DESIGNING FAULT TOLERANT WIRELESS ACCESS NETWORKS[1]

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ABSTRACT

Providing fault tolerance in wireless access networks has become crucial as user dependence on mobile services increases, especially for business and emergency services. Unlike wired access networks, the fault tolerant wireless network design can be costly and highly complicated due to unique characteristics of wireless mobile networks such as user mobility that can significantly worsen network performances after failures. We present a novel network design model that incorporates the effect of user mobility for fault-tolerant wireless access networks. The problem was formulated as an integer programming (IP) model to minimize the total network interconnect cost while user demands and survivability requirements are satisfied.

INTRODUCTION

Wireless mobile networks have become crucial to provide communication services to mobile users. As user dependence on mobile services increases, especially for business and emergency services, network failures that inhibit communications or results in loss of critical data cannot be tolerated. Many human-made and natural causes (e.g., incorrect maintenance, fires, earthquakes, etc.) can result in network failures and disrupt communication services. Therefore, it is essential to take into account such failure scenarios and their potential effects when designing wireless access networks. Due to the complexity of wireless network architecture and unique characteristics of wireless mobile networks such as user mobility, and quality of service requirements of voice and emerging data services in mobile cellular systems, fault tolerant wireless network design can be costly and highly complicated. The challenge is to design a cost-effective wireless network to meet user demands with acceptable reliability and quality of services.

Traditional wireless mobile access networks including third-generation (3G) mobile communication systems typically have a tree-like topology. In a network design, the tree network topology could be the least-cost network design due to the minimum connectivity and the advantage of economy of scale in the cost of higher capacity links. However, the disadvantage of a tree topology is its vulnerability to failures. For example, a single cable cut causes a network separation into two sub-trees leading to the disconnection of one or more nodes. This has increased a great concern in the survivability of wireless access networks. There are several strategies in designing fault-tolerant network topologies. In the tree-like topology, additional connectivity and automatic protection switches are required in the network topology to achieve an automatic recovery from a single failure. Other network topologies like self-healing ring and mesh topologies are capable of rerouting traffic around the point of failure through other existing facilities and switches.

The importance of providing communication services in the face of network failures has been recognized in public switched telephone and data networks. A great deal of attention has been placed to making these networks survivable and self-healing (e.g., [1]). Survivability of wireless access networks has recently begun to receive attention. In [2,3,4], techniques and solution algorithms for the design of a survivable topology for wireless mobile networks were presented. However, the approach and assumptions used in these articles were identical to techniques used in wired backbone network designs and did not include any of the unique aspects of wireless networks such as user mobility which is an important issue that needs to take into accounts in the wireless access network design. Unlike wired networks, user mobility in wireless mobile networks can significantly worsen network performances after failures, as disconnected users move among adjacent cells and attempt to reconnect to the network [5]. Therefore, the capacity requirement for

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network dimensioning is different in wireless access networks when compared to wired networks due to the movement of users. The importance of providing fault tolerance together with unique characteristics of wireless access networks has necessitated the development of new network design models.

In this paper, we propose a novel network design model that incorporates the effect of user mobility to satisfy user demand and survivability requirements for wireless access networks. Our approach is to formulate the problem of fault-tolerant wireless access network design as an integer-programming (IP) model to minimize the total network interconnection cost. In the next section, we discuss the details of survivable wireless network design and present problem formulations that includes unique aspects of wireless access networks. In section 3, we present results and discussion of our approach in designing fault tolerant wireless access networks. Finally, section 4 presents conclusions and comments on our research work.

SURVIVABLE WIRELESS NETWORK DESIGN

The survivable wireless access network design problem has a number of unique aspects which differentiate it from conventional wired network design (i.e., public switched telephone networks, and data packet switched networks). A typical wireless mobile network consists of a collection of network components (i.e. base stations, base station controllers and mobile switching centers) and links interconnecting between these components. Each base station (BS) or cell site generates traffic that represents demands of the BS to be carried through links between BS and base station controller (BSC) in the wireless backhaul network. These traffic demands are aggregated into higher capacity links and routed (via hubs) to the mobile switching center (MSC).

The network is organized into a facility hierarchy. That is, each BS is controlled by a BSC and all BSCs are connected directly or indirectly with the MSC. This hierarchical structure tends to suggest that traffic be concentrated into high capacity routes to central locations. Therefore, the tree-like network topology has traditionally been used for the wireless mobile network design due to the total network interconnect cost. However, the tree topology is sensitive to any link failure. For the network to be survivable, alternate routes must exist between network components with appropriate traffic restoration methods. In addition, sufficient spare capacity should be allocated in the network infrastructure in advance so that the effects due to system level failures such as loss of links or nodes can be mitigated. This has to be done in the network design process. Other factors in wireless networks like user mobility and cell site location must be taken into account for a survivable wireless network design. For example, the impact of failures in cell sites serving mobile users on highways can be worse than those in residential areas [6]. We consider the problem of designing fault tolerant wireless access network as follows.

A. Problem Description

In this paper, we focus on designing fault tolerant wireless mobile networks to guard against a link failure in the wireless backhaul network. Nonetheless, we include the effect due to user mobility after base station failures. The problem is to design a cost-effective wireless network to meet user demand and survivability requirements.
The survivable wireless network design problem typically consists of the following elements.

- Nodes: Nodes in the wireless network design can be classified into different types which are base station (BS), base station controller (BSC), hub, and mobile switching center (MSC). The BS node can be considered as the access node that generates traffic and connects to a transit node in the network. The BSC and hub acts as a transit node that aggregates traffic from access nodes or other hub nodes and routes the aggregated traffic through the MSC node.

- Links: A link in the network is the connection between two nodes. Each link is bi-directional and has the minimum capacity no less than total traffic demands that pass through it.

- Demands: Each traffic demand refers to the amount of bandwidth required on each link that carries it from the source node to the destination node. In voice service networks, the voice traffic is typically expressed in the number of digital signal-level 0 (DS-0) lines. Each DS-0 line represents one voice conversation channel. Therefore, the demand of each base station is given in the number of (DS-0) channels. In order to meet a desired quality of service for voice services, the minimum number of channels is required to support traffic load (in Erlang) at a certain level of call blocking probability in each cell site. For example, 70 channels are required to support a traffic load of 59.1 Erlangs at 2% call blocking probability.

- Costs: The costs of network design problem include both the cost of installing new nodes and links. Each node and link has a cost associated with it. Typically, the node cost is fixed and the link cost is based on tariff data from the local exchange carrier (LEC). The link cost may consist of a fixed charge for establishment of a link and an incremental charge for adding every unit of capacity to the link.

- Survivability requirements: Survivability requirements are important factors considered during the design process. In survivable network design, the network should be able to carry traffic load with acceptable level of services for certain failure scenarios. For example, 100% restoration may be required for any single link failure.

We assume that the location of MSC and BS nodes, the traffic demands of each BS node, the fixed charge and incremental unit charge of each possible link, and survivability requirements are known in advance for designing fault-tolerant wireless access networks.

There are three main tasks involved in the network design process: (i) designing fault-tolerant network topology, (ii) dimensioning links between network components, and (iii) routing traffic demand. We recognize that in practice there would often be some existing wireless mobile networks with tree-like topology. Therefore, we divide the problem of designing fault tolerant wireless access networks into two phases. In the first phase, we consider the minimum-cost topology design. The problem is to assign the locations of base station controllers, interconnection links and their capacity to satisfy traffic demands routed from BS nodes to the MSC with minimum cost. In the second phase, we consider the incremental topology design problem where a set of links and nodes already exists and the existing network topology is modified to satisfy survivability requirements. This two-phase approach can be applied to both new and incremental fault-tolerant network design.

B. Problem Formulation

The problem of fault-tolerant wireless access network design can be formulated as an integer programming model. We first present the definition and formulation for the minimum-cost topology design problem as follows.

Notation

B	Set of base station (BS) nodes or cell sites in the network service area
H	Set of potential hubs or base station controller (BSC) nodes
M	Mobile switching center (MSC)
N	Set of all nodes, $B \cup H \cup M$
E	Set of possible bi-directional edges (links) between nodes in N
Q	Maximum number of BSCs
K	Maximum number of BS nodes controlled by a BSC
d_i	Traffic demands originated at BS node i
w_{ij}	Capacity of working link between node i and j, $w_{ij} \in I^+$
w_{ij}^b	Amount of working flow for BS node b routed over the link between node i and j, $w_{ij}^b \in I^+$
x_{ij}	BS to BSC node assignment variable; 1 if BS node i is assigned to BSC node j, 0 otherwise
y_j	BSC node selection variable; 1 if node $j \in H$ is selected to be a BSC node, 0 otherwise
φ_{ij}	Edge decision variable $(\varphi_{ij} = \varphi_{ji})$; 1 if edge $(i,j) \in E$ between node i and node j is selected for connection, 0 otherwise
c_{ij}	Cost of adding one unit of capacity to edge $(i,j) \in E$ between node i and j ($c_{ij} = c_{ji}$ which is a function of distances between node i and j)
FC_{ij}	Fixed cost for adding an edge $(i,j) \in E$ between node i and j
Ψ	Arbitrary positive constant that is sufficiently larger than any link capacity expected in the network

P1:

$$\text{Minimize} \quad \sum_{ij \in E} c_{ij} \cdot w_{ij} + \sum_{ij \in E} FC_{ij} \cdot \varphi_{ij}$$

Subject to:

$$(1.1) \quad w_{ij}^i = x_{ij} d_i \quad ; \forall i \in B, \forall j \in H$$

$$(1.2) \quad \sum_{j \in H} w_{jk}^i = d_i \quad ; \forall i \in B, k \in M$$

$$(1.3) \quad \sum_{n \in B \cup H, n \neq j} w_{nj}^j = \sum_{n \in H \cup M, n \neq j} w_{jn}^j \quad ; \forall i \in B, \forall j \in H$$

$$(1.4) \quad w_{ij} = \sum_{b \in B} w_{ij}^b \quad ; \forall ij \in E$$

$$(1.5) \quad \sum_{j \in H} x_{ij} = 1 \quad ; \forall i \in B$$

$$(1.6) \quad \sum_{i \in B} x_{ij} \leq \mathrm{K} y_j \quad ; \forall j \in H$$

$$(1.7) \quad \sum_{j \in H} y_j \leq Q$$

$$(1.8) \quad w_{ij} \leq \Psi \cdot \varphi_{ij}; \ \varphi_{ij} = \varphi_{ji} \quad ; \forall ij \in E$$

$$(1.9) \quad \varphi_{ij} \in \{0,1\} \quad ; \forall ij \in E$$

$$(1.10) \quad w_{ij} \in I^+ \quad ; \forall ij \in E$$

In the formulation (P1), each base station is assigned and connected to a BSC. All BSC nodes are connected directly or indirectly to the MSC. The objective function is to minimize the total interconnection cost in the backhaul network. This model includes the cost of establishing new edges and working capacity on each edge in the topology. Constraints (1.1)-(1.3) are flow-balance constraints from each source node to the destination node. Constraints (1.1) guarantee that the working capacity of the link from each base station to its BSC node equals to the traffic demands of the base station. Constraints (1.2) ensure that all traffic demands from each base station node reach the MSC node. Constraints (1.3) ensure that the total capacity of incoming links to a hub node equals the total capacity of its outgoing links. Constraints (1.4) define the required edge (link) capacity to satisfy all simultaneous flows over the edge. Constraints (1.5) guarantee that each BS node can be assigned to exactly one BSC node. Constraints (1.6) restrict the maximum number of connections from BSs assigned to a BSC node. Constraint (1.7) limits the maximum number of BSCs employed in the network design. Constraints (1.8) ensure that the working capacity is assigned on an existing edge in the network. Constraints (1.9)-(1.10) express the binary requirements and non-negativity of decision variables. The solution of solving the problem formulation will give the minimum-cost network topology that contains locations of BSC, a set of selected interconnect links and its assigned capacity as well as routes of traffic demands.

Based on the network topology obtained from P1 or given an existing network topology, we can apply the second phase to provide fault tolerance in wireless access networks. The objective of formulation P2 presented next is to minimize the total cost of spare capacity for network restoration to satisfy survivability requirements. Due to the complexity of incremental topology design problem, we consider span (or link) restoration as the technique to guard against a link failure. In addition, we include mobility factor in the problem that needs extra capacity for traffic demands to serve users moving from neighboring areas due to the loss of BS nodes. The following definition is added for the problem formulation that follows.

A	Set of existing edges between nodes in N, $A \subseteq E$ given from the working links in the existing network
s_{ij}	Capacity of spare link between nodes i and j, $s_{ij} \in I^+$
s_{ij}^{kl}	Amount of minimum restoration bandwidth assigned on edge $(k,l) \in E$ from node k to l for restoration due to the failure of edge $(i,j) \in A$, $s_{ij}^{kl} \in I^+$
a_{ij}^{b}	Amount of extra bandwidth assigned on edge $(i,j) \in E$ from node i to j for cell (node) b to serve traffic demands from neighboring cells due to user movements after BS node failures, $a_{ij}^{b} \in I^+$
α_i	Mobility factor indicating the estimated proportion of traffic demands from neighboring cells served at BS node i due to user movements after network failures, $0 \le \alpha_i \le 1$

P2:

$$\text{Minimize} \qquad \sum_{ij \in E} c_{ij} \cdot s_{ij} + \sum_{ij \in \{E-A\}} FC_{ij} \cdot \varphi_{ij} .$$

Subject to:

$$\text{(2.1)} \quad a_{bj}^{b} \ge x_{bj} \alpha_b d_b \qquad ; \forall b \in B, \forall j \in H$$

$$\text{(2.2)} \quad \sum_{j \in H} a_{jk}^{b} \ge \alpha_b d_b \qquad ; k \in M, \forall b \in B$$

$$\text{(2.3)} \quad \sum_{n \in B \cup H, n \ne j} a_{nj}^{b} = \sum_{n \in H \cup M, n \ne j} a_{jn}^{b} \qquad ; \forall j \in H, \forall b \in B$$

$$\text{(2.4)} \quad \sum_{\substack{ik \in E, \\ k \in H-\{j\}}} s_{ij}^{ik} = w_{ij} \qquad ; \forall ij \in A$$

$$\text{(2.5)} \quad \sum_{\substack{kj \in E, \\ k \in H-\{i\}}} s_{ij}^{kj} = w_{ij} \qquad ; \forall ij \in A$$

$$\text{(2.6)} \quad \sum_{\substack{nk \in E, \\ k \in H \cup \{j\} - \{i\}}} s_{ij}^{nk} = \sum_{\substack{kn \in E, \\ k \in H \cup \{i\} - \{j\}}} s_{ij}^{kn} \qquad ; \forall ij \in A, \forall n \in H-\{i,j\}$$

$$\text{(2.7)} \quad s_{kl} \ge s_{ij}^{kl} + s_{ji}^{kl} \qquad ; \forall ij, ji \in A, \forall kl \in E-\{ij, ji\}$$

$$\text{(2.8)} \quad s_{kl} \ge \sum_{b \in B} a_{kl}^{b} \qquad ; \forall kl \in E$$

$$\text{(2.9)} \quad s_{ij} \le \Psi \cdot \varphi_{ij}; \quad \varphi_{ij} = \varphi_{ji} \qquad ; \forall ij \in \{E-A\}$$

$$\text{(2.10)} \quad \varphi_{ij} = 1 \qquad ; \forall ij \in A$$

$$\text{(2.11)} \quad \varphi_{ij} \in \{0,1\} \qquad ; \forall ij \in E$$

$$\text{(2.12)} \quad s_{ij} \in I^+ \qquad ; \forall ij \in E$$

This model includes the cost of installing new edges and the cost of spare capacity on both existing and new edges in the topology. Constraints (2.1)-(2.3) are flow-balance constraints of extra capacity reserved for mobility factor from each BS node to the MSC node due to BS node failures that could not be recovered. Constraints (2.4)-(2.6) are flow-balance constraints of spare capacity to guard against any working link failure in the existing topology. Constraints (2.7)-(2.8) define the required spare capacity to satisfy all simultaneous flows over the edge $(k,l) \in E$ in the direction from node k to l. Constraints (2.9) ensure that the spare capacity is assigned on an edge existing in the new topology. Constraints (2.10) guarantee that edges in the existing topology are included in the new topology. Constraints (2.11)-(2.12) express the binary requirements and non-negativity of decision variables. The solution obtained from solving this problem formulation will give the fault-tolerant topology that includes spare capacity for network restoration to satisfy survivability requirements with minimum-cost. In the following section, we present some numerical results and discussion.

NUMERICAL RESULTS

The problem of designing fault-tolerant wireless access networks formulated in the previous section was tested using CPLEX 7.1 linear optimization solver on Sun Blade 1000 workstation. We report sample results for three generated networks with 30, 40, and 50 base stations (referred to as N30, N40, and N50 respectively) as shown in Table 1. Each BS is randomly placed with a minimum distance of 5 units to its neighbor BSs in the service area.

Network	# of BS	# of BSC	Service area ($unit^2$)
N30	30	4	1500
N40	40	5	2000
N50	50	6	2500

Table 1. Characteristics of tested networks

In our experiments, we first solve the initial topological design problem (P1) to satisfy traffic demands with minimum-cost. The solution obtained from the first phase is then used as the input for the incremental design (P2) to satisfy survivability requirements. Table 2 shows sample results of solving P1 and P2 for three tested networks with traffic demands of 70 units (DS0 channels for voice service) at each BS node. We compare the cost of each design phase (P1 and P2) as well as the cost of including extra capacity for serving traffic demands due to user mobility. We set the mobility factor to 10% ($\alpha_i = 0.1$) of traffic demands at each cell for extra capacity to mitigate the effects of BS node failure. From the result, we observe that the cost of adding extra capacity for mobility factor is quite small comparing with the total cost of spare capacity. Although the cost of spare capacity to protect any single link failure could be high, we might further reduce the cost by increasing the number of hubs in the network.

Network	P1 cost	P2 cost	
		$\alpha_i = 0$	$\alpha_i = 0.1$
N30	36970	66723	68626
N40	52567	67292	70558
N50	72916	99947	104090

Table 2. Network design cost

Table 3 shows results of solving the P2 problem with different number of hubs in the same N50 network. We can see that the larger number of hubs allowing spare links to be shared in the network results in smaller costs.

Number of Hubs	P2 Cost ($\alpha_i = 0.1$)
6	104090
10	80447
20	74948

Table 3. Spare capacity cost for the N50 network

CONCLUSIONS

We have proposed a novel network design model that incorporates the user mobility factor for fault-tolerant wireless access networks. We also presented a two-phase design approach to solve the problem. Numerical results show that we can have extra capacity with small additional cost comparing with the total cost of spare capacity to mitigate the effects of user mobility after network failures. In addition, we found that the two-phase approach proposed for fault-tolerant network design can be used to solve a medium problem size within reasonable computational time. The design model presented in this paper focuses on voice based wireless mobile networks. Additional characteristics of emerging mobile data services must be incorporated into the model to provide fault tolerance in wireless mobile data networks.

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