

Topology Design for Multihop Cellular Network

Jyh-Shyan Huang

Business Customer Solutions Lab.
Chunghwa Telecom Laboratories
Taipei, Taiwan, R.O.C.
frank210@cht.com.tw

Yao-Nan Lien

Department of Photonics and Communication Engineering
National Asia University
Taipei, Taiwan, R.O.C.
yaonanlien@asia.edu.tw

Abstract— Public communication systems often crash in large scale disasters, critically hindering coordination among disaster responders. Survival rates can be greatly increased by breaking communication bottlenecks. We proposed a contingency cellular network (CCN) that aims to provide communication service to large amount of voluntary workers and victims in the early hours. CCN connects crashed base stations using wireless links to construct a multihop cellular network. Since, topology design problem is one of the important issues of CCN design. This research proposes two algorithms to solve the network topology design problem of CCN which is constructed by multiple operators' base stations. The degree of emergency and population of each stricken area are taken as the priority measure as well as the available resources as the constraint to determine the network topology. The network topology design problem is formulated as a K-Maximum Spanning Tree Problem with degree bound and had been proven NP Hard. A binary integer linear programming (BILP) algorithm is proposed to solve the optimal solution. Since the network topology is needed in urgent, a heuristic algorithm is also proposed to solve this problem quickly.

Keywords— *Disaster Response, Mobile Communication, Rapidly Deployable Network, Ad Hoc Network, Emergency Communications*

I. INTRODUCTION

Public communication systems often crash in large scale disasters, critically hindering coordination among disaster responders. Survival rates can be greatly increased by breaking communication bottlenecks. We designed a contingency cellular network (CCN) [4,5] for large scale disaster response by connecting disconnected base stations in the disaster areas with wireless links to construct a multihop cellular network rapidly in Band-Aid fashion. Large amount of voluntary workers and victims can use their mobile phones to access CCN in the early hours of catastrophic natural disasters.

CCN reuses the existing disconnected base stations in the disaster area to save the construction times and resources significantly. The reasons of reusing base stations of cellular network are described as follows: (1) wide coverage of cellular network; (2) widespread use of mobile phones; (3) easy to repair a disconnected base station by adding a low cost add-on module; (4) user friendly, that are firstly important in disaster

response communication. Besides, there has a critical non-technical reason. Mobile phone might be the first thing carried by most victims and people who escape from their homes when a disaster comes. Hence, it is a good option to reconnect those disconnected base stations in the disaster area to provide a low-cost large-scale emergency communication service.

More details of CCN design issues, such as challenges, system requirements, design philosophy and system architecture, were discussed in paper [1,3,4,5,7].

The layout of this paper is as follows. Section II discusses related researches of topology design. Section III formulates the network topology design problem and describes our proposed algorithms. Section IV presents the experiment results. Finally, Section V concludes the paper and discusses the future work.

II. RELATED RESEARCHES

Charnsriponyo and Tipper [2] formulated topology design of 3G wireless backhaul network problem as a mixed linear integer programming (MLIP) problem that aim to find a tree-type network topology with minimum linking cost. Due to the limitation of network scale of MLIP, Charnsriponyo and Tipper also proposed a heuristic algorithm to find a near optimal solution in a reasonable computing time.

Topology design of CCN is similar to 3G wireless backhaul network but has more issues to consider. First, the depth of 3G wireless backhaul network topology is fixed, but the depth of CCN topology is variant. Secondly, all base stations in 3G wireless backhaul network will be selected into the tree-type topology; in CCN, only a part of base stations will be selected. Finally, the goal of topology design of 3G backhaul network is to minimize total link cost; while CCN aims to maximize the efficiency of disaster responses.

III. NETWORK TOPOLOGY DESIGN

A. Consideration of Network Topology Design using Multiple Operators' Base Stations

In CCN, most disconnected base stations require multiple hopping to connect to the core network. The topology can determine the efficiency of CCN, which is the efficiency of disaster response operation and its stability. The considerations

of disaster response efficiency include the emergency level of the afflicted areas or the level of the disaster and the number of disaster responders.

Given that the locations of the base station and the direction of the neighbors are predictable, the interconnection between base stations can be pre-planned to reduce deployment difficulty. In our previous study [6], we proposed to use tree-type topology for CCN. In which the root node is the only survival base station that has the backhaul connection to the core network. Other base stations have to connect to the core network using multihop relay through the root node.

In general, the coverage areas of base stations are well planned and mutual exclusive. Therefore, it's simpler to construct CCN network by using base stations from one operator than multiple operators. Nevertheless, enlarging the concurrent users of some critical areas may increase the disaster response efficiency. This can be achieved by including the base stations from multiple operators in the same covered area into CCN. However, the profit function of the base stations that cover the same area is a decreasing function of the number of base stations in service. The marginal benefit of profits will gradually decrease when multiple base stations covering the same area are selected into CCN.

Combinations of these considerations discussed above are simple forwarding tree (Simple FT), cross-forwarding tree (Cross FT). Simple FT design problem is to find a K-maximum spanning tree with degree bound. The original base stations of Simple FT belong to one operator. Dash lines denote the selected wireless links. Cross FT is also a tree-type topology. But, the original base stations of Cross FT are from multiple operators. Triangle and rectangle denote the base stations of different operators. Cross FT assumes that disaster response authority has the privilege to expropriate any operator's base stations in an emergency.

B. Mathematical Model for Network Topology Design

Consider a directed graph $G(V, E)$, CCN cross network topology design (CNTD) problem is to find a tree-type network topology $T(V', E')$ with degree constrain to maximize the efficiency of disaster response. The input parameters of CNTD problem are listed as follows.

- $V = \{v_i | i=1, 2, \dots, n\}$ is the set of nodes represent the disconnected base stations in the disaster area.
- $E = \{e_{ij} | v_i, v_j \in V\}$ is the set of links represent candidate wireless links between adjacency base stations, where e_{ij} denotes the wireless link between v_i and v_j .
- $C \in \mathbb{Z}^+$ is the total number of available resources (CRPs).
- $D \in \mathbb{Z}^+$ is the number of antennas in a CRP.
- $R = \{r_i | i=1, 2, \dots, n\}$ is the set of profits, where r_i is the profit of v_i , if v_i is recovered.
- $g(m_i)$ is a decreasing function which represents the profit earned by the m_i -th selected node in the same covered area, where m_i denotes the sequence order of v_i .

Optimization model of CNTD is shown as follows.

Maximize

$$f(T(V', E')) = \sum_{v_i \in V'} r_i \cdot g(m_i)$$

Subject to

$$|V'| \leq C \quad \text{---- (3.1)}$$

$$|E'| = |V'| - 1 \quad \text{---- (3.2)}$$

$$T(V', E') \text{ is a connected graph} \quad \text{---- (3.3)}$$

$$\text{Degree}(v_i) \leq D \quad \text{---- (3.4)}$$

$V' = \{v'_i | i=1, 2, \dots, C\}$ is the set of nodes representing the selected base stations that are equipped with CRPs; $E' = \{e'_{ij} | v'_i, v'_j \in V'\}$ is the set of links that represent the wireless links constructed by using the antennas in CRPs. The object function, $f(T(V', E'))$, is equal to the sum of profit multiply by $g(m_i)$, where m_i denotes the selected sequence of v_i in a covered area, for all v_i in V' . The optimization model can be easily degenerated into Simple FT design problem, by setting $g(m_i)$ to 1 for all nodes. Cross FT's optimization model is similar to Simple FT, except that $g(m_i)$ is equal or smaller than 1 due to the decreasing marginal profit earned by recovering more than one base station in the same covered area. Constraint 3.1 represents that the number of nodes in V' is less than or equal to the number of CRPs. Constraint 3.2 and 3.3 represent that $T(V', E')$ is a tree-type topology. Constraint 3.4 represents that the degree of v_i is less than or equal to the number of antennas in a CRP.

C. Toplogy Design Heuristic Algorithm

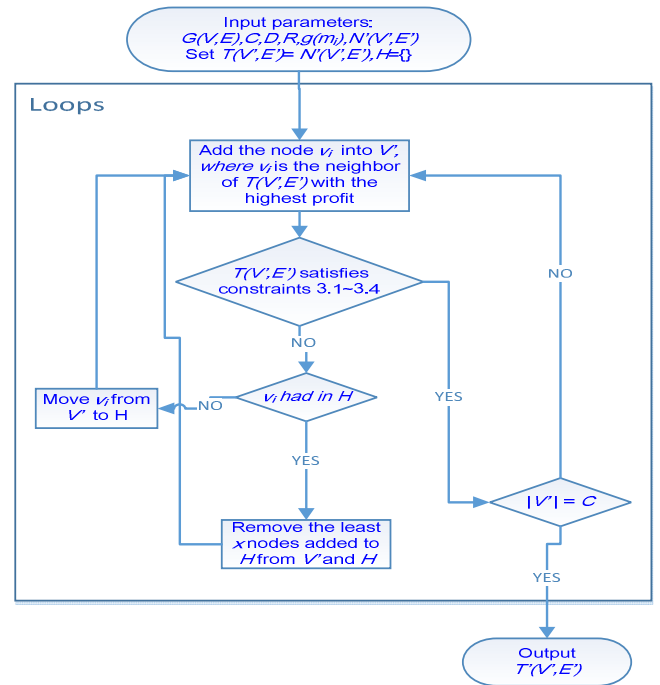


Fig. 1. Flow chart of TDHA

The flow chart of topology design heuristic algorithm (TDHA) is shown in Fig. 1. The input parameters are $G(V,E)$, C , D , R , $g(m_i)$, and $N'(V',E')$. The survival base stations are added into $N'(V',E')$ and set as the initial solution. H records the nodes that are probed and is set as null, initially. The output parameter is the network topology, $T(V',E')$. The purpose of TDHA is to maximize the total profit of $T(V',E')$ by adding the node which has the highest profit to V' , iteratively.

Let v_i represents the neighbor node of $T(V',E')$ that has the highest profit and has not been included into H . In Step1, the process selects v_i to include into H and V' .

In Step 2, if $T(V',E')$ satisfies all constraints after including v_i into V' , then goes back to Step 1 when $|V'| < C$. $|V'|$ denotes the number of nodes added into V' . Otherwise, $T(V',E')$ is not a feasible solution, then removing v_i from V' and goes back to Step 1.

If all neighbor nodes of $T(V',E')$ are included into H and $|V'| < C$, it means that the process is caught into a local optimal. In order to obtained better solutions by trying another probing sequence, the process randomly removes some nodes from V' and H and goes back to Step 1. The process will be repeated until $|V'| = C$. Then, $T(V',E')$ becomes the feasible solution of TDHA.

D. Binary Integer Linear Programming Transformation Methodology

To evaluate our heuristic algorithm, we use Binary Integer Linear Programming (BILP) to obtain optimal solutions, although optimal algorithms are not practical in real disaster response operation. In order to translate CCN CNTD problem into BILP problem, some new variables are introduced. The objective function and the constraints listed in the subsection B are rewritten as follows.

- bv_i is a binary variable, where $i=1,2,\dots,n$. $bv_i=1$ represents that v_i is selected;
- $be_{i,j}$ is a binary variable, where $i,j=1,2,\dots,n$. $be_{i,j}=1$ represents that $e_{i,j}$ is selected;
- $A^{div}(i)$ denotes the set of links diverge from node v_i ;
- $A^{conv}(i)$ denotes the set of links converge to node v_i ;
- $Sum(A^{div}(i))=\sum_{j=1,2,\dots,n} be_{i,j}$ denotes the number of edges diverge from node v_i ;
- $Sum(A^{conv}(i))=\sum_{j=1,2,\dots,n} be_{j,i}$ denotes the number of edges converge to node v_i ;
- $DG(v_i) = Sum(A^{div}(i)) + Sum(A^{conv}(i))$ denotes the degree of v_i ;
- $Sum(V) = \sum_{i=1,2,\dots,n} bv_i$ denotes the number of selected nodes.
- $Sum(E) = \sum_{i=1,2,\dots,n} be_{i,j}$ denotes the number of selected edges.
- $X = \{bv_1, bv_2, \dots, bv_n\}$ is the vector of binary variables.

Maximize

$$f(X) = \sum bv_i \times r_i \times g(m_i), \quad \bullet \quad v_i \in V$$

Subject to

$$be_{i,j} - bv_i \leq 0, \quad , \quad v_i \in V; e_{i,j} \in A^{div}(i) \quad \text{--- (3.5)}$$

$$be_{j,i} - bv_i \leq 0, \quad , \quad v_i \in V; e_{j,i} \in A^{conv}(i) \quad \text{--- (3.6)}$$

$$be_{i,j} + be_{j,i} \leq 1, \quad , \quad v_i, v_j \in V \quad \text{--- (3.7)}$$

$$Sum(V) \leq C \quad \text{--- (3.8)}$$

$$be_{j,i} - Sum(A^{conv}(j)) \leq 0, \quad , \quad v_i, v_j \in V - \{v_{root}\} \quad \text{--- (3.9)}$$

$$Sum(V) - Sum(E) = 1 \quad \text{-- (3.10)}$$

$$DG(v_i) \leq D, \quad , \quad v_i \in V \quad \text{-- (3.11)}$$

$$bv_j - bv_i \leq 0, \quad , \quad v_i, v_j \in cover_x; m_i < m_j \quad \text{-- (3.12)}$$

$f(X)$ denotes the profit function. Constraints 3.5 and 3.6 represent the relations between nodes and edges. All the diverge edges and converge edges of v_i can be selected only when v_i is selected. Because $e_{i,j}$ and $e_{j,i}$ denotes the same wireless link, $e_{i,j}$ and $e_{j,i}$ cannot be selected simultaneously to avoid double count of wireless links (refers to Constraint 3.7). Constraint 3.8 represents the number of selected nodes is less than or equal to the number of CRPs. Constraint 3.9 represents the network topology, $T(V',E')$, is a connected graph. If $e_{i,j}$ is selected ($be_{i,j}=1$), v_j is the parent node of v_i . In order to prevent v_i and v_j from disconnecting with other selected nodes, v_j must have a parent node. It implies that $Sum(A^{conv}(j))$ is greater than or equal to 1 when $be_{i,j}$ is equal to 1. Constraint 3.10 represents $T(V',E')$ is a tree where the number of selected nodes minus the number of selected edges is equal to 1. Constraint 3.11 represents the degree of v_i is less than or equal to the number of antennas in a CRP. Let $cover_x = \{v_i, v_j, v_k, \dots\}$ denotes the set of BSs that cover the same area x with corresponding selection sequence 1,2,3,... The order of v_i in the selection sequence precedes that of v_j . Constraint 3.12 indicates that v_i must be selected before v_j .

IV. PERFORMANCE EVALUATION

The input parameters of performance evaluation are showed in Table I. The profits of nodes are generated by uniform random function and the profits is varied from 1 to 1000. Each test instance corresponds to different combination of graph, number of antennas and CRPs as the input parameters.

TABLE I. THE INPUT PARAMETERS OF TEST CASES

Test Cases	Number of nodes (n)	Number of edges (e)	Antennas (d)	CRPs (c=n/2)
I	50	100,150,200	4,5,6	25
II	100	200,300,400	4,5,6	50
III	200	400,600,800	4,5,6	100

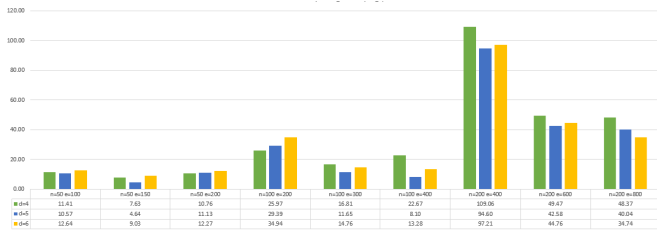


Fig. 2. Average computing times of BILP Algorithm

The average computing times of BILP Algorithm is shown in Fig. 2. The y axis is the average computing time of BILP Algorithm and the x axis is the test case with different input parameters. The average computing times grow exponentially as the number of nodes, n , grows. The minimum computing time is 4.64 sec ($n=50, e=150, d=5$); the maximum is 109.06 sec ($n=200, e=400, d=4$).

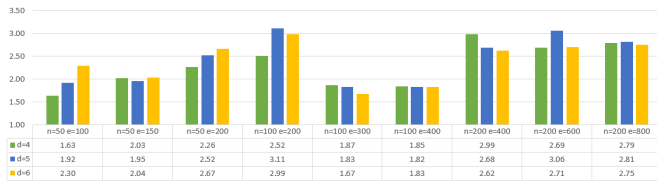


Fig. 3. Average computing times of TDHA Algorithm

Referring to Fig 3, the average computing times of TDHA are less than 3.5 sec in all test cases and grow slightly when the numbers of nodes increase from 50 to 200.

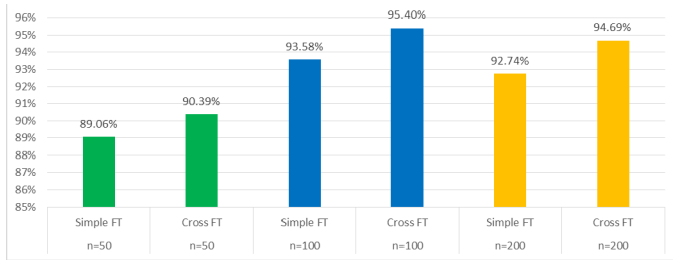


Fig. 4. The performance of TDHA

Referring to Fig 4, the y axis is the ratio of the profit of TDHA's solution to optimal solution. The y axis is used to evaluate the performance of TDHA. The x axis is the topology types and the number of nodes. The best case is 95.4% when the network type is Cross FT and $n=100$. The worst case is 89.06% when the network type is Simple FT and $n=50$.

V. CONCLUSION

The efficiency of disaster response operation much relies on the communication system. However, public communication systems usually crashed in a catastrophic natural disaster due to various causes. We propose a

Contingency Cellular Network (CCN) to support existing mobile phone users with limited capability. CCN builds a multihop wireless network to overlap on top of the disconnected base stations and recovers the connectivity between these base stations and core network. Since, the number of available CRPs may be far less than the number of disrupted base stations. Therefore, only part of the disrupted base stations can be selected and equipped with CRPs. The topology design problem is formulated as a K-Maximum Spanning Tree with degree bound Problem. We propose two algorithms, BILP and TDHA, to solve the topology design problem aiming to maximize the disaster response efficiency.

The experiment results showed that the computing time of BILP is much longer than TDHA. The average computing times of TDHA are less than 3.5 sec in all test cases. However, when the number of nodes is less than or equal to 200, all test cases could solved in 500 seconds by using BILP which may be acceptable in real cases. The performance of TDHA varied in the range of 89.06% and 95.40%. The topology design problem can be solved by TDHA quickly and the performance of TDHA is excellent.

If the topology is needed urgently, the operator of CCN can choose TDHA to solve the network topology problem quickly. Otherwise, the CCN's operator can choose the BILP Algorithm to solve the network topology problem to have the optimal solution.

Tree type topology is applied in this research due to its extensibility and simplify. However, tree type topology is fragile. In our future research, our proposed algorithms will take the reliability of the network topology into consideration.

REFERENCES

- [1] H. Aiache et al., "WIDENS: Advanced Wireless Ad-Hoc Networks for Public Safety," Proc. IST Mobile & Wireless Communications Summit, Dresden, Germany, Jun. 2005.
- [2] Chalernpol Chamsripinyo, "Topological design of 3G wireless access networks," in Proc. of TENCON 2004, Nov. 2004.
- [3] Weimin Dong et al., Chi-Chi, Taiwan Earthquake Event Report, Risk Management Solutions, Inc., http://forms2.rms.com/rs/729-DJX-565/images/eq_chi_chi_taiwan_eq.pdf, retrieved Mar. 2010.
- [4] Jyh-Shyan Huang and Yao-Nan Lien, "Challenges of emergency communication network for disaster response," in Proc. IEEE Int. Conf. Communication Systems (ICCS), Singapore, Nov. 2012, pp. 528-532.
- [5] Jyh-Shyan Huang, Yao-Nan Lien and Chih-Lin Hu, "Design of Contingency Cellular Network," in Proc. 2012 14th Asia-Pacific Network Operations and Management Symposium (APNOMS), Sept. 2012, pp. 1-4.
- [6] Jyh-Shyan Huang, Yao-Nan Lien, Y.C. Huang, "Network Topology Planning for Contingency Cellular Network," Proceedings of 17th Mobile Computing Workshop, August, 2012, Taiwan.
- [7] Zhenhong Shao, Yongxiang Liu, Yi Wu, Lianfeng Shen, "A Rapid and Reliable Disaster Emergency Mobile Communication System via Aerial Ad Hoc BS Networks," in Proc of IEEE Wireless Communications, Networking and Mobile Computing (WiCOM), Sep. 2011.