A Portable Base Station Optimization Model for Wireless Infrastructure Deployment in Disaster Planning and Management

Michael R. Bartolacci
Pennsylvania State University - Berks
mrb24@psu.edu

Christoph Aubrecht
AIT Austrian Institute of Technology, Austria
& The World Bank, USA
christoph.aubrecht@ait.ac.at

Dilek Ozceylan Aubrecht
Sakarya University, Turkey
ozceylan@sakarya.edu.tr

ABSTRACT

Disaster response requires communications among all affected parties including emergency responders and the affected populace. Wireless telecommunications, if available through a fixed structure cellular mobile network, satellites, portable station mobile networks and ad hoc mobile networks, can provide this means for such communications. While the deployment of temporary mobile networks and other wireless equipment following disasters has been successfully accomplished by governmental agencies and mobile network providers following previous disasters, there appears to be little optimization effort involved with respect to maximizing key performance measures of the deployment or minimizing overall 'cost' (including time aspects) to deploy. This work-in-progress does not focus on the question of what entity will operate the portable base during a disaster, but on optimizing the placement of mobile base stations or similar network nodes for planning and real time management purposes. An optimization model is proposed for the staging and placement of portable base stations to support disaster relief efforts.

Keywords

Wireless Communications, Disaster Planning and Management, Optimization, Portable Base Station

INTRODUCTION

Major impacts of disasters include wide spread power outages and failure of communication networks. Consequent disruption of communication capacities especially during emergency situations can significantly threaten response actions and hinder information dissemination. Power recovery can take days and this creates an urgent need to temporarily reinstall communication services via optimally placed portable wireless connection points in order to meet access demands. While discussions of the benefits of wireless communications during disasters and their aftermath have been detailed in the news media and academic works, little rigorous work exists with respect to its optimal deployment in order to maximize such benefits. While previous work focused somewhat on the technology of portable base stations (Bartolacci, et al., 2013), this work develops a portable base station planning and deployment model that takes a global approach with the flexibility for reoptimization during deployment. From such recent disasters as the 2012 "Superstorm" (Hurricane) Sandy in the United States where an average of about 25% of the base stations in the affected area lost service (Kwasinski, 2013) and population in parts remained without access for days to follow, it should be obvious that governmental agencies and even mobile network operators do not optimally plan or execute the deployment of their emergency management resources. We wish to examine a small subset of the overall planning and response modeling that such an agency should undertake, that of the wireless network infrastructure that is in place before, during, and after an emergency or disaster in a given area or region.

One method for ensuring that wireless communication in a region affected by a disaster is available is to utilize portable mobile network base stations (BSs) that can be deployed when conditions are appropriate. Having such devices available to first responders or an affected populace immediately following a disaster would be one goal for a governmental agency or mobile network operator. Unfortunately, enduring long transit times to move devices to an affected area or not having the required number of devices readily deployable to provide sufficient coverage for an affected area can hinder or delay relief efforts that rely on wireless communication networks. Although much work has been done on mobile network design optimization, such models are tailored for planning purposes for fixed base stations and not an ad hoc arrangement of portable ones. Also, previous work in the literature addressing ad hoc network use for disaster recovery looks at technical details and not such issues as portable base station placement or required connectivity in an overall optimization framework. Unlike some of this previous work, we recognize that some fixed mobile network infrastructure existed prior to the disaster and may be optionally integrated into the model if still operating..

WIRELESS PLANNING MODELS FOR EMERGENCY MANAGEMENT

One of the relevant works on wireless network design that addresses disaster recovery is by Lu and coauthors (Lu, et al., 2007). They outline hybrid ad hoc network designs for disaster recovery using WiFi, WiMax, and geostationary satellite technologies. It should be obvious from the mention of both WiMax and satellite technologies that the network architectures they propose assume no existing mobile network connectivity (functioning fixed BS's) to link to and require specialized WiMax and satellite equipment. Their work looked at 2 tier (WiFi linked to Satellite) and 3 tier (WiFi linked to WiMax linked to Satellite) architectures and merely proposed such hybrid network designs for disaster recovery without any notion of optimization. More recent work by Tsai and collaborators (Tsai, et al., 2011) provided an architecture design for applications utilized for emergency management. Much like the previous work described, their design is not an optimization model. The design they propose is also a higher level application layer design and assumes an existing radio network infrastructure is operable for it to utilize. The prototype system they describe, entitled "ALLSurvive" functions at the application layer and deals with location-based information sharing rather than wireless mobile network architecture design. Pace and Aloi's work involves the use of HAP (High Altitude Platform) technologies (Pace and Aloi, 2008). Much like the previously discussed architecture, the network designs discussed involve high altitude aircraft, satellites, and other costly technologies that would be essential in an area with no existing wireless infrastructure and no access for implementing terrestrial-only wireless infrastructures. A multinational group of researchers (Reynaud, et al., 2011; Kandeepan, et al., 2011) focused on a slightly different type of network design for supporting emergency management. They investigated a hybrid wireless network architecture involving LAP (Low Altitude Platform) technologies integrated with terrestrial ones. Much like all of the previously mentioned work, these two papers focus on the architecture and its functioning without any discussion of the costs of implementation or optimization. It is obvious that satellite-based and aerial technologies, be it or HAP or LAP, do not have the problems associated with portable base station placement; but they may have other problems such as the ability of the platform (for HAP or LAP) to maintain coverage of a given area over time and a lack of capacity for uplinks and downlinks (for LAP, HAP or satellites).

Although the discussions above only refer to a few of the many research papers on HAP and LAP network architectures, they are indicative of the engineering viewpoint expressed in the general literature regarding such networks. These discussions focus on the technology and details such as bandwidth sharing or battery usage, not on minimizing "cost/efforts" for implementation. Thus, in reviewing the literature, two important points regarding the implementation of temporary wireless networks to support emergency management come to light:

a. No public research exists (it is possible that FEMA or mobile network operators have their own unpublished models) that attempts to optimize the deployment of such networks from a physical and a cost viewpoint simultaneously (an integrated optimization model that assumes the technologies utilized are fixed)

b. Despite the emergence of LAP's and HAP's, the movement of portable BS's into areas affected by a natural disaster or other similar emergency represents the most efficient means of providing wireless communications given that such equipment is staged within proximity to an affected area and feasible transportation routes exist into such an area

The literature review to this point has focused on technology-based wireless network designs for emergency management, but a large body of literature exists that deals with the more general design of mobile networks and their BS's. Our approach seeks to bridge the gap between these two areas of research. This work builds upon previous work by the authors in that it uses a specific model in operations management; and does not focus primarily on the technology involved, but rather on the optimization and decision making.

OPTIMIZATION MODELS FOR MOBILE NETWORK BASE STATION PLANNING

Traditional optimization modeling approaches fall into two general categories based on their treatment of the notion of time: deterministic and stochastic. Deterministic modeling is more often used for the optimization modeling of wireless infrastructure. Optimization modeling that deals with the management aspect of some scenario is most often accomplished with a stochastic view of world. In other words, it takes time into account and attempts to adjust whatever is being optimized to any changes in variables and inputs on an ongoing basis. Both categories of optimization models have their advantages and disadvantages from ease of development, ease of use, and applicability points of view. While a deterministic optimization model would not be well suited to a scenario where its inputs vary widely over time; a stochastic optimization model would not be suited to a scenario where continuous re-optimization is not practical or even possible (such as where there are insufficient computing resources available or changes to models inputs are difficult to measure in real time). It should be obvious that for portable wireless infrastructure planning for a disaster scenario in a given region, a deterministic optimization model should be used since there are no real time changes to the model inputs; it is merely a planning activity (not accounting for possible chain event or cascading event scenarios). With respect to the deployment or implementation of a temporary wireless infrastructure in the wake of a disaster, a stochastic modeling could be taken; but a quasi-static approach could also work. In a quasi-static approach for optimization modeling, inputs and constraints are held constant for some time window and the model is optimized for that time window. Re-optimization is then required for a new set of inputs and constraints over a later time window. Our proposed optimization model that is outlined in the next section takes a quasi-static view of the world.

Despite the fact that the literature contains many optimization modeling approaches for BS placement, none of these deal directly with a disaster planning context in which portable BS's are utilized. They deal strictly with the implementation of fixed BS's to serve a given demand for wireless service in a region. Many of these optimization approaches are strictly deterministic in nature and take demand and construction/operational costs into account. Work by Menon and Amiri (2006) takes a broader temporal view of the cellular network design problem and combines ideas from simulated annealing and linear programming into the optimization approach. Nielsen, et al., (2009) investigate energy- and cost-efficient deployment of communication networks for a scenario where fiber technology delivers the last mile access (FTTH) through a multi-objective optimization planning problem. Olinick and Rosenberger (2008) take one of the few stochastic approaches in the literature with respect to the modeling of demand. Most of the previous work assumed some fixed amount of required capacity or demand in a given region. Unfortunately, their optimization goal deals with revenue maximization; which is certainly not a goal in the context of a disaster. A typical approach for assigning locations to fixed BSs deals with the assignment of BSs to groups of users or the fulfillment of demand for a given region. While similar in goal to a "cluster and assign" approach, Kalvenes, et al. (2006) take an integer programming approach for smaller sized problems of up to forty BSs. Integer programming is also utilized by Mathar and Schmeink (2001) in their optimization approach which seeks to place base stations and also conduct channel assignments. This same problem (base station location and channel assignment) is also addressed in other work by Kalvenes, et al. (2005). An extended discussion of the various wireless network optimization models in the literature can be found in (Bartolacci, et al., 2013).

PROPOSED PORTABLE BASE STATION PLACEMENT OPTIMIZATION MODEL

The optimization of the movement of portable base stations from centralized storage facilities to staging areas, and then finally to deployment sites in an area affected by a disaster can be generalized as the well-known "transshipment problem" in logistics. The transshipment problem is one in which products are transported from factories where they are produced to distribution centers and finally to customers. The goal of this optimization problem is usually to minimize total transportation costs subject to the requirements of satisfying demand for all customers. Further constraints may include the capacities for the factories, capacities for shipping routes between factories and distribution centers, and capacities for shipping routes between distribution centers and customers. The shipping costs per distance unit for each possible combination of factory and distribution center pair and distribution center and customer location pair provide the coefficients for the objective function variables in the optimization model. Our proposed optimization is similar in nature to the transshipment problem, but we are including additional decision variables in the objective function. Also, our "shipping cost" would not be a true cost in terms of monetary resources. In reality, the "shipping" cost coefficients in the objective function represent a combination of factors including transport cost in monetary terms, transport time, and severity of need at a location.

X = Total number of portable base stations available

S = Number of storage facilities for portable base stations

F_{xs} = 1 if storage facility s houses portable base station x, 0 otherwise, where $s = 1 \ldots S$ and $x = 1 \ldots X$

A = Number of predefined staging points for portable base stations prior to deployment

C_{xsa}= "Cost" to transport portable base station *x* from storage facility *s* to staging point *a*

P_{xa} = 1 if portable base station *x* is brought to staging area *a,* 0 otherwise, where *x* = 1 ... *X* and *a* = 1 ... *A*

U = Total number of candidate sites of possible deployment for portable base stations

R_{xu} = 1 if portable base station *x* is deployed at candidate site *u*

M_{xau} = "Cost" to transport base station *x* from staging point *a* to candidate site *u*

Minimize $\sum_1^X \sum_1^S \sum_1^A C_{xsa} F_{xs} P_{xa} + \sum_1^X \sum_1^A \sum_1^U M_{xau} P_{xa} R_{xu}$ subject to: (worded for ease of understanding)

Total number of portable base stations moved from storage facilities to staging areas has to be less than or equal to *X* .

Any capacity constraints for each staging area. (Maximum and/or minimum amounts of base stations)

Any capacity constraints for each storage facility. (Maximum and/or minimum amounts of base stations)

Conservation of base stations at storage facilities: for each storage facility, the total number of base stations moved from that storage facility area to staging sites added to the number remaining in the storage facility has to be equal to the number that originally was stored there.

Conservation of base stations at staging areas: for each staging area, the total number of base stations moved from that staging area to deployment sites added to the number remaining in that staging area has to equal the total number brought from storage facilities to that staging area.

Total number of portable base stations deployed at a candidate site from a given staging area has to be equal to 0 or 1.

If a deployment site has been allocated a base station from a staging area, another staging area cannot allocate another base station to that site.

Demand constraints for candidate sites - certain points or regions may require, and be suitable for, mobile base stations while others may be deemed unavailable due to current conditions

LINKING THE MODEL TO A GIS ENVIRONMENT

Considering this a two-stage problem of (1) staging and (2) deployment of portable BS's, GIS modeling efforts can be separated for each of those two phases. During the first phase (pre-event planning) the staging locations are predefined according to site suitability and proximity to the expected area affected. The main modeling step is then to minimize the time/ and travel costs of getting the portable stations from the storage to the staging points. Road network vector data (such as OpenStreetMap) may be applied for such efforts as well as predefined ‘travel constraints’ for the trucks carrying the devices (e.g., speed limits, limited usage to first and second order roads). That step is also relevant for the deployment phase, or post-event situational crisis management, which seeks to minimize time/ and travel costs for transferring the devices from staging to deployment locations. For that second phase, however, it is crucial to already have an ex-ante understanding of possible candidate sites in the expected area affected. That constitutes the second main spatial analysis effort, i.e. candidate site identification based on relevant parameters such as placement suitability (referring to basic constraint locations like water areas, dense forests, or steep slopes) and visibility (referring to coverage aspects). Land use/land cover as well as elevation data is used for that step as well as the portable stations’ technical characteristics in terms of signal range and multi-access capacity must be accounted for. Objective thereby is to provide a site selection basis to eventually address access outages and meet certain required coverage thresholds. The latter points to the last GIS modeling aspect, i.e. integrating spatially-distinct information on population distribution (‘horizontal’ dimension) and density (‘vertical’ dimension) patterns (Aubrecht et al., 2013) in order to identify coverage needs. Meeting those needs or rather a certain predefined threshold can then be modeled either based on a fixed given number of available portable stations to deploy or (e.g. if the threshold cannot be met with that number) in iterative manner identifying the number of stations required to reach acceptable coverage status.

SUMMARY AND ONGOING WORK

This paper describes a work-in-progress that was motivated by the lack of existing literature addressing an important problem in the management of disaster relief: the optimization of the placement of portable cellular network base stations and related telecommunications equipment in an affected region. Presented in this paper is a description of an overall optimization model based on the classical transshipment problem in logistics. This mixed integer formulation of the objective function contains two major terms: total costs for staging and total costs for deployment. The objective function is subject to several constraints including the number of portable base stations available and connectivity coverage constraints. The uncertainty of the exact region requiring deployment of the portable base stations creates the opportunity to separate the parts of the overall problem since the first can be deterministic and the second more stochastic in nature. This "divide and conquer" optimization approach is quite common in the modeling of complex problems without sacrificing a great deal of overall optimality if the proper linking between variables in the two levels occurs. We are in the initial stages of developing a test case where we will utilize geographic information systems (GIS) to identifying potential sites for both staging and subsequent placement in an affected test region. One such disaster area we are investigating is the region affected by Superstorm Sandy. To plan for a specific disaster impact event (referring to a hurricane scenario), various forecasting services such as provided by NOAA's National Hurricane Center can be consulted in order to get an understanding of the potential and expected area affected. This is crucial to identify appropriate staging locations in close proximity to areas of expected need of support. Eventually certain adjustable parameters can be defined in the model with regard to a decision support system context. For example, if the hazard intensity is higher, more stations are expected to be inoperable and consequently more portable BS's would be needed. If situation-specific population clusters develop (e.g. population in evacuation areas), thereby creating larger wireless access demands in small regions, certain parameters in the model such as number or type (increased/transmission range) of BS's can be adjusted to meet predefined coverage thresholds.

REFERENCES

1. Aubrecht, C., Özceylan, D., Steinnocher, K., Freire, S. (2013) Multi-level geospatial modeling of human exposure patterns and vulnerability indicators, *Natural Hazards*, 68, 1, 147-163.
2. Bartolacci, M., Mihovska, A. and Ozceylan, D. (2013) Optimization Modeling and Decision Support for Wireless Infrastructure Deployment in Disaster Planning and Management, *Proceedings of the 10th International ISCRAM Conference*, Baden Baden, Germany.
3. Kalvenes, J., Kennington, J. and Olinick, E. (2005) Hierarchical Cellular Network Design with Channel Allocation, *European Journal of Operational Research*, 160, 1, 3-18.
4. Kalvenes, J., Kennington, J. and Olinick, E. (2006) Base Station Location and Service Assignments in W-CDMA Networks, *INFORMS Journal on Computing*, 18, 3, 366-376.
5. Kandeepan, S., Gomez, K., Rasheed, T., and Reynaud, L. (2011) Energy Efficient Cooperative Strategies in Hybrid Aerial-Terrestrial Networks for Emergencies, *Proceedings of 2011 IEEE 22nd International Symposium on Personal, Indoor, and Mobile Radio Communications*, 294-299.
6. Kwasinski, A. (2013) Lessons from Field Damage Assessments about Communication Networks Power Supply and Infrastructure Performance during Natural Disasters with a Focus on Hurricane Sandy, *FCC Workshop on Network Resiliency 2013*, Brooklyn, NY, USA.
7. Lu, W., Seah, W., Peh, E., and Ge, Y. (2007) Communications Support for Disaster Recovery Operations using Hybrid Mobile Ad-Hoc Networks, *Proceedings of the 32nd IEEE Conference on Local Computer Networks*, 763-770.
8. Mathar, R. and Schmeink, M. (2001) Optimal Base Station Positioning and Channel Assignment for 3G Mobile Networks by Integer Programming, *Annals of Operations Research*, 107, 225-236.
9. Menon, S. and Amiri, A. (2006) Multiperiod Cellular Network Design via Price-Influenced Simulated Annealing (PISA), *IEEE Transactions on Systems, Man, and Cybernetics*, 36, 3, 600-610.
10. Nielsen, R.H., Mihovska, A., Madsen, O.B., and Prasad, R., (2009) Energy-Efficient Deployment Through Optimizations in the Planning of ICT Networks, *Chapter in Towards Green ICT,* River Publishers
11. Olinick, E. and Rosenberger, J. (2008) Optimizing Revenue in CDMA Networks Under Demand Uncertainty, *European Journal of Operational Research*, 186, 2, 812-826.
12. Pace, P. and Aloi, G. (2008) Disaster Monitoring and Mitigation using Aerospace Technologies and Integrated Telecommunication Networks, *IEEE Aerospace and Electronic Systems Magazine*, 23, 4, 3-9.
13. Reynaud, L., Rasheed, T., and Kandeepan, S. (2011) An integrated Aerial Telecommunications Network that supports emergency traffic, *Proceedings of the 14th International Symposium on Wireless Personal Multimedia Communications*, 1-5.
14. Tsai, M., Chen, R., Sung, J., Wu, E., Wei, E., Wu, Z. and Liang, J. (2011) Efficient and Flexible Emergency Communications in Next Generation Mobile Network, *Proceedings of the 2011 Eighth IEEE Conference on e-Business Engineering*, 96-101.