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***Abstract*—Challenged Networks (CNs) are characterized by frequent varying network conditions and intermittent connectivity. In general, CNs emerge in different scenarios including the disaster and emergency situations when the traditional cellular infrastructure is dysfunctional or unavailable as well as in the undeserved areas such as rural and developing regions. This paper aims to evaluate the performance of a mobile edge infrastructure adopting Unmanned Aerial Vehicles (UAVs) for CN scenarios. Specifically, we assume that the UAVs can host micro Base Stations (BSs) and edge computing resources, which can be dynamically moved over the zones where the terrestrial mobile network is not properly working. After presenting the proposed UAV-mounted edge architecture, we propose a simple model to evaluate the performance in terms of coverage to users. Our preliminary results show that the UAV-based mobile edge architecture can guarantee a good coverage to users, even if the number of traditional BSs that are not working correctly is large.**

Keywords: Challenged networks, Disaster communications, Mobile edge network, Unmanned aerial vehicles

I. Introduction

Challenged Networks (CNs) emerge when traditional terrestrial network infrastructures fail to effectively provide reliable communications [1]. CNs can be characterized by the irregularities of communication performance arising from power constraints, as well as intermittent or no connectivity [2]. Such characteristics emerge as a consequence of disaster and emergency situations, especially when the terrestrial infrastructure is unavailable or dysfunctional. Not surprisingly, current disaster and emergency communications systems are still limited in network capacity, coverage, interoperability and technological gaps with regards to the newest commercial technologies and evolving standards such as 5G [3]. On the other hand, user devices are getting smarter, with new applications supporting packet data with integrated high-resolution cameras, sensors and multi-mode heterogeneous receivers. Such improvements call for a marked increase in capacity and energy demands for First Responder (FR)'s devices. Specifically, the ability to send and receive multimedia data (other than text or voice) allows rescuers to be better prepared and coordinated e.g., after emergencies like the Christchurch earthquake in 2010 [4]. These factors underline an urgent requirement for a rapidly deployable multi-service interoperable infrastructure capable of supporting reliable high data rate applications to serve large-scale disaster situations.

In addition, the network connectivity is not just being challenged during the disasters. Nowadays, rural and developing regions are still facing CN behavior due to their sparsely spread populations living in physically remote locations as well as the fact that in these regions the power grid is not always reliable. Clearly, it is simply not cost effective for mobile and Internet Service Providers (ISPs) to install a dense network infrastructure for mobile and broadband Internet access in such areas. Apart from the physical limitations of terrestrial infrastructures to provide last mile access (mainly due to the distance between the network devices and the users), the remote communities also incur higher cost for connectivity between the edge network and backbone network when using wired technologies. On the other hand, the edge networks in dense zones are characterized by a large number of users, thus generating large revenues for the operator (even when competition among operators is enforced). While a rural or remote broadband edge network often does not offer the same economies of scale, raising the cost per user for the operator. As a result, the expenses of access for rural and developing area is considered a major impairment for the goal of Global Access to the Internet for All (GAIA) [5].

In this context, several questions arise such as: (1) How to design a network infrastructure to support a terrestrial mobile operator in CNs ? (2) How to control the service performance to the users? The answers to these questions are the primary goal of this paper. Specifically, we assume to deploy a mobile edge network based on Unmanned Aerial Vehicles (UAVs), which are used to host Base Stations (BSs) as well as edge computing capabilities. The proposed architecture is able to guarantee the coverage and services to users in CNs scenarios, e.g., natural disasters and rural/remote locations. More in depth, thanks to the fact that the mobility feature of the UAVs is exploited, it is possible to deploy the BSs and computing nodes where (and when) they are needed, e.g., in the zones where the BSs are failed, thus guaranteeing the services to the users. In addition, we also deploy a methodology to evaluate the performance of the proposed infrastructure in terms of coverage. Our preliminary results demonstrate the coverage improvement when the proposed UAVs-mounted edge infrastructure is deployed, even when a large ratio of the network devices of the terrestrial operator are failed.

The paper is organized as follows: Section II highlights the related work. Section III introduces the proposed UAVs-based mobile edge infrastructure. The formal model to evaluate the performance is detailed in Section IV. Results are presented in Section V. Finally, Section VI concludes our work and also layouts the future works.

II. Related Work

Mobile Edge Computing (MEC) [6] is an emerging technology that provides cloud and information services to mobile users, which is significantly reducing the network latency by enabling computation and storage capacity located at the edge network compared to the conventional far-end cloud solutions. In addition, many end-user devices with low processor and storage capacity are able to offload their computation to the MEC so as to prolong the battery life-time [7]. Our mobile network architecture takes advantage of the MEC concept in order to install computing resources on the UAVs. In addition, we assume that UAVs are able to accommodate Base Stations (BSs) to provide also radio resources to the users.

The UAVs such as drones have been used for humanitarian settings, e.g., in disaster and emergency relief. There are organizations dealing with drone solutions for disaster responses [8]. Drones have a relevant role in the entire disaster cycle from risk reduction to preparedness, response, search and rescue, recovery, and reconstruction. From the communications perspective, to tackle the challenges of mobile coverage optimization, the research [9] has shown that mobility of aerial nodes can increase the throughput, wireless coverage, and other network performance [10].

In addition, the UAVs can be used to extend wireless coverage or provide relaying services to end-users during limited or no network connectivity [11]. The study in [12] has developed a 3D optimal deployment of UAVs to achieve the maximum coverage with minimum revenues. Moreover, the study in [13] discussed the UAVs communications in public safety situations where the UAV-mounted base stations can be rapidly deployed to recover the communications. In addition, some recent studies have also demonstrated that UAVs can host computing units such as cloudlet or server [14], [15]. In this paper, we advance previous works to propose an UAVs-mounted mobile edge infrastructure to support both computing and communications services to the users.

III. UAVs-based Edge Infrastructure

In the UAV-assisted edge infrastructure, we envision that both services and networks are managed in a converged way, following the emerging trend recommended in the 5G architecture [16]. In the proposed infrastructure, the edge network is orchestrated in conjunction with the metro and core ones. Additionally, through Network Function Visualization (NFV), the network operators can enable both computing and storage within network devices. NFV capabilities enable the possibility to implement optimal resource allocation policies to flexibly move the network and computing capacities to where it is necessary or where the sources of renewable energy are available. We intend to exploit the advances of NFV and lightweight Operating System (OS) visualization technologies such as Dockers [17] and Unikernels to instantiate services on demand in the proposed UAV-assisted edge infrastructure.

The Fig. 1 presents the proposed infrastructure for the CN scenario of rural and developing regions. Specifically, the coverage and capacity are provided by Remote Radio Heads (RRHs) mounted on top of UAVs and balloons i.e., RRH-UAV and RRH-Balloon according to the various coverage scales. Each RRH-UAV establishes communication with other RRH-UAV and/or RRH-Balloon flying in the same zone. In addition, the RRH-UAV is able to establish a radio link with a Baseband Unit (BBU) mounted in selected Solar-Powered (SP) Nodes for edge computing and information processing. Notice also that the UAV can be recharged by power stations fed by solar panels in this rural case. Both the UAVs and balloons are continuously flying in the atmosphere in order to provide basic mobile coverage and emergency communications services. Moreover, each local community has been connected to such an infrastructure may deploy Delay Tolerant Networks (DTNs) approach to further disseminate the information. In addition to the UAVs, we foresee the exploitation of BS Large Cells (LCs), with coverage radius in the order of 50 km. BSs LCs are also powered by solar panels, since the power grid is assumed to be not present or unreliable. In addition, we foresee the exploitation of the flexible, efficient, low-cost, low-power nodes (i.e., SP-Nodes). Such devices can virtualize the various functionalities including radio, computing, communications, caching and transportation. Each functionality can be activated or deactivated based on the requirements from the users and also the operator needs. For example, during the high traffic period, the computing resources could be moved into the nodes close to users, while the opposite can be implemented during the low traffic periods. At the same time, the coordinations among UAVs, balloons, BSs LCs, and also to decrease/increase their mobile coverage according to the users' density and needs variation over the time.

The Fig. 2 presents the deployment of the UAVs-assisted mobile edge infrastructure in the disaster and emergency communications scenarios. In this case, a number of BSs belonging to the traditional terrestrial network are failed or dysfunctional. Therefore, the RRH-UAVs and the RRH-Balloons are sent over to fill the coverage gaps in order to guarantee the communications and computing services, especially in the presence of emergency and disaster situations. In the following, we concentrate on this latter case to propose a model in order to compute the coverage to the users when the UAVs-assisted mobile edge infrastructure is deployed.

IV. System Model

For an arbitrary user equipment (UE) n at a distance d_{nm} from its serving BS or UAV-BS (UBS) m, the average received

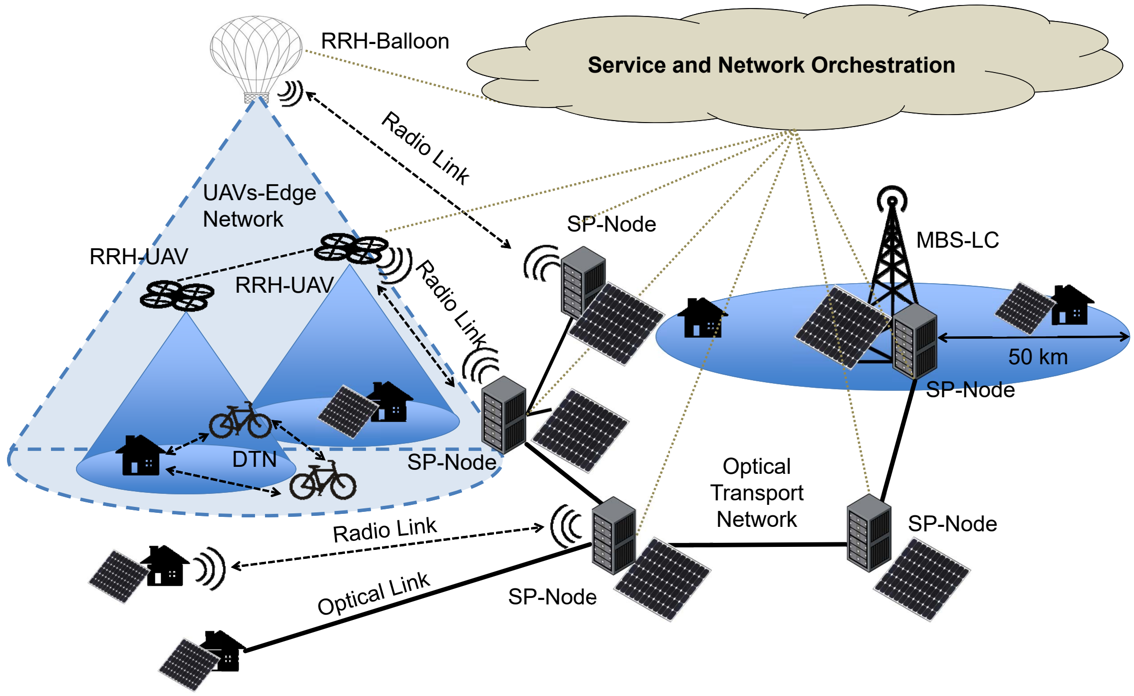

Fig. 1. Vision of the UAV-assisted edge infrastructure for challenged network scenario (i) rural and developing area. SP = solar powered, MBS= Macro Base Station LC = Large Cell, RRH = Remote Radio Head, UAV = Unmanned Aerial Vehicle, DTN = Delay Tolerant Network, NODE = Flexible component that can act as micro edge/cloud server, BBU=Baseband Unit, SDN switch and optical router.

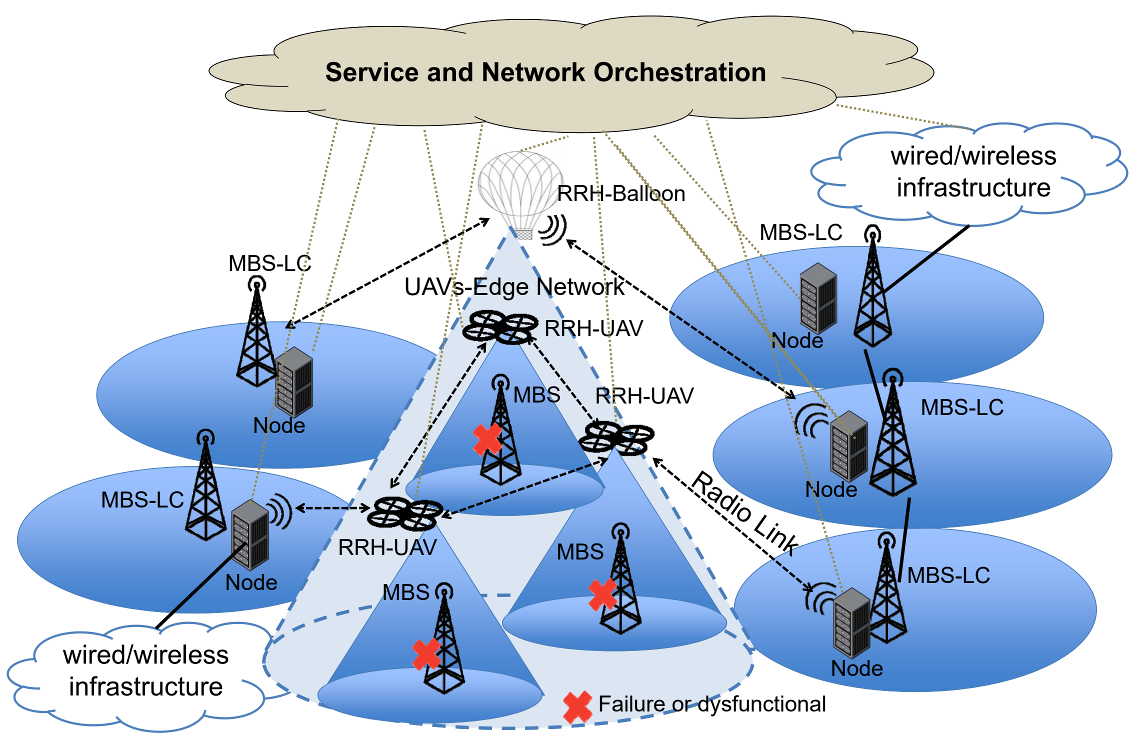

Fig. 2. Vision of the UAV-assisted edge infrastructure for challenged network scenario (ii) disaster and emergency communications cases

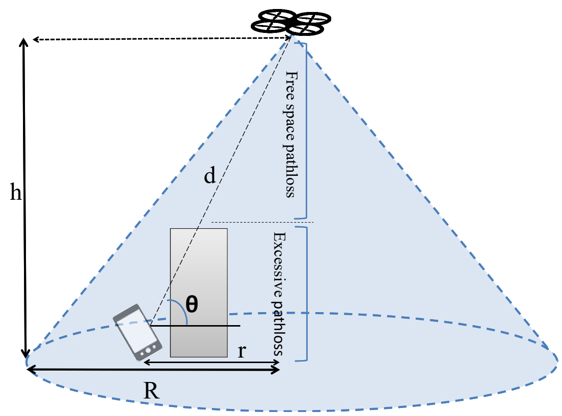

Fig. 3. The coverage model by BS (and UBS)

signal power strength is given by [13]:

$$S(d_{nm}) = \frac{P_{tx}G}{d_{nm}^{\delta}} \tag{1}$$

where

- P_{tx} - BS transmission power or P'_{tx} for UBS
- G - the factor that accounts for the geometrical parameters such as transmitter and receiver antenna heights.
- δ - pathloss exponent (PLE)
- d_{nm} - distance between the UE and BS

Specifically, δ represents the reduction in power of the electro magnetic wave as it passes through the a medium. Clearly, if δ is increased in Eq. (1), the average received signal strength is decreased and vice versa. More in depth, the signals emitted by the BS propagate through free space until reaching the ground where they might incur scattering and shadowing caused by the man-made structures. In this case, an additional loss has to be included in the pathloss. The resulting total mean pathloss δ_ξ (in dB) is computed as below:

$$\delta_\xi = \psi + \eta_\xi \tag{2}$$

where ψ is the free space pathloss between the user and the BS, η represents the mean value of excessive pathloss and ξ represents the dominant propagation groups i.e., line-of-sight (LoS) and non-line-of-sight (NLoS). To find the spatial expectation of the pathloss Λ between an UAV-BS (UBS) and all ground receivers having a common elevation angle θ, shown as in Fig.3, which can be calculated as below:

$$\Lambda = \sum_{\xi} \delta_\xi \mathbf{P}(\xi, \theta) \tag{3}$$

where $\mathbf{P}(\xi, \theta)$ is the probability on the occurrence of a certain propagation group associated with the elevation angle θ which can be further decoupled as:

$$\mathbf{P}(NLoS, \theta) = 1 - \mathbf{P}(LoS, \theta) \tag{4}$$

The probability of LoS depends on three factors including α, β, and γ, which are the ratio of build-up land area to the total land area; the mean number of buildings per unit of area; a scale parameter that describes the buildings' heights distribution. Thus it can be calculated as below [18]:

$$\mathbf{P}(LoS) = \prod_{n=0}^{m}[1 - exp(-\frac{\frac{[h(n+\frac{1}{2})(h-h')]^2}{m+1}}{2\gamma^2})] \tag{5}$$

where $m = floor(r\sqrt{\alpha\beta} - 1)$ and r is the ground distance between the transmitter (h) and the receiver (h'). The cell radius of the coverage zone can be written as:

$$R = r|\Lambda = \delta_{max} \tag{6}$$

Accordingly, the optimization problem is to find the best altitude that will maximize R. In order to do so, we deduce a relation between the UBS altitude h and the cell radius r by rewriting equation (2) as:

$$\delta_{LoS} = 20logd + 20logf + 20log(\frac{4\pi}{c}) + \eta_{LoS} \tag{7}$$

$$\delta_{NLoS} = 20logd + 20logf + 20log(\frac{4\pi}{c}) + \eta_{NLoS} \tag{8}$$

where f is the system frequency, and d is the distance between the UBS and a receiver at a circle of radius r, given by $d = \sqrt{h^2 + r^2}$. The maximum PLE can be calculated as:

$$\delta_{max} = \frac{Z}{1+\alpha exp(-b[arctan(\frac{A}{R})-a])} + 10log(h^2 + r^2) + B \tag{9}$$

$$Z = \eta_{LoS} - \eta_{NLoS} \tag{10}$$

$$B = 20logf + 20log(\frac{4\pi}{c}) + \eta_{NLoS} \tag{11}$$

where a and b are the S-curve parameters [18]. The problem here is to find the best altitude that will increase the coverage area R but with an acceptable level of PLE. In addition, the UEs and their nearest BSs are communicating, there would be some interferences to each other from the signals generated which is defined as the Signal to Interference Ratio (SIR). That can be calculated at each UE n as below:

$$\Gamma_n = \frac{S(d_{nm})}{\sum_{i \in M, i \neq m} S(d_{ni})}, \tag{12}$$

where M is the set of all BSs, and d_{ni} is the distance of n-th UE to the i-th BS. The total interference power at UE from all the BSs is denoted by denominator except that serving BS. After the calculation of signal interference, we can mathematically calculate the spectral efficiency (SE) of a marco cell UE (MUE) below which is using Shannon capacity formula in [19], and considering the round-robin scheduling for simplicity, the SE of MUE can be calculated as:

$$Cn = \frac{log_2(1 + \Gamma_n)}{N}, \tag{13}$$

The coverage improvement by using UBSs is:

$$S(d_{nm}) = \frac{P_{tx}G}{d_{\delta_{nm}}}, S'(d_{nu}) = \frac{P'_{tx}G'}{d_{\delta_{nu}}} \tag{14}$$

where $S(d_{nm})$ and $S'(d_{nu})$ are the average received signals by BSs and UBSs respectively for n number of UE, let the closest BS m at a distance d_{nm} be its BS of interest (BoI) and the nearest UBS u at a distance d_{nu} be its UBS of interest (UoI). Thus the average received signal power (SIRs) from the BoI and UoI are shown as below respectively:

$$\Gamma_n = \frac{S(d_{nm})}{\sum_{i\in M, i\neq m} S(d_{ni}) + \sum_{j\in U} S'(d_{nj})} \tag{15}$$

$$\Gamma'_n = \frac{S'(d_{nu})}{\sum_{i\in m} S(d_{ni}) + \sum_{j\in U, j\neq u} S'(d_{nj})} \tag{16}$$

Here M is the number of all BSs and U is the number of all UBSs, and j is the distance of UE to jth UBS. We assume that the UBS's employment during the UE association process in order to associate with more number of UEs. Each UE performs cell selection by using Γ_n, Γ'_n, n. The UE cell selection can be performed using the following equations:

$$if(\Gamma_n > \Gamma'_n) \tag{17}$$

Select BoI:

$$if(\Gamma_n \leq \Gamma'_n) \tag{18}$$

Select UoI:

Finally, the spectral efficiency of UBS UE can be expressed as:

$$C'_n = \frac{log_2(1+\Gamma'_n)}{N'} \tag{19}$$

where N' is the number of UEs in the UBS cell.

V. Results

The ability of UAVs to move to any location and height on an incident area provides a powerful mechanism to maintain a high throughput coverage in the network. To illustrate the potential gains that can be obtained, we investigate how the optimized deployment of UAVs can improve the network throughput. Unless otherwise specified, the system parameters for the simulations were set to the values shown in Table I and II, and the locations of all UAVs were optimized through brute force search to maximize a 5th percentile spectral efficiency (SE) of the network. We chose brute force search for simplicity, however, other optimization techniques can also be used for more efficient implementation. In

TABLE I
PATH LOST EXPONENT SETTINGS [20]

Environment	δ
In-door	1.6 to 1.8
Free space	2
Urban area	2.7 to 3.5
SubUrban area	3 to 5

Fig. 4 and 5, we show the deployment of 0 UAV, 4 and 8 UAVs where the X-axis is the PLE and the Y-axis is SE and network coverage respectively. Here N_{dst} is the number of BSs destroyed out of 400. With the increase of PLE, the effective throughput coverage increases. When the UAVs deployment number is 8, it results in maximum gain when 50% of the BSs are destroyed. In general, both the 5th percentile SE and throughput coverage improve as PLE increases as shown in Fig.4-5, because the interference power at an UE decreases more rapidly than the signal power as PLE increases, thereby improving SIR from the UE perspective. This is also due to the fact that the UEs distance to its connected BS is less than that all other interfering BSs. Fig.5 also shows that the throughput coverage improves when using more number of UAVs, and the improvement is more significant with a higher PLE. For example, in the case of 390 out of 400 BSs are destroyed, about 90% area can still be covered with 8 UBSs, given that

TABLE II
SIMULATION PARAMETERS

Parameter	Description	Value
λ,λ'	BS and UE intensities	4,100 per km^2
P_{tx},P'_{tx}	BS and UBS transmit power	46dBm and 30dBm
G,G'	Factors accounting for geometrical parameters of antenna	-11dB, -11dB
d_h	Altitude of UAVs	400 feet
T_c	Throughput coverage threshold	2.55*10^{-3} bps/hz
A_{sim}	Simulation Area	10*10 km^2
δ	Pathloss Exponent	1.5 to 6

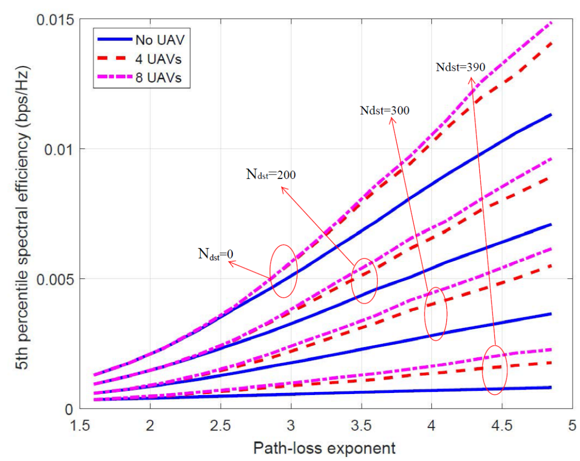

Fig. 4. Spectral efficiency vs. PLE

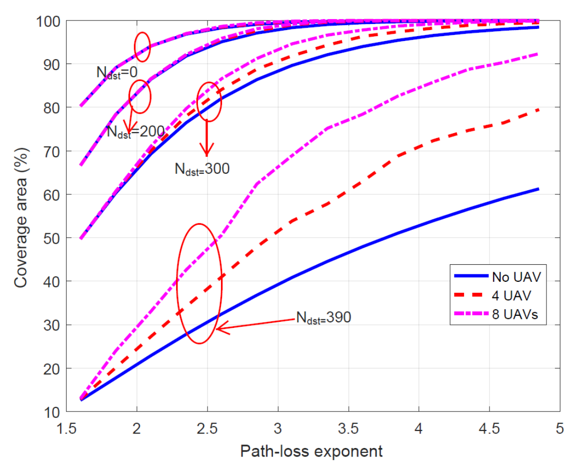

Fig. 5. Effective coverage vs. PLE

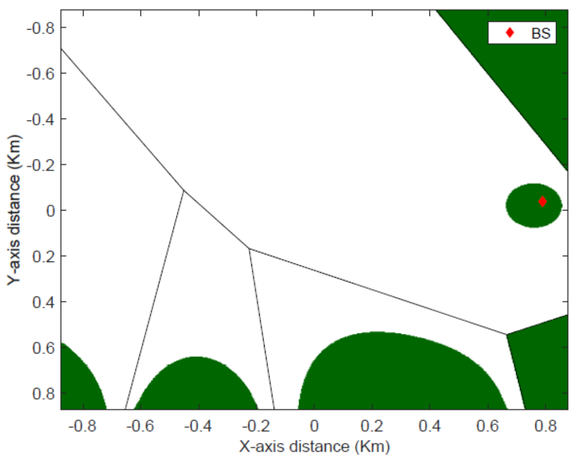

Fig. 6. 50% BSs are destroyed after disaster

PLE is 4.6. The Fig.6 shows the gaps after 50% BSs are destroyed while Fig.7 demonstrates the optimal deployment of 5 UAVs can provide effective coverage. The grey area indicates coverage given by UAV's and green area with red sign indicates number of BS remain operational after disaster.

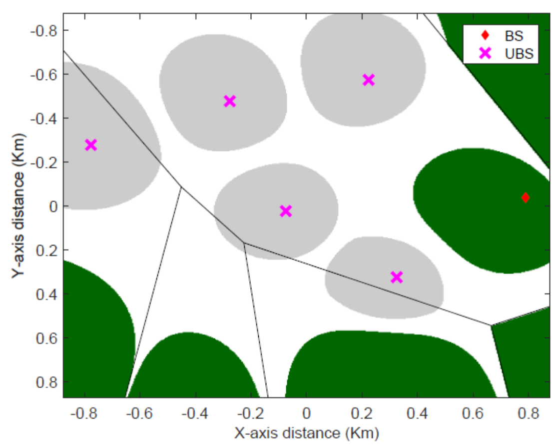

Fig. 7. PLE is increased to 4 and similarly we can see the coverage area is increased, for 5 UBSs at 121.92 m (400 feet) altitude

VI. Conclusions and Future Work

We have proposed an UAV-assisted mobile edge infrastructure for challenged networks those used in rural or under disaster situations. With a mix of theoretical and simulation studies, we have proved that UAVs can support better communications when terrestrial mobile network infrastructure does not exist or is partially dysfunctional. The throughput coverage and 5th percentile spectral efficiency can be improved by deploying the UAVs at optimal locations. More complex scenarios such as user mobility sensitive analysis and coverage optimization techniques are to be explored in our future research work.

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