Autonomous Relocation of Mobile Base Stations in Emergency Scenarios

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***Abstract*—Limited access to communication services is one of the challenges that emergency personnel and first responders could face during environmental disasters or other emergencies. Networking infrastructure can partially (or sometimes fully) breakdown during a catastrophe. At the same time, unusual peaks in traffic load could lead to much higher blocking probability for critical communication. A possible solution for such scenarios is through the use of mobile cellular base stations that can be quickly deployed in the disaster area. These mobile cells can effectively complement the existing undamaged infrastructure or enable a temporary emergency network by themselves. Given the limited capacity of each cell, variable and spatially non-uniform traffic across the disaster area can make a big impact on the network performance. Not only judicious deployment of the cells can help to meet the coverage and capacity demands across the area, but also intelligent relocation strategies can optimally match the network resources to potentially changing traffic demands.In practical scenarios, these mobile base stations may not be able to relocate to all positions within the target field. Such prohibited areas introduce additional constraints on designing an intelligent relocation strategy. We propose a decentralized relocation algorithm that enables mobile cells to adapt their positions in response to potentially changing traffic patterns in a field with prohibited areas. Extensive simulations show considerable improvement in supporting spatially variable traffic throughout the target field.**

I. Introduction

Emergency scenarios such as natural or man-made disasters are typically characterized by unusual peaks in traffic demand caused both by people in the disaster area as well as the first responders and public safety personnel. Such traffic hotspots that typically involve vital life-saving information are a major challenge for the communication network covering the disaster area. The exact locations and magnitudes of these traffic hotspots within a disaster area are usually unknown apriori. As the size of these possible emergency incidents are unpredictable, estimating the capacity requirements to meet the resulting variable excess traffic is nearly impossible.

Designing the communication network for peak traffic is clearly inefficient and prohibitively expensive due to the large peak-to-average traffic ratio. In addition, an over-provisioned network infrastructure itself may be subject to break-downs or target of attacks; and therefore, not able to address the peak communication needs during emergencies. A reasonable solution to this problem is using a set of mobile base stations that can be quickly deployed to service the excess traffic during the disaster recovery and augment the remaining communication infrastructure. By properly deploying these mobile connection points, we can create a temporary network to support first responders need and manage critical public safety communication throughout the disaster area. Such mobile networks that can be easily deployed, configured and adapted, offer an ideal solution to any disaster response effort. These networks would allow public safety personnel and agencies to maintain communication connectivity throughout their operation.

We propose adaptive self-deployment algorithms where base stations use to autonomously relocate and maximize network coverage subject to their capacity limits. Our proposed algorithms are sub-optimal solutions to a stochastic optimization problem that aims to maximize network coverage subject to capacity constraints. We assume that each base station has access to information about the location of its neighboring base stations and their capacity demand.

II. Problem Statement

Consider a region $Q \subset \mathbb{R}^2$ and a set of mobile nodes (i.e. base stations). These base stations can wirelessly communicate with each other. Let $P_0 = \{p_{0,1}, p_{0,2}, p_{0,3}, ..., p_{0,N}\}$ denote the initial position of these base stations where $p_{0,i} \in Q,\ \forall i \in \{1, 2, .., N\}$. For simplicity, we assume that shadow fading characteristics depend mostly on the immediate environment surrounding the user. This results in the shadow fading intensity experienced by a user at point q to be independent of its corresponding base station location.

We assume each user in Q connects to the base station from which it receives the strongest control reference signal that is greater than some specified threshold (i.e. receiver sensitivity denoted by η_r). We also assume existence of interference-coordination among neighbor base stations. For example, Inter-Cell Interference Cancelation algorithms (ICIC) such as dynamic frequency reuse schemes can be used to mitigate inter-cell interference. There is also non-inter-cell coordinated schemes in which each base station uses orthogonal channel.

We define coverage area of a base station as the region where its average downlink transmitted reference signal is the strongest signal received by users and its value is greater than or equal to η_r. This corresponds to 50% coverage probability at cell-edge when shadow fading has log-normal distribution. In order to increase reliability of connection in coverage area, we can also consider a fade margin eta_F to increase link reliability. Based on the propagation and channel loss assumptions, that is not necessary for communication; however, it is necessary for reliability prediction. Based on our propagation and channel loss assumptions, there exists a R_{cov}

such that the average downlink transmitted reference signal is greater than $\eta = \eta_F + \eta_r$ for all points within distance R_{cov} of each base station. In order to formalize total covered area over region Q, we define Voronoi region $V_i = V(p_i)$ as follows:

$$V_i = \{q \in Q \mid \mathbb{E}[P_{rx}(p_i, q)] \geq \mathbb{E}[P_{rx}(p_j, q)], \\ \forall j \in \{1, ..., N\} - \{i\}\} \quad (1)$$

where $P_{rx}(p_i, q)$ is the received signal strength of base station i at point q.

Since all base stations are transmitting using equal power, Voronoi region $V_i = V(p_i)$ will be the set of all points $q \in Q$ such that $\mathbb{E}[L_p(p_i, q)] \leq \mathbb{E}[L_p(p_j, q)]$ where L_p represents pathloss. This is equivalent to $dist(q, p_i) \leq dist(q, p_j)$. As a result, the Voronoi region $V_i = V(p_i)$ is the set of all points $q \in Q$ such that $dist(q, p_i) \leq dist(q, p_j)$ for all $i \neq j, i \in S$. To construct the Voronoi diagram, the bisectors of each base station and its neighbors need to be drawn first. Among all polygons generated by these bisectors, the smallest one which contains the base station is the Voronoi polygon of that base station. It follows from defined coverage model and Voronoi polygon, that any point in a Voronoi polygon which is not in coverage area of the base station associated with that polygon cannot be in coverage area of any other base station either. Thus, in order to find the coverage gaps, i.e. the points that are not in coverage area of any base station, each base station would only need to check its own Voronoi polygon.

The coverage area of each base station within its Voronoi polygon is called the local coverage area of that base station. Total covered area in Q is equal to sum of local covered areas, so we define the coverage metric as follows:

$$O(p_1, ..., p_N) = \sum_{i=1}^{N} \int_{V_i} f(dist(q, p_i)) d_q \quad (2)$$

Where $f(x)$ is equal to 1 if $x \leq R_{cov}$ otherwise $f(x) = 0$.

We are also assuming that the spatial distribution of traffic sources in the target field is non-uniform, and slowly variable. This is due to changes in users demand and their geographical position, and will lead to occurrences of traffic hotspots throughout the target field. As a result, a base station deployment that is servicing traffic at time t_0, may not meet the traffic demand at time t_1. This can be either due to having congested (i.e. overloaded) or having traffic which is not in coverage area of any base station. If we assume that the total traffic demand throughout the target field is less than the total network capacity (i.e. capacity of a base station multiplied by the number of base stations), then it is imaginable that the overload scenarios faced by few base stations can be eliminated by judicious relocation of all base stations in the network. Besides that, autonomous relocations that aim to increase coverage in the area, are needed to service the users that are not in coverage area of any base station.

We propose strategies where mobile base stations adaptively and autonomously adjust their positions in order to maximize the supported traffic and eliminate the base station overload situations in traffic hot-spot zones. Given the aforementioned traffic constraint, our proposed relocation algorithm also tries to maximize the network coverage area at the same time. Let P_n denote the locations of base stations at iteration n, we are interested to find a distributed algorithm in which P_n converges to P^* for a given traffic distribution and such that:

$$P^* = \underset{p_1, ..., p_M}{\arg\max} \sum_{i=1}^{N} \int_{V_i} f(dist(q, p_i)) d_q \quad (3)$$
$$s.t. \quad \mathbb{E}[\rho_i] \leq 1 \qquad \forall i \in \{1, ..., N\}$$

where ρ_i denotes the capacity demand of base station i.

III. Proposed Algorithms and Simulation Results

Our proposed relocation strategies are iterative algorithms; where in each iteration every base station first broadcasts its location along with the capacity demand from users in its coverage area to other neighboring base stations. Each base station then uses this information to calculate its new location. The basic strategy of the algorithms is to generate a sequence of feasible and improving solutions. If the constraint is well satisfied, then the variables change in the direction which improves the objective function. If the constraint function is not satisfied, the variables change in a direction which satisfies the constraint.

Intuitively, the proposed algorithms aim to maximize network coverage while ensuring that base stations can meet their corresponding traffic demand. Each base station tries to increase its local coverage, when the capacity constraints of itself and its neighbors are satisfied. On the other hand, if the capacity constraint of a base station is not satisfied (i.e. overload situation), it makes a request for help by sending a signal to the neighboring base stations. In fields with prohibited area, base stations may not be able to relocate in all directions. In such situations, each base station moves in a feasible direction which improves its local coverage or offloads traffic from overloaded neighbors the fastest.

Figure 1 shows the performance of our proposed algorithm for a sample target field by averaging over 100 different scenarios assuming a uniform initial deployment and random spatial traffic demands. With an initial uniform deployment of base stations, occurrences of traffic hot-spots will cause several base stations to face traffic demands above their capacity limits. These situations result in a low average supported traffic of only 67%. Using our proposed algorithm, the base stations will adaptively relocate to meet such highly non-uniform traffic demand; and therefore, the average supported traffic in the network will increase to 93%.

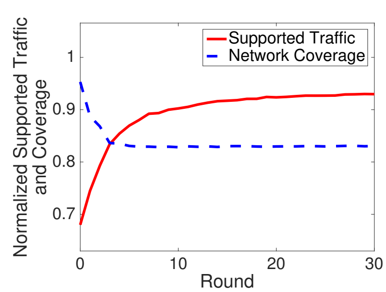

Fig. 1. Average network coverage and supported traffic during execution of Algorithm (assuming a uniform initial deployment)