Drone Base Station Positioning and Power Allocation using Reinforcement Learning

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Abstract—**Large scale natural disasters can cause unpredictable losses of human lives and man-made infrastructure. This can hinder the ability of both survivors as well as search and rescue teams to communicate, decreasing the probability of finding survivors. In such cases, it is crucial that a provisional communication network is deployed as fast as possible in order to re-establish communication and prevent additional casualties. As such, one promising solution for mobile and adaptable emergency communication networks is the deployment of drones equipped with base stations to act as temporary small cells. In this paper, an intelligent solution based on reinforcement learning is proposed to determine the best transmit power allocation and 3D positioning of multiple drone small cells in an emergency scenario. The main goal is to maximize the number of users covered by the drones, while considering user mobility and radio access network constraints. Results show that the proposed algorithm can reduce the number of users in outage when compared to a fixed transmit power approach and that it is also capable of providing the same coverage, with lower average transmit power and using only half of the drones necessary in the case of fixed transmit power.**

Keywords—*Emergency Communication Network, Machine Learning, Reinforcement Learning, Q-Learning, Drone Small Cells*

I. INTRODUCTION

One of the most vital aspects during emergency situations is the ability of isolated people and survivors to communicate with the outside world. In addition, search and rescue teams also need to communicate not only among themselves in order to establish which areas need to be or were already covered and may contain survivors [1]. However, natural disasters, such as hurricanes, earthquakes and tsunamis often lead to a complete failure in existing communication infrastructure, hindering the performance of the on-field workers [1]. Since the first 72 hours after a tragedy, also known as the *Golden Hours*, are the most crucial ones to find survivors, the deployment of a quick, adaptable and efficient Emergency Communication Network (ECN) is vital in catastrophic situations [1], [2].

Existing methods to deploy an efficient ECN lack adaptability, and are restricted by environment and space, such as debris blockage or flooding. To overcome these challenges, one emerging technology that has received increased attention recently is the deployment of drone small cells (DSCs) [3]. For instance, in 2017, when the communications infrastructure of Puerto Rico was devastated by hurricane Maria, AT&T

and Verizon deployed Long-Term Evolution (LTE) equipped drones to provide wireless service, while the network was being restored [4]. It was the first time DSCs were utilized to provide large scale wireless communication after a disaster. This was made possible due to the flexibility, adaptability and mobility provided by the DSCs. As such, they are able to be deployed quickly and to provide service exactly where required [1], [4]. Moreover, these DSC capabilities can be coupled with machine learning algorithms to enable a fast, autonomous and intelligent deployment of an aerial ECN.

Based on that, in this paper, a joint 3D positioning and power allocation algorithm based on Reinforcement Learning (RL), more specifically Q-learning, is proposed. Assuming an area in which a catastrophe has occurred, completely destroying the previous wireless communication infrastructure, the aim is to deploy a flexible and efficient local area ECN based on DSCs. The proposed solution determines the more appropriate position and transmit power of each DSC in order to minimize overall user outage, therefore improving the network performance.

A. Related Work

The usage of DSCs in communication networks has attracted a significant attention from both academia and industry recently [1], [2], [5]–[9]. Several studies focus on the problem of drone positioning in mobile networks. For instance, in [5], the authors attempt to find the best position of multiple DSCs analytically. They propose a drone management framework for efficient operation, considering different environments. In [10], the optimal altitude of DSCs for maximum coverage is derived, with results showing that to maximize coverage, there is an optimal separation distance between drones. Wang *et al.*, in [6], propose an expression for determining the optimal position of a DSC to maximize its coverage area considering energy constraints. In [7] the utilization of DSCs with a new path loss model is proposed. Results show that higher backhaul data rates can be achieved when compared to a solution with only a terrestrial infrastructure. Another work that investigates wireless backhaul constraints is [8], in which the authors study the usage of drones considering different types of backhaul links in order to analyze user coverage and throughput.

Moreover, other related works focus on ECN. In [9], for example, the positioning of DSCs in an emergency scenario is

investigated, with the aim of improving the network throughput. In addition, the work in [2] surveys network architectures for different scenarios, using DSCs for disaster management. Zhao *et al.* propose in [11] a framework of DSC-assisted ECNs with or without a terrestrial Base Station (BS) and also optimize the flight trajectory of the DSC in both scenarios.

Although the importance and contributions of previous works are clear, all surveyed works consider only analytical solutions for positioning drones, while just a few considered emergency situations. As such, to apply the above solutions to an ECN, a great amount of previous network knowledge would be necessary, such as the number of users, their positions, channel state information, *etc.*, which would be unrealistic in a constantly changing environment. Considering this issue, Klaine *et al.* in [1] propose the intelligent positioning of multiple DSCs utilizing a RL-based algorithm. Such algorithm can analyze the environment, adapt itself and explore its possibilities to determine the best actions to be taken by the DSCs. The proposed solution employs Q-learning in every DSC to find their best position in a disaster scenario. Moreover, the algorithm considers user mobility and network constraints, with results showing better coverage than fixing the drones either in random or circular positions, or positioning them in the locations of hot-spots that existed when the network was fully operational.

B. Contributions

This paper is an extension of [1]. However, we assume that the previous cellular network infrastructure was completely destroyed, while in [1] the authors consider the assistance of a terrestrial macro BS. Similarly to [1], to restore cellular coverage, a number of DSCs is deployed to create an ECN, without any prior knowledge of position and channel state information, thus demanding self-optimization. In this sense, we propose a new solution based on Q-learning that jointly optimizes DSC positioning and allocates transmit power for maximizing coverage, while mitigating interference between DSCs and minimizing the number of users in outage. Results show that when power allocation is used, instead of a fixed power as in [1], it is possible to either increase the number of users covered, or even to use considerably fewer DSCs to achieve the same performance.

The remainder of this paper is organized as follows. Section II describes the urban path loss model, the network and the users distribution. Section III presents the proposed solution and the metrics used to measure the system performance. Section IV discusses simulation results. Lastly, Section V highlights the key findings and concludes the paper.

II. SYSTEM MODEL

This section introduces the parameters used in the urban path loss model in Section II-A, the DSCs network in Section II-B and the user distribution in Section II-C, respectively.

A. Urban Model

The urban environment model used in this paper follows the International Telecommunication Union (ITU-R) document [12], as in [1], [13], which recommends a standardized model for urban area based on the following parameters:

- α: the ratio of built-up land area to the total land area.

- β: average number of buildings per square kilometer.

- γ: scale parameter describing building height distribution.

In order to model an urban scenario for this paper, ITU statistical parameters and a Manhattan grid layout are considered for building distribution, following [1], [13]. The buildings have a square area of width W and are separated by a space S. The height of the buildings are generated following Rayleigh distribution using the parameter γ. The selected urban scenario is deployed in an $L \times L$ square area, while W and S are given, in meters, by [1], [13]

$$W = 1000\sqrt{\frac{\alpha}{\beta}}, \qquad (1)$$

$$S = \frac{1000}{\sqrt{\beta}} - W. \qquad (2)$$

B. Temporary Network

The solution proposed in this paper considers the deployment of DSCs to create an ECN in a disaster scenario. To provide the necessary coverage to support the communication of rescue teams and to minimize users in outage, the DSCs are equipped with an antenna which has a given directivity. As such, it is considered that the DSCs antenna has an aperture angle θ, as in [1], which is the region that concentrates the major lobe of the antenna and has the highest gain. Thus, the coverage radius of a DSC can be expressed as

$$\rho = h_{\mathrm{d}} \cdot \tan\left(\frac{\theta}{2}\right), \qquad (3)$$

where h_{d} is the DSC height. Moreover, we also consider that the irradiated signal outside ρ is highly attenuated [1].

Considering a set of $\mathbb{U} = \{1, 2, ..., N_{\mathrm{u}}\}$ users randomly distributed in the $L \times L$ square area and a set of $\mathbb{D} = \{1, 2, ..., N_{\mathrm{d}}\}$ DSCs, the path loss $\chi_{i,j}$ between user i and DSC j, with $i \in \mathbb{U}$ and $j \in \mathbb{D}$, can be determined. The path loss (in dB) is composed by a free-space path loss component, with an additional loss ξ depending on the line of sight (LOS) between a DSC and a user [13], so that

$$\chi_{i,j} = 20 \log_{10}\left(\frac{4\pi f_{\mathrm{c}} d_{i,j}}{c}\right) + \xi, \qquad (4)$$

where $d_{i,j}$ is the distance between user i and DSC j, c is the speed of light and f_{c} is the carrier frequency. According to [10], ξ adopts different deterministic values for LOS and non line of sight (NLOS) links.

C. Users Association

In order to associate users to DSCs, the Reference Signal Received Power (RSRP) between user i and DSC j, needs to be computed, and can be expressed, in dB, as

$$\mathrm{RSRP}_{i,j} = \mathrm{EIRP}_j - \chi_{i,j}, \qquad (5)$$

where the Equivalent Isotropically Radiated Power (EIRP) is the sum of the transmit power with the antenna gain [1]. Based

on that, the Signal to Interference plus Noise Ratio (SINR) is expressed as

$$\text{SINR}_{i,j} = \frac{\text{RSRP}_{i,j}}{N + \sum_{k=1, k \neq j}^{N_d} \text{RSRP}_{i,k}}, \qquad (6)$$

where N is the additive white Gaussian noise power.

Users are allocated to the DSC with the best SINR. Besides that, the association also depends on the available capacity of the DSC Radio Access Network (RAN). If the SINR is above a specific threshold and there is enough RAN capacity for the user, then it is associated to the DSC. However, if the user SINR is below a threshold or if the DSC has no resource blocks (RB) available in its RAN, the next DSC (in terms of SINR) is considered as a candidate for association[1]. If a user is unable to connect to a DSC in a time slot after trying to connect to all DSCs at range, then the user is considered in outage for that time slot.

III. PROPOSED SOLUTION

This work proposes a RL-based method, using Q-learning, to jointly optimize DSCs 3D position and transmit power, creating a local network of DSCs, with the intention of minimizing the number of users in outage in a disaster scenario where the previous network infrastructure was destroyed.

A. Q-learning

Machine learning algorithms have played an important role in communication networks in recent years [14], with special attention to intelligent applications offered by RL algorithms, which can be used, *e.g.*, as a solution for positioning DSCs in wireless networks [1], [3]. A RL system is composed of an agent, which interacts with an environment and acquires knowledge from it. This knowledge is gathered in a trial and error approach, in which the agent tries different actions and collects the responses from the environment, in what is known as the reward. This is performed in order to discover which actions to take at specific states and this knowledge is stored in a table, known as the action-value function [15].

Q-learning, one of the most practical algorithms in RL, utilizes this idea and updates its action-value function, also known as the Q-table, via [15]

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \qquad (7)$$
$$\lambda \left[r_{t+1} + \phi \max_a Q(s_{t+1}, a) - Q(s_t, a_t) \right],$$

where λ is the learning rate, r_{t+1} is the reward yielded by the environment and ϕ is the discount factor (which dictates the value given to future rewards).

This table defines the value of being in a state s_t, at time t, and taking an action a_t. After the agent performs an action, the environment takes the agent to a new state and generates a reward. The agent will then evaluate the reward in the new state and update the value of the previous state, now that it has the complete knowledge. Based on that, the algorithm can try different actions in different states (exploring) or choose the highest value of the Q-table which leads to better rewards at other states (exploiting) [15].

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[1]It is considered that each user consumes 1 RB when associated to a DSC.

B. Proposed Method

In this paper, the goal of the proposed solution is to maximize user coverage by allocating power and positioning the DSCs in a dynamic system where users are moving and have different requirements. Next, the Q-learning parameters are presented.

- *Environment:* the disaster scenario, with buildings and moving users.

- *Agents:* each DSC is an independent agent, each having a different Q-table.

- *States:* three dimension position of a DSC plus its transmit power.

- *Actions:* each drone can take nine possible actions: move up, down, right, left, forward, backward, increase or decrease its transmit power, or do nothing.

- *Reward:* the reward r is given by the total number of allocated users,

$$r = \sum_{j=1}^{N_d} U_j, \qquad (8)$$

where U_j is the number of users allocated to DSC j. The DSCs are assumed to have access to the total number of allocated users by means of a central entity. Note that the DSCs must have backhaul connection to the core network, and such central entity is in the core network. The backhaul is assumed ideal in this work.

- *Policy:* DSCs choose their actions according to an ϵ-greed policy, with ϵ decaying over time [15].

- *Update:* each DSC updates its Q-table as in (7).

- *Initialization:* all the drones are initialized at random locations and with their Q-tables set to zero.

- *Episode:* the episodes are subsequences of the agent-environment interaction. In the proposed problem, an episode can be described as a snapshot of the network. In each episode, DSCs take actions based on their current state and evaluate their reward. This process is repeated for a certain number of iterations until one of the stopping criteria is met.

- *Stopping criteria:* three different conditions are stopping criteria for the proposed method: *i.)* the reward has not improved after a certain number of iterations $\text{Max}_{it,r}$, *ii.)* a maximum number of iterations Max_{it} has been carried out, or *iii.)* the DSC has used all RBs. When the DSC meets one of these conditions, it moves to the state which yields the best reward and stops until the next episode.

The proposed method runs in a distributed and independent fashion in each DSC, and is summarized in Algorithm 1.

C. Outage Metric

The metric utilized to analyze the results of the proposed solution is the percentage of users in outage, which is given by $D_u = 100 \cdot N_o / N_u$, where N_o is the number of users in outage and is given by $N_o = N_u - \sum_{j=1}^{N_d} U_j$.

Algorithm 1 DSCs Power Allocation and Positioning

Require: Initialize DSC locations and Q-tables
Ensure: Power allocation and positioning of DSCs
  for *Every episode* **do**
    while *Stopping criteria not met* **do**
      DSC selects action according to ϵ-greedy policy
      Update DSC state
      Allocate users and receive reward, r_{t+1}
      Update Q-tables
    end while
    Allocate power and move to state with best reward
    Allocate users
  end for

IV. SIMULATION RESULTS

In this section we compare the proposed solution to the method in [1], in which every DSC employs a fixed transmit power of EIRP = 0 dBW. A summary of the simulation parameters is shown in Table I. Simulation results are generated and averaged out by 15 independent runs, each with 100 episodes. Before the first episode, user positions are generated. Each episode is divided into iterations, in which users are considered static and DSCs try to find the best power allocation and position. After a certain number of iterations, depending on the stopping criteria, DSCs decide their transmit power and best position for that episode. For the next episode users move randomly, with a maximum displacement of 3 m in either X-axis or Y-axis, while DSCs start in the same learned position of the previous episode with the knowledge of the computed Q-tables. This series of actions is repeated for each run.

Figure 1 plots the evolution of the percentage of users in outage versus the number of episodes, in a scenario with 9 DSCs, comparing the proposed solution and the method in [1]. As we can observe, the percentage of users in outage decreases rapidly with the number of episodes, reaching near zero for both methods after around 10 episodes. In order to consider only the steady state performance, in the following we present numerical results using the average of a number of episodes beyond such transient behavior. In particular, next we consider the average performance during episodes 11 to 100.

Figure 2 shows the percentage of users in outage per number of DSCs. It can be seen that the performance achieved by the fixed transmit power solution using 9 DSCs, [1], can be achieved with just 5 DSCs when using the proposed solution. In addition, the new method yields the best overall results, having a percentage of users in outage much smaller than the case with fixed transmit power when considering 9 DSCs. Moreover, in the case of 9 DSCs the average transmit power is only EIRP $= -10$ dBW, whereas the average transmit power for the fixed power solution is EIRP $= 0$ dBW, as shown in Figure 3. Hence, the proposed solution presents a better performance not only in terms of users in outage, but also in average transmit power.

Finally, Figure 4 illustrates the position of 9 DSCs for a particular episode, including their transmit power and RAN load. Different drones prefer different heights, in order to maximize coverage and minimize interference. DSCs with higher altitude use the increased coverage to serve users that

Table I: Simulation parameters.

| Parameters	Value
Ratio of build-up to total land area (α)	0.3
Average number of buildings (β)	500 buildings/km
Scale parameter for building heights (γ)	15 m
ξ LOS	1 dB
ξ NLOS	20 dB
Side of the square area (L)	500 m
Drone X-axis and Y-axis step	50 m
Drone Z-axis step	100 m
Minimum Drone height	200 m
Maximum Drone height	1,000 m
Users X-axis and Y-axis step	1 m
Number of users (N_u)	200
User height (h_u)	1.5 m
DSC antenna directivity angle (θ)	60º
Possible DSC EIRP	$\{-20, -10, 0\}$ dBW
RBs in DSC	50
Carrier frequency (f_c)	1 GHz
Total number of episodes	100
Number of independent runs	15
Max iterations per episode (Max_{it})	3600
Max iterations, same reward ($\mathrm{Max}_{it,r}$)	70
Min iterations per episode ($\mathrm{Min}_{it,r}$)	200
Learning Rate (λ)	0.9
Discount Factor (ϕ)	0.9
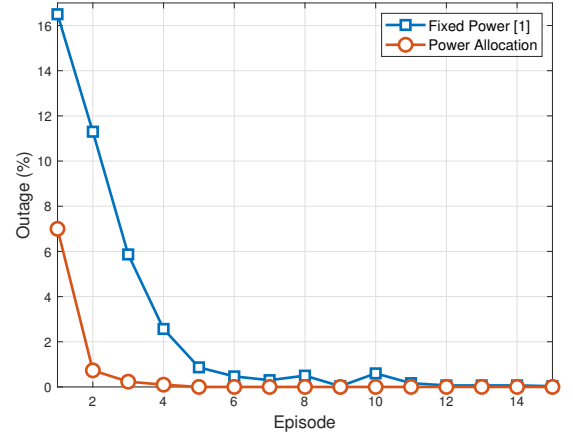
Figure 1: Example of algorithm evolution as a function of the episodes, in a scenario with 9 DSCs.

would be in outage. Regarding RAN load, none of the DSCs uses full capacity, resulting in more DSCs using lower transmit power, mitigating interference and improving coverage.

V. CONCLUSION

In this paper, DSCs were used to deploy an ECN in a catastrophe scenario. The proposed solution consisted of a distributed implementation of Q-learning, to optimize the position and power allocation of each DSC, while maximizing the number of covered users. Results showed that power allocation at the DSCs positively impacts the network performance.
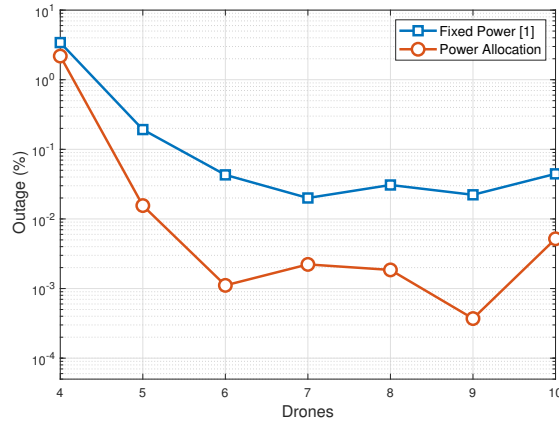
Figure 2: Percentage of users in outage as a function of the number of DSCs.
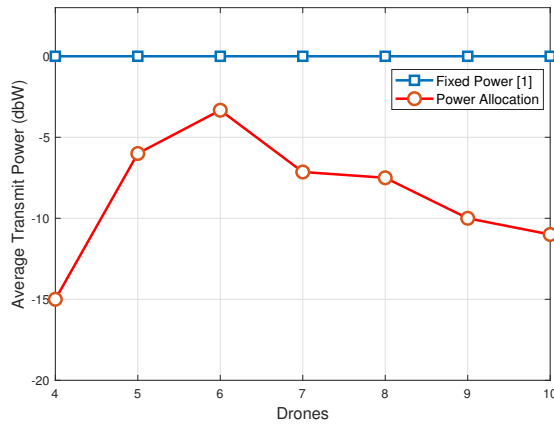
Figure 3: DSCs average transmit power.

Figure 4: Final deployment of 9 DSCs.

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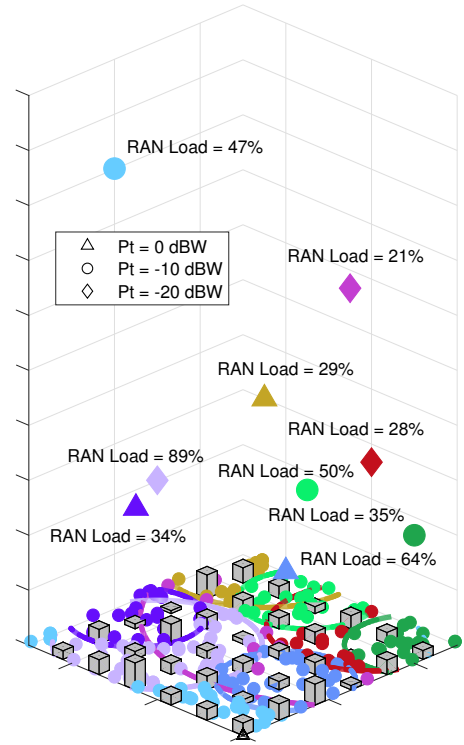
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