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Discrete Optimization

Mobile phone tower location for survival after natural disasters

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ABSTRACT

This paper discusses the location or strengthening of cell phone towers so as to maximize service coverage and minimize the loss of communications if a natural disaster happens. This paper demonstrates that, under a high likelihood of destruction of antennas (towers), the customary method of maximizing coverage provides poor solutions as compared to the proposed method. In addition to the maximization of service coverage, the objectives of our model include the minimization of expected and worst-case losses. The model is applied to a region in the south of Chile that was stricken by one of the most destructive earthquakes registered in history. Computational results are provided for a variety of scenarios.

1. Introduction

Natural disasters such as earthquakes, hurricanes, flooding, landslides, and volcanic eruptions have a strong impact on roads and bridges, communications systems, the supply of electricity and the availability of other utilities. In such crisis situations, it is difficult to supply emergency services. In many cases, even if they could be alerted, appropriate facilities such as ambulances, emergency helicopters, fire brigades, police, or army units are not able to reach the location of the emergency rapidly enough, especially in rural areas. Furthermore, due to the disruption of communications, people cannot contact or help each other.

There are several examples of such situations. A particularly strong such disaster was the magnitude 8.8 earthquake on February 27, 2010 in the south of Chile, which was followed by a tsunami. This earthquake was among the five strongest ever recorded in history. After the earthquake, many bridges collapsed, the supply of electricity was interrupted and communications systems, including cellular phones, stopped working in large areas for a long time. In addition to the destruction, the most distressing effect was the lack of communications. Even though it may be impossible to set up contingency plans for a disaster of such proportions, the disruption in the communications system caused by this earthquake was considered unacceptable by the general public. The failures had different causes: interrupted electricity supply; misaligned microwave antennas between the cells (or base stations, or antennas) and the rest of the system; broken fiber optics lines, or plain destruction of base stations. To make things worse, there was congestion due to the huge number of call attempts made in the few hours after the earthquake. While it is impossible to design a failure-proof system, these communications systems should be set up (or modified) so as to be at least somewhat effective in the case of medium strength earthquakes, or similar disasters.

Traditionally, cell phone systems are set up without special consideration of disasters or other disruptions. The process typically proceeds in two stages. The first stage solves a covering problem. In this stage of the design, there is no consideration of the amount of traffic that is demanded at each city or village. Since each cell can serve up to a certain amount of traffic, the second stage consists of both locating new cells and increasing the traffic capacity of the existing cells, so that the traffic demand is satisfied during the busy hour, so that at least 98 in every 100 calls find the system available. This second stage continues throughout the life of the system, as the traffic increases or its geographic distribution pattern changes. These changes are usually impossible to predict and to plan for, so the system must be redesigned as the spatial pattern of the demand develops. Due to cost considerations, moving already located cells is not an option at any period during the life of the system. The consequence is that, after the initial period, the spatial distribution of cells at any time is not optimal.

In contrast to the above procedure, we propose to include in the process considerations concerning natural disasters, i.e., to consider the survivability of the system. This process can take any of two forms. It is either done when planning the network, in which case we propose locating the transmitters not only with covering but also a potential loss objective, or, in case the network already exists, we allow strengthening some of the existing towers, so as to ensure that they will still function after a (moderate) disruption of the system. Naturally, no system can be designed to survive large natural disasters with no damage at all. Such an indestructible system

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would require extremely high capital expenditures for robust structures, duplicated communications between the components of the network and power backups for all the base stations. In turn, these expenditures would have to be recovered through very high customer everyday charges. Instead, a wiser alternative would be to invest in the fortification of part of the system; i.e., a subset of the infrastructure that should survive in order to provide a minimum standard of communications to the public in case of a disaster. Particularly, a cellular system should at least keep the capacity of providing short messaging service (SMS) to all the cities, towns and villages in the area of the disaster. Since SMS does not require much bandwidth, a surviving coverage network would be able to handle the extraordinary high traffic volume in these cases. Naturally, in addition to the covering subset of active cells, the central facilities of the network need to be also built to survive the disaster.

Since some communication system exists in all countries, this paper considers an existing system, in which the task is to fortify some of the transmitters, so as to minimize the loss of covered demand in case a single transmitter fails. This analysis of a single failure is standard in many electrical and communications systems, see, e.g., Eiselt et al. (1996), IRGC (2006). From a practical point of view, ''strengthening'' in this context refers to adding power backup for longer outages, making more robust structural designs, adding redundant communications between the cell and the remainder of the network, and similar improvements.

Research on cell phone towers and their properties and problems is far from new. An optimization problem that could be used to locate cell phone towers was formulated by Lee (1991), whose *Communications Design Problem* was primarily designed for the location of radio and television transmitters. Mathar and Niessen (2000) formulate a variety of models that include transmitter locations and fixed and dynamic channel assignments. They solve some of the smaller problems to optimality with the optimization package CPLEX, and design an approximation procedure for the others. Anderson and McGeehan (1994) also employ heuristic methods to solve small instances of a microcell covering problem. Tutschku (1998) uses a Greedy heuristic for the maximum cellular coverage problem. Other algorithmic contributions in the area are those by Karaata (2001), who discusses p-center and p-median problems in the context of mobile computing, as well as Button et al. (1996), whose software contains a two-step procedure that sites transmission towers in Step 1 and determines the power of the tower (and with it its reach) in Step 2. The most recent related papers are Touhami et al. (2006), who study the location of cell phone towers and the selection of their transmitting power, Dutta and Hsu (2001), who select cell phone tower sites, power levels and antenna tilts, and Melachrinoudis and Rosydi (2001), who present a model seeking the best locations, power levels and antenna heights of the radio base stations in a cellular network. Common to all these last papers in the selection of sites for the radio base stations. None of them consider emergency situations.

Our contribution is similar to Mathar and Niessen (2000) in that we also formulate a number of problems as mixed integer programming problems and solve them. The main difference between previous contributions and our paper is our focus on strengthening part of a network and the potential loss of a single signal, issues that has been studied separately by Chu and Lin (2006) from the point of view of probability that the destruction of a transmitter blocks some of the calls. Dutta and Kubat (1999) allow the strengthening of the connections between radio base stations and the remainder of the network. Finally, Church and Scaparra (2005), Scaparra and Church (2005), investigate the possibility of what they call ''facility hardening''. Note that we do not address power allocation, since under emergency situations, the transmitters are supposed to use their maximum power, so to increase coverage.

The paper is organized as follows: Section 2 contains the model, Section 3 presents a real application with data from a region in Chile, and Section 4 discusses conclusions and extensions.

2. The model

As in each location model, we must choose the appropriate space. Since radio coverage depends largely on Euclidean distances between transmitter and receiver (except where there are obstructions), we have chosen to employ the Euclidean plane. Due to the fact that in practice, transmitters (i.e. antennas, base stations) need electricity and adequate access, we may locate these base stations only at a finite number of points where these utilities can be made available at a reasonable cost, making this a discrete location problem in the Euclidean plane. In addition to the aforementioned practical considerations, there are also theoretical difficulties related to locating base stations at arbitrary locations in the continuous plane. To demonstrate, consider that on a perfectly flat plane, the reach of each transmitter would be a circle, so that the task would be to locate a given number of circles, in order to capture the largest possible number of customers. Even this highly simplified problem, investigated by, for example, Bhadury et al. (2003), is known to be very difficult from a computational point of view. These difficulties already occur in the absence of potential secondary objectives, as we consider here. In our model, the customers are assumed to be present at a finite number of known locations, and there is also a finite number of potential locations for the cells. Furthermore; the coverage area of each base station is not circular in the real world, unless the region is flat and homogeneous. Actually, for each potential location of an antenna, the coverage pattern and, consequently, covered demand nodes can be found using appropriate software tools (CRC-COVWEB, 2010). However, the mathematical treatment of the problem does not change with the shape of the coverage area of the antennas. Given feasible facility locations, the task is now to strengthen p transmitter locations (an endogenous number determined by the budget).

Note that there is no need to assume that customers are located in fixed places. There are, however, places where there is a high density of cell phones. These are modeled as demand nodes.

Our model includes existing facilities and it decides optimally—given objectives to be elaborated upon below—which of the existing facilities to fortify. Given a disaster, all unfortified facilities will no longer be usable. In addition, a single fortified facilities may also fail.

The strengthened transmitters will be equipped with the technology that allows them to transmit at maximum power. In a normal situation, they can transmit at less than full power, thus reducing its coverage radius so as to be able to handle all calls in a high-traffic environment. In contrast, the main means of communication in emergency situations is not voice traffic, but short messages, whose throughput is to be maximal. In consequence, in an emergency situation, the strengthened base stations use maximum power, and there is no need of dealing with power allocation. The effect of this is that the coverage radius is not variable.

Consider now the objective of the model. In the absence of losses due to the destruction of facilities based on natural causes (such as earthquakes, landslides, power outages, or similar reasons) and those that are caused deliberately (such as terrorist attacks), it stands to reason to maximize coverage. Maximization of coverage was pioneered by Toregas et al. (1971); for an introduction to the subject, see, e.g., Snyder (2011). In case there exists a potential for disturbances, decision makers may want to guard against those occurrences by introducing added protection of the facilities. Some such means include power backup, duplicated communications and robust structural design of the facilities, a