Deployment of Drone-Based Small Cells for Public Safety Communication System

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***Abstract*—In the event of a natural disaster, communications infrastructure plays an important role in organizing effective rescue services. However, the infrastructure-based communications are often affected during severe disaster events such as earthquakes, landslides, floods, and storm surges. Addressing this issue, the article proposes a novel drone-based cellular infrastructure to revive necessary communications for out-of-coverage user equipment (UE) which is in the disaster area. In particular, a matching game algorithm is proposed using one-to-many approach wherein several drone small cells (DSCs) are deployed to match different UEs to reach a stable connection with optimal throughput. In addition, a medium access control framework is then developed to optimize emergency and high priority communications initiated from the rescue workers and vulnerable individuals. The simulation results show that the throughput for the out-of-coverage UEs are significantly improved when the DSCs are deployed in public safety network while the channel access delay is also notably reduced for emergency communications within the affected areas.**

***Index Terms*—Drone based communications, drone small cells, energy efficiency, MAC design for critical applications, public safety networks.**

I. Introduction

COMMUNICATIONS system plays an important role in public safety operations. The cellular communication networks are mainly dependent on the fixed infrastructure which could be severely disrupted in case of natural disasters. In addition, earthquakes, tsunamis, hurricanes floods, and landslides cause great calamity, loss of lives, displacement of inhabitants, and huge financial losses. The sudden disruptive behavior of natural disasters requires a rapid and cost-effective provisional recovery solution to cope with such calamities. In this matter, the *ad hoc* wireless networks can play an important role. As the Federal Communications Commission (FCC) posits, the public safety communications can make use of the cutting edge broadband technologies to allow first responders to send and receive critical voice, video, and data to save lives, reduce injuries, and prevent acts of crime and terror [1]. Hence, the on-demand deployment of wireless networks will not only reduce the network recovery time but will also provide necessary communications support for the first responders to effectively execute help and rescue services. Furthermore, the network efficiency, cost reduction, flexibility, self-sustainability, reach, and robustness are some of the added benefits of ad hoc wireless networks to assist first responders and rescue teams in a disaster zone.

The wireless cellular communications infrastructure mainly depends on base station systems (BSS) which are responsible for ensuring communications of the associated nodes and user equipment (UE). Under normal circumstances, the cellular and infrastructure-based systems work effectively. However, in events of natural disasters, such systems are relatively fragile and can easily be disrupted. During a natural calamity, the wireless communications infrastructure can be severely affected where one or more BSS can stop working. The disruption in the operation of BSS affects the communications of interconnected devices. In such circumstances, ad hoc networks and device-to-device (D2D) communications can assist as a substitute to provide structureless communications framework for communicating emergency and safety information. However, due to the sensitivity of the situation, the added constraints of delay and reliability required for the critical communications can become challenging hurdles for the deployment of those ad-hoc networks.

In a disaster, all connections (e.g., television, radio, broadband) to information sources are eliminated. Therefore, it is necessary that the relevant information about the geographical surroundings must be provided to the trapped survivors to guide them to proceed to the nearest rescue point or to the safe zone. For guidance purposes, risk maps need to be communicated to the users in the critical area. Relevant information in the form of detailed maps of the region, covering working bridges, roads, safe passage ways, recent disaster updates, nearby medical treatment centres, information on the rescue teams, and means to approach them needs to be transferred to the trapped survivors rapidly which requires high data rate to make the process swift and effective. The recent past studies show that in developed countries, the dedicated communications mechanisms are lacking and usually the drivable cellular BS are used by the rescue management services to communicate with the rescue teams.

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Furthermore, we know that public safety communication still largely use dedicated system, such as Project 25 (P25) and terrestrial trunked radio (TETRA). These systems have been in use for about more than 20 years. They are mature and reliable in supporting critical communication applications but limited to only recuse teams not for affected area victims. Moreover, they are also not designed to support higher bandwidth applications, because they are mostly based on narrowband system [2] and [3].

The videos/images provide an appropriate account for understanding the situation (e.g., information about the river stage, flood depth, etc.) The incorporation of appropriate information-based urgency index in ad hoc networks is also very important. The communications in emergency networks can be classified into a number of precedence levels where alerting messages, well-being messages, control messages, distress calls, data collection, and relevant and irrelevant communications can be characterized separately to optimize communications. Therefore, a suitable mechanism is needed to associate priority levels with these calls, messages, and schedule them accordingly [4]. The study and appropriate improvements in approaches for infrastructure-less communications for emergency networks can also support in disaster communications, e.g., D2D, machine-to-machine (M2M) communications, Internet of Things, smart networks, largescale sensor networks, and unmanned aerial vehicles (UAVs) communications [4].

Recent developments in microelectromechanical systems technology and very-large-scale-integration have been very influential in transforming large BSS to minute structures, which enables the adaptation of small-sized drones (UAVs). The UAVs are capable of replicating technology features of a BSS and can be used to form a small coverage area. Drones, with the ability to move autonomously and to hover over the affected area, can function as a small cell to establish communications with the UE active in the designated emergency coverage area. Hypothetically, with the presence of sufficient drones, the communications outage area in vulnerable regions can be fully covered. The restoration of a communications network in such areas using drones provides a rapid and reliable alternative to reconfigure and replicate necessary functionalities of the affected BSS. These drone small cells (DSCs) can also be used to enhance and extend communications coverage in disaster areas where on-ground repairs are not feasible.

The ability of the DSCs to reposition itself and respond to the UE by reducing distance extends coverage, decreases outage probability of the UE in coverage zones, improves bandwidth efficiency and optimizes system throughput. Research in DSC is still in its infancy and many practitioners and academics are keen to pursue their research in this scholarly area [5].

In this article, a DSC-based coverage network is proposed to establish emergency communications within the disaster affected and communications outage areas. The main contributions of this article are as follows.

1) The article offers optimized on-demand communications with enhanced throughput to support highly resilient networks within critical and emergency scenarios. Ad hoc on-demand formation of small cells is proposed to re-establish communications within disaster-affected and communications outage areas.
2) Different from traditional small cell networks, this article focuses on emergency aspects of communications. The proposed scheme not only enhances the number of users to be served by the DSC but also prioritizes the communications of the rescue workers and first responders, reporting from the disaster affected areas.
3) A priority-wise channel access scheme is established to reduce channel access delay within the DSCs to only 1 ms, in the proposed scheme, for low-density regions, and to less than 3 ms for the densely populated user equipment (UE) regions.
4) MAC-based communication optimization and delay minimization for effective channel access are also introduced along with matching-based one-to-many optimization for overall system throughput improvement.
5) Further to this, the MAC layer is specially designed to offer optimized queueing system for improved channel accessibility for rescue teams, first responders and vulnerable and trapped survivors within the disaster affected areas.

This article proposes a novel approach to address the communication issues developed in the event of natural disasters. The proposed work allows ad hoc drone-based communications network formation for the restoration of necessary communications in the communications outage area, ensures minimal delay for emergency communications and improves the network throughput ensuring better bandwidth efficiency and network optimization compared to minimum distance approach. The results show that the proposed work effectively provides coverage to the UE in out-of-coverage areas, minimizes delay, and optimizes network throughput and spectral efficiency (SE).

The rest of the article is organized as follows. Section II provides a literature review of existing work and discusses the main contributions and limitations of the existing research in this domain. Section III discusses the system model, and in Section IV, a DSC-based public safety network (PSN) is proposed while using matching game approach to enhance the network throughput. The results and relevant discussion are provided in Section V. Finally, Section VI concludes this article.

II. Related Work

Notable research advances in wireless technology have provided the necessary platform for future developments. The recent growth in 5G and developments on ultra-reliable and low-latency communications (URLLC) offer a suitable solution for reliable communications in ad hoc wireless networks. The preliminary developments in URLLC offer great potential to address the communication issues in emergency and time-critical communications [6]. Further developments in this domain will not only introduce reliable means to interconnect people but will also permit connectivity of a large number of smart devices to form smart automated environments [7]. URLLC is desirable in applications with strict time and reliability requirements [8]. The need for critical, time-sensitive, and emergency communications in the infrastructure-less network is evident in emergency and safety applications. Post-disaster rescue activities, highly sensitive process control, feedback systems, necessary M2M communications, and emergency and safety systems are some of the examples of time critical and reliability sensitive applications. To offer improved reliability and optimized network communications, MAC layer plays an important role. It handles access to the physical channel, generation of beacons, time-slotted access, device security, reliability, and link assurance between the MAC entities. Due to the added features and access to critical processes, improvements in MAC can be very influential in achieving URLLC. The existing work in MAC layer optimization targets various aspects of communication optimization. Raza *et al.* [4] and Huang *et al.* [9] classified MAC protocols in several categories including periodic, slotted, random, synchronous, asynchronous, hybrid, multichannel, and priority-enabled schemes. Each of these classifications offers certain benefits including network lifetime enhancement, reliability, data-rate improvements, etc. Out of various MAC classifications, to ensure effective communication in emergency networks, priority-based communications plays an important role.

It is evident that the cellular network operators have a strong interest in localization technology mainly due to their needs for network planning and optimization during both normal and critical situations. Besides the need for location information to support network planning and optimization, network operators have recently identified several scenarios for monetizing on the huge volume of location data that is daily logged on the network side. These scenarios include public safety services, smart city use-cases and large-scale event response, emergency response E911/E112, tracing lost children and elderly, etc. [10]–[12].

Laoudias *et al.* [13] presented a survey of various enabling technologies for network localization and tracking using 3D location information, and discussed the resulting potential of location awareness and enable new progressive location-based services.

In the post-disaster rescue activities drones are considered, both in the context of cellular link and data delivery. Use of drones allows formulating a two-layer communications hierarchy where the information is communicated from UE to drone and from drone to the core network. This limits the maximum delay in such networks. As developments in drones-based communications networks are in initial stages, the existing work is relatively scarce. However, few attempts have been made to produce a workable infrastructure for drone-based communications. In [14], the authors have highlighted the placement technique that uses drones as relays for cell overloading and outage compensation. However, only an analytical model was created for system performance evaluation. The article was also lacking details of drone base station coverage and deployment methods. In [15], the authors analyzed the altitude of a drone base station that minimizes transmission power requirements while covering the desired area. The interference of adjacent drone cells was also analyzed. In [15] and[16], the authors studied optimal drone position for the drone while serving the target zone. Similarly, Al-Hourani *et al.* [17] provided an analytical model to discover an optimal altitude for a drone to offer maximum coverage area. A service edge was defined as maximum allowable path loss. In [18], authors discussed the problem of finding the optimal cell boundaries and deployment location for multiple noninterfering UAV. Their aim was to minimize the transmission power of the UAVs. Merwaday *et al.* [19] analyzed the throughput gains that can be obtained by exploiting the mobility feature of the unmanned aerial base stations (UABs). They presented a genetic algorithm (GA) to optimize the location and provide better throughput coverage when network infrastructure is lost. The work showed that the throughput coverage and fifth-percentile throughput of the network can be improved significantly by optimally placing the UABs. However, in our approach, we have adopted a different method to take advantage of UABs; we are considering DSCs— we combine D2D communications (i.e., UEs) with UABs capabilities and propose a matching game algorithm (using one-to-many approach) to match different UEs with UABs. Kumbhar *et al.* [20] represented the role of agile UABSs in LTE-advanced HetNets by applying 3GPP Release-11 further-enhanced intercell interference coordination (FeICIC) and cell range expansion (CRE) techniques. The authors compare the system-wide fifth percentile SE when UABSs are deployed in a hexagonal grid and when their locations are optimized using a GA, while also jointly optimizing the CRE and the FeICIC parameters. This article is the extension of our previous research carried out on the approach toward PSN in [21] and [22]. While using UE Relay (UER) we extensively examined how the in-coverage UEs deliver the elementary network services to out-of-coverage UEs by relaying their data to evolved node B (eNB). We highlighted that the UER selection process was also highly critical because both in and out-of-coverage UEs had very limited energy and processing capability. In addition, [23] highlighted that UE selection process was also highly critical because both in and out-of-coverage UE had very limited energy and processing capability. There was limited reliability in terms of availability, throughput, and trafc handling capabilities of UER because it had limited energy, processing power, and coverage area. They could not concurrently handle PSN demands. Therefore, we posit that DSCs are exclusively suitable for such PSC situations due to their self-organization and mobility capabilities as they are helpful not only in delivering information rapidly but also give better connection in time and location where it is most needed for its being agile and ubiquitous communication infrastructure. This research advocate following reasons of DSC deployment in a PSN: 1) drones can hover at higher altitude to provide suitable height gain; 2) drones are suitable for PSN while hovering which allow energy sustainability; 3) while hovering, drones improve connection reliability, offer better connectivity and efficiency for UE and itself; 4) the usage of DSCs can allow efficient use of bandwidth and improve frequency reusability; and 5) the use of DSCs will result in rapid deployment of communication network in disaster-affected areas. However, the utilization of DSCs is in critical scenarios is extremely advantageous, as due to their mobility, flexibility, and adaptability, the DSCs are able to provide coverage and capacity exactly where and when it is needed.

III. System Model

A total of K UEs are considered in the communications outage area, previously affiliated to BSS as shown in layer 2 of Fig. 1. Based on the logs of the currently nonfunctional BSS

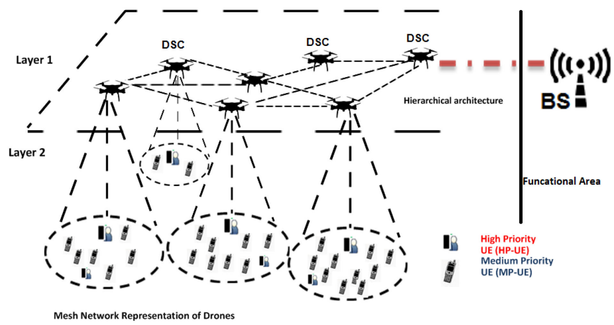

Fig. 1. Disaster scenario and system model.

and the communications outage area, the core network decides as to how many drones are needed to cover the outage area effectively. A total of N drones are considered to serve the UE in the disaster-affected area. Each DSC is connected to the core network via a wireless backhaul (see Fig. 1). DSC are connected to the core network via the wireless backhaul. It is assumed that the active base station (BS) near the DSC provides dedicated bandwidth to the drone where the link is assumed to be relatively high quality due to the ability of the drone to adjust its position and to enable line-of-sight (LoS) connection due to the respective height of the drone. In this scenario, a time division multiple access (TDMA)-based channel access scheme is used, and hierarchical access to the core network is ensured with maximum two hop delay from UE to the BSS. TDMA is used to allow several drones to share the same backhaul and further frequency channel by dividing the signals into different time slots for UEs. As communication between the drones and the relevant UE use both requests-oriented and on-demand communication in the given scenario. Furthermore, multichannel access between the drone and BSS is ensured to establish multiple data streams. The UE association is carried out prior to communication and each UE in the affected area is affiliated to the most appropriate DSC based on the resource unit. In every DSC, drone acts as a base station for UE and will replicate the necessary functionalities of BSS. The mobility of UE is facilitated using the control channel and the moving UE can request affiliation to new DSC based on the link quality. A resource sharing mechanism is also introduced for the effective management of nonlinear density of the UE in the drone coverage area.

A. Channel Model

This article considers, both LoS and nonline-of-sight (NLoS) transmissions. More practically, the path loss model is expressed as probabilistic portions of LoS and NLoS transmissions. As in real scenario, the channel between the UE and DSC depends on the elevation angle of the transmission link due to which the latter impacts the probability of LoS or NLoS transmissions. According to [17] and [24], the loss probability functions for LoS and NLoS transmission from the kth UE (denoted by UE_k, $k \in \mathcal{K} = \{1, 2, \ldots, K\}$) connected to the nth DSC (denoted by DSC_n, $n \in \mathcal{N} = \{1, 2, \ldots, N\}$) are expressed as

$$P_{\text{LoS}}(h, d_{kn}) = \frac{1}{1 + \alpha \exp(-\beta[\theta - \alpha])} \quad (1)$$

$$P_{\text{NLoS}}(h, d_{kn}) = 1 - \text{P}_{\text{LoS}}(h, d_{kn}) \quad (2)$$

respectively, where α and β are environment-dependent constants, $\theta = \arcsin(h/d_{kn})$ [17]. Here, h and d_{kn} denote the drone height (assuming it is the same for all drones) and the distance from the drone DSC_n to the UE_k.

For simplicity, let path denote either LoS or NLoS. The signal-to-interference-plus-noise ratio (SINR) of UE_k connected to DSC_n via the path (either LoS or NLoS) is expressed as

$$\gamma_{kn}^{\text{path}} = \frac{S_{\text{path}}(h, d_{kn})}{I_k + N_k} \quad (3)$$

where $S_{\text{path}}(h, d_{kn})$ is the received power by the UE_k via the path, I_k is the interference signal from neighboring cells received at the UE_k and N_k is the total noise power including the thermal noise. The achievable rate in UE_k from DSC_n is expressed as follows:

$$r_{kn} = \text{RB}\Big(P_{\text{LoS}}(h, d_{kn}) \times \log_2(1 + \gamma_{kn}^{\text{LoS}}) + P_{\text{NLoS}}(h, d_{kn}) \times \log_2(1 + \gamma_{kn}^{\text{NLoS}})\Big) \quad (4)$$

where RB is the available bandwidth from the DSC_n to each UE, then the total number of available resource allocations to the UEs by DSC_n is

$$q_n = \frac{\omega_n}{\text{RB}}.$$

Here, ω_n is the available resource (i.e., bandwidth) from DSC_n. Finally, the accumulative throughput of all UEs, denoted by R_{total}, can be written

$$R_{\text{total}} = \sum_{k \in K} \sum_{n \in N} \eta_{kn} r_{kn} \quad (5)$$

where η_{kn} is a binary variable with value of 1 if UE_k is allocated to DSC_n, and 0 otherwise.

IV. Proposed DSC-Based Public Safety System

First, a matching game approach is considered to maximize the overall throughput for the drone-based PSN. Once the connections between the drones and the ground users are established, the access and control mechanism is optimized in the MAC layer for the priority of emergency and rescue services.

A. Matching Game Approach

It is aimed to maximize the throughput of all UEs by formulating the following optimization problem:

$$\max R_{\text{total}} \quad (6)$$

subject to:

$$r_{kn} \le C_o, \quad \forall n \in \mathcal{N} \quad (7)$$

$$\sum_{n \in N} \eta_{kn} \le 1, \quad \forall k \in \mathcal{K} \quad (8)$$

$$\sum_{k \in K} \eta_{kn} \le q_n, \quad \forall n \in \mathcal{N} \quad (9)$$

$$\eta_{kn} \in \{0, 1\}, \quad \forall k \in \mathcal{K}, \forall n \in \mathcal{N}. \quad (10)$$

1) The objective function in (6) represents the overall throughput of all present UEs in the disaster area.
2) The constraint in (7) implies that the rate for each user should not exceed the Shannon capacity limit C_o of the channel.
3) The constraint in (8) implies that each UE_k may be allocated to maximum one DSC or not allocated to any DSC at all.
4) The constraint in (9) suggests that the maximum number of allocated UE to DSC$_n$ cannot exceed its capacity (i.e., the maximum number of servable UE).
5) The constraint in (10) defines the binary nature of η_{kn} variable.

The above optimization can be solved using matching approach. The DSCs have designated resources available to assign to the UEs and each UE needs to be assigned to a DSC to have access to the network. This is a mixed integer optimization problem which is hard to solve with classical optimization approaches [25]. Therefore, a matching algorithm is proposed to address this two-sided nature of the system (DSC-to-UE) in a disaster situation.

A matching approach is a two-sided assignment problem. Each side represents a separate set of entities seeking for their best match among the entities. In this article, each UE identifies its possible match among the available DSCs and then initiates communication for a selection procedure as shown in Fig. 1. This choice of procedure is based on a preference relationship defined for each side In the chosen context, a two-sided one-to-many matching game is presented, where all the DSCs are ready to provide their available backhaul capacity to the UEs and can be described as follows:

Definition: A matching approach μ is a function defined as $\mathcal{K} :\rightarrow \mathcal{N}$, where

1) $\forall n \in \mathcal{N}, \mu(n) \subseteq \mathcal{K}$,
   i.e., for each DSC$_n$, its matching UE set is a subset of $\mathcal{K}$
2) $\forall k \in \mathcal{K}, \mu(k) \in \mathcal{N}$,
   i.e., for each UE$_k$, its matching is in the set $\mathcal{N}$
3) $\mu(k) = n$ if and only if $k \in \mu(n)$,
   i.e., the matching of UE$_k$ is the DSC$_n$ if and only if UE$_k$ is in the matching set of DSC$_n$.

Let V_{kn} and U_{nk} are the utility functions of the members of the sets $\mathcal{K}$ and $\mathcal{N}$, respectively. We also define S_k to be the set of available DSCs. Each UE will be looking for the most suitable DSC. So, the UE utility function V_{kn} of the UE$_k$ to the DSC$_n$, based on achievable rate, can be expressed as

$$V_{kn}(\gamma_{kn}^{\text{LoS}}, \gamma_{kn}^{\text{NLoS}}) = \text{RB}\left(P_{\text{LoS}}(h, d_{kn}) \log_2(1 + \gamma_{kn}^{\text{LoS}}) + P_{\text{NLoS}}(h, d_{kn}) \log_2(1 + \gamma_{kn}^{\text{NLoS}})\right). \quad (11)$$

The DSC utility function U_{nk} for the opposite direction is similarly obtained with SINR pair of $\gamma_{nk}^{\text{NLoS}}$ and γ_{nk}^{LoS} as both parties need to agree on the same benefit.

The matching algorithm, to ensure optimal system performance while considering the system constraints is presented in Algorithm 1.

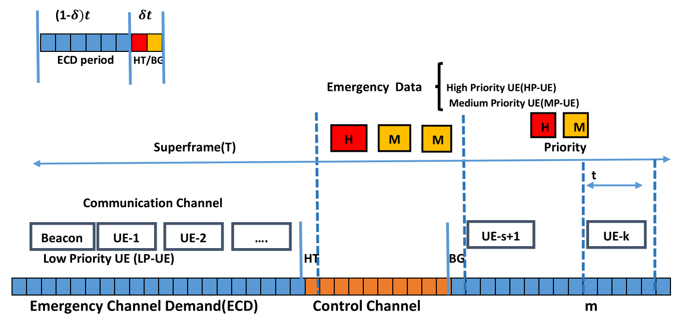

Fig. 2. Priority MAC (P-MAC) operation.

Algorithm 1: UE Matching Algorithm.

Data $\mathcal{K}$, $\mathcal{N}$, q_n
Result Optimal matching μ^*
Initialization
S_k: the total available DSCs for a given UE_k that are within a distance κ
q_n: the total number of available resource allocations (i.e., resource blocks) in DSC_n

Phase 1 – UEs Applications

UEs rank all DSCs based on V_{kn}
Every UE_k applies for the DSC^* from S_k with the highest V_{kn}, and removes DSC^* from S_k

Phase 2 – DSCs Selections

i) DSCs rank applicant UE using U_{nk} (i.e., V_{kn})
ii) Among all the applicant UE, the DSC_n accepts each UE^* with the highest U_{nk} while not exceeding its capacity limit q_n and rejects the other UE that don't respect these conditions.
IF UE_k is accepted by DSC_n, then:
$|\mu(n)| = |\mu(n)| + 1$ and $|\mu(k)| = 1$

Phase 3 – Repetition

Repeat *Stage 1* and *Stage 2* for every $UE_k \in K$ until:
$S_k = 0$ or $|\mu(n)| = q_n$

Further details on throughput analysis and suitability of the matching approach, in comparison to state-of-the-art techniques, are presented in Section V.

B. MAC Design: Prioritized Access and Control Channel

The varying circumstances of users within the emergency networks urge the implementation of prioritized access for critical users such as the first responders or any users in highly vulnerable regions (e.g., survivors trapped in a building). To further assist the communications optimization, a three-level priority mechanism is proposed to offer an early channel access for the critical users. The proposed superframe structure along with segmented control channel slots are presented in Fig. 2. Each superframe is divided into n timeslots each of duration t. In the control channel, each time slot is divided in emergency channel demand (ECD) and halt/begin (HT/BG) period. The control channel is used to communicate urgent requests to the servicing drones which communicate critical information on priority basis [26]. The proposed scheme permits UE with emergency data to request channel access and the λ is emergency channel requests originated per second. The hybrid scheme is introduced because of the asynchronous nature of emergency communication requests. Within the network, to ensure prioritized access, a control channel-based slotted request mechanism is proposed. In case of an emergency channel request, low priority communications can be stopped to initiate emergency communications. In case, numerous emergency requests are received simultaneously, a queuing function is introduced to sequentially assign resources. For such cases the communication of regular TDMA requests can be stopped for multiple timeslots. However, to ensure the collision free transition, halt (HT) and begin (BG) sequences are defined, which stop and reinitiate communication. Different types of UE located in the DSC are designated with high, medium, and low (H/M/L-UE) priorities and communication takes place according to the predefined UE priority. The priority establishment for the normal UEs can be location-based, depending on the risk maps of the region and higher priority can be given to the UE in critical areas. As represented in (12), a cost function is developed to establish priority. The queuing theory and priority-based access is used based on the cost function presented as follows:

$$F_x(t) = \alpha \times \delta_x + \beta \times R_x(t) + \gamma \times E_f(t) \tag{12}$$

where $F_x(t)$ is the cost function (expressed in terms of numerical value, higher the value higher the priority), δ_x is the priority level of the requesting class (e.g., rescue worker(high priority <3>) /volunteers (medium Priority <2>)/normal citizens (Low Priority <1>)), R_x (t) is the information of the region from which request is originating (e.g., highly vulnerable building <3>, relatively safe open ground space <1>) and E_f (t) is the emergency factor, depending on the critical nature of the request (e.g., rescue worker may label a request from a building caught in fire as highly urgent <3>, whereas the request from a rescue worker in nonthreatening situation should have low urgency <1>). E_f (t) is a value sent by requesting UE depending on the critical nature of the situation in his/her perception. α, β, and γ serve as the weighing factors. Based on the cost function, $F_x(t)$, the priority allocation can be provided to the requesting users within the cell. At the moment, priority access is provided as a function of δ_x. As represented in Fig. 2, high and medium priority UE will be provided the prioritized access to the channel based on the value of cost function, $F_x(t)$.

As represented in the Fig. 2, TDMA-based channel access scheme is implemented with beacons to synchronize communication of affiliated UE. The default low priority channel assignment is represented in original superframe whereas in case of an emergency request, the high priority communications are provided optimized channel access.

The mathematical representation of average access delay d [27], between channel requests to transmission for both long-term evolution (LTE) and proposed scheme Priority MAC (P-MAC) is presented below

$$d_{\text{LTE}} = \frac{1}{2}T_{\text{LTE}} \tag{13}$$

$$d_{\text{P-MAC}} = \sum_{x=1}^{m} \left[\left(\delta t + \frac{1}{2}t + (x-1)\times t + \left(\frac{x}{n}\times(\text{PL- delay})\right)\right)\times P_X(x)\right] \tag{14}$$

where, m is the number of emergency UEs, x is emergency occurrences in ECD, t is the duration of time slot, and PL-delay is payload transmission time, respectively.

The proposed delay reduction allows the high priority users (rescue teams and first responders) to access the channel on priority. Prioritized access not only results in marginal delay reduction but also reduces chances of denial of service for high priority UE. The proposed P-MAC not only allows channel access in timely fashion but also prevents from extensive delay that can occur in case access to the channel is denied. In extreme circumstances, along with the average delay, the blockage probability (probability of denial of service) for high priority UE requests is much higher in the traditional LTE systems compared to the proposed P-MAC.

The delay in the LTE system in emergency situations can be given by

$$d_{\text{LTE}} = \sum_{x=1}^{y} \left\{\left(\frac{1}{2}\times T_{\text{LTE}}\right) + \left(\left\lfloor\frac{x-n}{n}\right\rfloor \times T_{\text{LTE}} \times P_X(x)\right)\right\} \tag{15}$$

where, y is the total number of UE within a specific cell. $P_X(x)$, probability mass function for number of requests is given by

$$P_X(x) = \frac{(\lambda T_{\text{LTE}})^x e^{-\lambda T_{\text{LTE}}}/x!}{\sum_{x=1}^{y}(\lambda T_{\text{LTE}})^x e^{-\lambda T_{\text{LTE}}}/x!}$$
$$\text{where } x = 0, 1, 2, 3, 4, \ldots, y \tag{16}$$

where, λ is the number of requests per unit time. The blockage probability of emergency communications within traditional LTE system can be given by

$$B_{\text{LTE}} = \sum_{x=n+1}^{y} \left\{\frac{(\lambda T_{\text{LTE}})^x e^{-\lambda T_{\text{LTE}}}/x!}{\sum_{x=1}^{y}(\lambda T_{\text{LTE}})^x e^{-\lambda T_{\text{LTE}}}/x!}\right\} \tag{17}$$

whereas the blockage probability of emergency communications in proposed P-MAC is presented as follows:

$$B_{\text{P\_MAC}} = \sum_{x=2}^{m} \left\{\frac{(\lambda t)^x e^{-\lambda t/x!}}{\sum_{x=0}^{m}(\lambda t)^x e^{-\lambda t}/x!}\right\}. \tag{18}$$

According to the proposed approach, DSCs are willing to cede their available capacity to the UE on a competitive basis amongst them. All the K UEs will compete to obtain the resources from N to DSCs each having a total available bandwidth of ω_n. More

TABLE I
PARAMETER VALUES IN OUR SIMULATION

Definition	Symbols	Value(s)
Set of User Equipment (UE)	K	-
Set of Drone Small Cells (DSC)	N	16
Available resource in DSC_n	ω_n	10,15,20 MHz
Signal-to-noise-plus-interference ratio	γ_{kn}	2.09/3.75
Drone height	h	15 m, 20 m
DSC Transmission power	P_{tx}	24 dBm
Interference distance	κ	200 m
UE noise figure	I_k	9 dB
Environment-dependent constants	α, β	9.61,0.16
Binary variable	η_{kn}	0,1
Emergency channel requests / second	λ	1,5,10,25, 100,500
Payload transmission time	$PL - delay$	3.84 ms
Shannon limit	C_0	-
Communication window duration	$(1-\delta) \times t$	-
Acknowledgement window duration	$\delta \times t$	-

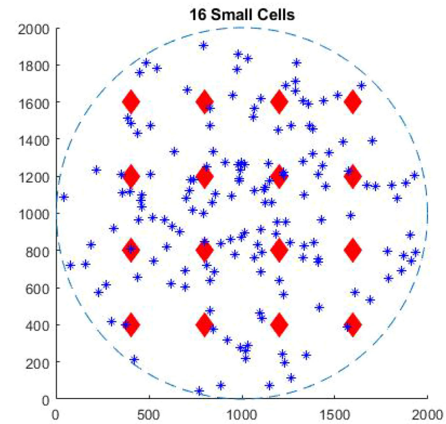

Fig. 3. Initial scenario before UE allocation to DSC.

practically, each UE will compete to access the DSC that will provide the best connection. On the other hand, each DSC has a limited bandwidth as a result limited number of UE will be served by this Small Cell.

V. RESULTS

The overall system performance of the proposed strategy for drone-based communication restoration is thoroughly investigated through simulations (Matlab) and analytical analysis. The parameters are set according to Table I.

In the proposed P-MAC, average channel access delay for high priority UE is evaluated in comparison to the traditional access delay in LTE. The overall system throughput is also evaluated to analyse the throughput optimization using the matching algorithm. Both aspects of analysis are discussed in detail along with the setup establishment and preliminary setup phase operation. Furthermore, the suitability of drone-based PSNs is also evaluated. The ability of drones to move in any incident location provides a suitable optimization mechanism toward achieving improved system throughput and reliable network formation. To illustrate possible improvements different aspects of drone deployment were considered to improve the network throughput for the given scenario in Fig. 1

The Fig. 3 represents the distribution of UE in disaster-affected areas where initially drones are uniformly distributed. At first, none of the UE is allocated to any DSC. The proposed allocation method ensures the suitability of the UE-drone pair for optimal performance. In Fig. 3 the allocated UE to the relevant DSCs are represented with a distinct color code. Note that for allocation of UE to suitable DSC, two techniques are used, namely, matching game algorithm and minimum distance allocation.

In Fig. 4(a) matching algorithm-based UE association is established where as Fig. 4(b) uses minimal distance allocation [also referred as k nearest neighbor (kNN)]. In Fig. 4, the affiliated UE is represented by a star of the same color of the diamond, representing a drone. The black stars signify the UE that are not affiliated with any DSC. Once the UE are affiliated to the DSC, a relevant priority level is defined for each of the affiliated UE.

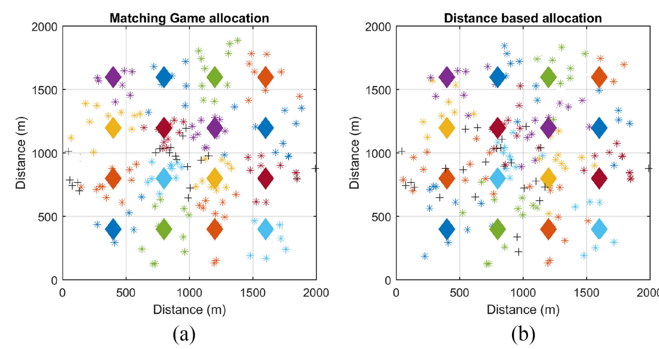

Fig. 4. UE allocation using: (a) Matching game algorithm (left), and (b) minimum distance allocation (right).

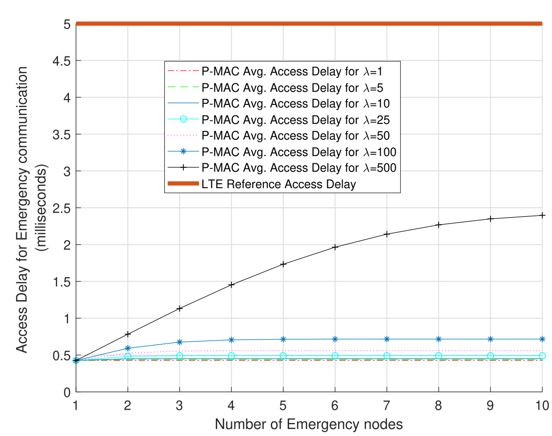

Fig. 5. Average channel access delay (P-MAC).

Based on the priority level, the UE will access the channel resources accordingly. The use of the prioritized access allows the reduction in delay of highly critical communications. In Fig. 5, the average channel access delay of highly critical information is represented. It can be seen that access delay is evaluated for various number of channel requests, λ, originated per second. The simulation results show that the average access delay in critical UE is reduced notably in comparison to LTE. This ensures low-level latency in communications from the critical

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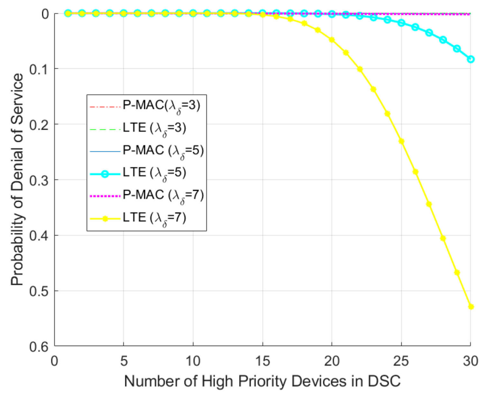

Fig. 6. Probability of denial of services.

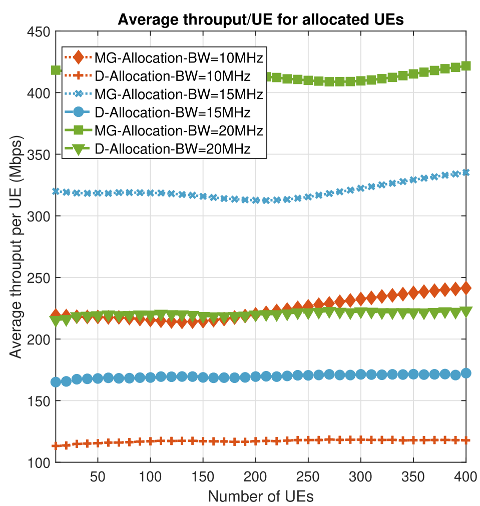

Fig. 7. Average throughput per UE as a function of number of UEs.

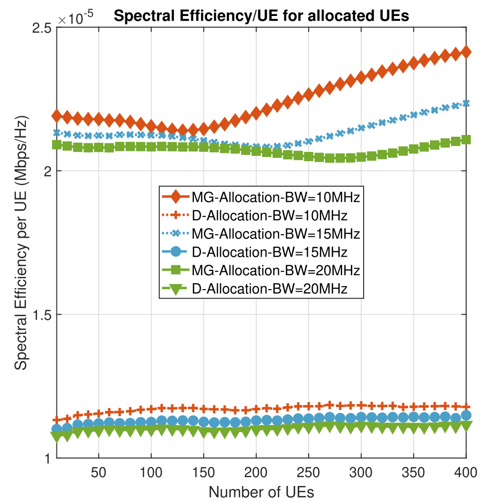

Fig. 8. SE per-UE as a function of number of UE.

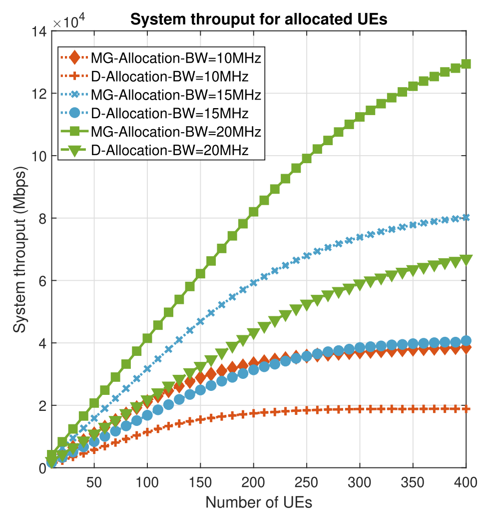

Fig. 9. System throughput for allocated UE.

users. Probability of denial of service is represented in Fig. 6. Since P-MAC provides prioritized access to emergency devices within DSC, therefore, the blockage probability of devices of high importance is relatively much lower in P-MAC compared to LTE. As represented in Fig. 2, the blockage probability is almost zero in case of P-MAC, especially in case the timeslots required per device in a superframe (λ_δ) reaches to 7. As represented in the figure, when the high-priority devices reach 30 for $\lambda_\delta = 7$, blockage probability in LTE exceeds 50% whereas in P-MAC the blockage probability is still almost zero. For evaluation, please note that emergency UE are assumed to be 10% of the total UE.

The use of matching algorithm also gives a notable improvement in the individual (UE) as well as the collective throughput of the system. In Fig. 7, the average achievable data rate per UE is presented in both allocation methods (matching approach and kNN). It was observed that the average throughput obtained using matching allocation was better than the one obtained with minimal distance allocation (kNN). The average achievable rate almost doubled with matching algorithm. The overall SE improved as well. In Fig. 8 SE for an active UE in disaster area is represented. The proposed matching-based algorithm provides better SE than the traditional minimal distance-based efficiency. The results presented in Figs. 7 and 8 show notable improvements in comparison to traditional schemes.

Fig. 8 represents the SE for an active UE in disaster area as a function of number of UE. Again we notice that our proposed matching game-based algorithm provides better SE than the traditional minimal distance-based one. This confirms how efficiently the bandwidth resources are used by UE in disaster area where resources are keenly observed before allocation. Fig. 9 represents the system throughput obtained from allocated UEs single throughputs for both matching game and distance-based allocation mechanisms. The first observation we can make is that system throughput increases as the number of present UEs increases for wider bandwidth systems and reaches a saturation level for shorter bandwidth systems. This is due to resource limitations dictated by system bandwidth. Second, the plots show that matching game algorithm provides better system throughput than distance-based technique. This proves how the matching game performs better in enhancing both UE and system throughputs.

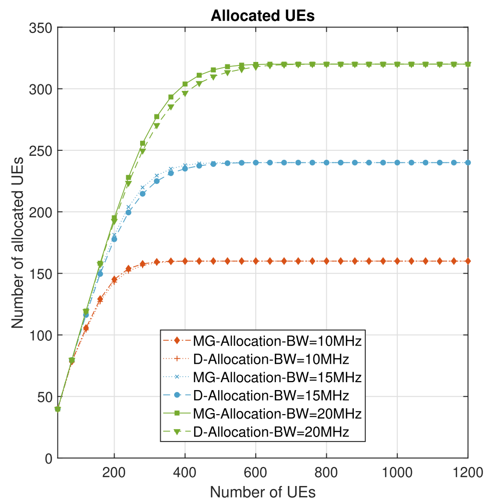

Fig. 10. Number of allocated UE as a function of number of UE.

To further investigate the ability to match approach and kNN, the maximum number of manageable UE are investigated for a variety of UE densities in the coverage area. In Fig. 10, the results for both, kNN and the proposed scheme are represented. The figure shows that the number of affiliated UE within the DSCs (in both schemes) show similar performance. However the matching approach still offers slightly better performance out of the two by examining it more closely. In case of increasing bandwidth from 10 to 15 and 20 MHz, a linear increase in allocation ability of UE is observed.

VI. Conclusion

Public safety communications can benefit from deploying drones to facilitate interrupted communications in the event of natural catastrophes. The establishment of DSCs is highly beneficial in re-establishing communication links to the first responders, rescue workers, and trapped survivors by conducting coordinated rescue activities. The proposed drone-based resilient communication architecture, presented in this article not only enables effective communication in disaster-affected out of coverage areas but also ensures communication optimization in individual DSCs. A novel drone-based cellular infrastructure is proposed to revive communication by proposing a matching algorithm with the one-to-many approach, wherein several DSCs can be matched to UE to reach an optimal and stable solution. Furthermore, a dynamic priority scheme is also proposed which classifies various types of communication which take place within disaster situations to improve channel access delay. This classification helps in prioritizing the communication of critical UE (rescue workers and vulnerable survivors). The simulations results show that the channel access delay is notably reduced for emergency communication within the affected areas. It was also observed that the throughput in the out-of-coverage area notably improves with the use of DSCs in PSN.

The research in ad hoc drone-based emergency and safety networks is still in its infancy. Therefore, it has great potential for future improvements. The work can further be improved with an establishment of multihop drone networks and communications for larger coverage area. The proposed work of energy evaluation will also give a more accurate evaluation to the network lifetime and replacement mechanism of the drones used in the drone-based large-scale coverage. We will also consider additional constrains such as limited inter-DSCs link capacity with joint topology and routing optimization.

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