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A Sequential Routing Algorithm in Virtual Circuit Networks Considering Realtime Admission Control

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Abstract

In this paper, we study the problem of sequential routing problem for multiple-connectivity M/G/m/m networks. In general, there is a trade-off between quality of service, the implementation complexity of admission control, and system performance. Under the assumption of given average traffic demands and candidate routes for each origin-destination pair, we propose a sequential routing algorithm to determine realtime connection-setup sequence for reliable multiple-connectivity networks to optimize total system call-blocking rate.

The emphasis of this work is to develop a centralized sequential routing policy to support distributed realtime admission control for optimizing total revenue of generic M/G/m/m networks purpose. We formulate this algorithm as a combinatorial optimization problem, where the objective function is to minimize the average system call-blocking rate. For considering realtime admission control purpose, we decide the routing sequence for each O-D pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. In the computational experiments, we compare the proposed algorithm with the shortest-based heuristic on GTE network. The proposed algorithm can achieve up to 99.99% improvement of the total call-blocking rate. We also apply this algorithm as our kernel and develop a realtime admission control application for reliable wireless networks. That application can achieve up to 99.9% improvement of the total call-blocking rate for admission control applications.

1. Introduction

Due to the rapid growth of communication applications in the world, the reliability property is become a critical issue for any uninterrupted networks. Multiple-connectivity is one promising technique to avoid connection unstable property. For supporting reliable wireless communication network, system designer must well deploy base stations (BSs) and arrange enough spectrum resource to ensure individual connectivity requirement [9]. In this paper, we model a generic M/G/m/m queueing system to accommodate different communication systems by assuming that (1) traffic behaves as Poisson arrival process, (2) Erlang-B formula is used to model M/G/m/m queueing system, and (3) average traffic load is used to estimate realtime traffic load.

Admission control is the acceptance or blocking of call requests [7]. Admission control combined with flow enforcement can support preventive congestion control mechanism to maximize system revenue [6]. In general, there is a trade-off between quality of service, the implementation complexity of admission control algorithms, and system performance.

In this paper, we propose a sequential routing algorithm to decide realtime connection-setup sequence for reliable multiple-connectivity networks. We decide the routing sequence for each O-D pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. The emphasis of this work is to develop a centralized sequential routing policy to support distributed realtime admission control for optimizing long-term system revenue of generic M/G/m/m networks. That is, we apply the proposed sequential routing algorithm as our kernel and combine with fixed channel assignment mechanism to support realtime admission control for reliable wireless networks [4][5].

We formulate this algorithm as a combinatorial optimization problem, where the objective function is to minimize the average system call-blocking rate that represents the loss revenue of systems. This kind of problems is by nature highly complicated and NP-complete. Thus, we apply the Lagrange relaxation approach and the subgradient method to find better feasible solutions.

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 two solution approaches to optimally solve dual problem. In Section IV, several computational experiments will be supported to verify the proposed algorithms. In Section V, we apply the proposed sequential routing algorithm to realtime admission control application. Finally, the conclusion of this paper is in Section VI.

2. Sequential Routing Problem

A. Problem Description

In this chapter, we intend to establish a model to discuss sequential routing problem for generic communication networks. We study how multiple-connectivity property will influence the routing policy and communication grade of service (GoS). We develop a mathematical model to deal with sequential route problem in order to minimize total call-blocking rate in the system.

The system parameters are: (1) candidate set of O-D pairs, (2) candidate paths for each O-D pair, (3) the mean arrival rate of new traffic for each O-D pair, and (4) the capacity assigned for each link. The objective function of this formulation is to minimize the total call-blocking rate of system subject to: (1) single route constraint and (2) sequential routing constraint. We assume that (1) all of paths for each O-D pair are link disjoint, (2) link call-blocking probability is independent with others, (3) overflow traffic also behaves as Poisson arrival process, (4) use Erlang-B formula to model M/G/m/m queueing system, and (5) average traffic load is used to estimate realtime traffic load.

B. Notations

Table 1: Given parameters

Given Parameters	
Notations	**Descriptions**
W	The set of O-D pairs
P_w	The set of paths which can support requirement of OD pair *w*
L	The set of links
S	The set of permutations which belong to integer value
λ_w	The mean arrival rate of new traffic for each O-D pair $w \in W$
c_l	Capacity assigned for link *l*
$\overline{g_l}$	Upper bound of aggregate traffic
δ_{pl}	Indicator function which is 1 if link *l* belongs to path *p* and 0 otherwise
$d(c_l, g_l)$	Blocking probability of link *l* which is a function of traffic demand g_l and link capacity c_l

Table 2: Decision variables

Decision Variables	
Notations	**Descriptions**
b_{wl}	Blocking probability of link *l* which is referenced by O-D pair *w*
g_l	Aggregate flow on link *l* (in Erlangs)
x_{ps}	Routing decision variable which is 1 if path $p \in P_w$ is selected as the *s*th candidate path for $w \in W$ and 0 otherwise
B_{ws}	Call-blocking probability for the *i*th candidate path for $w \in W$ which belongs to a limited discrete set $B_{ws} \in K_{ws} = \{0, 0.01, 0.02, ..., \overline{B}_{ws}\}$

C. Program Formulation

Objective function (IP):

$$Z_{IP1} = \min \sum_{w \in W} \left(\lambda_w \prod_{s \in S} B_{ws} \right) \quad \text{(IP)}$$

subject to:

$$\sum_{p \in P_w} x_{ps} \sum_{l \in L} \delta_{pl} b_{wl} = B_{ws} \qquad \forall w \in W, s \in S \quad (1)$$

$$d(c_l, g_l) = b_{wl} \qquad \forall w \in W, s \in S \quad (2)$$

$$\sum_{w \in W} \sum_{p \in P_w} \left(\lambda_w \delta_{pl} \sum_{s \in S} \left(x_{ps} \prod_{k=1}^{s-1} B_{wk} \right) \right) = g_l \qquad \forall l \in L \quad (3)$$

$$\sum_{p \in P_w} x_{ps} = 1 \qquad \forall w \in W, s \in S \quad (4)$$

$$\sum_{s \in S} x_{ps} \le 1 \qquad \forall w \in W, p \in P_w \quad (5)$$

$$x_{ps} = 0 \text{ or } 1 \qquad \forall w \in W, p \in P_w, s \in S \quad (6)$$

$$0 \le B_{ws} \le 1 \qquad \forall w \in W, s \in S. \quad (7)$$

The objective is to minimize the call-blocking rate of total system. Constraint (1) calculates the call-blocking probability. It is reformulated from the original product form of transmission success probability $\prod_{p \in P_w} \left(1 - x_{ps} \prod_{l \in L} \left(1 - \delta_{pl} d(c_l, g_l) \right) \right) = B_{ws}$ to become solvable formulation. Constraint (2) decomposes the call-blocking probability of link *l* by introducing one additional notation b_{wl}. Constraint (3) calculates the aggregate traffic for link *l*.

Constraint (4) enforces only one candidate route can be selected for each O-D pair *w* on each routing sequence. Constraint (5) allows the number of candidate path is larger than the number of routing selection sequence. One path may be selected as a candidate path or not that is dependent by its blocking probability. Constraint (6) enforces the integer property of the decision variable x_{ps}. Constraint (7) enforces the feasible region of call-blocking probability B_{ws}.

3. Solution Procedure

Because the above sequential routing problem is NP-complete, we do not expect to develop an optimal algorithm for large-scale problems. Instead, an efficient Lagrangean-based algorithm, which has been successfully adopted to solve many famous NP-complete problems, is developed in this section.

By using the Lagrangean Relaxation method [1], we relax two complicate constraints. One is non-linear programming problem, which is Constraint (2), and the other is signomial problem, which is Constraint (3). After dualizing these complicating constraints, we can construct the following Lagrangean relaxation problem (LR):

A. Lagrangean Relaxation

For a vector of Lagrangean multipliers, a Lagrangean relaxation problem of IP1 is given by

Objective function (LR):

$$Z_{LR1}(\mu_{wl}^1, \mu_l^2) = \min \sum_{w\in W}\left(\lambda_w \prod_{s\in S} B_{ws}\right)$$

$$+ \sum_{w\in W}\sum_{l\in L}\mu_{wl}^1\left(d(c_l, g_l) - b_{wl}\right)$$

$$+ \sum_{l\in L}\mu_l^2\left(\sum_{w\in W}\sum_{p\in P_w}\left(\lambda_w \delta_{pl}\sum_{s\in S}\left(x_{ps}\prod_{k=1}^{s-1}B_{wk}\right)\right) - g_l\right) \quad \text{(LR)}$$

subject to: (1), (4), (5), (6), and (7).

In this formulation, μ_{wl}^1 and μ_l^2 are Lagrange multipliers. To solve this problem, we can decompose (LR) into the following two independent and solvable optimization subproblems.

Subproblem (SUB1): (related with decision variables B_{ws}, x_{ps}, and b_{wl})

Objective function:

$$Z_{SUB1} = \min \sum_{w\in W}\left(\lambda_w \prod_{s\in S} B_{ws}\right) - \sum_{w\in W}\sum_{l\in L}\mu_{wl}^1 b_{wl}$$

$$+ \sum_{w\in W}\sum_{l\in L}\sum_{p\in P_w}\sum_{s\in S}\left(\mu_l^2 \lambda_w \delta_{pl} x_{ps}\prod_{k=1}^{s-1}B_{wk}\right) \quad \text{(SUB1)}$$

subject to: (1), (4), (5), (6), (7), and

$$\underline{B}_{ws} \le B_{ws} \le \overline{B}_{ws} \qquad \forall w\in W, s\in S, B_{ws}\in K_{ws} \quad (8)$$

$$\underline{b}_{wl} \le b_{wl} \le \overline{b}_{wl} \qquad \forall w\in W, l\in L. \quad (9)$$

Because multiplier μ_l^2 may be positive or negative, 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_{ws} to a discrete set $K_{ws} = \{\underline{B}_{ws}, \underline{B}_{ws}+0.01, \underline{B}_{ws}+0.02, ..., \overline{B}_{ws}-0.01, \overline{B}_{ws}\}$ by introducing an additional Constraint (8) where notations $\underline{B}_{ws}$ and $\overline{B}_{ws}$ are a sensible lower bound and upper bound. According to experience, the upper bound $\overline{B}_{ws}$ 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 paths. The lower bound $\underline{B}_{ws}$ can be determined by only routing the traffic of this O-D pair to candidate path and than calculate the coordinate blocking probability.

As the discrete property of B_{ts}, we can exhaustively search for all possible values of B_{ts} for each permutation *s*. Therefore, decision variable b_{wl} can be determined by multiplier μ_{wl}^1 if link *l* is not one candidate link of O-D pair *w*. To improve dual solution quality, we introduce an additional Constraint (9) to limit decision variable b_{wl} in sensible region. We can describe this situation by

$$b_{wl} = \begin{cases} \overline{b}_{wl}, & \text{if } \sum_{p\in P_w}\sum_{l\in L}\delta_{pl} = 0 \text{ and } \mu_{wl}^1 \ge 0 \\ \underline{b}_{wl}, & \text{if } \sum_{p\in P_w}\sum_{l\in L}\delta_{pl} = 0 \text{ and } \mu_{wl}^1 < 0 \end{cases}$$

If link *l* may be one candidate link of O-D pair, i.e. $\sum_{p\in P_w}\sum_{l\in L}\delta_{pl} = 1$, we can determine its value by maximizing $\sum_{l\in L}\mu_{wl}^1 b_{wl}$ subject to constraint $\sum_{p\in P_w} x_{ps}\sum_{l\in L}\delta_{pl} b_{wl} = B_{ws}$. We can decompose this problem into |*W*| independent subproblems, denoted as (SUB1*w*) and formulate as follows.

Objective function (SUB1*w*):

$$Z_{SUB1w} = \min \lambda_w \prod_{s\in S} B_{ws} - \sum_{l\in L} \mu_{wl}^1 b_{wl}$$

$$+ \sum_{l\in L}\sum_{p\in P_w}\sum_{s\in S}\left(\mu_l^2 \lambda_w \delta_{pl} x_{ps} \prod_{k=1}^{s-1} B_{wk} \right) \qquad \text{(SUB1}w\text{)}$$

subject to: (1), (4), (5), (6), (7), (8), and (9).

We can solve each subproblem by the following steps.

Step 1.	Initial variable *minValue*=MAX_VALUE.
Step 2.	Select one kind of candidate path sequences, assign the associate decision variable $tempX_{ps}$ to equal one and zero otherwise.
Step 3.	Select one feasible set of blocking probability values, which satisfy the feasible region defined by Constraint (8), and assign to temporary set *tempSetB* for each permutation $s \in S$.
Step 4.	For each link *l*, we assign $temp\_b_{wl}$ to equal $\bar{b}_{wl}$ if $\sum_{p\in P_w}\sum_{l\in L}\delta_{pl} = 0$ and $\mu_{wl}^1 \ge 0$. If $\sum_{p\in P_w}\sum_{l\in L}\delta_{pl} = 0$ and $\mu_{wl}^1 < 0$, we assign $temp\_b_{wl}$ to equal $\underline{b}_{wl}$. Otherwise, try to maximize $\sum_{l\in L}\mu_{wl}^1 b_{wl}$ when all of this kind $temp\_b_{wl}$ satisfy $\sum_{p\in P_w} x_{ps}\sum_{l\in L}\delta_{pl} b_{wl} = B_{ws}$.
Step 5.	Under this certain routing sequence $tempX_{ps}$ and blocking probability set *tempSetB*, calculate the objective value of (SUB1*w*). If *tempMin* smaller than *minValue*, we assign x_{ps}, b_{wl}, B_{ws}, and *minValue* to equal $tempX_{ps}$, $temp\_b_{wl}$, $tempB_{ws}$, and *tempMin*, respectively.
Step 6.	Go to Step 3 to exhaustively search other possible set *tempSetB*. If there is no any blocking probability case, go to Step 2 to exhaustively search other routing sequences.

Subproblem (SUB2): (related with decision variable g_l)

$$Z_{SUB2} = \min \sum_{w\in W}\sum_{l\in L}\mu_{wl}^1 d(c_l, g_l) - \sum_{l\in L}\mu_l^2 g_l \qquad \text{(SUB2)}$$

subject to:

$$0 \le g_l \le \bar{g}_l \qquad \forall l \in L. \quad (10)$$

We add a redundant Constraint (10) to improve dual solution quality. We decompose this problem into |*L*| independent sub-problems, denoted as (SUB2*l*) and formulate as follows.

Objective function (SUB2*l*):

$$Z_{SUB2l} = \min -\mu_l^2 g_l + d(c_l, g_l)\sum_{w\in W}\mu_{wl}^1 \qquad \text{(SUB2}l\text{)}$$

subject to (10).

Because c_l is a given parameter, the call-blocking probability function $d(c_l, g_l)$ is a well-know Erlang-B formula that is a convex function of decision variable g_l. If multiple $\sum_{w\in W}\mu_{wl}^1 \ge 0$, problem Z_{SUB2l} becomes a convex function. To minimize objective value, the optimal g_l can be found by using line search technique (e.g. golden section method). Otherwise, if multiple $\sum_{w\in W}\mu_{wl}^1 < 0$, problem Z_{SUB2l} becomes a concave function and the optimal solution will occurs either $g_l = 0$ or $g_l = \bar{g}_l$. The upper bound $\bar{g}_l$ can be determined by function $d(c_l, g_l) = \bar{b}_{wl}$ where $\bar{b}_{wl}$ is an artificial probability threshold for O-D pair *w* being blocked by its candidate link *l*.

B. The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem [2], for any μ_{wl}^1 and μ_l^2, $Z_D = \max Z_{LR}\left(\mu_{wl}^1, \mu_l^2\right)$ is a lower bound of Z_{IP}. The dual problem (D) is then constructed to calculate the tightest lower bound.

Let a ($|W|\times|L|+|L|$)-tuple vector g be a subgradient of problem $Z_{LR}\left(\mu_{wl}^1, \mu_l^2\right)$. In iteration *k* of the subgradient method [3], the multiplier vector $\pi = \left(\mu_{wl}^1, \mu_l^2\right)$ is updated by $\pi^{k+1} = \pi^k + t^k g^k$. The step size t^k is determined by $t^k = \delta \dfrac{Z_{IP}^h - Z_D(\pi_k)}{\left\|g^k\right\|^2}$, where Z_{IP}^h is the primal objective function value from a heuristic solution (an upper bound of Z_{IP}) and δ is a constant between zero and two.

C. Getting Primal Feasible Solution

When we use Lagrange relaxation and subgradient method to solve the problem, we not only get a theoretical lower bound but also get some hints that are helpful for getting primal feasible solutions purpose. Owing to the complexity of the primal problem, we propose two Lagrange-relaxation-based approaches in this section, denoted as Approach 1

■ Approach 1

In this approach, we adopt the coefficient of decision variable x_{ps} in LR dual problem as a hint for initial routing policy. We denote the coefficient as $Coef(x_{ps}) = \lambda_w \prod_{k=1}^{s-1} B_{wk} \times \sum_{l \in L} \left(\mu_l^2 \delta_{pl}\right)$. To minimize the objective value, we arrange x_{ps} for each O-D pair in descending order of $Coef(x_{ps})$ as our initial routing sequence. To tune the routing decision to better result, we also develop a drop-and-add procedure. We specify the detail in the following.

Step 1. Use the results of decision variable x_{ps} as our initial routing policy.

Step 2. Sequential route the associated traffic into the corresponding path and then calculate the call-blocking probability.

Step 3. Arrange O-D pairs in descending order of objective value $\lambda_w \prod_{s \in S} B_{ws}$.

Step 4. Choice the maximum objective value O-D pair as our tuning target and run drop-and-add procedure to exhaustive search the better routing sequence for this O-D pair.

Step 5. Record the decision of Step 4 as our next routing policy. Go to Step 1 for next tuning procedure.

4. Computational Experiments

For comparison purpose, we develop three primal heuristics to solve the same problems.

A. Primal Heuristic

We apply Dijkstra algorithm to find the first s shortest paths for each O-D pair as our candidate path set. We develop four intuitive primal heuristics:

(1) Shortest-path approach (SP): only adopt the sequence of path length as our routing sequence to calculate the total call-blocking rate,

(2) Shortest-random approach (SR): adopt the shortest path as our first routing sequence and random select the second and third routing decision for each iteration,

(3) Full-random approach (FR): all of routing sequences are random selected from candidate path set ,

(4) Exhaust maximum approach (EM): adopt the same drop-and-add procedure as LR-based Algorithm to find maximum objective value of O-D pair as our target one and exhaust its possible routing sequence. For comparison purpose, we develop one primal heuristics to solve the same problems.

B. Lagrange Relaxation Based Algorithm

We deal with this sequential routing problem by solving the LR dual problem to find the lower bound and adopt the LR-based approaches as our LR-based algorithm to find the upper bound of this problem. We describe the detail of LR-based algorithm as following.

Step 1. Read network file to construct links, capacity and nodes.

Step 2. Random generate required number of O-D pairs. Apply Dijkstra's algorithm to find *s* candidate paths and traffic load. Input the maximum iterations and assign Lagrange relaxation improvement counter to equal 40.

Step 3. According to given multipliers, optimally solve the LR subproblems of SUB1 and SUB2 to get the value of Z_D.

Step 4. According to two LR-based approach, Approach 1, get primal feasible solutions, denoted as *LR*. The objective value is denoted as Z_{IP}.

Step 5. If Z_D is larger than Z_D*, we assign Z_D* to equal Z_D as our best lower bound. If Z_{IP} is smaller than Z_{IP}*, we assign Z_{IP}* to equal Z_{IP} as our best upper bound. Otherwise, we minus one from the improvement counter.

Step 6. Adopt subgradient method to calculate the subgradient vector and determine the step size in order to adjust Lagrange relaxation multipliers.

Step 7. Increase iteration counter by one. If interaction counter is over threshold of system or the solution procedure is converged, stop this program and Z_{IP}* is our best feasible solution., Otherwise, go to Step 3 to repeat the next iteration.

C. Experiment Scenarios

In the computational experiments, we test the proposed algorithms for efficiency and effectiveness.

The test network is the GTE network, which contains 12 nodes with 50 directed links and is depicted in Figure 1. We randomly generate 20 O-D pairs and apply Dijkstra's algorithm to find the first three candidate shortest paths for each O-D pair. The average traffic load of each O-D pair is 20 Erlangs when the capacity of each link is 100 trunks. Under an average traffic load environment, we also random generate four test scenarios with different traffic distribution, denoted as Run 1 to 4.

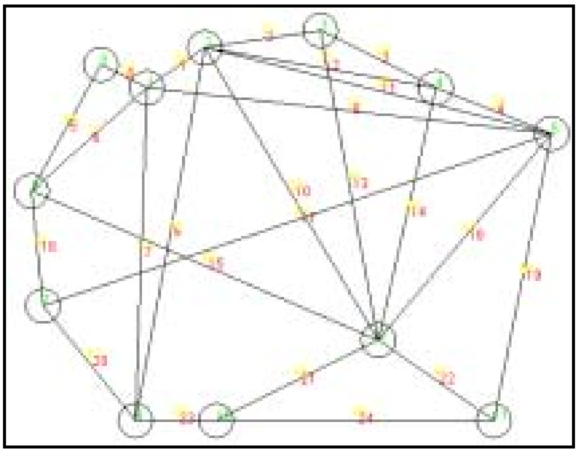

Fig. 1: The GTE network

D. Experiment Results

We list the experiment results of primal heuristics in Table 3 and the results of LR-based algorithm in Table 4 The one routing sequence case (s=1) is not necessary because only the shortest path can be choice for each O-D pair. In Table 3, we depict the results of three primal heuristics, *SP*, *SR*, and *FR*. We can observe that the best case of *FR* always achieve better result than others, but the average and worst case of *FR* are worse. On the average, *EM* can achieve better result than other primal heuristics.

We can observe that the total system performances of multiple-connectivity cases are greater than that of single connectivity cases. When we adopt multi-connectivity concept, the proposed *LR* can achieve better system performance than the four primal heuristics. Specifically, although the *EM* is the best primal approach, the proposed LR-based algorithm *LR* can achieve 99.99 % improvement from the result of *EM*.

E. Computational Time

All the experiments are performed on a Pentium IV 2.0 GB PC with 1 GB DRAM running Microsoft Windows 2000 Server. The program is implement by pure C language. Each run is initially performed 2000 iterations to get the best solution. On the average, each experiment only take about 1500 iterations to converge to the final solution when the improvement counter is initiated by 40. The computational time, listed in the last column of Table 4, is the total time (seconds) for 1000 iterations.

5. An Application of Sequential Routing Mechanism

A. Realtime Admission Control

For channelized wireless systems, flow enforcement mechanisms must cooperate with channel assignment to pre-allocate precious spectrum resource for supporting communication services. Channel allocation schemes can be divided into two kinds: fixed channel allocation (FCA) and dynamic channel allocation (DCA). In general, FCA strategies are more efficient under high load conditions than DCA but provide less flexibility and traffic adaptability. Therefore, our realtime distributed admission control does not cooperate with DCA but with sequential routing based FCA mechanism in our previous paper [5].

We apply the proposed sequential routing algorithm as our kernel to determine homing sequences and together apply FCA mechanism to achieve efficient of channel resources. Admission control is source-driven. That is, mobile terminals initial the call setup phase and inspect the QoS feasibility of candidate homes sequentially. These admittance computations are avoided at intermediate nodes to support distributed and realtime characteristics. Therefore, we intend to pre-determine the homing sequence for each mobile off-line. Another design philosophy behind the construction of the algorithm is that the speed of the decisions is more important than how close the solution is to an optimal solution [7].

The emphasis of that work is to develop a centralized sequential routing algorithm together with FCA scheme to support realtime distributed admission control. We extend the sequential routing algorithm to formulate the admission control problem for reliable wireless networks. The objective function is to minimize the total call-blocking rate, which represents the long-term loss revenue of the system, subject to configuration, sequential routing, and grade-of-service (GoS) constraints. The configuration constraints require that the assigned channels for each sector be admissible. Whereas, the GoS constraints require that the call-blocking probability constraint for each sector and CIR constraint received by each mobile terminal must be satisfied.

B. Computational Experiments

In the computational experiments, we randomly generate a sectorization wireless network topology as our experiment environment. In this topology, there are 5 BSs constructed by 15 smart antenna to service 20 MT clusters under the GSM-like situation that frequency (f_c) is on 900 MHz, bandwidth (*W*) is 12.5 MHz, CIR (γ) is 9 dB, average MT height (h_m) is between 1 m to 10 m, average BS height (h_b) is between 30 m to 200 m. For comparison purpose, we also develop a power dominant heuristic (Heuristic *H*) to compare with the proposed algorithm (Algorithm *A*) on test networks. In these experiments, we can observe that as the traffic load increasing, Algorithm *A* can achieve feasible solution but Heuristic *H* cannot. Furthermore, the proposed Algorithm *A* achieved average up to 99.9% improvement of the total call-blocking rate. We depict the experiment results of admission control application, which use sequential routing algorithm, in Table 5 [5].

6. Conclusion

To achieve long-term performance optimization, centralized resource allocation and routing arrangement are critical mechanisms for complicate communication systems. In this paper, we study the key issues of sequential routing problem for multiple-connectivity M/G/m/m networks about the trade-off between quality of service and system performance.

Under the assumption of given average traffic demands and candidate routes for each O-D pair, we propose a sequential routing algorithm to decide realtime connection-setup sequence for reliable multiple-connectivity networks. We formulate this algorithm as a combinatorial optimization problem, where the objective function is to minimize the average system call-blocking rate. Because this problem is NP-complete, we apply an efficient Lagrangean-based algorithms to solve large-scale problems.

The emphasis of this work is to develop a centralized sequential routing policy to support distributed realtime admission control for well-designed multiple-connectivity communication networks. That is, we successfully apply this algorithm as our kernel and develop a realtime admission control application for reliable wireless networks. We decide the routing sequence for each O-D pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. The routing information can be used to process admission control, resource allocation, connection-setup, and QoS assurance. In these computational experiments, the proposed Lagrangean-based algorithms achieved average up to 99.99% improvement of the total call-blocking rate at both sequential routing problem and admission control problem.

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Table 3. Experiment results of three primal heuristics

λ_w	S	R	*SP*	*SR*			*FR*		
				Best	Average	Worst	Best	Average	Worst
20	2	1	1.5579e-002	1.5579e-002	1.5579e-002	1.5579e-002	6.1999e-006	2.9950e-001	2.2277e+000
20	2	2	2.4317e-001	2.4317e-001	2.4317e-001	2.4317e-001	9.8821e-004	6.6257e-001	2.7804e+000
20	2	3	3.0744e-007	3.0744e-007	3.0744e-007	3.0744e-007	5.8066e-007	2.8898e-001	2.4938e+000
20	2	4	1.5235e-007	1.5235e-007	1.5235e-007	1.5235e-007	3.2101e-00	1.2964e-001	2.1542e+000
20	3	1	1.9211e-007	5.6828e-009	5.5732e-008	1.9565e-007	3.3025e-008	1.0514e-002	1.5558e-001
20	3	2	2.7428e-007	2.5825e-008	1.3722e-007	2.9255e-007	2.1094e-007	5.2667e-002	4.3360e-001
20	3	3	6.1668e-014	6.1668e-014	6.2618e-014	6.3307e-014	1.5948e-008	1.9961e-002	2.6586e-001
20	3	4	3.1639e-014	3.0001e-014	3.0853e-014	3.1639e-014	1.5164e-013	9.0511e-003	8.9728e-002

Table 4. Experiment results of primal heuristics *EM* and LR-based algorithm

λ_w	S	Run	*LB*	Gap	*EM*	*LR*	Improvement	Time
20	2	1	3.8882e-007	164.35%	2.0062e-003	1.0278e-006	99.95%	352
20	2	2	3.8907e-007	140.51%	5.2602e-003	9.3573e-007	99.98%	335
20	2	3	2.1794e-010	69843.48%	3.0477e-007	1.5244e-007	49.98%	328
20	2	4	3.0062e-011	499.98%	1.4958e-007	1.8037e-010	99.88%	334
20	3	1	4.7047e-017	15771.25%	7.4822e-015	7.4669e-015	0.20%	821
20	3	2	4.6274e-013	154.30%	9.5394e-009	1.1767e-012	99.99%	812
20	3	3	3.0684e-022	179379.93%	5.7293e-019	5.5071e-019	3.88%	807
20	3	4	5.5059e-018	905.42%	1.3055e-015	5.5357e-017	95.76%	820

Table 5. Experiment results for Admission Control Application [5]

Case	Areas [10]	Δi [8]	λ_t	Algorithm *A*	Heuristic *H*	Improvement (*H*-*A*)/*H**100%
1	open	50	2	8.4781 e-10	1.1600 e-04	99.9%
2	open	100	2	5.8552 e-19	8.2101 e-04	100%
3	open	200	2	2.6054 e-13	1.0501 e-02	100%
4	open	300	2	2.6515 e-04	1.7376 e-01	99.8%
5	open	50	5	6.6102 e-03	9.0580 e-01	99.2%
6	open	100	5	3.2364 e-09	9.6843 e-01	99.9%
7	open	200	5	2.0477 e-03	3.0707 e+00	99.9%
8	open	300	5	5.0930 e+00	N/A	---
9	open	100	10	1.7254 e-07	N/A	---
10	open	200	10	5.4591 e+00	N/A	---