BS is the first tier facility for accessing the network (RAN). Generally speaking, hundreds to thousands of users are covered/served by the BSs, so those users would be out of service if a RAN were to fail. Thus, network survivability is very important in the planning of RANs.

The survivability of telecommunication networks is a crucial issue for both service providers and end users. Actually, the problem of network survivability stems from network planning. The planning process can be categorized into the three phases: topological design, traffic routing, and circuit routing design in the transmission facility network (Medhi, 1994). In traffic routing, for example, the primary goal is to provide optimal capacity with quality of service (QoS) guarantees, while minimum-cost routing is primarily concerned with circuit routing design.

Network failures can occur as a result of natural disasters (floods, hurricanes, etc.), human actions (war, terrorism, hacker attacks) or the failure of software or control systems. The network must be designed for survivability, so that traffic can still be carried immediately after a failure. Efforts should focus on designing networks so that service can be maintained at a reasonable cost if there is a failure. A wireless or mobile network consists of a

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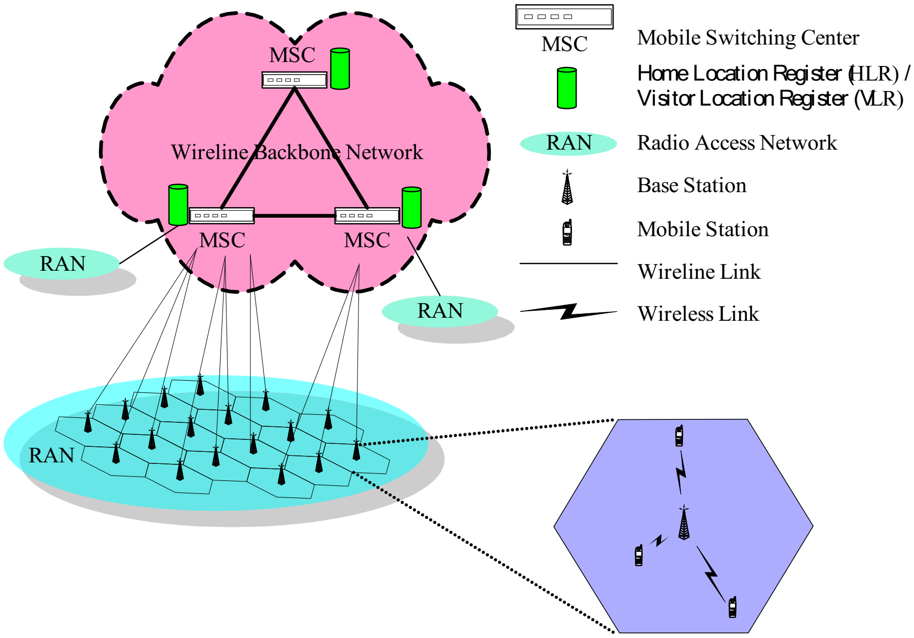


Fig. 1. System architecture of an integrated wireline/wireless network.

Table 1
The effects of wireless component failure and mitigation strategies.

Failure	Cause	Number of users affected	Time to fix	Ways to reduce the risk of failure	Time to fix after improvements
MSC	Hardware, software, operators	100,000	Hours to days	Spare components, extra power, smaller switches, Sonet ring, training	Seconds to minutes
HLR/VLR	Hardware, software	100,000	Hours to days	Replicated database, redundant components	Seconds to minutes
BS/BSC	Hardware, software, nature	$1000 \sim 20{,}000$	Hours to days	Overlay BS, redundant components, Sonet ring	Seconds to minutes
Device interface	Hardware	1	Hours to days	Multiple interfaces, access different wireless networks	Seconds to minutes

number of components, such as BSs, BS controllers (BSCs), MSCs, home location registers (HLRs) and visiting location registers (VLRs), signaling system 7 (SS7), and high-capacity trunks. A failure could involve one or more of these components, so survivability is also an important research issue in mobile wireless networks (Chuprun & Bergstrom, 1998; Snow, Varshney, & Malloy, 2000). The impact of a failure can be measured in terms of the number of users affected and the duration of the outage. Table 1 summarizes the effects of failures and the mitigation strategies applied in a wireless environment (Snow et al., 2000). To provide reliable and survivable wireless and mobile services, network providers must devise ways to reduce the number of network failures and ways to cope with failures when they do occur. In the scenario of BS failure, redundant components and overlaying BSs can be considered jointly in the network planning stage (Chu & Lin, 2006).

1.2. Approaches of capacity management

Call admission control (CAC) is a popular mechanism to admit as many users as possible so that the system benefit can be optimized (Chu, Wang, & Lin, 2010), while CAC-based adaptive channel reservation approach is proposed for priority soft handoff (Chu, Hung, & Lin, 2009). In addition, cell sectorization is widely used to increase system capacity in cellular systems. Basically, system capacity is considered as a multiple factor that is equal to the number of sectors. This is the case in an ideal antenna system, but due to the non-ideal antenna radiation pattern, the sectorization gain is smaller than the number of sectors in reality (Castañeda-Camacho, Uc-Rios, & Lara-Rodríguez, 2003; Wibisono & Darsilo, 2001). The gain is approximately 2.39 for a non-ideal antenna pattern (Castañeda-Camacho et al., 2003). Even if the cell is not uniformly sectorized, sectorization still helps increase the system capacity (Wibisono & Darsilo, 2001). However, many studies that evaluate the capacity of CDMA systems assume a uniform spatial traffic distribution, as it best fits CDMA's characteristics if all signals share the whole spectral resource (Liberti & Rappaport, 1994; Wu, Chung, & Sze, 1997). The whole bandwidth is divided equally among the cells, so that cells with the heaviest loads have the same frequency resources as any other cell. Nevertheless, uniformly distributed traffic among cells (equal cell loads) is very uncommon, especially in an urban environment, where the traffic distribution is usually non-uniform.

Although non-uniform traffic reduces the system capacity, very few works have considered the problem in conjunction with network planning (Tutschku & Tran-Gia, 1998; Wu et al., 1997). Even if sufficient capacity is planned, uneven/non-uniform (the two terms are used interchangeably hereafter) traffic distribution may occur in a cellular system, creating a "hot spot" that exceeds the pre-determined capacity and introducing a large call blocking probability. For non-uniform traffic distributions, adaptive sectorization is an effective way to maximize the network capacity (Lee, Kang, & Park, 2002; Saraydar & Yener, 2001). Sectors are rotated and resized adaptively to improve the system's performance when traffic is not uniformly distributed. These studies consider sectorization as a optimization problem. In Saraydar and Yener (2001), given the number of sectors and MS locations, the objective is to minimize the total power consumed by a cell, subject to QoS requirements. Meanwhile the sectorization problem is formulated as an integer linear programming model in which the objective is to minimize call blocking for handoff calls between cells in the same sector (Lee et al., 2002).

Although sectorization is widely used to increase system capacity, the communications quality expressed by the signal-to-interference ratio (SIR) differs between cells due to the diversity of the traffic distribution. The variance in communications quality degrades the efficiency of spectrum reuse by the whole system. A previous work on non-uniform traffic in CDMA (Takeo, Sato, & Ogawa, 1999) dealt with the imbalance of load levels among cells. When non-uniform traffic distribution occurs, it is desirable to reallocate the radio resources to allow all cells to carry the desired amount of traffic. Since the ability to accommodate the expected growth in traffic and broadband services is limited by the scarce radio spectrum, it is necessary to design a more spectral efficient technique, such as spectrum resource management. In Zhuge and Li (2002, 2003), capacity analysis in multi-band overlaid CDMA is proposed as a way to maximize spectrum utilization. More specifically, the multi-band spectrum is used to meet heterogeneous requirements. Combining traditional FDMA with CDMA is an alternative strategy that mitigates interference moderately. Kim and Prabhu (1998) show that the current frequency reuse factor of 1 is not always optimal. Meanwhile, the results in Hamidian and Payne (1997) demonstrate that it is possible to increase cell capacity without deploying additional cells by applying proper FDMA frequency reuse to minimize interference. In addition, the adaptive sectorization scheme is also applied to balance the system load in a scenario of non-uniform distributions.

1.3. Complexity of integrated network planning

Mobile network planning involves a sequence of tasks starting from coverage analysis and ending with channel assignment. We need to determine the amount of network equipment (e.g. MSCs, BSs) required and find suitable placements for the different components. Effective planning has a significant impact on costs and the quality of service (QoS), as the operator has to assign channels to the BSs such that QoS is guaranteed. Even though cell planning is a basic task, it is subject to several constraints (Merchant & Sengupta, 1995; Pierre & Houeto, 2002). In addition, network planning requires a large number of algorithms, each of which focuses on a problem with specific constraints. A quite common task is the necessity to trade-off all design objectives against each other, while respecting their individual importance. Thus, integrated network planning becomes a combinatorial optimization problem comprised of several issues, such as network planning (Ali, 2002; Garg, Simha, & Xing, 2002; Hao et al., 1997; Tutschku, 1998), survivability requirements (Ghashghai & Rardin, 2002), and channel assignment (Duque-Anton, Kunz, & Ruber, 1993; Wang & Rushforth, 1992), which are NP-complete or NP-hard.

Since the network planning problem is NP-complete, its solution is difficult, even if we succeed in formulating the planning problem as an optimization task. Although there has been a great deal of research into exact algorithms that work for small- and medium-size problems, the proposed solutions for large-scale problems are only approximations. Model developers must make a lot of important planning decisions by deciding which aspects to include in a model and which aspects to leave out. As a result, developing a very accurate model or trying to reach the exact optimum is not a very practical goal. It can even be risky because, when a network is optimized very tightly to achieve one goal, typically profit, it might be expensive to adapt the network to changing needs. Therefore, instead of trying to find optimal solutions, planning models should allow the user to understand a network's behavior and trade-offs better.

For most problems, there is no known algorithm that guarantees finding a global optimum in polynomial time. In many cases, sophisticated heuristics have to be developed to achieve satisfactory results. The exact solution is practically impossible to achieve due to an exponentially growing calculation time. Moreover, existing heuristics do not guarantee convergence to a truly global optimal solution, and the use of non-global optimal solutions would probably lead to significant unwarranted costs in network planning.

Traditional planning models that use 2G cellular systems are not suitable for 3G systems, since they do not consider QoS, power control, or traffic diversity (Amaldi, Capone, & Malucelli, 2003). Thus, the planning model for CDMA-based 3G networks should be further developed. Generally, the objective of cell planning in cellular networks is to determine the number of BSs, the location and capacity of each BS, and the BS configurations with given constraints, such as budget, cell capacity, traffic, and maximum allowable interference. Most studies have dealt with network planning issues by using optimization models, and several algorithms have been proposed to solve such models. For example, Tabu search is used to determine the number and location of BSs in Amaldi et al. (2003); Lee and Kang (2000); simulated annealing is employed for site selection and BS configuration in Hurley (2002); neural/fuzzy networks are used to find the optimal BS locations and for automatic BS placement and dimensioning in Binzer and Landstorfer (2000); Huang, Behr, and Wiesbeck (2000); and non-exhaustive search algorithms are applied to determine the optimal locations for BSs in Bose (2001). Another study (Hanly & Mathar, 2002) proposes using an analytical model to determine the minimal BS density, subject to the outage probability threshold. The model is formulated as a function of traffic intensity and MUs are randomly distributed according to a two-dimensional Poisson point pattern.

Although there has been extensive research on different network planning issues, there are relatively few works in the literature that deal with the overall planning and management problem in an integrated manner. Previous studies of CDMA planning have focused on cell arrangements (Amaldi et al., 2003; Hanly & Mathar, 2002), and did not consider sectorization and spectrum resource allocation. In this paper, we build an integrated network planning model that considers adaptive sectorization with a hybrid F/CDMA scheme jointly under QoS constraints, and investigate the scenario of BS failure/error.

The remainder of this paper is organized as follows. In Section 2, we describe the hybrid F/CDMA scheme, based on which the associated SIR models are formulated. Section 3 describes the proposed integrated model for network planning as well as the solution approach. In Section 4, we discuss the computational experiments. Section 5 contains some concluding remarks.

2. The SIR models

2.1. Hybrid F/CDMA scheme

In the hybrid F/CDMA scheme (HFCS) (Eng & Milstein, 1994), the available wideband spectrum is divided into a number of subspectra with smaller bandwidths. Each subspectrum employs direct sequence (DS) spectrum spreading with a reduced processing gain, which is transmitted in one and only one subspectrum. We assume that BW_{WHOLE}, which is the whole frequency bandwidth on both the uplink (UL – from the MS to the BS) and the downlink (DL – from the BS to the MS), consists of a number of

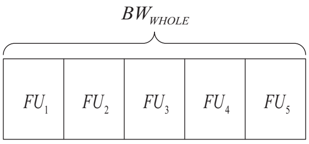


Fig. 2. An example of bandwidth decomposition.

Table 2
The FSs in the above example.

FS I.D.	Combination of FUs	FS I.D.	Combination of FUs	FS I.D.	Combination of FUs
1	(1)	6	(1,2)	11	(2,3,4)
2	(2)	7	(2,3)	12	(3,4,5)
3	(3)	8	(3,4)	13	(1,2,3,4)
4	(4)	9	(4,5)	14	(2,3,4,5)
5	(5)	10	(1,2,3)	15	(1,2,3,4,5)

frequency units (FUs). Each FU has a bandwidth BW_{FU}. We denote the set of FUs as F_U, then $|F_U| = BW_{WHOLE}/BW_{FU}$. Furthermore, several frequency segments (FSs) from consecutive FUs can be combined, and we denote the set of FSs as F_S. For example, if the bandwidth allocated to the DL is decomposed into five FUs, $|F_U| = BW_{WHOLE}/BW_{FU} = 5$ (as shown in Fig. 2), the FSs can be categorized into five groups based on the FS length. The notation (•) represents the FS and the notation • represents the FU. Based on $F_U = \{1, 2, 3, 4, 5\}$, $F_S = \{(1), (2), (3), (4), (5), (1,2), (2,3), (3,4), (4,5), (1,2,3), (2,3,4), (3,4,5), (1,2,3,4), (2,3,4,5), (1,2,3,4,5)\}$; thus, the total number of FSs is $|F_S| = |F_U| \times (|F_U| + 1)/2 = 5 \times 6/2 = 15$. The FSs and their IDs are enumerated in Table 2. The capacity of the HFCS is calculated as the sum of the capacities of the subspectra.

2.2. SIR models

When performing sectorization, we denote K as the set of sector configurations and S as the set of sector candidates; the sector candidate $s_{k,i}$ is defined by both the sector configuration ($k \in K$) and the sector identity (i). For simplicity, we substitute s for $s_{k,i}$, and denote sector$_{js}$ as the sector s in BS j ($s \in S_k, j \in B$), where B is the BS set (Chu, Lin, & Wang, 2010). Assume that both the UL and the DL have the same number of FSs, i.e., the same $|F_S|$. We then further define SIR models with the HFCS. For example, on the UL, we denote y_{js} as the decision variable (DV), which is m if sector$_{js}$ deploys FS m, $m \in F_S$. Thus, the bandwidth allocated to the UL and the DL is calculated by (1) and (2), respectively, where $L(y_{js})$ is the length of FS m. The indicator function, $\Psi(y_{js}, y_{j's'})$, of interference from sector$_{js}$ using FS $y_{js} = m$ to sector$_{j's'}$ using FS $y_{j's'} = m'$, can be pre-calculated.

$$W^{UL}_{js} = L(y_{js}) \cdot BW^{UL}_{FU} \quad \forall j \in B,\ s \in S, \tag{1}$$

$$W^{DL}_{js} = L(y_{js}) \cdot BW^{DL}_{FU} \quad \forall j \in B,\ s \in S. \tag{2}$$

To better describe the calculation of the indicator function $\Psi(y_{js}, y_{j's'})$, Fig. 3 illustrates the mutual interference between FSs.

We denote L_m as the length of FS m, and let H_m and T_m be the beginning and ending FUs of FS m, respectively. Then, $L_m = |T_m - H_m + 1|$, and $\Delta = |T_m - H_{m'} + 1|$ is the degree of overlap between FS m and FS m'. In addition, we denote $I_{m,m'} = \Psi(y_{js}, y_{j's'})$ and $I_{m',m} = \Psi(y_{j's'}, y_{js})$ as the interference between FS m and FS m' and between FS m' and FS m, respectively. To calculate $I_{m,m'}$ and $I_{m',m}$, we only focus on segment Δ, since the residual part I_{Δ_m} of I_m and the residual part $I_{\Delta_{m'}}$ of $I_{m'}$ will not interfere with each other. Thus, the interference strength of length Δ of FS m will be converted into the interference strength $I_{m,m'}$ with length $L_{m'}$ in (3), so we get $I_{m,m'}$ in (4). The calculation of $I_{m',m}$ is similar to that of $I_{m,m'}$, and is defined in (5) and (6).

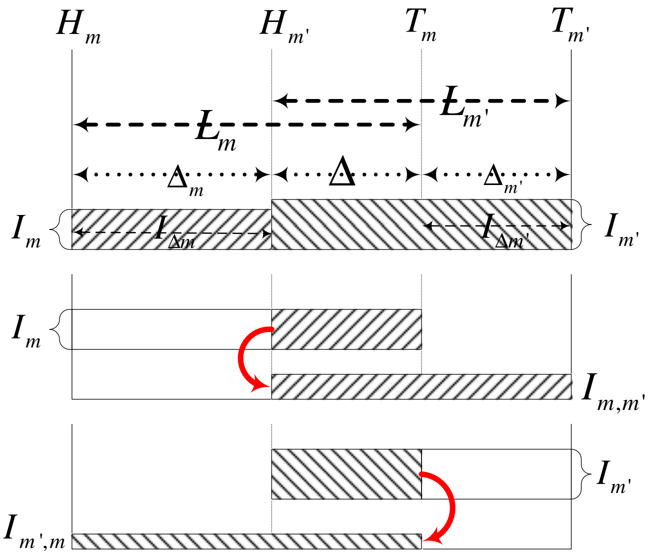


Fig. 3. Mutual interference between FSs.

$$\Delta = L_{m'} \cdot I_{m,m'} \tag{3}$$

$$I_{m,m'} = \frac{\Delta}{L_{m'}} \tag{4}$$

$$\Delta = L_m \cdot I_{m',m} \tag{5}$$

$$I_{m',m} = \frac{\Delta}{L_m} \tag{6}$$

To express the SIR models effectively when HFCS is combined with sectorization, we simplify the inter-cellular and intra-cellular interference in the worst case, where the MSs are located near a cell boundary. Fig. 4 shows an interference scenario in which the UL interference in the reference BS received from the MSs in the interfering BS is maximal; and the DL interference of the MSs received from the interfering BS is also maximal. We denote a^e_j as a DV, which is 1 if BS j is active in network state e, and 0 otherwise; q^e_{jsc} is a DV, which is the number of aggregate channels required in sector$_{js}$ for traffic class-c in network state e. The SIR $SIR^{UL}_{js,c(t)}$ in the UL is defined in (7), where the intra-cellular $I^{UL}_{jst,intra}$ and inter- cellular $I^{UL}_{jst,inter}$ interference can be further expressed by (8) and (9), respectively. Eq. (9) considers the effect of both inter-sector and inter-FS interference.

$$\begin{aligned} SIR^{UL}_{js,c} &= \frac{W^{UL}_{js}}{d^{UL}_{c(t)}} \cdot \frac{P^{UL}_c + \left(1 - a^e_j\right)V}{(1-\rho^{UL})I^{UL}_{jst,intra} + I^{UL}_{jst,inter}} \\ &= \frac{L\left(y^e_{js}\right) \cdot BW^{UL}_{FU}}{d^{UL}_{c(t)}} \cdot \frac{P^{UL}_{c(t)} + \left(1 - a^e_j\right)V}{(1-\rho^{UL})I^{UL}_{jst,intra} + I^{UL}_{jst,inter}} \end{aligned} \tag{7}$$

$$I^{UL}_{jst,intra} = \sum_{c' \in C} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{jsc'} - \alpha^{UL}_c P^{UL}_c \tag{8}$$

$$I^{UL}_{jst,inter} = \sum_{\substack{j' \in B \\ j' \neq j}} \sum_{\substack{s' \in S \\ s' \neq S}} \sum_{c' \in C} \Omega^{UL}_{j's'js} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{j's'c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{j's'}} \right)^{\tau} \Psi\left(y^e_{j's'}, y^e_{js}\right) \tag{9}$$

For the DL connection, the SIR models are expressed in (10)–(12).

$$I^{DL}_{jst,intra} = \sum_{c' \in C} \alpha^{DL}_{c'} P^{DL}_{c'} q^e_{jsc'} - \alpha^{DL}_c P^{DL}_c \tag{10}$$

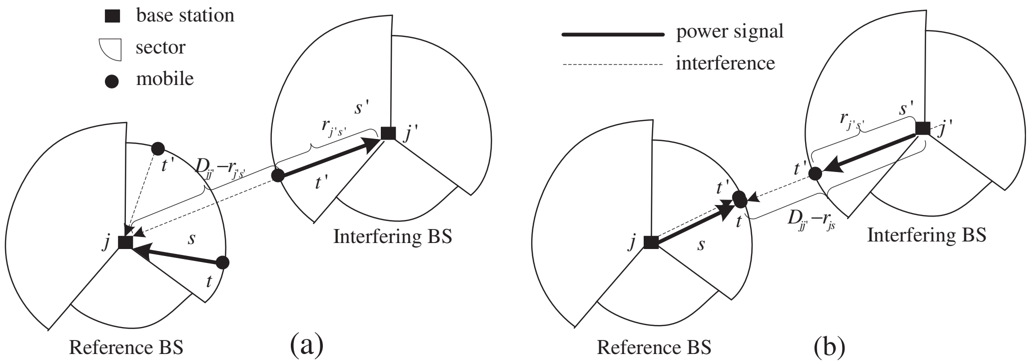


Fig. 4. An interference scenario: (a) UL interference and (b) DL interference.

$$I^{DL}_{jst,inter} = \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{s'\in S\\ s'\neq S}} \sum_{c'\in C} \Omega^{DL}_{j's'js} \alpha^{DL}_{c'} P^{DL}_{c'} q^{e}_{j's'c'} \left(\frac{r^{e}_{j's'}}{D_{jj'} - r^{e}_{js}}\right)^{\tau} \Psi\left(y^{e}_{j's'}, y^{e}_{js}\right) \qquad (11)$$

$$SIR^{DL}_{js,c} = \frac{L(y_{js})\cdot BW^{DL}_{FU}}{d^{DL}_{c(t)}} \cdot \frac{P^{DL}_{c} + (1 - z_{jst})V}{(1-\rho^{DL}) I^{DL}_{jst,intra} + I^{DL}_{jst,inter}} \qquad (12)$$

3. The network planning model

3.1. Problem formulation

The problem of integrated network planning is investigated in terms of the following subproblems (Wu et al., 1997): (i) BS allocation and configuration; (ii) network topology, traffic routing, and cell capacity management; (iii) MS homing (call admission control) and channel assignment; (iv) power transmission radius control; and (v) bandwidth allocation. In this paper, the network plan is treated as an embedded system in which a lot of equipment preexists or is reused from previous networks. Thus, the capacity of the MSC nodes and transmission links may be constrained. The overall concept of the problem is shown in Fig. 5, and Table 3 lists the notations used in the formulation.

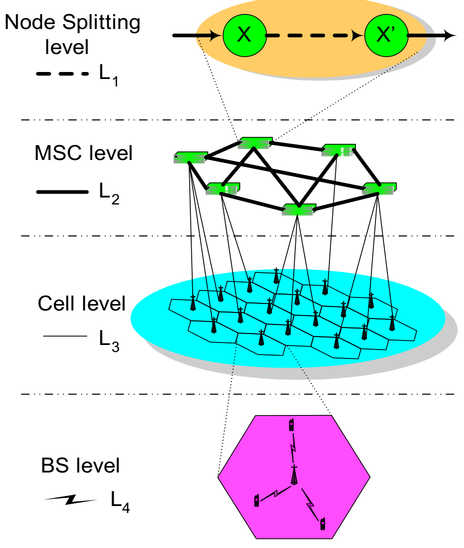


Fig. 5. The levels of the integrated network planning problem.

Table 3
Notations used for the integrated network planning problem.

Notation	Description
$\Omega^{dir}_{jsj's'}$	Indicator function of interference in direction *dir* from sector$_{js}$ to sector$_{j's'}$
β^{e}_{jsc}	Call blocking probability threshold of traffic class-*c* in sector$_{js}$ in state *e*
ε^{e}_{lc}	Call blocking probability threshold of traffic class-*c* on link *l* in state *e*
χ_{lt}	Indicator function, which is 1 if MS *t* is an end of link *l*
$\Psi(y_{js}, y_{j's'})$	Indicator function of interference from sector$_{js}$ using FS y_{js} to sector$_{j's'}$ using FS $y_{j's'}$
φ_l	Capacity threshold of link *l*
Δ_B	Cost of BS installation
Δ_k	Cost of sector configuration
$\Delta_l(c_l)$	Cost of link with traffic c_l
ϕ_{ljs}	Indicator function, which is 1 if sector$_{js}$ is an end of link *l*, and 0 otherwise
Δ_m	Cost of bandwidth allocation
δ_{pl}	Indicator function, which is 1 if link *l* belongs to path *p*, and 0 otherwise
$A_{c(o)}$	Traffic intensity of OD pair *o* with traffic class $c(o)$
E	The set of base station (BS) states {normal, failure/error}
F_S	The set of FSs
F_U	The set of FUs
L	The set of links $L = L_1 \cup L_2 \cup L_3 \cup L_4$
L_1	The set of links between two split nodes for all MSCs
L_2	The set of links between two MSCs
L_3	The set of links between an MSC and a BS
L_4	The set of links between a BS and an MS
$LB_{lc}(\cdot)$	CBP of Kaufman's model for traffic class-*c* on link *l*
$L(y_{js})$	The length and multiple value of BW_{FU}, of FS indicated by y_{js}
n^{e}_{lc}	The number of channels required on link *l* for traffic class-*c*
n_l	The total number of channels allocated to link *l*
O	The set of OD pairs
P_O	The set of paths for OD pair *o*
$q_{c(o)}$	The number of channels required for OD pair *o* with traffic class $c(o)$
q_{js}	The total number of channels allocated in sector$_{js}$
R_{js}	UB on the radius of the power transmission in sector$_{js}$
$SB_{jsc}(\cdot)$	CBP of Kaufman's model for traffic class-*c* in sector$_{js}$
$SIR^{dir}_{js,c(t)}$	SIR value for MS *t* in sector$_{js}$ in direction *dir*
u^{e}_{jst}	Indicator function, which is 1 if MS *t* is covered by sector$_{js}$ in state *e*, and 0 otherwise
VG^{e}_{js}	A vector of the aggregate traffic intensity in sector$_{js}$, $VG^{e}_{js} = \left\{g^{e}_{jsc_1}, g^{e}_{jsc_2}, \ldots, g^{e}_{jsc_{\lvert C\rvert}}\right\}$
VM^{e}_{js}	A vector of the channels required in sector$_{js}$, $VM^{e}_{js} = \left\{q^{e}_{jsc_1}, q^{e}_{jsc_2}, \ldots, q^{e}_{jsc_{\lvert C\rvert}}\right\}$
VG^{e}_{l}	A vector of the aggregate traffic intensity on link $l, VG^{e}_{l} = \left\{f^{e}_{lc_1}, f^{e}_{lc_2}, \ldots, f^{e}_{lc_{\lvert C\rvert}}\right\}$
VM^{e}_{l}	A vector of the channels required on link $l, VM^{e}_{l} = \left\{n^{e}_{lc_1}, n^{e}_{lc_2}, \ldots, n^{e}_{lc_{\lvert C\rvert}}\right\}$

Let L_1, L_2, L_3, and L_4 denote, respectively, the sets of links for node splitting in a single MSC, between two MSCs, between an MSC and the BS, and between the BS and an MS; then, we assign $L = L_1 \cup L_2 \cup L_3 \cup L_4$. If the costs of BS installation, sector configuration, and link connection are Δ_B, Δ_k, and $\Delta_l(n_l)$ with traffic intensity n_l, respectively, the objective is to minimize the total cost in an integer programming (IP) problem. The associated DVs in this problem are described in Table 4.

$$Z_{IP} = \min \sum_{j\in B} \Delta_B h_j + \sum_{j\in B} \sum_{k\in K} \Delta_k b_{jk} + \sum_{l\in L-\{L_4\}} \Delta_l \left(\sum_{e\in E} \sum_{c\in C} n^e_{lc} \right), \tag{IP}$$

subject to:

$$\left(\frac{E_b}{N_{TOTAL}}\right)^{UL}_c \leqslant SIR^{UL}_{js,c} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{13}$$

$$\left(\frac{E_b}{N_{TOTAL}}\right)^{DL}_c \leqslant SIR^{DL}_{js,c} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{14}$$

$$\sum_{l\in L_4} \sum_{o\in O} \sum_{p\in P_o} A_{c(o)} x^e_p \delta_{pl} \phi_{ljs} = g^e_{jsc} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{15}$$

$$\sum_{l\in L_4} \sum_{o\in O} \sum_{p\in P_o} q_{c(o)} x^e_p \delta_{pl} \phi_{ljs} \leqslant q^e_{jsc} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{16}$$

$$\sum_{o\in O} \sum_{p\in P_o} A_{c(o)} x^e_p \delta_{pl} \leqslant \varphi_l \quad \forall l \in L - \{L_4\},\ e \in E \tag{17}$$

$$\sum_{o\in O} \sum_{p\in P_o} q_{c(o)} x^e_p \delta_{pl} = n^e_{lc} \quad \forall l \in L - \{L_4\},\ c \in C,\ e \in E \tag{18}$$

$$SB_{jsc}\left(VG^e_{jsc}, VM^e_{jsc}\right) \leqslant \beta^e_{jsc} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{19}$$

$$LB_{lc}\left(VG^e_l, VM^e_l\right) \leqslant \varepsilon^e_{lc} \quad \forall l \in L - \{L_4\},\ c \in C,\ e \in E \tag{20}$$

$$\sum_{p\in P_O} x^e_p \leqslant 1 \quad \forall o \in O,\ e \in E \tag{21}$$

$$\sum_{o\in O} \sum_{p\in P_o} x^e_p \delta_{pl} \phi_{ljs} \chi_{lt} \leqslant z^e_{jst} \quad \forall j \in B,\ s \in S,\ l \in L_4,\ t \in T,\ e \in E \tag{22}$$

$$z^e_{jst} D_{jt} \leqslant r^e_{js} u^e_{jst} \quad \forall j \in B,\ s \in S,\ t \in T,\ e \in E \tag{23}$$

$$r^e_{js} \leqslant a^e_j R_{js} \quad \forall j \in B,\ s \in S,\ r^e_{js} \in Y,\ e \in E \tag{24}$$

$$a^e_j \leqslant h_j \quad \forall j \in B,\ e \in E \tag{25}$$

$$\sum_{k\in K} b_{jk} = h_j \quad \forall j \in B \tag{26}$$

$$y^e_{js} \leqslant h_j V \quad \forall j, \in B,\ s \in S,\ e \in E \tag{27}$$

$$z^e_{jst} \leqslant a^e_j \quad \forall j \in B,\ s \in S,\ t \in T,\ e \in E \tag{28}$$

$$\sum_{j\in B} \sum_{s\in S} z^e_{jst} = 1 \quad \forall t \in T,\ e \in E \tag{29}$$

$$q^e_{jsc} \leqslant a^e_j M_{js} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{30}$$

$$a^e_j = 0 \text{ or } 1 \quad \forall j \in B,\ e \in E \tag{31}$$

$$b_{jk} = 0 \text{ or } 1 \quad \forall j \in B,\ k \in K \tag{32}$$

$$x^e_p = 0 \text{ or } 1 \quad \forall o \in O,\ p \in P_o,\ e \in E \tag{33}$$

$$z^e_{jst} = 0 \text{ or } 1 \quad \forall j \in B,\ s \in S,\ t \in T,\ e \in E \tag{34}$$

$$h_j = 0 \text{ or } 1 \quad \forall j \in B \tag{35}$$

$$y^e_{js} \in F_S \quad \forall j, \in B,\ s \in S,\ e \in E \tag{36}$$

The SIR constraints for the UL and the DL are expressed in (13) and (14), respectively; while the aggregate traffic intensities in sector$_{js}$ and the required numbers of channels are calculated by (15) and (16), respectively. The total capacities of the transmission links are constrained by (17), and the total number of channels for the links is computed by (18). Constraints (19) and (20) require that a blockage in a sector or on a link should be less than a pre-defined threshold of probability β^e_{jsc} and ε^e_{lc}, respectively, where the call blocking probability functions are defined by Kaufman's model (Kaufman, 1981). Constraint (21) ensures that each OD pair is transmitted on one path. Constraint (22) guarantees that if a BS does not provide service to an MS, the link between them cannot be selected as a part of the routing path. MS t can only be serviced in the coverage of sector$_{js}$ by (23). BS j only provides service in the coverage of r^e_{js} if BS j is installed by (24). Under Constraint (25), BS j cannot be active if it is not installed. Without installation, sectorization will not be applied to BS j by (26). Constraint (27) requires that bandwidth is only assigned if the BS is installed. If the BS is not sectorized, no MS can be serviced by (28). Constraint (29) guarantees that each MS will be serviced. The total number of channels allocated in sector$_{js}$ for traffic class-c is limited by (30). Constraints (31)–(35) are integer properties of the DVs. Finally, when using the HFCS, only one FS can be deployed on both the UL and the DL by DV y^e_{js} under Constraint(36).

3.2. Solution approach

The problem (IP) becomes an LR problem (LR) by relaxing nine constraints: (13)–(17), (22), (23), (25) and (28). We multiply the relaxed constraints by the vector of corresponding Lagrangean multipliers $V = \left(v^1_{jsce}, v^2_{jsce}, v^3_{jsce}, v^4_{jsce}, v^5_{le}, v^6_{jslte}, v^7_{jste}, v^8_{je}, v^9_{jste}\right)$, where all the multipliers, except v^3_{jsce}, are greater than or equal to zero and add them to the primal objective function.

$$\begin{aligned}
&Z_D\left(v^1_{jsce}, v^2_{jsce}, v^3_{jsce}, v^4_{jsce}, v^5_{le}, v^6_{jslte}, v^7_{jste}, v^8_{je}, v^9_{jste}\right) \\
&\quad = \min \sum_{j\in B} \Delta_B h_j + \sum_{j\in B} \sum_{k\in K} \Delta_k b_{jk} + \sum_{l\in L-\{L_4\}} \Delta_l \left(\sum_{e\in E} \sum_{c\in C} n^e_{lc} \right) \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{c\in C} \sum_{e\in E} v^1_{jsce} \\
&\qquad \times \Bigg[(E_b/N_{TOTAL})^{UL}_c d^{UL}_c \Bigg((1-\rho^{UL}) \left(\sum_{c'\in C} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{jsc'} - \alpha^{UL}_c P^{UL}_c \right) \\
&\qquad + \sum_{\substack{j'\in B \\ j'\neq j}} \sum_{\substack{s'\in S \\ s'\neq S}} \sum_{c'\in C} \Omega^{UL}_{j's'js} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{j's'c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{j's'}} \right)^{\tau} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg) \\
&\qquad - L\left(y^e_{js}\right) \cdot BW^{UL}_{FU} \cdot \left(P^{UL}_c + \left(1 - a^e_j\right) V\right) \Bigg] + \sum_{j\in B} \sum_{s\in S} \sum_{c\in C} \sum_{e\in E} v^2_{jsce} \\
&\qquad \times \Bigg[(E_b/N_{TOTAL})^{DL}_c \, d^{DL}_c \Bigg((1-\rho^{DL}) \left(\sum_{c'\in C} \alpha^{DL}_{c'} P^{DL}_{c'} q^e_{jsc'} - \alpha^{DL}_c P^{DL}_c \right) \\
&\qquad + \sum_{\substack{j'\in B \\ j'\neq j}} \sum_{\substack{s'\in S \\ s'\neq S}} \sum_{c'\in C} \Omega^{DL}_{j's'js} \alpha^{DL}_{c'} P^{DL}_{c'} q^e_{j's'c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{js}} \right)^{\tau} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg) \\
&\qquad - L\left(y^e_{js}\right) \cdot BW^{DL}_{FU} \cdot \left(P^{DL}_c + \left(1 - a^e_j\right) V\right) \Bigg] \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{c\in C} \sum_{e\in E} v^3_{jsce} \left(\sum_{l\in L_4} \sum_{o\in O} \sum_{p\in P_o} A_{c(o)} x^e_p \delta_{pl} \phi_{ljs} - g^e_{jsc} \right) \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{c\in C} \sum_{e\in E} v^4_{jsce} \left(\sum_{l\in L_4} \sum_{o\in O} \sum_{p\in P_o} q_{c(o)} x^e_p \delta_{pl} \phi_{ljs} - q^e_{jsc} \right) \\
&\qquad + \sum_{l\in L-\{L_4\}} \sum_{e\in E} v^5_{le} \left(\sum_{o\in O} \sum_{p\in P_o} A_{c(o)} x^e_p \delta_{pl} - \varphi_l \right) \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{l\in L_4} \sum_{t\in T} \sum_{e\in E} v^6_{jslte} \left(\sum_{o\in O} \sum_{p\in P_o} x^e_p \delta_{pl} \phi_{ljs} \chi_{lt} - z^e_{jst} \right) \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{t\in T} \sum_{e\in E} v^7_{jste} \left(z^e_{jst} D_{jt} - r^e_{js} u^e_{jst} \right) + \sum_{j\in B} \sum_{e\in E} v^8_{je} \left(a^e_j - h_j \right) \\
&\qquad + \sum_{j\in B} \sum_{s\in S} \sum_{t\in T} \sum_{e\in E} v^9_{jste} \left(z^e_{jst} - a^e_j \right),
\end{aligned} \tag{LR}$$

subject to: (18)–(21), (24), (26), (27), (29)–(36).

Table 4
Description of DVs in the formulation of integrated network planning.

Notation	Description
a_j^e	BS activation DV, which is 1 if BS j is active in state e, and 0 otherwise
b_{jk}	BS configuration DV, which is 1 if BS j is with sector configuration k, and 0 otherwise
f_{lc}^e	Aggregate intensity of traffic class-c on link l in state $e, f_{lc}^e = \sum_{o\in O}\sum_{p\in P_o} A_{c(o)} x_p^e \delta_{pl}$
g_{jsc}^e	Aggregate intensity of traffic class-c in sector$_{js}$ in state e
h_j	BS installation DV, which is 1 if BS j is installed in state e, and 0 otherwise
n_{lc}^e	The number of channels required on link l for traffic class-c
q_{jsc}^e	The aggregate number of channels required in sector$_{js}$ for traffic class-c
r_{js}^e	Power transmission radius of sector$_{js}$ in state e
x_p^e	Traffic routing DV, which is 1 if path p is selected in state e
y_{js}^e	Bandwidth allocation DV, which is m if sector$_{js}$ deploys FS m in state e
z_{jst}^e	CAC DV, which is 1 if MS t is granted by sector$_{js}$ in state e, and 0 otherwise

Problem (LR) can be decomposed into four independent subproblems: (SUB 1), (SUB 2), (SUB 3), and (SUB 4), each of which can be solved optimally by the proposed algorithms.

Subproblem (SUB 1) related to h_j, b_{jk}:

$$Z_{SUB\ 1} = \min\sum_{j\in B}\Delta_B h_j + \sum_{j\in B}\sum_{k\in K}\Delta_k b_{jk} - \sum_{j\in B}\sum_{e\in E} v_{je}^8 h_j$$

$$= \min\sum_{j\in B}\left[h_j\left(\Delta_B - \sum_{e\in E} v_{je}^8\right) + \sum_{k\in K}\Delta_k b_{jk}\right] \tag{SUB1}$$

subject to:

$$\sum_{k\in K} b_{jk} = h_j \quad \forall j\in B \tag{26}$$

$$b_{jk}^e = 0 \text{ or } 1 \quad \forall j\in B,\ k\in K,\ e\in E \tag{32}$$

$$h_j = 0 \ or\ 1 \quad \forall j\in B \tag{35}$$

To solve this subproblem optimally, we further decompose it into $|B|$ independent subproblems, each of which deals with the probable values of h_j. If $h_j = 0$, it forces $b_{jk} = 0$, so the subproblem value is zero. If $h_j = 1$, one b_{jk} must be assigned to 1 under Constraint (26). Then, we choose the smallest value of Δ_k, and assign $b_{jk} = 1$. Given that Δ_k and b_{jk} in the state $h_j = 1$, we calculate tempmin=$h_j\left(\Delta_B - \sum_{e\in E} v_{je}^8\right) + \sum_{k\in K}\Delta_k b_{jk}$. Comparing tempmin with zero, if it is less than zero, we assign $h_j = 1$ and associate $b_{jk} = 1$; otherwise, we assign zero to both h_j and b_{jk}.

Subproblem (SUB 2) related to $x_p^e, n_{lc}^e, f_{lc}^e$:

$$\begin{aligned} Z_{SUB\ 2} = \min &\sum_{l\in L-\{L_4\}}\Delta_l\left(\sum_{e\in E}\sum_{c\in C} n_{lc}^e\right) + \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v_{jsce}^3 \sum_{l\in L_4}\sum_{o\in O} \\ &\times \sum_{p\in P_o} A_{c(o)} x_p^e \delta_{pl}\phi_{ljs} + \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v_{jsce}^4 \\ &\times \sum_{l\in L_4}\sum_{o\in O}\sum_{p\in P_o} q_{c(o)} x_p^e \delta_{pl}\phi_{ljs} + \sum_{l\in L-\{L_4\}}\sum_{e\in E} v_{le}^5 \sum_{o\in O}\sum_{p\in P_o} A_{c(o)} x_p^e \delta_{pl} \\ &- \sum_{l\in L-\{L_4\}}\sum_{e\in E} v_{le}^5 \varphi_l + \sum_{j\in B}\sum_{s\in S}\sum_{l\in L_4}\sum_{t\in T}\sum_{e\in E} v_{jslte}^6 \\ &\times \sum_{o\in O}\sum_{p\in P_o} x_p^e \delta_{pl}\phi_{ljs}\chi_{lt} \end{aligned} \tag{SUB2}$$

subject to:

$$\sum_{o\in O}\sum_{p\in P_o} q_{c(o)} x_p^e \delta_{pl} = n_{lc}^e \quad \forall l\in L-\{L_4\},\ c\in C,\ e\in E \tag{18}$$

$$LB_{lc}\left(VG_l^e, VM_l^e\right) \leqslant \varepsilon_{lc}^e \quad \forall l\in L-\{L_4\},\ c\in C,\ e\in E \tag{20}$$

$$\sum_{p\in P_O} x_p^e \leqslant 1 \quad \forall o\in O,\ e\in E \tag{21}$$

$$x_p^e = 0 \ or\ 1 \quad \forall o\in O,\ p\in P_o,\ e\in E \tag{33}$$

The subproblem (SUB 2) is rewritten as follows, where $n_{lc}^e = \sum_{o\in O}\sum_{p\in P_o} q_{c(o)} x_p^e \delta_{pl}$ is replaced by Constraint (18)

$$\begin{aligned} \min\sum_{e\in E}\sum_{o\in O}\Bigg\{ x_p^e \Bigg[&\sum_{p\in P_o}\sum_{j\in B}\sum_{s\in S}\sum_{l\in L_4}\Bigg[\sum_{c\in C}\left(v_{jsce}^3 A_{c(o)} + v_{jsce}^4 q_{c(o)}\right)\delta_{pl}\phi_{ljs} \\ &+ \sum_{t\in T} v_{jstle}^6 \delta_{pl}\phi_{ljs}\chi_{lt}\Bigg] + \sum_{p\in P_o}\sum_{l\in L-\{L_4\}}\left[v_{le}^5 A_{c(o)} + \Delta_l \sum_{c\in C} q_{c(o)}\right]\delta_{pl}\Bigg]\Bigg\} \\ &- \sum_{l\in L-\{L_4\}}\sum_{e\in E} v_{le}^5 \varphi_l \end{aligned}$$

To solve (SUB 2) optimally, we further decompose it into $|E| \times |O|$ independent subproblems. Then, for each $|E| \times |O|$ subproblem, we define $coefx_p^e$ in (37), so that each subproblem finds a minimal value by choosing x_p^e correctly. Because the term $-\sum_{l\in L-\{L_4\}}\sum_{e\in E} v_{le}^5 \varphi_l$ is a constant value, only one x_p^e should be chosen. The solution is easier. We calculate all $coefx_p^e$, and choose the smallest value of $coefx_p^e$. If it is less than or equal to zero, and QoS constraint (20) for aggregate traffic n_{lc}^e is satisfied, we assign $x_p^e = 1$; otherwise, we assign $x_p^e = 0$, and all other $x_p^e = 0$.

$$\begin{aligned} coefx_p^e = &\sum_{p\in P_O}\sum_{j\in B}\sum_{s\in S}\sum_{l\in\{L_4\}}\Bigg[\sum_{c\in C}\left(v_{jsce}^3 A_{c(o)} + v_{jsce}^4 q_{c(o)}\right)\delta_{pl}\phi_{ljs} \\ &+ \sum_{t\in T} v_{jstle}^6 \delta_{pl}\phi_{ljs}\chi_{lt}\Bigg] + \sum_{p\in P_O}\sum_{l\in L-\{L_4\}}\left[v_{le}^5 A_{c(o)} + \Delta_l \sum_{c\in C} q_{c(o)}\right]\delta_{pl} \end{aligned} \tag{37}$$

Subproblem (SUB 3) related to z_{jst}^e:

$$\begin{aligned} Z_{SUB\ 3} = \min &\sum_{j\in B}\sum_{s\in S}\sum_{t\in T}\sum_{e\in E} v_{jste}^7 z_{jst}^e D_{jt} + \sum_{j\in B}\sum_{s\in S}\sum_{t\in T}\sum_{e\in E} v_{jste}^9 z_{jst}^e \\ &- \sum_{j\in B}\sum_{s\in S}\sum_{l\in L_4}\sum_{t\in T}\sum_{e\in E} v_{jslte}^6 z_{jst}^e \\ = \min &\sum_{t\in T}\sum_{e\in E} z_{jst}^e \left\{\sum_{j\in B}\sum_{s\in S}\left(v_{jste}^7 D_{jt} + v_{jste}^9 - \sum_{l\in L_4} v_{jslte}^6\right)\right\}, \end{aligned} \tag{SUB3}$$

subject to:

$$\sum_{j\in B}\sum_{s\in S} z_{jst}^e = 1 \quad \forall t\in T,\ e\in E \tag{29}$$

$$z_{jst}^e = 0 \text{ or } 1 \quad \forall j\in B,\ s\in S,\ t\in T,\ e\in E \tag{34}$$

We decompose (SUB 3) into $|T| \times |E|$ independent subproblems, each of which calculates the total $|B| \times |S|$ values of $temp_{js} = \left(v_{jste}^7 D_{jt} + v_{jste}^9 - \sum_{l\in L_4} v_{jslte}^6\right)$. We than assign $z_{jst}^e = 1$ with the smallest value of $temp_{js}$.

Subproblem (SUB 4) related to $g^e_{jsc}, q^e_{jsc}, r^e_{js}, y^e_{js}, a^e_j$:

$$\begin{aligned}
Z_{SUB\ 4} = \min & \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v^1_{jsce} \\
& \times \Bigg[(E_b/N_{TOTAL})^{UL}_c d^{UL}_c \Bigg((1-\rho^{UL}) \Bigg(\sum_{c'\in C} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{jsc'} - \alpha^{UL}_c P^{UL}_c \Bigg) \\
& + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{s'\in S\\ s'\neq S}} \sum_{c'\in C} \Omega^{UL}_{j's'js} \alpha^{UL}_{c'} P^{UL}_{c'} q^e_{j's'c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{j's'}} \right)^{\tau} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg) \\
& - L\left(y^e_{js}\right) \cdot BW^{UL}_{FU} \cdot \left(P^{UL}_c + \left(1 - a^e_j\right)V\right) \Bigg] \\
& \times \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v^2_{jsce} \\
& \times \Bigg[(E_b/N_{TOTAL})^{DL}_c\ d^{DL}_c \Bigg((1-\rho^{DL}) \Bigg(\sum_{c'\in C} \alpha^{DL}_{c'} P^{DL}_{c'} q^e_{jsc'} - \alpha^{DL}_c P^{DL}_c \Bigg) \\
& + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{s'\in S\\ s'\neq S}} \sum_{c'\in C} \Omega^{DL}_{j's'js} \alpha^{DL}_{c'} P^{DL}_{c'} q^e_{j's'c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{js}} \right)^{\tau} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg) \\
& - L\left(y^e_{js}\right) \cdot BW^{DL}_{FU} \cdot \left(P^{DL}_c + \left(1 - a^e_j\right)V\right) \Bigg] \\
& - \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v^3_{jsce} g^e_{jsc} - \sum_{j\in B}\sum_{s\in S}\sum_{c\in C}\sum_{e\in E} v^4_{jsce} q^e_{jsc} \\
& - \sum_{j\in B}\sum_{s\in S}\sum_{t\in T}\sum_{e\in E} v^7_{jste} r^e_{js} u^e_{jst} + \sum_{j\in B}\sum_{e\in E} v^8_{je} a^e_j \\
& - \sum_{j\in B}\sum_{s\in S}\sum_{t\in T}\sum_{e\in E} v^9_{jste} a^e_j
\end{aligned} \tag{SUB4}$$

subject to:

$$SB_{jsc}\left(VG^e_{jsc}, VM^e_{jsc}\right) \leqslant \beta^e_{jsc} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{19}$$

$$r^e_{js} \leqslant a^e_j R_{js} \quad \forall j \in B,\ s \in S,\ r^e_{js} \in Y,\ e \in E \tag{24}$$

$$q^e_{jsc} \leqslant a^e_j M_{js} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{17}$$

$$a^e_j = 0 \text{ or } 1 \quad \forall j \in B,\ e \in E \tag{31}$$

$$z^e_{jst} = 0 \text{ or } 1 \quad \forall j \in B,\ s \in S,\ t \in T,\ e \in E \tag{34}$$

$$LB_{js} \leqslant g^e_{jsc} \leqslant UB_{js} \quad \forall j \in B,\ s \in S,\ c \in C,\ e \in E \tag{38}$$

Besides the constraints shown in the (IP), we pre-calculate the LB_{js} and the UB_{js} of q^e_{jsc} to improve efficiency when solving this subproblem, for which a constraint is given in (38). We then rewrite (SUB 4) as follows:

$$\begin{aligned}
& \sum_{j\in B}\sum_{e\in E} \Bigg\{ a^e_j \Bigg[v^8_{je} + \sum_{s\in S} L\left(y^e_{js}\right) \Bigg(\sum_{c\in C} \left(v^1_{jsce} BW^{UL}_{FU} + v^2_{jsce} BW^{DL}_{FU} \right) V - \sum_{t\in T} v^9_{jste} \Bigg) \Bigg] \\
& - \sum_{s\in S} L\left(y^e_{js}\right) \Bigg(\sum_{c\in C} \left(v^1_{jsce} BW^{UL}_{FU} \left(P^{UL}_c + V\right) + v^2_{jsce} BW^{DL}_{FU} \left(P^{DL}_c + V\right) \right) \Bigg) \\
& - \sum_{s\in S}\sum_{t\in T} v^7_{jste} r^e_{js} u^e_{jst} \\
& + \sum_{s\in S}\sum_{c\in C} \Bigg[q^e_{jsc} \Bigg[\sum_{c'\in C} \Bigg(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \alpha^{UL}_{c'} P^{UL}_{c'} \\
& + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \alpha^{DL}_{c'} P^{DL}_{c'} \\
& + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{s'\in S\\ s'\neq S}} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \\
& \times \Omega^{UL}_{j's'js} \alpha^{UL}_{c'} P^{UL}_{c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{j's'}} \right)^{\tau} + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \\
& \times \Omega^{DL}_{j's'js} \alpha^{DL}_{c'} P^{DL}_{c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{js}} \right)^{\tau} \Bigg) \Bigg) - \left(v^3_{jsce} + v^4_{jsce} \right) \Bigg] \\
& - \Bigg(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \alpha^{UL}_c P^{UL}_c \\
& + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \alpha^{DL}_c P^{DL}_c \Bigg) \Bigg] \Bigg\}
\end{aligned}$$

To develop an algorithm for solving this subproblem, we define the following notations used in (SUB 4): $coefa^e_j\left(y^e_{js}\right)$ (a function of y^e_{js}), $coefLy^e_{js}$ (a constant value), $coefq^e_{jsc}\left(y^e_{j's'}, y^e_{js}, r^e_{j's'}, r^e_{js}\right)$ (a function of $y^e_{j's'}, y^e_{js}, r^e_{j's'}, r^e_{js}$), and *constant* (a constant value) as shown in (39)–(42), respectively.

$$coefa^e_j\left(y^e_{js}\right) = v^8_{je} + \sum_{s\in S} L\left(y^e_{js}\right) \Bigg(\sum_{c\in C} \left(v^1_{jsce} BW^{UL}_{FU} + v^2_{jsce} BW^{DL}_{FU} \right) V - \sum_{t\in T} v^9_{jste} \Bigg) \tag{39}$$

$$coefLy^e_{js} = \sum_{c\in C} \left(v^1_{jsce} BW^{UL}_{FU} \left(P^{UL}_c + V\right) + v^2_{jsce} BW^{DL}_{FU} \left(P^{DL}_c + V\right) \right) \tag{40}$$

$$\begin{aligned}
& coefq^e_{jsc}\left(y^e_{j's'}, y^e_{js}, r^e_{j's'}, r^e_{js}\right) \\
& = \sum_{c'\in C} \Bigg(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \alpha^{UL}_{c'} P^{UL}_{c'} \\
& + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \alpha^{DL}_{c'} P^{DL}_{c'} \\
& + \sum_{\substack{j'\in B\\ j'\neq j}} \sum_{\substack{s'\in S\\ s'\neq S}} \Psi\left(y^e_{j's'}, y^e_{js}\right) \Bigg(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \\
& \times \Omega^{UL}_{j's'js} \alpha^{UL}_{c'} P^{UL}_{c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{j's'}} \right)^{\tau} + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \\
& \times \Omega^{DL}_{j's'js} \alpha^{DL}_{c'} P^{DL}_{c'} \left(\frac{r^e_{j's'}}{D_{jj'} - r^e_{js}} \right)^{\tau} \Bigg) \Bigg) - \left(v^3_{jsce} + v^4_{jsce} \right)
\end{aligned} \tag{41}$$

$$\begin{aligned}
constant = & \Big(v^1_{jsce} (E_b/N_{TOTAL})^{UL}_c d^{UL}_c (1-\rho^{UL}) \alpha^{UL}_c P^{UL}_c \\
& + v^2_{jsce} (E_b/N_{TOTAL})^{DL}_c d^{DL}_c (1-\rho^{DL}) \alpha^{DL}_c P^{DL}_c \Big)
\end{aligned} \tag{42}$$

$$\begin{aligned}
\min \sum_{j\in B}\sum_{e\in E} & \Bigg\{ a^e_j coefa^e_j\left(y^e_{js}\right) - \sum_{s\in S} L\left(y^e_{js}\right) coefLy^e_{js} - \sum_{s\in S}\sum_{t\in T} v^7_{jste} r^e_{js} u^e_{jst} \\
& + \sum_{s\in S}\sum_{c\in C} \left[q^e_{jsc} \mathrm{coef} q^e_{jsc}\left(y^e_{j's'}, y^e_{js}, r^e_{j's'}, r^e_{js}\right) - constant \right] \Bigg\}
\end{aligned} \tag{43}$$

Then, (SUB 4) can be simply expressed as (43) and further decomposed into $|B| \times |E|$ independent subproblems, each of which is denoted by $\mathrm{SUB}\,4_{je}$ as follows:

$$\begin{aligned}
\mathrm{SUB}\ 4_{je} = & a^e_j \mathrm{coef} a^e_j - \sum_{s\in S} L\left(y^e_{js}\right) \mathrm{coef} L\left(y^e_{js}\right) - \sum_{s\in S}\sum_{t\in T} v^6_{jste} r^e_{js} u^e_{jst} \\
& + \sum_{s\in S}\sum_{c\in C} \left[q^e_{jsc} \mathrm{coef} q^e_{jsc} - constant \right]
\end{aligned}$$

The *constant*, which is irrelevant to the minimum value of (43), is ignored when solving this subproblem. Algorithm 1 optimally solves subproblem (43). The steps are as follows.

Algorithm 1

Step 1. If $a^e_j = 0$, DVs r^e_{js} and q^e_{jsc} must be assigned 0 under Constraints (24) and (30). Thus, to calculate the minimum value of (43), DV y^e_{js} is given any value that yields a maximal length $L\left(y^e_{js}\right)$. Then, calculate temp $a^e_j 0 = -\sum_{s\in S} L\left(y^e_{js}\right) coefLy^e_{js}$.

Step 2. If $a_j^e = 1$, assign a value of y_{js}^e that gets a maximal length $L\left(y_{js}^e\right)$, and assign r_{js}^e equal to R_{js}. Each subproblem $\mathrm{SUB}\,4_{je}$ can be further decomposed into $|S| \times |C|$ independent subproblems to optimally solve the $coefq_{jsc}^e\left(y_{j's'}^e, y_{js}^e, r_{j's'}^e, r_{js}^e\right)$ by repeating Steps 2.1 and 2.2 given a pair of y_{js}^e and r_{js}^e.

- Step 2.1 Assign LB_{js}, which is defined in Constraint (38) to q_{jsc}^e.
- Step 2.2 Each $coefq_{jsc}^e$ exhaustively searches all combinations of $|B| \times |S|$, and gets DVs $y_{j's'}^e$ and $r_{j's'}^e$ when the minimum value of $coefq_{jsc}^e$ is calculated. Assign the minimum value to tempmin $a_j^e 1$
- Step 2.3 Update tempmin $a_j^e 1$, if a smaller value of tempmin $a_j^e 1$ is calculated.
- Step 2.4 Increase q_{jsc}^e by one if it is less than UB_{js} and Constraint (19) is satisfied, and go to Step 2.1; otherwise, end Step 2.

Step 3. Select the minimal value from $|S| \times |C|$ of tempmin $a_j^e 1$, and assign it to temp $a_j^e 1$.

Step 4. In each of the $|B| \times |E|$ subproblems, compare temp $a_j^e 0$ with temp $a_j^e 1$, and choose the smaller one. If the smaller one is temp $a_j^e 0$, assign 0 to a_j^e, r_{js}^e and q_{jsc}^e, and select any one of y_{js}^e that gets a maximal length $L\left(y_{js}^e\right)$; else, if the smaller one is temp $a_j^e 1$, assign $a_j^e = 1$, and assign r_{js}^e, q_{jsc}^e, and y_{js}^e to associated values.

3.3. Getting primal feasible solutions

After solving subproblems (SUB 1), (SUB 2), (SUB 3), and (SUB 4), the objective value of $Z_D\left(v_{jsce}^1, v_{jsce}^2, v_{jsce}^3, v_{jsce}^4, v_{le}^5, v_{jslte}^6, v_{jste}^7, v_{je}^8, v_{jste}^9\right)$ is a lower bound (LB) of Z_{IP}. Based on the problem (LR), the dual problem $Z_D = \max Z_D\left(V_{jsce}^1, v_{jsce}^2, v_{jsce}^3, v_{jsce}^4, v_{le}^5, v_{jslte}^6, v_{jste}^7, v_{je}^8, v_{jste}^9\right)$ is constructed to calculate the tightest LB of the problem (IP), subject to $\left(v_{jsce}^1, v_{jsce}^2, v_{jsce}^4, v_{le}^5, v_{jslte}^6, v_{jste}^7, v_{je}^8, v_{jste}^9\right) \geqslant 0$ and v_{jsce}^3. Because of the complexity of an integrated comprehensive planning model, we further propose the following primal heuristics to calculate an upper bound (UB): (1) a BS configuration and call admission control (CAC) subproblem, (2) resource and capacity management, and (3) a traffic routing and topology design subproblem.

3.3.1. BS configuration and CAC subproblems

There are two issues to be considered by this primal heuristic: (1) cost minimization of network planning; (2) all MSs should be completely serviced by the network. Thus, we try to serve all MSs with the smallest number of BSs with $\sum_{j\in B}\sum_{s\in S} z_{jst}^e = 1$, irrespective of the antenna type (omni-directional or smart antenna) adopted. However, this raises the question: How many BSs are required and where should they be placed? The answers to these questions depend primarily on the MS distribution. In the BS allocation subproblem, if $\sum_{e\in E}\sum_{s\in S}\sum_{t\in T} z_{jst}^e = 0$, the implication is that installing BS j is unnecessary. Furthermore, each BS configuration uses an omni-directional antenna if $\sum_{t\in T} z_{js_1t}^e > \sum_{s\in\{s_2,s_3,s_4\}}\sum_{t\in T} z_{jst}^e$; otherwise, it uses a smart antenna.

For each BS j (written as BS_j), denote maxBS_j as the total number of MSs that can be serviced by BS_j, and let minBS_j be the total number of MSs that are only serviced by BS_j. Based on both minBS_j and maxBS_j, the traffic load in BS_j is given by $\mathrm{loadBS}_j = \mathrm{minBS}_j \times |T| + \mathrm{maxBS}_j$ (actually $|T|$ can be any large number). Then, all loadBS_j are sorted in descending order to minimize costs. Thus, in Algorithm 2, the installation and configuration of BSs and CAC for MSs are considered jointly.

Algorithm 2

Step 1. For each network state e, calculate all loadBS_j and sort them in descending order.

Step 2. Sort the elements in set F_S in ascending order of the element length.

Step 3. Build ($h_j = 1$) and activate ($a_j^e = 1$) BSs that cover MSs only served by one BS.

- Step 3.1 Build BS_j from which minBS_j is nonzero. Configure BS_j with an omni-directional antenna ($b_{j1} = 1$), and allocate the first element in the set F_S to y_{js}^e. Activate BS_j with the maximum radius of power transmission r_{js}^e if it satisfies the QoS constraint; or deactivate BS_j $\left(a_j^e = 0\right)$.
- Step 3.2 Repeat Step 2 until the BSs are built.

Step 4. Select a BS that has not been placed yet by Step 2 in descending order of loadBS_j until $\mathrm{loadBS}_j = 0$.

- Step 4.1 Build BS_j, configure it with an omni-directional antenna ($b_{j1} = 1$), and allocate the first element in the set F_S to y_{js}^e. Activate BS_j with increasing power transmission radius r_{js}^e to cover MSs that have not been admitted, until the total number minBS_j in BS_j are covered.
- Step 4.2 In the coverage r_{js}^e, if MS t has not been admitted yet and is covered by BS_j, then admit it to BS_j, i.e., assign $z_{jst}^e = 1$ (where s is the sector I.D. of BS_j with an omni-antenna), if the QoS constraint is satisfied; otherwise $z_{jst}^e = 0$.
- Step 4.3 Repeat Step 3 until all BSs are checked.

Step 5. Deal with the MSs that have not been admitted, and rehome them in the nearest active BS.

Step 6. For each BS_j, calculate the aggregate traffic $\left(g_{jsc}^e\right)$ and the required channel $\left(q_{jsc}^e\right)$.

Step 7. Check QoS, and repeat this step until the QoS requirement in each BS_j is satisfied.

- Step 7.1 If MS t was previously assigned to an omni-directional antenna ($b_{j1} = 1$), we re-assign the MS to a smart antenna (adjust $b_{j2} = 1$), and vice versa. Then, we adjust z_{jst}^e to fit the antenna type of each BS_j.
- Step 7.2 Re-assign y_{js}^e with the next element if the QoS requirement is violated.

Step 8. Adjust the power transmission radius r_{js}^e for all BS_j to cover the MS that is farthest away from each BS_j.

3.3.2. Topology design, capacity management, and traffic routing subproblems

The backbone topology design is by nature a minimum cost spanning tree problem. As shown in Fig. 5, the traffic on link L2 is aggregated by link L3 from several BSs that are jointly connected to a specific MSC node. Furthermore, to model the node constraint, we add an auxiliary link, L1, with weight zero. To fulfill the node splitting requirement. Irrespective of whether the link or the node constraints are considered, they are expressed jointly in Constraint (17). The steps of the primal Algorithm 3 for solving this subproblem are as follows:

Algorithm 3

Step 1. For each network state e, define a link weight. Applying the minimum spanning tree algorithm to solve this subproblem, each $\sum_{e\in E} v_{le}^5$ means a specific link and its length is the weight cost (actually the link cost is a function of the link length).

Step 2. Check the aggregate traffic and capacity.

Step 2.1 For each link L3, calculate the aggregate traffic (f_{lc}^{e}) generated by all OD pairs.

Step 2.2 Properly assign the transmission capacity (n_{lc}^{e}), subject to the pre-defined call blocking probability threshold in (20).

Step 3. Construct a minimum cost spanning tree.

Step 3.1 Calculate the aggregate traffic on link L2, where the traffic is aggregated by link L3 from several BSs that are jointly connected to a specific MSC node.

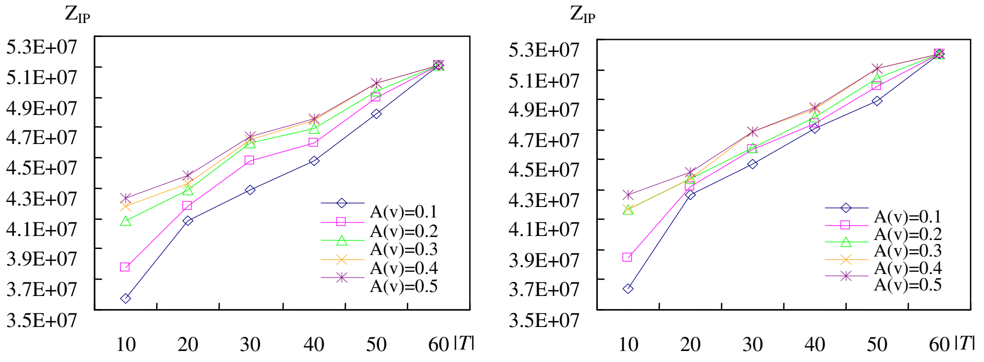
Step 3.2 Construct a minimum cost spanning tree subject to the pre-defined capacity constraint in (17).

Step 4. Repeat Steps 1–3 to consider all network states, each of which chooses the maximum capacity for each link as a primal solution.

4. Computational experiments

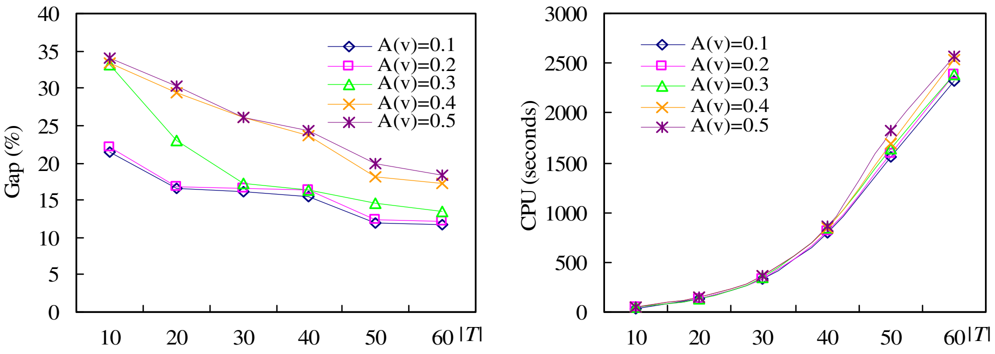
4.1. Parameters

In this work, we consider voice traffic (v) and data traffic (d), where $v, d \in C$. The number of OD pairs is half the total number of MSs($|O| = |T|/2$). Each OD pair belongs to only one traffic type, either voice or data traffic, and the amount of voice-data traffic



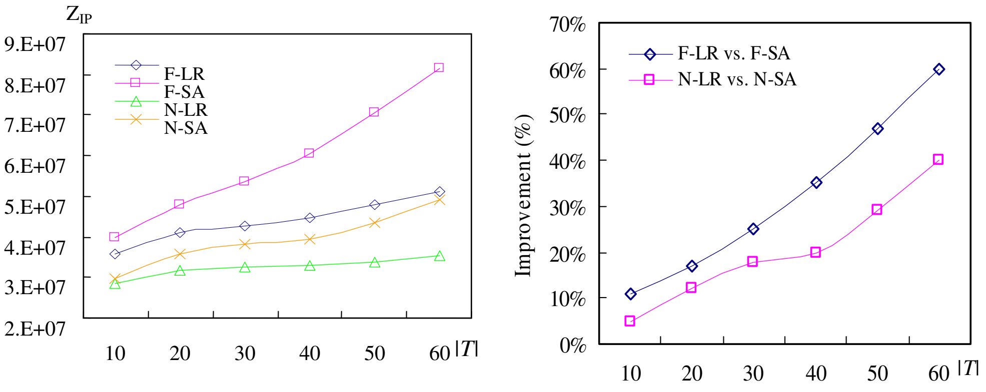
(a) Given A(d)=1.5 Erlangs (b) Given A(d)=3.0 Erlangs

Fig. 6. Planning costs as a function of $|T|$ with respect to voice traffic intensities.



(a) Error gap (b) CPU time

Fig. 7. Performance analysis of the network planning model, given $A(d) = 1.5$ Erlangs.



(a) Total cost (b) Improvement over SA

Fig. 8. Cost comparison of various scenarios and approaches.

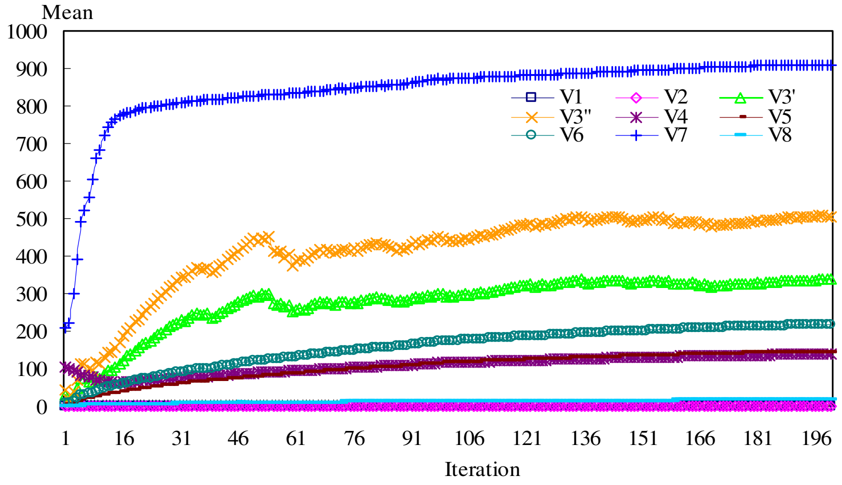


Fig. 9. Sensitivity analysis of Lagrangean multipliers for the planning problem.

in all OD pairs is 50–50. The experiment environment is given as $|B| = 15$, and $|K| = 2$ (omni-directional antenna and three uniform sectors) introduces $|S| = 4(1+3)$. The associated QoS parameters are given as $\varepsilon_{lv} = 0.01$, $\varepsilon_{ld} = \beta^{e}_{jsv} = 0.03$, $\beta^{e}_{jsd} = 0.05$ (Chu & Lin, 2004, 2006), and the required bit energy to noise ratio (BENR) for voice (v) traffic and data (d) traffic is $(E_b/N_{TOTAL})^{UL}_{v} = (E_b/N_{TOTAL})^{DL}_{v}$=7 dB and $(E_b/N_{TOTAL})^{UL}_{d} = (E_b/N_{TOTAL})^{DL}_{d}$=6 dB (Kim, Jeong, Jeon, & Choi, 2002) respectively. Activity factors (AFs) are given as $\alpha^{UL}_{v} = \alpha^{DL}_{v} = \alpha^{UL}_{d} = \alpha^{DL}_{d} = 0.5$ (Jeon & Jeong, 2001, 2002; Kim et al., 2002). The unit costs are assigned as $\Delta_B = 5{,}000{,}000$, $\Delta_k = 100{,}000$, and $\Delta_l = 50$ per kilometer per channel. The information rates are $d^{UL}_{v} = d^{DL}_{v} = 9.6$ kbps (Choi & Kim, 2001; Kim & Jeong, 2000; Kim et al., 2002), and $d^{UL}_{d} = d^{DL}_{d} = 38.4$ kbps (Kim & Jeong, 2000); and the numbers of channels required are $q_v = 1$ and $q_d = 4$. The orthogonality factors are $\rho^{UL} = 0.5$ and $\rho^{DL} = 0.5$, and the power is perfectly controlled by $P^{UL}_{v} = 10$ dB, $P^{DL}_{v} = 15$ dB, $P^{UL}_{d} = 15$ dB, and $P^{DL}_{d} = 20$ dB (Kim et al., 2002).

4.2. Results

The computational experiments focus on $|B| = 10$, and the planning cost is a function of $|T|$. It is given that $\varphi_{l\in L_1} = 100$ Erlangs, and $\varphi_{l\in\{L_2,L_3\}} = 50$ Erlangs. With regard to voice traffic intensity, we simply denote the voice intensity $A_{v(o)}$ and data intensity $A_{d(o)}$ of OD pair o as $A(v)$ and $A(d)$, respectively. For given $A(d) = 1.5$ and $A(d) = 3.0$ Erlangs, the costs are shown in Fig. 6 (a) and (b), respectively. The cost of $A(d) = 3.0$ is more than 1% higher than that of $A(d) = 1.5$. Irrespective of which $A(d)$ is given, the more $A(v)$ is loaded, the higher will be the calculated the cost. However, irrespective of which $A(v)$ is given, the costs converge whenever $|T|$ is in the largest value. The results indicate that the total number of MSs in the system significantly affects the overall planning cost.

Given $A(d) = 1.5$, other measurements, namely the error gap and CPU time, are also reported, as shown in Fig. 7. Both measurements are also expressed as a function of $|T|$ with respect to the voice traffic intensities. In Fig. 7(a), the total number of gaps is calculated in the range 12–34%; the more intensity $A(v)$ is given, the looser will be the calculated gap. In contrast to a smaller value of $|T|$, a larger $|T|$ has a tighter gap. With regard to the effect of $|T|$ on the CPU time, Fig. 7(b) shows that the CPU time is an increasing function of the total number of MSs. Nevertheless, the traffic intensity $A(v)$ of each MS is not a significant factor in the CPU time.

To evaluate the performance of the planning model, which is solved by the LR approach, we implement a simple algorithm (SA), and also consider two network state scenarios: one for a normal state (N), where there are no failures among BSs, and the other for a failure state (F), where there are failures among the BSs. Fig. 8(a) summarizes the cost comparison of the solution approaches in conjunction with the states. In terms of BS failures, the total cost is 26% more than in the normal state given $|T| = 10$, while it is more than 45% given $|T| = 60$. Clearly, the proposed LR approach outperforms the SA algorithm. In addition, the larger the number of MSs, the more improvement there will be in the total planning cost. For a failure state, the results in Fig. 8(b) show that the improvements, denoted by F-LR vs. F-SA, are within the range 10–60% when $|T|$ is set between 10 and 60. Meanwhile, in the normal state, the improvements, denoted by N-LR vs. N-SA, are in the range 5–40%.

4.3. Sensitivity analysis

After solving the integrated network planning problem, we have a rough representation of a real case. From a management perspective, the most important insights are gained from the analysis after finding a primal feasible solution for the original model. This analysis is commonly called sensitivity analysis and answers questions about what would happen to the optimal solution if the parameters in the model were varied. In addition, by using the LR approach to solve the model, some constraints are relaxed and multiplied by the corresponding Lagrangean multipliers. From the analysis of the multipliers, we can understand the managerial implications of the constraints. We run the analysis up to 1000 iterations, but the values of the multiplier almost converge to the corresponding constant values after 200 iterations. Fig. 9 shows the results up to 200 iterations. The greater the value of the multiplier, the more important will be the corresponding constraint in the problem. Multiplier V7 related to constraint (23) converges to the largest value 900. This means the service requirement is the most important issue in solving the planning problem, as any call requests are admitted to the coverage area of a cell. The importance of the service requirement stems from the decision variation of the BS installation, as well as the BS configuration. Multipliers V3′ (related to the node constraint) and V3″ (related to the link constraint) converge to 320 and 500, respectively, which implies that the link constraint is of more concern than the node constraint for an MSC. Other multipliers calculate much smaller values than the previous three; for example, the multipliers V1 and V2 are close to 10 or lower. Because the traffic load is unsaturated, we do not discuss V1 and V2 here.

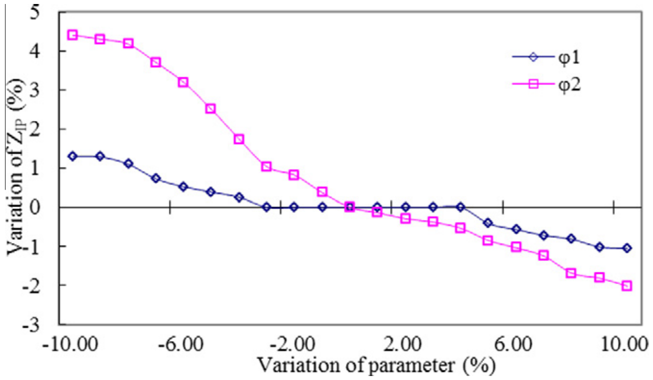


Fig. 10. Sensitivity analysis of the effect of the capacity constraints on the planning cost.

The proposed network planning model considers an embedded system in which some of the equipment pre-exists, as well as a desert system in which all of the equipment is newly installed. The multiplier analysis indicates that the capacity constraints in the model are significant. To further investigate the effects of the constraints, Fig. 10 shows that Z_{IP} is varied when the parameter (capacity threshold) is changed. Denote $\varphi1$ and $\varphi2$ as the thresholds for the node constraint and the link constraint, respectively. The link constraint affects the total cost more significantly than the node constraint. For the link constraint ($\varphi2$), the effect on the cost is more significant with the decreasing threshold (4.4%) than the increasing threshold (-2%).

5. Conclusion

5.1. Research contributions

Because of ever-growing user demand and advances in technology, CDMA has received increasing attention in recent years. However, it is still a challenge for system planners, managers and administrators to plan and manage such complex systems in an efficient and effective way. To address this issue, we propose an integrated planning model for survivable CDMA networks. The model considers the following issues jointly: (1) wireline network issues: topology design and link capacity management; (2) cellular network issues: cell/BS planning (site selection), cell/BS coverage (power transmission radius), sectorization (BS configuration), and survivability; and (3) CDMA issues: uplink/downlink SIR analysis, voice/data traffic, and bandwidth allocation (the hybrid F/CDMA scheme).

We highlight the following findings. With an increasing traffic load, more expenditure is required to provide sound service, subject to a pre-defined capacity constraint. The proposed model and solution approach yield a better solution quality as the system load increases. With regard to the computational results, the cost of providing network survivability in the planning stage is 45% more than that of non-survivability. The proposed LR approach outperforms the SA algorithm, with a cost improvement of 60%. In addition, the link constraint is more important to the total cost than the node constraint. Given a link constraint, the cost is affected more significantly by a decreasing threshold than by an increasing threshold. Thus, the threshold value should be set appropriately. If the right hand-sides (thresholds) of the capacity constraints for both nodes and links are given very large values, the proposed planning model also uses such values for a desert scenario. In other words, the nodes as well as the links can be assigned as much capacity as necessary after the planning stage. Generally speaking, the model directs network planning as well as capacity management to meet the requirements of CDMA-based 3G systems.

5.2. Managerial implications

Network planning is a complex task that has to meet many system requirements. A quite common requirement is the necessity to trade off all design objectives against one another, while respecting their individual importance. The solution to the planning problem requires a large number of algorithms, each of which focuses on a problem with specific constraints. When the survivability issue is considered in the planning stage, the cost is lower than that of deploying redundant equipment in each BS. We also consider capacity management in links and nodes. The proposed model is not only a valuable reference for network planning in a new field (desert scenarios), but also fits the planning requirements when some equipment pre-exists (embedded scenarios). This is because we give a constant value to several decision variables, so the model is adaptable to various scenarios. We consider link and node constraints that fit the requirements for embedded systems. With increasing traffic, the planning costs are higher, which indicates that capacity needs to be expanded to meet the scenario of constantly increasing traffic. It is noteworthy that the proposed model provides survivability in the network planning stage. With regard to capacity management, the link constraint affects the total planning cost more significantly than the node constraint. Thus, cell planning that addresses MS coverage as well as topological design plays an important role in an integrated network planning problem.

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References

Ali, S. Z. (2002). An efficient branch and cut algorithm for minimization of number of base stations in mobile radio networks. In *Proceedings of IEEE PIMRC* (Vol. 5, pp. 2170–2174).

Amaldi, E., Capone, A., & Malucelli, F. (2003). Planning UMTS base station location: Optimization models with power control and algorithms. *IEEE Transactions on Wireless Communications, 2*(5), 939–952.

Binzer, T., & Landstorfer, F. M. (2000). Radio network planning with neural networks. In *Proceedings of IEEE VTC-Fall* (Vol. 2, pp. 811–817).

Bose, R. (2001). A smart technique for determining base-station locations in an urban environment. *IEEE Transactions on Vehicular Technology, 50*(1), 43–47.

Castañeda-Camacho, J., Uc-Rios, C. E., & Lara-Rodríguez, D. (2003). Reverse link Erlang capacity of multiclass CDMA cellular system considering nonideal antenna sectorization. *IEEE Transactions on Vehicular Technology, 52*(6), 1476–1488.

Choi, W., & Kim, J. Y. (2001). Forward-link capacity of a DS-CDMA system with mixed multirate sources. *IEEE Transactions on Vehicular Technology, 50*(3), 737–749.

Chu, K. C., Hung, L. P., & Lin, F. Y. S. (2009). Adaptive channel reservation for call admission control to support prioritized soft handoff calls in a cellular CDMA system. *Annals of Telecommunications, 64*(11–12), 777–791.

Chu, K. C., & Lin, F. Y. S. (2004). Network planning and capacity management considering adaptive sectorization in survivable FDMA–CDMA systems. In *Proceedings of IEEE APCCAS* (pp. 465–468).

Chu, K. C., & Lin, F. Y. S. (2006). Survivability and performance optimization of mobile wireless communication networks in the event of base station failure. *Computers and Electrical Engineering, 32*(1–3), 50–64.

Chu, K. C., Lin, F. Y. S., & Wang, C. S. (2010). Modeling of adaptive load balancing with hybrid FCDMA and sectorization schemes in mobile communication networks. *Journal of Network and Systems Management, 18*(4), 395–417.

Chu, K. C., Wang, C.-S., & Lin, F. Y. S. (2010). An admission control-based benefit optimization model for mobile communications: the effect of a decision time budget. *Journal of Network and Systems Management, 18*(2), 169–189.

Chuprun, S., & Bergstrom, C. S. (1998). Comparison of FH/CDMA and DS/CDMA for wireless survivable networks. In *Proceedings of IEEE GLOBECOM* (Vol. 3, pp. 1823–1827).

Duque-Anton, M., Kunz, D., & Ruber, B. (1993). Channel assignment for cellular radio using simulated annealing. *IEEE Transactions on Vehicular Technology, 42*(1), 14–21.

Eng, T., & Milstein, L. B. (1994). Comparison of hybrid FDMA/CDMA systems in frequency selective Rayleigh fading. *IEEE Journal on Selected Area in Communications, 12*(5), 938–951.

Garg, N., Simha, R., & Xing, W. (2002). Algorithms for budget-constrained survivable topology design. In *Proceedings of IEEE ICC* (Vol. 4, pp. 2162–2166).

Ghashghai, E., & Rardin, R. L. (2002). Using a hybrid of exact and genetic algorithms to design survivable networks. *Computers and Operations Research, 29*(1), 53–66.

Hamidian, K., & Payne, J. (1997). Performance analysis of a CDMA/FDMA cellular communication system with cell splitting. In *Proceedings of IEEE ISCC* (pp. 545–550).

Hanly, S., & Mathar, R. (2002). On the optimal base-station density for CDMA cellular networks. *IEEE Transactions on Communications, 50*(8), 1274–1281.

Hao, Q., Soong, B.-H., Gunawan, E., Ong, J.-T., Soh, C.-B., & Li, Z. (1997). A low-cost cellular mobile communication system: A hierarchical optimization network resource planning approach. *IEEE Journal on Selected Areas in Communications, 15*(7), 1315–1326.

Huang, X., Behr, U., & Wiesbeck, W. (2000). Automatic base station placement and dimensioning for mobile network planning. In *Proceedings of IEEE VTC-Fall* (Vol. 4, pp. 1544–1549).

Hurley, S. (2002). Planning effective cellular mobile radio networks. *IEEE Transactions on Vehicular Technology, 51*(2), 243–253.

Jeon, W. S., & Jeong, D. G. (2001). Call admission control for mobile multimedia communications with traffic asymmetry between uplink and downlink. *IEEE Transactions on Vehicular Technology, 50*(1), 59–66.

Jeon, W. S., & Jeong, D. G. (2002). Call admission control for CDMA mobile communications systems supporting multimedia services. *IEEE Transactions on Wireless Communications, 1*(4), 649–659.

Kaufman, J. S. (1981). Blocking in a shared resource environment. *IEEE Transactions on Communications, 29*(10), 1474–1481.

Kim, W. S. & Prabhu, V. K. (1998). Enhanced capacity in CDMA systems with alternate frequency planning. In *Proceedings of IEEE ICC* (Vol. 2, pp. 973–978).

Kim, D., & Jeong, D. G. (2000). Capacity unbalance between uplink and downlink in spectrally overlaid narrow-band and wide-band CDMA mobile systems. *IEEE Transactions on Vehicular Technology, 49*(4), 1086–1093.

Kim, S. W., Jeong, D. G., Jeon, W. S., & Choi, C.-H. (2002). Forward link performance of combined soft and hard handoff in multimedia CDMA systems. *IEICE Transactions on Communications, E85-B*(7), 1276–1282.

Lee, C. Y., & Kang, H. G. (2000). Cell planning with capacity expansion in mobile communications: A tabu search approach. *IEEE Transactions on Vehicular Technology, 49*(5), 1678–1691.

Lee, C. Y., Kang, H. G., & Park, T. (2002). A dynamic sectorization of microcells for balanced traffic in CDMA: Genetic algorithms approach. *IEEE Transactions on Vehicular Technology, 51*(1), 63–72.

Liberti, J. C., & Rappaport, T. S. (1994). Analytical results for capacity improvements in CDMA. *IEEE Transactions on Vehicular Technology, 43*(3), 680–690.

Medhi, D. (1994). A unified approach to network survivability for teletraffic networks: Models, algorithms and analysis. *IEEE Transactions on Communications, 42*(2–4), 534–548.

Merchant, A., & Sengupta, B. (1995). Assignment of cells to switches in PCS networks. *IEEE/ACM Transactions on Networking, 3*(5), 521–526.

Pierre, S., & Houeto, F. (2002). A tabu search approach for assigning cells to switches in cellular mobile networks. *Computer Communications, 25*(5), 464–477.

Saraydar, C. U., & Yener, A. (2001). Adaptive cell sectorization for CDMA systems. *IEEE Journal on Selected Areas in Communications, 19*(6), 1041–1051.

Snow, A. P., Varshney, U., & Malloy, A. D. (2000). Reliability and survivability of wireless and mobile networks. *IEEE Computer, 33*(7), 49–55.

Takeo, K., Sato, S., & Ogawa, A. (1999). A base station selection technique for up/downlink in CDMA systems. In: *IEEE VTC-Spring* (Vol. 3, pp. 1804–1808).

Tutschku, K. (1998). Demand-based radio network planning of cellular mobile communication systems. In *Proceedings of INFOCOM* (Vol. 3, pp. 1054–1061).

Tutschku, K., & Tran-Gia, P. (1998). Spatial traffic estimation and characterization for mobile communication network design. *IEEE Journal on Selected Areas in Communications, 16*(5), 804–811.

Wang, W., & Rushforth, C. K. (1992). An adaptive local-search algorithm for the channel-assignment problem. *IEEE Transactions on Vehicular Technology, 45*(3), 459–466.

Wibisono, G., & Darsilo, R. (2001). The effect of imperfect power control and sectorization on the capacity of CDMA system with variable spreading gain. In *Proceedings of IEEE PACRIM* (Vol. 1, pp. 31–34).

Wu, J.-S., Chung, J.-K., & Sze, M.-T. (1997). Analysis of uplink and downlink capacities for two-tier cellular system. *IEE Proceedings – Communications, 144*(6), 405–411.

Zhuge, L., & Li, V. O. K. (2002). Reverse-link capacity of multiband overlaid DS-CDMA systems. *Mobile Networks and Applications, 7*(2), 101–113.

Zhuge, L., & Li, V. O. K. (2003). Overlaying CDMA systems with interference differentials. *Mobile Networks and Applications, 8*(3), 269–278.