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# Reliability Optimization for 3G Cellular Access Networks

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***Abstract*****—**This paper address the network reliability optimization problem in the optical access network design for the 3G cellular systems. We presents a novel 0-1 integer programming model for designing optical access network topologies comprised of multi-rings with common-edge in order to guarantee always-on services. The results show that the proposed model yields access network topologies with the optimal reliablity and satisfies both network cost limitations and traffic demand requirements.

***Keywords*****—** Network Reliability, Topological Network Design, 3G Cellular Networks.

## I. Introduction

THIRD-generation (3G) cellular networks are being deployed throughout the world to support voice, data, and multimedia services at high communication speed. To provide always-on services, network designers must pay special attention on network reliability issues, especially the reliability of the access network topology [1].

In the 3G network topology as shown in Fig. 1, a set of radio access network subsystems (RNS) connecting to the core network (CN) which consists of Mobile Switching Center (MSC), Media Gateway (MGW), serving GPRS (General Packet Radio Service) support node (SGSN) and gateway GPRS support node (GGSN). Each RNS consists of a radio network controller (RNC) which controls the radio resources and services and one or more access points called Node B or radio base stations (RBS). Each RBS transmits/receives data traffic to/from mobile stations (MS) in the cell site. These traffic demands go through a set of links in the optical access networks which interconnect RBS and RNC. The traffic demands are aggregated at the RNC and then passed to the higher capacity links in the core networks. The networks are designed around several different variables. Two of the most essential factors which network designers need to take into account when designing networks are service and cost of the networks. Service is a necessary factor to maintain customer satisfactions. Cost is also an inevitable factor to maintain profitability. To overcome the factors, network designers need well-designed network topologies to properly size network capacity as the networks grow and guarantee the quality of the services in the 3G cellular networks.

The network designers aim to interconnect all components in the 3G cellular networks and ensure that they remain connected in case of a variety of network failures may occur [1]. The quality of the networks protect against the failures is termed network reliability. Network reliability is characterized by either the node functionality or the operational probability of the links among all nodes. To compute network reliability, every operational state of the network which all nodes are connected is mathematically considered [2].

Since different network topologies yield different values of network reliability, the problem of optimal network topology design on the issue then arises. Several works existing in literature address the physical network design by finding minimized network cost. D. Devaraj and S. Veerakumar proposed the formulation of minimum spanning tree topology and genetic algorithm to design minimum network cost. The spanning tree topology, however, is vunerlable to links failure and also gives the minimum network reliability [3]. C. Charnsripinyo and N. Wattanapongsakorn proposed the formulation of multi-rings with common-node topology for the wireless access network design and mixed-integer programming model to minimize network cost [4]. In such topology type, two rings are interconnected at one node which is the vulnerable point of failure. A. Billionnet, S. Elloumi and

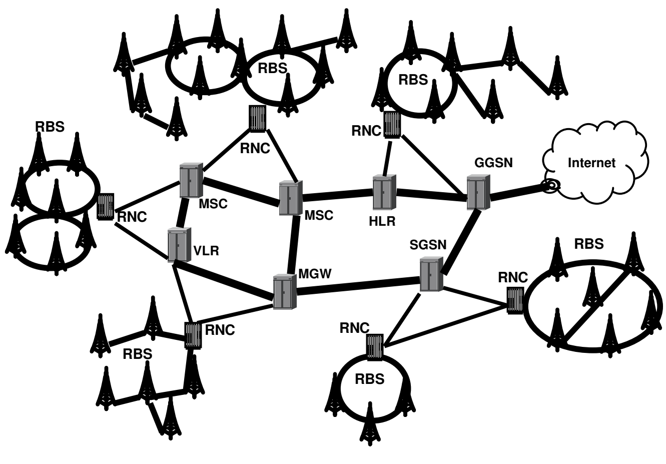


Fig.1 3G cellular network topology

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L. G. Djerbi proposed the radio access network design based on synchronous hierarchy rings and the formulation of mixed-integer programming model to minimize network cost [5]. H. Luss et al. proposed the multi-rings with common-edge topology for the SONET ring architecture, using a heuristic algorithm to minimize network cost [6]. The minimum-cost approach, however, is not suitable for the optical access network design with the reliable service requirements.

In this paper, we focus on the optical access networks of the 3G cellular network which is relatively sparse networks. We propose a novel access network design that aims to optimize reliability of the optical access network based on the multi-rings with common-edge topology because of its high reliability against a single link and single node failure [6]. The design problem is formulated as a 0-1 integer programming model, which maximizes total network reliability by maximizing the number of rings used in the network and selects the proper type of the node equipment in order to be able to accommodate traffic demand requirements within the access network. Furthermore, the proposed design model considers the network cost as one of several design constraints.

The rest of the paper is organized as follows. Section II defines notation used in the proposed model and presents the access network design formulation as the 0-1 integer programming model. In section III, we present the network reliability analysis and describe the reliability model. Section IV shows numerical results from real access network study cases and provide discussion on the efficiencies of the propose design model. Finally, section V provides conclusion and describes on-going work.

## II. Optical Access Network Design Model

Given a set of optical nodes at RBS in the cellular access network and a set of existing fiber links that connect such nodes, the problem is to select an optimal subset of rings from a set of candidate rings using only existing fiber links such that each node is included in the access network and each selected ring is connected to at least one other ring at one or more links. The selected rings then form the multi-ring with common-edge network topology. Such a multi-ring network will ensure the service reliability in case of a single link or single node failure. In addition, our problem select equipment type for each optical node at RBS based on the amount of traffic demand generated from member of nodes in the ring. The selection of rings and the node equipment types are done under the network cost limitation and the traffic demand requirements.

In order to formulate the optical access network design problem, we use the following notation.

***Notation:***

$N$ number of optical nodes at RBS
$R$ number of candidate rings
$E$ number of equipment types
$i$ denotes the set of indices of nodes, $i \in I = \{1, \ldots, N\}$
$j$ denotes the set of indices of candidate rings, $j \in J = \{1, \ldots, R\}$
$k$ denotes the set of indices of equipment types, $k \in K = \{1, \ldots, E\}$
$T_i$ traffic demand at node $i$ (E1)
$rc_j$ cost of candidate ring $j$
$ec_k$ cost of equipment type $k$
$cap_k$ capacity of equipment type $k$ (E1)
$NC$ total network cost
$n_{ij}$ = 1 if node $i$ is in a candidate ring $j$, and 0 otherwise.
$r_j$ = 1 if candidate ring $j$ is selected and 0 otherwise.
$t_{ik}$ = 1 if equipment type $k$ is selected for node $i$, and 0 otherwise.

The cellular access network design problem for the 3G cellular system can be formulated as follows:

***Objective:***

$$\text{maximize} \sum_{j \in J} r_j \qquad (1)$$

subject to

$$\sum_{j \in J} n_{ij} r_j \geq 1 \quad , \forall i \in I \qquad (2)$$

$$\sum_{j \in J} rc_j r_j + \sum_{i \in I} \sum_{k \in K} ec_k t_{ik} \leq NC \qquad (3)$$

$$\sum_{k \in K} cap_k t_{ik} \geq T_i \ , \forall i \in I \qquad (4)$$

$$\sum_{k \in K} t_{ik} = 1 \quad , \forall i \in I \qquad (5)$$

$$n_{ij}, r_j, t_{ik} \quad \in \{0,1\} \qquad (6)$$

The objective function (1) is to maximize the number of rings used in the access network topology in order to achieve the highest network reliability. Constraint (2) guarantees that every node is connected to the network. Constraint (3) ensures that the cost of selected rings and the cost of selected node equipments do not exceed the total network cost. Constraint (4) ensures that the capacity of the equipment type of each node can accommodate the traffic demand generated from each node. Constraint (5) specifies that each node can select only one equipment type. Constraint (6) is the binary decision variables.

## III. Network Reliability Analysis

Network topology is a physical configuration of a network that determines how the nodes and links are connected. The reliability analysis predicts the operational performance and evaluates a measure of the performance of the network topology to ensure all nodes in the network remain connected when link failures may occur. The reliability of the network is modeled by a probabilistic graph $G=(V,E)$, in which $V$ is the set of nodes, and $E$ is the set of links. We assume that all nodes are perfectly reliable but links may work with the probability

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of $p$ or fail with the probability of $q=(1-p)$. All link failures are assumed to occur independently of one another. The unavailable state ($\Omega_i$) is defined as the probability of each $i$-th event that causes all nodes in the networks cannot communicate to one another while links in the networks fail [7]. Let $l \subseteq L$ be the set of operational links, $l \subseteq L'$ be the set of fail links, and $n=|V|$ be the number of nodes. We determine $k_i$ as the coefficient of unavailability of the $i$-th state which is defined by the combination $C_{n,i}$. The network reliability of the graph $G$, denoted by $R(G)$, can be mathematically written as follows:

$$R(G) = 1 - \left( \sum_{\Omega_i} k_i (\prod_{l \subseteq L'} q)(\prod_{l \subseteq L} p) \right) \tag{7}$$

Let us first review the existing network reliability models. Jan [2] presented the reliability model for the single ring ($G_r$) as:

$$R(G_r) = p^n + np^{n-1}(1-p) \tag{8}$$

In this paper, we consider the unavailable state, $\Omega_i = n-1$ , that cause the network failures for a ring topology with $n$ nodes and let $j$ be the number of operational links in the $\Omega_i$ state. For instance, we have a single ring with 4 nodes shown in Fig. 2; we can categorize the ring into three unavailable states. The first state ($\Omega_1$,$j=0$) is when all four links fail, the second state ($\Omega_2$,$j=1$) is when three links fail while one link is operational, and the third state ($\Omega_3$,$j=2$) is when two links fail while two links are operational.

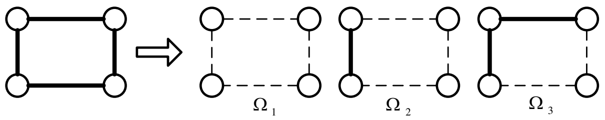


Fig. 2 the unavailable state example

We can rewrite the reliability of the single ring topology with $n$ nodes in the form of equation (10) as follows:

$$R(G_r) = 1 - \left( \sum_{\forall i} \Omega_i \right) \tag{9}$$

$$R(G_r) = 1 - \left( \sum_{j=0}^{n-2} \frac{n!}{(n-j)!\,j!} q^{n-j} p^j \right) \tag{10}$$

C. Charnsripinyo and N. Wattanapongsakorn proposed to use multiring network topology for the reliable wireless network design problem [4]. Therefore, assuming that the design problem is solved and we obtain a set of $m$ selected rings. The total reliability model of the solution can be written as follows:

$$R_{total}(G) = 1 - \left( \prod_{\forall m} (1 - R_m(G_r)) \right) \tag{11}$$

Where $m$ is the amount of selected rings obtained by (1).

## IV. Numerical Results and Discussion

In this section, we present numerical results of solving the network design problem. We consider a practical network from a service provider which contains a set of 12 nodes at RBS in the cellular access network and a set of existing fiber links that connect such nodes as shown in Fig 3. The problem is to select an optimal subset of rings from a set of candidate rings using only existing fiber links such that each node is included in the access network and each selected ring is connected to at least one other ring at one or more links. Such the multi-ring network will ensure the service reliability in case of a single link or single node failure. Each link has the operational probability of 0.9 ($p=0.9$), so the unavailable probability is 0.1 ($q=1-p$). We assume that all nodes are perfectly reliable. The network reliability depends only on the operational probability of fiber links among all nodes. The optical cable cost is calculated at rate 25 unit/2-core fiber/Km which is the practical rental rate from an optical cable network provider, and the total network cost ($NC$) is the summation of the optical cable cost ($rc_j$) and the equipment cost ($ec_k$).

We also give the cost of three different types of network equipment ($E=3$) with the capacity ($cap_k$). The cost of equipment is based on the practical equipment rate of a network supplier as shown in Table I and the traffic demands at each node, $T_i$, which are based on the practical data from the network provider required at each node is shown in Table II.

We first generate a set of candidate rings topology ($R=39$) using ring-generation procedures described in [6]. By equation (10), we obtain the network reliability of each ring, and approximate the ring cost based on the number of nodes in the ring and the length of fiber constituted the ring as shown in Table V.

The problem is to select an optimal subset of rings from a set of candidate rings using only existing fiber links such that each node is included in the access network and each selected ring is connected to at least one other ring at one or more links. The selected rings then form the multi-ring with common-edge network topology. Such a multi-ring network will ensure the service reliability in case of a single link or single node failure.

We input the set of candidate rings and the associated ring cost to the proposed 0-1 integer programming problem. We then solve the optical access network design by implementing with ILOG OPL development studio and solving with CPLEX 5.2 optimization solver. Computations are performed on an Intel Centrino Core2 Duo Processor 1.83GHz and 1GB of RAM.

In the experiment, we obtain the minimum network cost from [6]. We then consider five total network cost constraints which are 11000, 21000, 31000, 41000 and 51000 units. Table IV shows the results of solving the network topology design problem of the given sample network with different total network cost. The total reliability of the multi-ring with common-edge topology problem obtained by using (11) is shown in Table IV. Table III shows the result of equipment type required at each node.

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The ITU-T recommendations G.801, G.821, and G.826 define error performance and availability objectives that the access networks should be engineered with appropriate protection schemes so that short- or long-term outages are tolerated [8]. And reliabilities should be acceptable, perhaps approaching 99.99% or about 3600 outage seconds per year (SES/yr). To comply the recommendation, the multi-ring with common-edge topology is assigned to optimize the reliability of the networks.

As the result in Table IV, with the total reliability of solution 1 from Table IV, the outage time is 0.0074 SES/yr, for instance. The reliability of the network increases when the numbers of selected rings increase. The increasing reliability of the network, therefore, decreases the outage time of the network.

## V. CONCLUSION

In this paper, we proposed the reliability optimization problem for 3G cellular access network design. We formulated the design problem as a 0-1 integer programming model. The model aims to optimize the network reliability and select the proper equipment type at each node that accommodates traffic demands and satisfies the cost constraints. From the extensive study, we found interesting relationship between the number of rings used in the access network and the network service reliability. With the limitation of network cost considered in each study case, our approach can find the optimal set of rings that yields the highest network reliability and satisfy the traffic demand requirements. In the future, dynamic traffic demands are added into the network and the network become more complex because IP technology is indispensable to modern network design. The ongoing work is to formulate an optimal IP network design model and find an effective heuristic approach to solve the larger IP network design problem.

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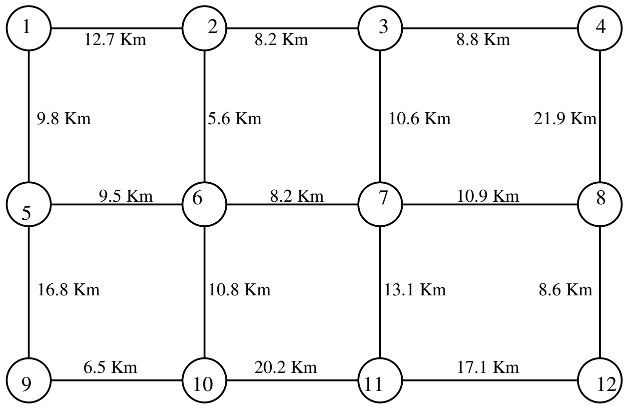


Fig. 3 sample network

TABLE I
THE SAMPLE NETWORK EQUIPMENT COST SET

| Equipment Type($k$) | Number of Capacity ($cap_k$) (E1) | Equipment Cost ($ec_k$)(unit) | Installation Cost (unit) |
|---|---|---|---|
| STM-1 Type1 | 63 | 500 | 1500 |
| STM-1 Type2 | 21 | 250 | 600 |
| STM-1 Type3 | 7 | 150 | 300 |

TABLE II
TRAFFIC DEMAND REQUIRED AT EACH NODE

| Node($i$) | Traffic Demand (E1) ($T_i$) | Node($i$) | Traffic Demand (E1) ($T_i$) |
|---|---|---|---|
| 1 | 1 | 7 | 30 |
| 2 | 3 | 8 | 4 |
| 3 | 2 | 9 | 3 |
| 4 | 2 | 10 | 2 |
| 5 | 3 | 11 | 7 |
| 6 | 1 | 12 | 2 |

TABLE III
EQUIPMENT TYPE REQUIRED AT EACH NODE

| Node | Equipment Type | Node | Equipment Type |
|---|---|---|---|
| 1 | STM-1 Type3 | 7 | STM-1 Type1 |
| 2 | STM-1 Type3 | 8 | STM-1 Type3 |
| 3 | STM-1 Type3 | 9 | STM-1 Type3 |
| 4 | STM-1 Type3 | 10 | STM-1 Type3 |
| 5 | STM-1 Type3 | 11 | STM-1 Type3 |
| 6 | STM-1 Type3 | 12 | STM-1 Type3 |

TABLE IV
COMPUTATIONAL RESULT FOR THE MULTIRING WITH COMMON-EDGE NETWORK DESIGN PROBLEM

| Solution No. | Network Cost (*NC*) | Number of Rings | Ring List | Reliability |
|---|---|---|---|---|
| 1 | 11000 | 7 | 1,2,19,30,34, 37,39 | 0.999999997661575430000000 |
| 2 | 21000 | 13 | 1,2,3,19,20, 21,30,31,34,35, 37,38,39 | 0.999999999999994780000000 |
| 3 | 31000 | 17 | 1,2,3,4,5, 19,20,21,23,26, 30,31,34,35,37, 38,39 | 0.999999999999999936496752 |
| 4 | 41000 | 21 | 1,2,3,4,5, 6,8,19,20,21, 23,25,26,30,31, 34,35,36,37,38, 39 | 0.999999999999999999922520 |
| 5 | 51000 | 25 | 1,2,3,4,5, 6,7,8,19,20, 21,22,23,24,25, 26,30,31,32,34, 35,36,37,38,39 | 0.999999999999999999999905 |

TABLE V
CANDIDATE RING GENERATION AND RING RELIABILITY

| Candidate Ring No. ($r_j$) | Node List | Distance (Km) | Ring Cost (unit) ($rc_j$) | Reliability $R(G_r)$ |
|---|---|---|---|---|
| 1 | 1-2-6-5-1 | 37.6 | 940.00 | 0.94770000000000000000 |
| 2 | 1-2-3-7-6-5-1 | 59 | 1475.00 | 0.88573500000000100000 |
| 3 | 1-2-6-10-9-5-1 | 62.2 | 1555.00 | 0.88573500000000100000 |
| 4 | 1-2-3-4-8-7-6-5-1 | 90 | 2250.00 | 0.81310473000000100000 |
| 5 | 1-2-3-7-6-10-9-5-1 | 83.6 | 2090.00 | 0.81310473000000100000 |
| 6 | 1-2-3-7-11-10-6-5-1 | 94.9 | 2372.50 | 0.81310473000000100000 |
| 7 | 1-2-3-7-11-10-9-5-1 | 97.9 | 2447.50 | 0.81310473000000100000 |
| 8 | 1-2-6-7-11-10-9-5-1 | 92.9 | 2322.50 | 0.81310473000000100000 |
| 9 | 1-2-3-4-8-7-6-10-9-5-1 | 114.6 | 2865.00 | 0.73609892910000100000 |
| 10 | 1-2-3-4-8-7-11-10-6-5-1 | 125.9 | 3147.50 | 0.73609892910000100000 |
| 11 | 1-2-3-4-8-7-11-10-9-5-1 | 128.9 | 3222.50 | 0.73609892910000100000 |
| 12 | 1-2-3-4-8-12-11-7-6-5-1 | 117.9 | 2947.50 | 0.73609892910000100000 |
| 13 | 1-2-3-4-8-12-11-10-6-5-1 | 127.6 | 3190.00 | 0.73609892910000100000 |
| 14 | 1-2-3-4-8-12-11-10-9-5-1 | 130.6 | 3265.00 | 0.73609892910000100000 |
| 15 | 1-2-3-7-8-12-11-10-6-5-1 | 118.4 | 2960.00 | 0.73609892910000100000 |
| 16 | 1-2-3-7-8-12-11-10-9-5-1 | 121.4 | 3035.00 | 0.73609892910000100000 |
| 17 | 1-2-6-7-8-12-11-10-9-5-1 | 116.4 | 2910.00 | 0.73609892910000100000 |
| 18 | 1-2-3-4-8-12-11-7-6-10-9-5-1 | 142.5 | 3562.50 | 0.65900225178900100000 |
| 19 | 2-3-7-6-2 | 32.6 | 815.00 | 0.94770000000000000000 |
| 20 | 2-3-4-8-7-6-2 | 63.6 | 1590.00 | 0.88573500000000100000 |
| 21 | 2-3-7-11-10-6-2 | 68.5 | 1712.50 | 0.88573500000000100000 |
| 22 | 2-3-4-8-7-11-10-6-2 | 99.5 | 2487.50 | 0.81310473000000100000 |
| 23 | 2-3-4-8-12-11-7-6-2 | 91.5 | 2287.50 | 0.81310473000000100000 |
| 24 | 2-3-4-8-12-11-10-6-2 | 101.2 | 2530.00 | 0.81310473000000100000 |
| 25 | 2-3-7-8-12-11-10-6-2 | 92 | 2300.00 | 0.81310473000000100000 |
| 26 | 2-3-7-11-10-9-5-6-2 | 90.5 | 2262.50 | 0.81310473000000100000 |
| 27 | 2-3-4-8-7-11-10-9-5-6-2 | 121.5 | 3037.50 | 0.73609892910000100000 |
| 28 | 2-3-4-8-12-11-10-9-5-6-2 | 123.2 | 3080.00 | 0.73609892910000100000 |
| 29 | 2-3-7-8-12-11-10-9-5-6-2 | 114 | 2850.00 | 0.73609892910000100000 |
| 30 | 3-7-8-4-3 | 52.2 | 1305.00 | 0.94770000000000000000 |
| 31 | 3-7-11-12-8-4-3 | 80.1 | 2002.50 | 0.88573500000000100000 |
| 32 | 3-7-6-10-11-12-8-4-3 | 106.2 | 2655.00 | 0.81310473000000100000 |
| 33 | 3-7-6-5-9-10-11-12-8-4-3 | 128.2 | 3205.00 | 0.73609892910000100000 |
| 34 | 5-9-10-6-5 | 43.6 | 1090.00 | 0.94770000000000000000 |
| 35 | 5-9-10-11-7-6-5 | 74.3 | 1857.50 | 0.88573500000000100000 |
| 36 | 5-9-10-11-12-8-7-6-5 | 97.8 | 2445.00 | 0.81310473000000100000 |
| 37 | 6-10-11-7-6 | 52.3 | 1307.50 | 0.94770000000000000000 |
| 38 | 6-10-11-12-8-7-6 | 75.8 | 1895.00 | 0.88573500000000100000 |
| 39 | 7-11-12-8-7 | 49.7 | 1242.50 | 0.94770000000000000000 |

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