Optimization Modeling and Decision Support for Wireless Infrastructure Deployment in Disaster Planning and Management

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ABSTRACT

Natural disasters and emergencies create the need for communication between and among the affected populace and emergency responders as well as other parties such as governmental agencies and aid organizations. Such communications include the dissemination of key information such as evacuation orders and locations of emergency shelters. In particular, the coordination of efforts between responding organizations require additional communication solutions that typically rely heavily on wireless communications to complement fixed line infrastructure due to the ease of use and portability. While the deployment of temporary mobile networks and other wireless equipment following disasters has been successfully accomplished by governmental agencies and 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 to deploy. This work does not focus on the question of what entity will operate the portable base stations or wireless equipment utilized during a disaster, only the question of optimizing placement for planning and real time management purposes. This work examines current wireless network optimization models and points out that none of them include the necessary variables for a disaster planning or emergency deployment context. Due to the fact that the choice of wireless technology impacts the nature of an overall model, a brief discussion of exemplar wireless technologies is included. The work also proposes criteria that must be taken into account in order to have a useful model for deployment of mobile base stations and related wireless communications equipment.

Keywords

Wireless Communications, Disaster Planning and Management, Optimization

INTRODUCTION

The last twenty years have seen a proliferation in the deployment of all types of wireless networks. In particular, mobile cellular networks and their hybrid kin have been relied upon for increasing the effectiveness of emergency and disaster planning and management. 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. This ongoing work was inspired by a previous ISCRAM presentation (Avery-Gomez and Bartolacci, 2011) in that it examines how wireless devices can be effectively and efficiently utilized for emergency and disaster planning and management; but diverges in that it reviews current optimization modeling approaches for wireless network deployment. While previous work focused on the technology, this work examines wireless infrastructure planning models in the literature and proposes additional factors that must be taken into account in a disaster planning and management context. From such recent disasters as Hurricane Katrina and "Superstorm" (Hurricane) Sandy in the United States, it should be obvious that governmental agencies do not optimally plan or execute the deployment of their resources. Likewise, even corporate entities such as mobile network providers, power utilities, and cable television providers suffer from similar problems of misplaced resources, poor coordination, and the lack of an optimized model (which would hopefully provide an optimized priority list of actions to be taken) for dealing with the results of a disaster. FEMA (Federal Emergency Management Association) in the United States has been soundly criticized for its response, or lack thereof, to various emergencies, and for its poor coordination with other governmental and non-governmental organizations (NGO's). 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. Such a scenario can be similar in nature to the uncoordinated deployment of "plug-and-play" type pico BSs in a wireless heterogeneous network. Pico BSs offer smaller ranges of coverage for each unit, but can be used to gain an overall improved area coverage since they are generally less costly and easier to deploy. Part of the cost savings is due to their reduced power consumption and this fact also allows for less intrusive placement. Having such devices available to first responders or an affected populace immediately following a disaster would provide a common “picture” of an emergency situation to allow for a more rapid and coordinated response. Enduring long transit times to move devices to an affected area or not having the required number of devices to provide sufficient coverage for an affected area can hinder or delay relief efforts that rely on wireless communication networks.

THE TECHNOLOGY INVOLVED

This work examines the modeling for an optimal deployment of wireless networks that can be utilized prior to, during, and immediately following an emergency or disaster. It should be noted that we are not strictly looking at the general deployment of planned wireless mobile networks for everyday use that might be utilized during a disaster (as discussed in the work presented at the ISCRAM Conference in 2012) (Ozceylan and Bartolacci, 2012). Instead this work looks to the specific deployment of wireless networking equipment in areas with little or no existing wireless connectivity for disaster management purposes prior to, during, or immediately after a disaster has occurred. Wireless networks available for such usage can be of several different types. The first type, and most commonly relied upon in times of disaster, is the existing mobile network that uses groups of fixed BSs connected through controller stations to the greater public switched telephone network and the Internet. This category includes the third generation (3G) and fourth generation (4G) cellular mobile networks that operate on a variety of standards depending upon the service provider. Such networks are operated by companies and would not be deployed specifically by agencies such as FEMA for responding to a disaster. Nevertheless, these networks should be taken into account in any optimization modeling for wireless network coverage during a disaster since they provide a communications resource that can be utilized. The key to their correct inclusion in such modeling is the estimation of their coverage given the aftermath of a disaster which might include destroyed BS towers, broken links within the fixed infrastructure of the mobile network, and power outages that limit the "uptime" of surviving base stations that may or may not have generator or long life battery backup systems. One approach that could be applied to an emergency scenario is the SON concept(Self-Organized Network) proposed by 3GPP (LTE Rel.8/9/10) as means to reduce operational expenditures. SON provides greater autonomy to wireless networks in configuration and optimization by reducing manual intervention. Self-Optimization, in terms of actual performance, is conducted by auto-tuning the network with the help of user equipment and cell performance reports (e.g. Channel Quality Information Reports-CQI, cell load reports). In the currently proposed LTE heterogeneous scenarios/networks (HetNet), picocells can be deployed with minimal pre-planning in order to fulfill temporary needs for service. In an uncoordinated deployment, neither the position, nor the number of cells is known *a priori*. Also, the pico BSs do not require interface links (e.g., X2) to share information and coordinate actions with other cells.

The second type of wireless network is an IEEE 802.11-based (WiFi) one that can be connected to the Internet or be acting in a mesh or ad hoc fashion as described by Panitzek, et al. (2012). Such networks rely on a variety of methods to connect to the greater Internet including satellite, wireless mobile, Digital Subscriber Line (DSL) and landline phone-based, and cable television-based links. As with the existing mobile network, this type of network relies heavily on existing telecommunications infrastructure and available power to remain viable in the aftermath of a disaster.

The third type of wireless network is one that is just being introduced into the mobile network infrastructure and mainly for "backhaul" purposes that do not directly connect to wireless devices. This network is the IEEE 802.16-based (WiMAX) network which uses microwave technologies instead of traditional radio frequency ones.

A fourth type of network is defined by its topology and not necessarily the frequency spectrum of its transmissions; that is the mobile ad hoc or MANET network (sometimes simply called ad hoc network). This type of network has no fixed infrastructure and most implementations of it rely on peer to peer transmissions. The final type of network again deals more with the topological structure rather than the frequency spectrum utilized; this is the hybrid network which may contain any combination of the previous four network types.

PORTABLE BASE STATION PLANNING AND MANAGEMENT: CAN THEY BE LINKED

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 planning of wireless infrastructure or the placement of wireless resources assuming a relatively static view of the world. 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. Simulation of real time changes can then be pitted against the model's results in order to assess the robustness of the model's results. Although simulation can help to assess the deterministic results' quality, it does not provide a means for truly optimizing the management phase when dealing with a disaster both during its occurrence and its aftermath. Stochastic optimization modeling might be used to deal with the changing nature of a disaster scenario where resources are limited and evolving risks must be dealt with.

In the context of this work-in-progress, the linking of both types of models to create an overall optimization approach for mobile BSs in a disaster context is the goal. A deterministic planning model that takes into account the existing number of mobile BSs, transportation and setup costs, availability of connections to a fixed line infrastructure, and other related factors might be useful for staging mobile BSs near or within regions that may incur a disasters in the near future. Accordingly, a stochastic optimization model may be used to take into account such factors as the severity of damage to existing wireless and fixed line infrastructure, locations of "hard hit" areas, locations of the affected populace, and locations of command and control centers for emergency responders.

Stochastic optimization modeling is meant to take changing conditions into account and to create a series of decisions that would dictate the placement of mobile BSs on a temporary basis and their subsequent changes in locations as time moves forward. In the context of a post-disaster scenario, it should be obvious that such models, which derive a sequence of placement decisions *a priori*, become less useful or irrelevant as conditions evolve. Such a model would be myopic if used blindly and would in reality need to be rerun again and again over time. An alternative approach that will be explored (as opposed to a strictly stochastic programming approach) will be a "quasi-static" one that is "geographically and culturally aware". This approach would be a set of models that are altered over small time horizons in order take into account the variable nature of events unfolding during disaster and its aftermath. Such a modeling approach would take the nature of demographics, physical topography, and related factors into account while dividing an area into zones for regional optimization. Decisions made within zones could be controlled within the context of a larger regional model. This "divide and conquer" optimization approach is quite common in the modeling of very difficult problems without sacrificing a great deal of overall optimality if the proper linking between variables in the two levels occurs. This modeling approach is essentially "quasi-static" in nature in that each zone must rerun its optimization model periodically; but still it allows for a more precise modeling of a zone's unique factors. Such an approach can take into account information known *a priori* about potential areas for severe damage (such as a low lying populated area that is prone to flooding) or a critically affected populace (such as a rural village that does not have great mobility to flee from an impending disaster).

MOBILE NETWORK BASE STATION PLANNING MODELS

The literature contains many modeling approaches for fixed base stations placement, but none of these deal directly with a disaster planning context. As for the placement of mobile BSs for emergency planning and management, we were unable to locate any published work that deals directly with this topic. One of us (Bartolacci) had worked previously on a similar problem, but not in a disaster context (Bartolacci, et, al., 2004). The two stage heuristic approach of clustering potential mobile wireless users and then placing BSs to serve clusters of these users of that work has potential as a heuristic optimization approach for mobile BSs optimization. Such an approach would allow for the servicing of clusters of emergency responders in a disaster scenario. Other optimization modeling approaches with respect to the fixed BS planning problem may also provide some insight or applicability in a disaster context as well. 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, Mihovska, et al., (2009) investigated 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 problems. Olinick and Rosenberger (2008) took 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 dealt with revenue maximization; which is certainly not a goal in the context of a disaster. As previously mentioned, a typical approach for assigning locations to fixed BSs dealt with the assignment of BSs to groups of users or the fulfillment of demand for a given region. While similar in goal to the cluster and assignment approach previously mentioned., Kalvenes, et al. (2006) took an integer programming approach for smaller sized problems of up to forty BSs in problem size. Integer programming was also utilized by Mathar and Schmeink (2001) in their optimization approach which sought to place base stations and also conduct channel assignments. This same problem (base station location and channel assignment) was also addressed in other work by Kalvenes, et al. (2005).

Many BS assignment models proposed in the literature, such as Kim and Kim (1997) deal with the notion of "handoffs" where the placement of one BS affects the placement of nearby base stations due to the fact that there must be a seamless transition for a mobile user when moving between coverage areas of base stations. The ability of emergency responders to move from area to area within a disaster zone with seamless wireless communications capabilities would be a definite advantage. The approach from these types of models should be ideally included in an overall optimization approach for the portable base station assignment model. Related to the notion of seamless handoffs is the ability of a network to locate mobile users and effectively communicate with them. Related work by Paik and Soni (2007) dealt with two technical areas of cellular network functioning: paging and registration. Their modeling approach used simulated annealing in partitioning the overall network for ease in optimizing these functions within the context of base station placement. Again, the ability of linked portable BSs within an affected area to locate individual emergency responders' devices and effectively communicate with them throughout an extended period of time is vital for real time management.

A viable approach for the deployment of disaster-deployed wireless networks can be based on research related to interference avoidance and load balancing schemes in a wireless heterogeneous scenario. Eduardo and Mihovska (2012) propose a self-optimizing, uncoordinated (distributed) admission control algorithm, which supports uncoordinated deployment of small cells. It avoids interference by spreading channel assignments throughout the spectrum while congestion control diverts assignments to channels with spare resources. In short, system enhancement is achieved by avoiding channels with poor signal quality and higher congestion/utilization which thus translates into better performance for individual channels.

ADDITIONAL VARIABLES THAT MAY BE INCLUDED

The BS placement models described in the previous section tend to focus on the optimization of two distinct aspects of a wireless cellular network: the cost of placement (which includes the costs to link fixed base stations to controllers) and the satisfaction of demand (placement of necessary capacity). While a cluster of fixed BSs must work in a coordinated fashion through a controller, mobile BSs providing ad hoc connectivity in the wake of a disaster do not necessarily need such costs taken into account since their locations may change and they will not be part of a cluster for long term management purposes. Such costs for fixed BSs are important to network providers utilizing an optimization model to plan part of an overall cellular infrastructure; but these costs become almost irrelevant in the context of emergency management for mobile BS placement. The other factor usually considered in BS placement optimization models, the satisfaction of demand, is relevant in the context of emergency management. One might say that this is the most important factor in an emergency relief context: the ability to provide needed connectivity for emergency responders and an affected populace wherever and whenever it is required. A range of connectivity or coverage for fixed base stations is usually a given in optimization models. Sometimes connectivity for base stations is based on simulation modeling taking into account natural topographical features and manmade structure to allow for such propagation anomalies such as Rayleigh fading. An optimization model's results could be tested via simulation to ensure robustness prior to