Topological Design of Survivable Wireless Access Networks[1]

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Abstract – **Wireless mobile networks have become crucial in providing untethered communication services to mobile users. In this paper, we propose an optimization model for the design of survivable wireless access networks. The main objective of the model is to optimize the network design cost of wireless backhaul networks while meeting survivability requirements. This paper also presents a simple and efficient heuristic method to solve the network design model for large network problem sizes within a reasonable computational time while obtaining a near optimal solution.**

Index Terms – **topological design, survivable wireless access network, network survivability, network optimization.**

I. INTRODUCTION

Wireless mobile networks have become a critical part of the communication infrastructure. As user dependence on wireless mobile services increases, the reliability of service becomes a main issue. However, network components can fail and may remain in a failed state for an extended period of time. Moreover, many human-made and natural causes (e.g., incorrect maintenance, construction, storms, etc.) can result in network failures. The effects of failures in wireless access networks will vary and depend on failure scenarios which can be determined by the network component that fails and its location. Examples of typical failure scenarios in wireless access networks include failure of a base station and loss of the link between a base station and mobile switching center. A single component failure in wireless networks can disconnect communication services to a great number of mobile users in the service area. Therefore, it is essential to take into account such failure scenarios and their potential effects when designing wireless access networks.

The survivability of wireless access networks has been recently studied to improve their reliability and performance in the wake of network component failures. In [1]-[3], various survivability issues in wireless mobile networks were studied, such as the effects of network component/facility failures, metrics for characterizing outages, a survivability framework and strategies for designing survivable wireless networks. Recent simulation based survivability analysis [2],[3] show that user mobility in wireless mobile networks significantly worsens network performances after network failures, as interrupted users move and attempt to reconnect to the network. Several techniques and solution algorithms for designing a survivable topology for wireless access networks were also presented in [4]-[6]. Alevras, and et al. [4] considered models and solution methods for survivable mobile network architectures. The problem was to determine the topology and capacity of each physical link for a given transport network such that traffic demands between switching nodes are satisfied in normal operation and under component failure conditions. Dutta and Kubat [5] considered a design of partially survivable backhaul networks for cellular systems. Self-healing ring technology was used for the backbone transmission network. A diversity requirement, which enforces a cell site to interconnect with more than one hub on the ring, was specified to ensure survivability in the network. Cox and Sanchez [6] considered the least-cost backhaul network design while meeting survivability and capacity constraints. The survivability constraint was specified as the routing-diversity which enforces a given cell site to connect with different nodes whenever more than one link was assigned. However, these articles did not consider the effect of user mobility in the network design.

This paper proposes a survivable wireless backhaul network design model which incorporates the impact of user mobility in the event of network failures. We formulate the problem of survivable wireless access network design as a mixed integer-programming model to minimize the network cost while maintaining acceptable quality of service and survivability requirements. Due to the complexity of the survivable network design problem, standard approaches are computationally prohibitive in solving the problem, especially for large network sizes. Hence, we develop a simple and efficient heuristic method to solve the network design model within a reasonable computational time while obtaining a near optimal solution.

In the next section, we discuss the details of survivable wireless network design and our strategies to provide fault tolerance in wireless networks. In section III, we present the network design model for survivable wireless access networks. In section IV, we present a heuristic algorithm for efficient solution of the design model and numerical results for sample networks. Numerical solutions obtained by solving the optimization model using standard techniques and our heuristic method are compared and discussed. Lastly, section V gives the conclusion of this paper.

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II. SURVIVABLE WIRELESS NETWORK DESIGN

In general, survivable network design refers to the incorporation of survivability strategies (e.g., redundant network component, fault-tolerant topology, spare capacity allocation, traffic management, and restoration mechanism) into a network to mitigate the impact of failures [2]. In a survivable wireless network design, unique aspects including network architecture of wireless access networks must be taken into account.

A. Network Architecture and Topology

A generic 2G wireless mobile network architecture is illustrated in Figure 1. A wireless access network usually covers a large geographical service area which is partitioned into many small regions called cells. Each cell has a base station (BS) that serves as a fixed access point for all mobile terminals (MT) within the cell. The network may include base station controllers (BSC), which manage a group of base stations and perform radio level channel management and call handoff. The BS and BSC are connected to backbone networks via mobile switching centers (MSC). The MSC is connected both to transmission networks and to the signaling network. Associated with the signaling network and MSC are databases to support user and service mobility. These databases include a Home Location Register (HLR), Visitor Location Register (VLR), and normally an Equipment Identity Register (EIR), and Authentication center (AUC).

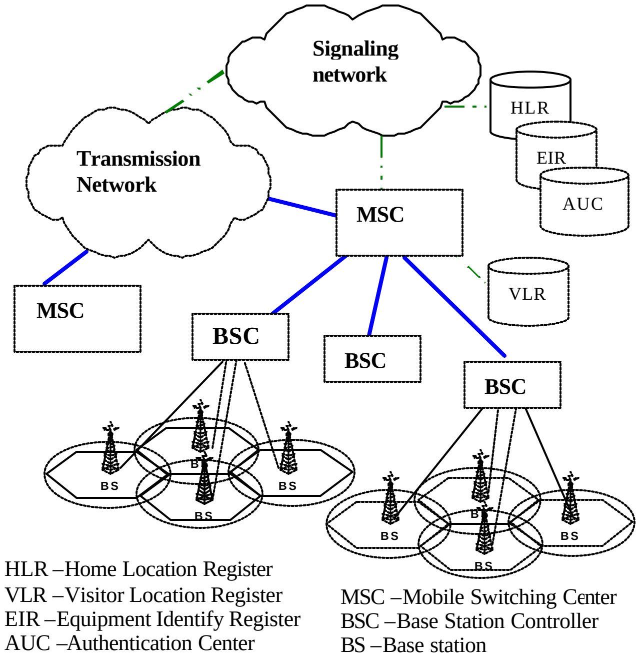

Figure 1 – Typical Wireless Network Architecture.

The network architecture is generally organized into a facility hierarchy. Each BS is connected to a BSC and the BSC is then connected to the MSC. The communications links between the BS, BSC, and MSC are typically wireline or fixed microwave links. This hierarchical structure suggests that traffic in the wireless backhaul network be concentrated into high capacity links to central locations. Hence, a tree-like network topology has been traditionally used for wireless mobile network design. The tree network topology could be the least-cost network design due to the minimum connectivity and the economy of scale on high capacity links. However, the tree topology is vulnerable to failures. For the network to be survivable, alternate routes with sufficient spare capacity and appropriate traffic restoration technique must be incorporated into the network infrastructure in advance.

B. Survivability Strategies

In survivable network design, several strategies can be used to protect network services against failures. Following the wireless network survivability framework in [3], survivability techniques can be deployed at different layers and multi-layer survivability strategies could be applied in a survivable network design.

At the radio network layer, the primary failure to be guarded against is failure of the wireless link to the mobile user. Due to the constraint of limited frequency spectrum, allocation of spare radio channels for use in case of the failure may not be economically feasible and such an approach decreases the radio channel capacity available during normal operating modes. A possible approach is to design the network with overlapping cell site architecture along with a dynamic channel allocation algorithm and adaptive power control to provide dual-homing at the wireless link level [7]. Figure 2 shows a cell site architecture with overlapping coverage area for radio-level survivability. Each BS supports two groups of radio channel namely: short-haul channels and long-haul channels.

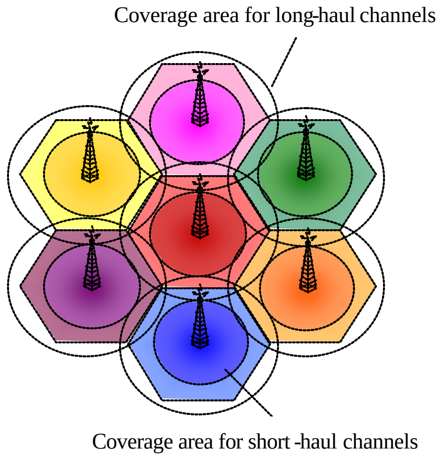

Figure 2 Cell Site Overlapping Architecture.

Ideally, the cell size and coverage areas of both radio channel groups are selected so that all mobile terminals can access at least two channel groups.

At the access network layer, the primary concern is link/component failure in the backhaul network. Hence, we propose to adapt a mesh-based restorable network topology with span- (link) restoration for survivable wireless mobile networks as shown in Figure 3. Any link that is vulnerable to failure is augmented with a backup path with sufficient spare capacity between its two end-nodes. If a link failure occurs, the end nodes of the failed link will automatically restore network services by rerouting traffic through the backup path within a short period of time.

Based on survivability strategies and restoration techniques described above, we consider the topological design of survivable wireless access networks to guard against any single link failure. We also take into account the effect of user mobility in the case of base station failures.

C. *User Mobility Effect*

In the event of a base station failure, communication in the area served by the failed BS will be terminated. Mobile users in the area covered by the failed BS can not access to the network unless a cell site overlapping coverage technique is employed or adjacent BS adaptively increase the signal power level to partially cover the area. Alternatively, mobile users move close to a neighbour cell and receive the radio channel from the neighbour BS. In any event, neighbour BS will have to serve increasing traffic demands from affected mobile users. Figure 4 illustrates the effect of user mobility in a BS failure scenario where mobile users move from the failed base station into neighbour cells. Mobile users whose calls were prematurely terminated may attempt to reconnect to the network in a near simultaneous fashion. This will increase traffic demands and the connection blocking probability in cells adjacent to the failed area [2,3]. Unlike conventional wired networks where some portions of traffic is lost after network node failures, a portion of affected traffic in wireless access networks will be diverted to neighbour cells. Hence, it is essential to take into account such failure scenarios and their potential effects when designing the backhaul network.

To mitigate the effect of BS failures, spare bandwidth must be allocated in the backhaul at each adjacent base station to absorb increased traffic due to user movement from a failed neighbour cell. Each BS node may have different spare bandwidth requirements depending upon its geographical location in the service area. For example, BS nodes serving mobile users on a highway will be affected by a large number of mobile users moving into the cell from one or two directions, whereas BS nodes serving residential areas may be affected less by user mobility after a failure. As a result, it is justified to assign more spare capacity to those BS nodes which are highly affected by user mobility in the event of adjacent BS node failures.

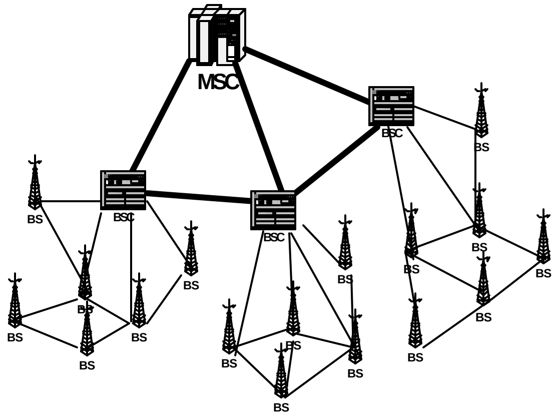

Figure 3 Mesh-based Restorable Network Topology.

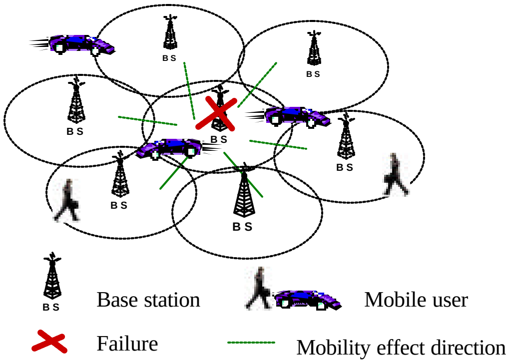

Figure 4 Base Station Failure Scenario and Its Mobility Effect.

We approximate the amount of extra bandwidth for mitigating user mobility effects at each BS node as follows. Let a_{ij} denote the mobility factor indicating the estimated proportion of traffic demands from a neighbour BS node i served at BS node j after BS node i fails (note that $0 \le a_{ij} \le 1$ and $\Sigma_j a_{ij} \le 1$). Let TD_i be total traffic demands served at BS node i in a normal operational state. Then, the amount of bandwidth at BS j in the event of BS i failing is $a_{ij} \cdot TD_i$. Let b_j denote the amount of spare bandwidth required at BS node j for any single BS i failure scenario. Then, $b_j = \mathrm{MAX}_i (a_{ij} \cdot TD_i)$, that is, b_j is the maximum bandwidth required to serve traffic from mobile users at BS j due to any single BS node i failure.

III. NETWORK DESIGN PROBLEM FORMULATION

Survivable wireless network design involves three main tasks which are determining a fault-tolerant network topology, dimensioning links between network nodes, and routing traffic demands subject to QoS and survivability requirements. It is well known that this type of network design problem is very hard to solve. We also recognize that existing wireless access networks have a tree-like topology. Hence, we propose a two-phase network design model similar to recent work on survivable wired backbone network design [9]. In the first phase, we formulate a minimum-cost network design problem which is solved to yield an initial network. Here, the problem is to determine the interconnection links, and their capacity to satisfy traffic demand with minimum cost. In the second phase, we consider the survivable incremental design problem where the minimum-cost network (from the phase one design) or an existing network topology is modified to satisfy survivability requirements. In the following, we present mathematical formulations for the two-phase survivable wireless network design approach. We first present the definition and formulation for the minimum-cost topology design problem and then the span-restoration network design problem.

The first phase minimum-cost wireless network design problem can be formulated as a mixed integer programming model using a node-link (arc-flow) formulation. This is to avoid the complexity of explicitly enumerating all possible routing paths which grows exponentially with the network size.

A. *Notation*

B	Set of base station nodes or cell sites in the network service area
H	Set of potential hub nodes
C	Set of base station controller nodes, $C \subseteq H$
M	Set of switching center nodes
N	Set of all nodes, $B \cup H \cup M$
E	Set of possible bi-directional edges (links) between nodes in N
$N(i)$	Set of neighbour nodes $j \in N$ of node i such that edge (i, j) belongs to edge set E
D	Set of all traffic demands between nodes indexed by k. Each k^{th} demand node-pair in D is associated with an origin node and a target node $(O[k], T[k])$
$O[k]$	The origin node of the k^{th} demand node-pair in D
$T[k]$	The target node of the k^{th} demand node-pair in D
d^k	The amount of traffic demands associated with the k^{th} demand pair in D
w_{ij}	Minimum capacity of working link between node i and j, $w_{ij} \in I^+$
$e_{ij}^{k,l}$	Traffic route binary variable that equals 1 if edge $(i, j) \in E$ is traversed by the k^{th} demand pair in D; 0 otherwise. The index $l \in \{1,2\}$ represents the levels (i.e. level 1 is from BS to BSC and level 2 is from BSC to MSC) in the hierarchical network design
j_{ij}	Edge decision binary variable ($j_{ij} = j_{ji}$) that equals 1 if edge $(i, j) \in E$ between node i and node j is selected for connection; 0 otherwise
VC_{ij}	Variable cost of adding one unit of capacity to edge $(i, j) \in E$ between node i and j
FC_{ij}	Fixed cost for adding an edge $(i, j) \in E$ between node i and j
x_{bc}	Binary assignment parameter that equals 1 if the BS node b is assigned to BSC node $c \in C$; 0 otherwise
Ψ	Positive constant that is sufficiently larger than any link capacity in the network

B. *Minimum-cost network design*

In the minimum-cost network design problem, we determine network topology and capacity of links to satisfy traffic demands in the wireless network. Given the notation above the problem can be formulated as follows.

$$M1: \quad \underset{e_{ij}^{k,l},\, j_{ij},\, w_{ij}}{Minimize} \quad \sum_{ij \in E} VC_{ij} \cdot w_{ij} + \sum_{ij \in E} FC_{ij} \cdot j_{ij}$$

Subject to:

$$\sum_{j \in N(i)} e_{ij}^{k,l} - \sum_{j \in N(i)} e_{ji}^{k,l} = 1 \quad ; \forall k \in D, i = O[k], l = 1 \tag{1.1}$$

$$\sum_{j \in N(n)} e_{nj}^{k,l} - \sum_{j \in N(n)} e_{jn}^{k,l} = -x_{bn} \quad ; \forall k \in D, b = O[k], l = 1 \quad \forall n \in N - \{O[k], T[k]\} \tag{1.2}$$

$$\sum_{j \in N(n)} e_{nj}^{k,l} - \sum_{j \in N(n)} e_{jn}^{k,l} = x_{bn} \quad ; \forall k \in D, b = O[k], l = 2 \quad \forall n \in N - \{O[k], T[k]\} \tag{1.3}$$

$$\sum_{j \in N(i)} e_{ij}^{k,l} - \sum_{j \in N(i)} e_{ji}^{k,l} = -1 \quad ; \forall k \in D, i = T[k], l = 2 \tag{1.4}$$

$$w_{ij} - \sum_{l \in \{1,2\}} \sum_{k \in D} e_{ij}^{k,l} \cdot d^k = 0 \quad ; \forall ij \in E \tag{1.5}$$

$$w_{ij} - \Psi \cdot j_{ij} \leq 0 \quad ; \forall ij \in E \tag{1.6}$$

$$j_{ij} - j_{ij} = 0 \quad ; \forall ij \in E \tag{1.7}$$

$$j_{ij} \in \{0,1\} \quad ; \forall ij \in E \tag{1.8}$$

$$e_{ij}^{k,l} \in \{0,1\} \quad ; \forall k \in D, l \in \{1,2\}, \forall ij \in E \tag{1.9}$$

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

The objective function is to minimize the total network link costs which include the cost of establishing edges (i.e., links) and the capacity of each edge in the topology. Constraint sets (1.1)-(1.4) are flow-balance constraints for each k^{th} traffic flow in set D from the source node $O[k] \in B$ to the corresponding target node $T[k] \in M$. Constraint sets (1.2) and (1.3) ensure that each k^{th} traffic flow with origin node $b = O[k] \in B$ is routed through its assigned BSC node $c \in C$ if X_{nc} equals 1. Constraint set (1.5) determines the required edge capacity to satisfy all simultaneous flows over the edge. Constraint sets (1.6)-(1.7) ensure that the working capacity is assigned on an edge which is selected for inclusion in the network topology. Constraint sets (1.8)–(1.10) express the binary requirements and non-negativity of variables. The solution of problem formulation M1 will give the minimum-cost network that has a tree-like topology.

Based on the minimum-cost network topology or given an existing network topology, we use span-restoration to recover from any single link failure in the second phase.

C. Span-restoration network design

In the span-restoration design, we modify the minimum-cost network to protect any single link failure. An alternate route for traffic is determined between two end-nodes of each protected edge (link) to provide a backup path in the event of the link failure. We define the following additional variables for the span-restoration formulation.

W	Set of working (existing) edges to be protected between nodes in N, $W \subseteq E$
b_{ij}^{st}	Backup path binary variable that equals 1 if edge $(i, j) \in E$ from node i to j is used for restoration due to the failure of edge $(s, t) \in W$; 0 otherwise
s_{ij}	Spare capacity of edge from nodes i to j, $s_{ij} \in I^+$
a_{ij}	Mobility factor indicating the estimated proportion of traffic demands served at base station node j due to user mobility after the failure of neighbour base station node i, $0 \leq a_{ij} \leq 1$ and $\Sigma_j a_{ij} \leq 1$
b^k	Amount of spare bandwidth assigned to a base station node associated with the k^{th} demand pair in D to absorb traffic loads due to user mobility after any neighbouring base station failure
HB	Hop count limit for backup route

$$M2: \quad \underset{b_{ij}^{st}, s_{ij}, j_{ij}}{Minimize} \quad \sum_{ij \in E} VC_{ij} \cdot s_{ij} + \sum_{ij \in \{E-W\}} FC_{ij} \cdot j_{ij}$$

Subject to:

$$\sum_{j \in N(s)-\{t\}} b_{sj}^{st} - \sum_{j \in N(s)-\{t\}} b_{js}^{st} = 1 \qquad ; \forall st \in W \tag{2.1}$$

$$\sum_{j \in N(i)-\{s\}} b_{ij}^{st} - \sum_{j \in N(i)-\{t\}} b_{ji}^{st} = 0 \qquad ; \forall st \in W, \forall i \notin \{s,t\} \tag{2.2}$$

$$\sum_{j \in N(t)-\{s\}} b_{tj}^{st} - \sum_{j \in N(t)-\{s\}} b_{jt}^{st} = -1 \qquad ; \forall st \in W \tag{2.3}$$

$$\sum_{ij \in E} b_{ij}^{st} \leq HB \qquad ; \forall st \in W \tag{2.4}$$

$$s_{ij} - (b_{ij}^{st} \cdot w_{st} + b_{ij}^{ts} \cdot w_{ts} + \sum_{k \in D} \sum_{l \in \{1,2\}} b^k \cdot e_{ij}^{k,l}) \geq 0 \qquad ; \forall st \in W, \forall ij \in E - \{st, ts\} \tag{2.5}$$

$$s_{ij} - \Psi \cdot j_{ij} \leq 0 \qquad ; \forall ij \in E - W \tag{2.6}$$

$$j_{ij} - j_{ji} = 0 \qquad ; \forall ij \in E - W \tag{2.7}$$

$$j_{ij} = 1 \qquad ; \forall ij \in W \tag{2.8}$$

$$j_{ij} \in \{0,1\} \qquad ; \forall ij \in E \tag{2.9}$$

$$b_{ij}^{st} \in \{0,1\} \qquad ; \forall st \in W, \forall ij \in E - \{st\} \tag{2.10}$$

$$s_{ij} \in I^+ \qquad ; \forall ij \in E \tag{2.11}$$

The objective is to minimize the total cost of spare resources for network restoration while satisfying survivability requirements. Constraint sets (2.1)-(2.3) are flow-balance constraints for each backup route of edge $(s, t) \in W$ obtained from the minimum-cost network design (M1). Constraint set (2.4) limits the number of hops for each route. This is to bound the restoration delay and to reduce the search space for the optimization problem. Constraint set (2.5) defines the required spare capacity to satisfy all simultaneous flows over the edge $(i, j) \in E$ in the direction from node i to j due to a failure of any link $(s, t) \in W$. The spare capacity on the edge includes extra bandwidth to absorb traffic due to user mobility from adjacent BS node failures or backhaul failures that may cause additional traffic on the edge. The amount of spare capacity (b^k) can be calculated as described previously and is given as an input parameter to the model. Constraint sets (2.6)-(2.7) ensure that the spare capacity is assigned on an edge in the new topology. Constraint set (2.8) guarantees that edges in the minimum-cost network topology from phase one design are included in the mesh restorable topology. Constraint sets (2.9)–(2.11) express the binary requirements and non-negativity of decision variables.

IV. HEURISTIC ALGORITHM AND NUMERICAL RESULTS

The integer programming model in the previous section can be solved using a standard branch and bound technique for small networks. However, the problem is NP-hard and the branch and bound technique will not scale for large networks. Our study of numerical results obtained from the network design formulations *M1* and *M2* above, for small networks, reveals patterns in the optimal solution. Specifically it was found that in the minimum-cost network design, traffic flows with large traffic demands use a short path (with small hop count) when the link cost is justified. Flows that have long distances between corresponding nodes and small traffic demands tend to be routed via a longer path (with larger hop counts), where some links in the path are also used for other flows. These longer-hop paths are justified due to fixed costs of establishing new links. Similarly, in the span restoration design, the backup path of each protected link tends to share spare resources (i.e., links and capacity) even though it may take a longer route, in order to minimize the network design cost. Hence, we propose a heuristic method based on a minimum-cost routing approach as shown in Figure 5. Note that similar heuristic approaches have been also efficiently applied to other network design problems [8].

The algorithm starts with randomly selecting the ordering of traffic demands (flows) to be routed. From the generated order of flows, each flow is sequentially routed with a minimum-cost routing algorithm based on the link-cost metric for each potential link that is calculated from the fixed charge and variable charge of using the link by the traffic demand. The link-cost metric is recalculated for each flow and the network topology is updated once a flow is routed using a new path. After all traffic demands are routed, the process is repeated with a new generated order of traffic flows until there is no update in the network topology or the maximum iteration is reached. Note that different orders of routing traffic demands can result in different solutions.

The proposed heuristic method is applied for both the minimum-cost network design and span-restoration network design with some modifications in the algorithm. In the minimum-cost design, the algorithm is straightforward. Every traffic flow has its bandwidth reserved along the path from the source to target node. The capacity of each link in the network is simply the total bandwidths of all traffic demands passing through it. At the end of the algorithm, the minimum-cost network topology will be given from links that have traffic demands passing through, along with the capacity of each link. The solution found in the minimum-cost network design will be used as the input for the span-restoration network design. In the span-restoration design, each link to be protected in the existing network topology will be considered as a traffic-demand node pair for the heuristic algorithm. Note that in span restoration, the protected working link can not be used in the backup route so that traffic can be rerouted through the backup path in the event of the working link failure. Also, bandwidth allocated to each link in the span restoration design can be shared over different failure scenarios. Hence, the maximum bandwidth among all flows passing through the same link is used for the link-cost metric calculation. The solution obtained from the heuristic algorithm for span restoration design includes backup routes for protected links, new established links and spare capacity in each link to recover from a network failure.

We present numerical results obtained from the CPLEX 7.1 optimization solver and our proposed heuristic algorithm implemented in C++ for different networks shown in Table 1. In our sample networks, the network service area is partitioned into many small regions and each base station is randomly placed with a minimum distance of 3 units to its neighbours in a service area. A set of potential links is selected in such a way that each node is potentially 5 or more connected and shortest links are preferred. Figure 6 shows a snapshot of N50 network with all nodes and possible links. We assume that the cost for adding a new edge and the cost per Euclidean-distance unit between two end-nodes of the edge is given to be 15. The cost of adding a bandwidth channel to an edge is set to 1 per Euclidean-distance unit.

In our experiments, the CPLEX 7.1 solver is run on a Sun Blade1000 workstation with 750 MHz processor and 2 gigabytes of memory and the proposed heuristic is run on a PC with Intel Pentium III 750 MHz processor and 128 megabytes of memory. We first solve the minimum-cost network design problem (M1). Solutions obtained from the minimum-cost design are then used as the input for the span restoration design problem (M2).

```
Begin
    Let $D$ = set of traffic demands or flows;
    Let $E$ = set of all potential links;
    do {
        randomly select an order of traffic
        demands in $D$ to be routed;
        for each traffic demand $k$ in the order
        {
          if (traffic demand $k$ has an existing route)
                temporarily remove its required
                bandwidth along the route;
          calculate new link-cost metric for all links
        in $E$ based on the updated topology, reserved
        bandwidth, and traffic demand $k$;
          find minimum-cost path from the calcu-
        lated link metric for traffic demand $k$;
          if (new route has been found)
              update network topology for new links
              and capacity;
          else
              maintain previous solution;
        }
    } until ( no_update or iteration > max_iteration);

End
```

Figure 5 Heuristic Routing Algorithm.

TABLE 1 – CHARACTERISTICS OF EXAMXPLE NETWORKS

Network	**Number of BS**	**Number of BSC**	**Number of links**	**Service area (unit^2)**
N17	17	2	89	400
N20	20	2	102	400
N50	50	5	548	900
N100	100	10	979	2500
N200	200	15	1268	4900
N300	300	15	1826	6400

Table 2 shows results of solving the network design model for two small networks with different traffic demands. The numerical results show that our proposed heuristic based on the minimum-cost routing algorithm finds good solutions for the network topology. In some cases, the heuristic algorithm can give a better solution compared to the solution obtained from the CPLEX solver implementing the branch and bound technique. We have investigated those cases and found that our heuristic method provide solutions with lower required bandwidths (but higher costs) in the first phase design and this result in lower costs in the second phase design. Since the proposed two-phase network design is solved sequentially, it is possible to have a sub-optimal solution in the first phase and give a better solution in the second phase. Note that the optimal solution obtained from the two-phase design is not the optimal solution of the topology design problem as a whole.

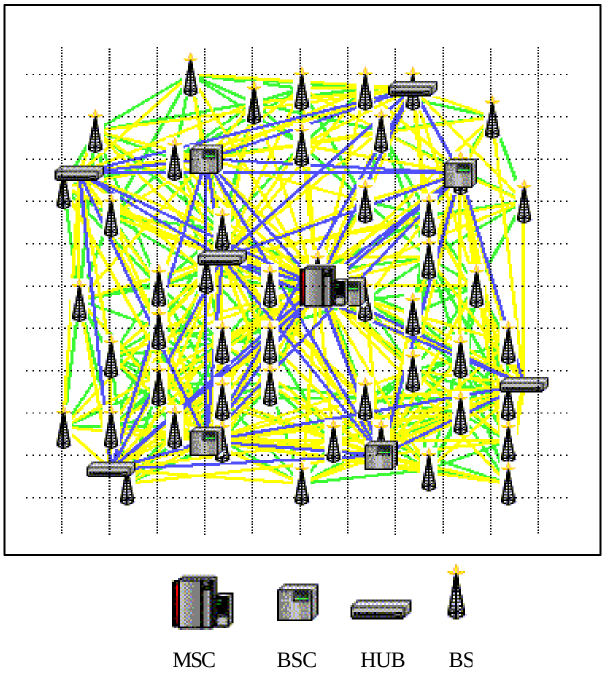

Figure 6 A Snapshot of Sample Network (N50).

Since the survivable network design problem is NP-hard, the CPLEX solver implementing the branch and bound technique can not solve large network size problems. To compare the computational time of our heuristic algorithm versus branch and bound technique, we solve a span-restoration problem with a larger network (N50). We use the optimal solution obtained from the CPLEX solver in the minimum-cost design as the input to both the heuristic algorithm and CPLEX implementing branch and bound technique in the second phase *M2* (span-restoration) design.

Table 3 shows results of solving the span restoration problem with different number of links, where links are randomly selected to be protected as the number of links increases, for N50 network. Since the problem can not be solved using the branch and bound technique for larger problem size within a reasonable computational time, a LP relaxation technique is used to give a lower bound solution for comparison. From the results shown, the heuristic method can give good solutions with less than 1% gap to those optimal solutions found by the CPLEX solver with branch and bound technique. For cases with a large number of protected links where the branch and bound technique cannot give the solution within days, the heuristic method can give solutions within minutes. Note that the computational time of the heuristic algorithm in Table 3 is the total time to find the best solution from 64 runs using different random seed numbers to generate the order of routing traffic flows.

We have tested the heuristic algorithm with large networks. The computational time required per run to solve large network problems is shown in Table 4. We can see that the heuristic method is very simple and efficient for solving the proposed survivable wireless access network design model.

TABLE 4 – AVERAGE COMPUTATIONAL TIME OF HEURISTIC ALGORITHM

Network	**Minimum-cost design**	**Span-restoration design**
N100	1.9 s	11.5 s
N200	10.4 s	62.8 s
N300	22.3 s	267.8 s

Table 5 shows the total network design cost of solving the two-phase design model using the heuristic method for different mobility factor parameter settings in N50 and N100 networks. In this paper, we set the mobility factor (a_{ij}) associated with each base station to a value within a given range by inspecting the location of each base station in the network map. If a base station is located close to its neighbour base stations, a higher mobility factor value is assigned. From the numerical results shown, the cost of wireless access network design incorporating spare bandwidth to mitigate the effect of user mobility in the event of base station failures increases according to the mobility factor values.

V. CONCLUSIONS

In this paper, we have proposed new network design models for building survivable wireless access networks. The model aims to find wireless network topology that satisfies traffic demands and survivability requirements while minimizing the network design cost. The network survivability strategy is based on mesh restorable network design and our approach to the network design problem is a two-phase design model. In the first phase, an initial network design problem is considered as the minimum-cost network design to satisfy traffic demands. In the second phase, an incremental network design problem is considered for the minimum-cost network of phase one, where the network topology is modified to satisfy survivability requirements. We also propose a simple heuristic based on minimum-cost routing to solve the network design model. The numerical results show that the proposed heuristic algorithm can efficiently find near-optimal solutions for small networks and easily scale to solve large network size problems.

TABLE 2 – NETWORK DESIGN COSTS OBTAINED FROM CPLEX 7.1 VERSUS PROPOSED HEURISTIC METHOD

Network	Traffic Demands (channels)	Network Cost						
		Min-cost design		Span restoration design		Total cost		Gap (%)
		Clex 7.1	Heuristic	Cplex 7.1	Heuristic	Cplex 7.1	Heuristic	
N17	60-80	13000	13060	25394	25125	38394	38185	0.54
	150-170	26267	26316	53102	49839	79369	76155	-4.05
	300-330	48339	48339	93660	94952	141999	143291	0.91
N20	60-80	18258	18325	32873	32303	51131	50653	-0.93
	150-170	37315	37378	67338	67048	104653	104426	-0.22
	300-330	70103	70126	125251	128208	195354	198334	1.53

TABLE 3 – RESULTS OF SPAN-RESTORATION DESIGN FOR N50 NETWORK WITH TRAFFIC DEMANDS 150-170 CHANNELS/BS

Number of protected links	Cplex 7.1 LP Relaxation		Cplex 7.1 Branch&Bound		Heuristic	
	Cost	Time (hh:mm:ss)	Cost	Time (hh:mm:ss)	Cost	Time (hh:mm:ss)
5	11637	2s	11637	8.5s	11644	16s
10	20892	12s	21564	3m:16s	21790	21s
15	25633	32s	26273	7m:43s	26500	29s
20	50401	56s	52727	7h:35m:15s	54688	36s
25	71506	1m:54s	76253	72h:00m:00s	78607	42s
35	87455	7m:48s	N/A	120h:00m:00s	99823	58s
45	106629	24m:39s	N/A	120h:00m:00s	130792	1m:17s
55 (all links)	128012	40m:14s	N/A	120h:00m:00s	148151	1m:40s

TABLE 5 – TOTAL NETWORK COST FOR N50 AND N100 NETWORK WITH DIFFERENT MOBILITY FACTOR VALUES

Network	Traffic Demands (Channels)	Total Network Design Cost						
		No Extra Bandwidth ($a_{ij} = 0$)	$a_{ij} = 0.01\text{-}0.1$	Cost Increase (%)	$a_{ij} = 0.1$	Cost Increase (%)	$a_{ij} = 0.01\text{-}0.15$	Cost Increase (%)
N50	60-80	140574	146167	3.98	146815	4.44	148451	5.60
	150-170	287341	299683	4.29	300850	4.70	304699	6.04
	300-330	538185	562163	4.45	564091	4.81	571987	6.28
N100	60-80	397130	414591	4.39	416223	4.81	421333	6.09
	150-170	836218	874536	4.58	877228	4.90	889703	6.40
	300-330	1577885	1652362	4.72	1657812	5.06	1680694	6.52

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