Survivor-Centric Network Recovery for Search-and-Rescue Operations

Alaa A. R. Alsaeedy
Dept. of Electrical and Computer Engineering
Colorado State University
Fort Collins, USA
alaa.alsaeedy@colostate.edu

Edwin K. P. Chong
Dept. of Electrical and Computer Engineering
Colorado State University
Fort Collins, USA
edwin.chong@colostate.edu

***Abstract*—In this paper, we introduce a new paradigm for Search-and-Rescue Operations (SAROs) after large-scale disasters, assuming wireless network cells are partially operational (called surviving eNBs, *ref-eNBs*) and exploiting the recent trend of using Unmanned Aerial Vehicles (UAVs) as a part of the network (called *UA-eNBs*), to search for survivors. The SAROs are based on the idea that almost all survivors have their own wireless mobile devices, called User Equipments (UEs). These SAROs (called *UE-based SAROs*) are life-critical missions intended to find potential survivors, as quick as possible, by searching and locating their UEs without their assistance even in the absence of radio frequency coverage, in which the UEs become human-based sensors on the ground. To the best of our knowledge, this paper is the first to propose this new paradigm, which is mainly aimed at providing significant information to the first responders, as follows: 1) generate immediate crisis maps for the disaster-impacted areas, called *UE-Based Crisis Maps (UEBCMs)*, 2) provide vital information about where the majority of survivors are clustered/crowded and how (e.g., whether located indoor or outdoor). The *UE-based SAROs* offer the first responders a vital tool to prioritize/manage SAROs efficiently and effectively in a timely manner, supporting the largest number of disaster victims.**

***Index Terms*—public safety communication, FirstNet, crisis maps, search-and-rescue, UAV.**

I. Introduction

Mission-Critical and Public Safety Communications (MCPSCs) are intended to provide vital mobile wireless communication services for first responder entities, such as police, firefighters, or other security agencies, enabling them to exchange information during emergency situations (i.e., emergency management). In the following subsection, we discuss the main trends in MCPSCs.

A. Most Popular MCPSC Systems

Many conventional communication systems have been deployed to support MCPSCs. Since the 1930s, Public Safety Agencies (PSAs) have considered Land Mobile Radio (LMR) systems as primary means to support MCPSCs for voice exchanging between emergency responders [1]. Although LMR systems have been used by some PSAs, they are limited to voice and low-speed data communication. Other MCPSC systems, known as Terrestrial Trunked Radio (TETRA) and Project 25 (P25) (used in North America), are still currently in service, although they are inefficient in terms of spectral utilization, data rate, and cost [2]. Thus, many PSAs have migrated from conventional LMR systems to more advanced mobile broadband systems. TETRA and Critical Communications Association (TCCA) have asserted that the commercial Long Term Evolution (LTE) is the most promising technology (i.e., broadband network) for MCPSCs [3]. For this reason, in 2012, the US developed a nationwide MCPSC system called FirstNet, which uses the current LTE network as a basic platform; the US has spent \$7 billion and reserved the use of the 700 MHz band for FirstNet communications. A major recent milestone along these lines is that AT&T announced that it will spend \$40 billion toward developing FirstNet as a global wireless network dedicated to the US first responders, according to the First Responder Network Authority-AT&T 2018 contract [4]. In the meantime, the 3rd Generation Partnership Project (3GPP) has developed a specific set of mission-critical standards for LTE to support the MCPSC functionalities, such as Proximity-Service (ProSe); see [5] for more detail.

From the preceding enormous efforts, it is obvious that there is a pressing need for reliable, extremely efficient and effective, and quick access networks for PSAs to handle life-critical missions. This interoperability between PSAs and existing commercial LTE networks will be extremely vital for MCPSC because the latter covers almost all the living population; around 98% of the US population live in areas covered by LTE technology [6]—in this case, the PSAs can communicate even without TETRA/P25 Radio Frequency Coverage (RFC). This is to keep the PSAs better informed about the emergency status of the disaster-impacted areas, called the Region of Interest (RoI), and hence prioritize their operations to save lives and manage the available resources. But MCPSC systems are susceptible to challenges that cannot be avoided and should be faced, which we address next.

B. Can Current MCPSC Systems Fail?

As we have seen above, there are numerous communication technologies dedicated to PSAs, the most prominent being the FirstNet-LTE system [4]. For example, the US (in Los Angeles) deployed about 231 sites as a first step toward the FirstNet project in March 2014 [2]. This is needed to keep the PSAs connected—anytime, almost anywhere, and in any emergency situation. At the same time, it is also much-needed to communicate between PSAs and other persons (e.g., potential victims) for life-saving purposes. However, LTE and FirstNet technologies can be dysfunctional temporarily after a hazard—the network infrastructure can be devastated partially or completely by natural disasters (e.g., earthquake, hurricane, or tsunami) or even by attacks. This is the worst-case scenario, making the communication between the PSAs and disaster victims impossible. Specifically, Search-and-Rescue Operations (SAROs), mostly location-based missions dedicated to life-saving, become extremely difficult. In such cases, it is important for the PSAs to have some awareness of where the disaster victims are mostly located or clustered, so that the PSAs can conduct SAROs in a timely and more effective manner. But, how do we obtain sufficient information on disaster victim locations without the ability to communicate? This is the main focus of this work.

C. Paper Organization

The rest of the paper is outlined as follows. Section II details how a disaster impacts the serving network, addressing the most critical situations. Section III introduces our solution approach, considering the uncovered concerns. Section IV defines and formulates the proposed system model. Section V proposes screening and searching procedures that are conducted by the related *UA-eNBs*, searching for both surviving *ref-eNBs* and surviving UEs. In Section VI, we introduce a technique for the *UA-eNB* location setup, in which it can move and search for survivors. Section VII details the generated crisis maps (*UEBCMs*). Concluding remarks are highlighted in Section VIII.

II. Network Status Aftermath

After a disaster, some of the LTE base stations (known as eNBs) may not survive. For example, after Hurricane Maria hit on September 21, 2017, 95.6% and 76.6% of the cellular sites were dysfunctional in Puerto Rico and the US Virgin Islands, respectively [7]. Accordingly, the serving network and its users in the RoI are adversely impacted in many different ways. In this context, we discuss here the most critical situations.

The surviving eNBs provide limited RFC only to User Equipments (UEs) in close vicinity. But not all UEs can exchange information with the surviving eNBs because the latter can serve only a limited number of UEs (limited capacity/bandwidth). Other UEs in the same area might receive a good level of Reference Signal Received Power (RSRP), but cannot access the available network. More specifically, these UEs try to associate with these eNBs by sending multiple access requests simultaneously with no success, thus producing congested eNBs in that area. As long as these UEs are not associated, they always conduct what is called the Cell Search Procedure (CSP), searching for a suitable eNB [8]. This operation consumes the battery power of the UEs. Eventually, they will be out of service and unreachable.

Potentially, the surviving eNBs are unable to communicate; e.g., if the necessary links (called X2 [9]) between them and the links between eNBs and the core network are disconnected, leaving these eNBs isolated from each other. Furthermore, as long as the surviving eNBs are scattered across the RoI (and isolated), it is difficult for the PSAs to reach these UEs by wireless communication. In such cases, the SAROs are crucial because of the lack of mobile communication; victims risk being trapped or isolated from being found and rescued.

III. Solution Approach

A. Issues to be Considered

This work deals with the most critical scenarios, as illustrated in Section II. So, we propose a solution to provide the corresponding PSAs with information on surviving UE locations (or distributions). On the contrary, recent studies have focused on how to provide RFC in the RoI instead of finding these UEs (e.g., as in [10] and [11]). More specifically, it is very important not only to provide RFC but also find the most majority of these UEs in a timely manner—where and how the UEs are clustered. It turns out that after disasters individuals tend to cluster into groups. Moreover, it is very important to give the corresponding PSAs better awareness on the UE locations in the RoI. In addition, it is important to locate these UEs without their assistance for life-saving purposes—these UEs might be unable to text/call because of the following: lack of wireless service, injuries, unconsciousness, or even unresponsiveness (finding surviving UEs is more important than providing RFC elsewhere). Awareness of victim locations is a very critical requirement for the MCPSCs, often racing against time.

B. Proposed Approach

Considering the above issues, we propose a new method for SAROs to find potential survivors by finding/locating their UEs without their assistance, even in the absence of RFC. This approach is effective especially because these UEs have become more ubiquitous—that is, each individual (likely) is equipped with at least one of the following: smart-phones, tablets, smart-watches, or even embedded sensors in the human body or clothing. This is a quick way (for SAROs) to provide vital information to the PSAs even before they arrive at the scene; accordingly, they can prioritize their SAROs beforehand. In this paper, the SAROs are based on the idea that each individual has its own UE and potentially is still alive and willing to be found, and hence (for ease of presentation) we name our solution ***UE-based SAROs***. Specifically, this work is mainly intended to generate an immediate crisis map[1], providing information to the corresponding PSAs to prioritize their progress (to have better insight) in disaster-affected regions. Essential entities of *UE-based SAROs* are discussed next.

[1] Google Crisis Map [12] is a well-known example of a crisis map, but its availability needs wireless networks and does not provide immediate information about how and where individuals are distributed.

IV. UE-based SARO System Model

In our solution, we use UAVs as mobile eNBs, called *UA-eNBs*, as a part of the network infrastructure in the RoI. We assume that the impacted network is only *partially* dysfunctional; some of eNBs are still able to broadcast and exchange signaling. Before proceeding further, we define the essential entities in our solution (illustrated in Fig. 1 in color for clarity), as follows.

A. Entity Definitions

1) *ref-eNBs*: These are the surviving eNBs, called reference eNBs (*ref-eNBs*); see Fig. 1. These *ref-eNBs* provide Radio Resources Management (RRM) functionalities, such as resource allocation, scheduling, and mobility control [13] and [14]. The deployment of a *UA-eNB* (see below) does not need its own RRM. Instead, the *ref-eNBs* provide the necessary RRM to the corresponding *UA-eNBs*. This is to minimize the load on these *UA-eNBs*, to address limitations in battery power and processing capabilities.
2) *UA-eNBs*: These are the deployed UAVs, to provide mobile picocells with range expansion capabilities, with a cell radius of 100–300 *m* and transmit power of 24–33 *dBm* [15]. Here, the *UA-eNBs* have four main functions: 1) search for a *ref-eNB* to associate with (establish X2 interface); 2) search for surviving UEs that are actively seeking a serving cell to camp on, around the detected *ref-eNB* (according to a screening procedure we define later), broadcasting UE-specific control messages; 3) feed back the screening results to the corresponding *ref-eNB*; 4) while conducting the screening procedures, the *UA/ref-eNBs* broadcast paging messages to the corresponding UEs, including emergency alert messages, using the already existing public warning system in LTE, known as Commercial Mobile Alert System (CMAS) [16]. For example, the *UA/ref-eNBs* may broadcast the following message: *"If your location is safe, stay; otherwise go the nearest safe location and remain there. Refrain from using your mobile phone to conserve battery; we will reach you by phone."*
3) *ref-UEs*: These are surviving UEs that have been associated and registered with *ref-eNBs* in close proximity, as shown in Fig. 1 (in green).
4) *UA-UEs*: These are surviving UEs that have been discovered and associated with *UA-eNBs* after the screening procedure. As mentioned above, the association information will be sent to the corresponding *ref-eNB* for further processing. The *UA-UEs* are shown in Fig. 1 (in blue).
5) *X-UEs*: These are surviving UEs but not associated to any eNB. While the RFC is not available (or the received RSRP is too low), the *X-UEs* are always involved in the CSP, which consumes the battery power of the UEs. These UEs need to be found as quickly as possible; otherwise, the *X-UEs* might go out of service (unreachable). Fig. 1 shows these *X-UEs* (in brown).
6) *Searching Zones (SZs)*: To facilitate the screening/searching efforts, the area around each *ref-eNB* is partitioned into a set of sub-areas, called zones, in which the *UA-eNBs* screen their assigned zones, called *SZs* (see below for further detail). These *SZs* are known to the *ref-eNBs*. More specifically, each *ref-eNB* has a specified *SZ* (as in Section VI) around its location (to assign to the associated *UA-eNB*); the *SZs* are also used to generate the required *UEBCM*.
7) *UE-Based Crisis Map (UEBCM)*: Based on the collected information (from the *SZs*), each *ref-eNB* generates a crisis map, called *UEBCM*, containing all the necessary information (*ref-eNB* locations, surviving UE location distributions and their *SZs*, and the corresponding RSRP reports). This map will be accessible to the PSAs later.

B. Entity Formulations

For ease of presentation, we represent the above entities as follows:

1) *ref-eNBs*: Defined by the location set $\mathcal{R} = \{(x_i^{\text{ref}}, y_i^{\text{ref}}) : i = 1, 2, \ldots, I\}$, where $(x_i^{\text{ref}}, y_i^{\text{ref}})$ is the location of *ref-eNB*$_i$ and I is the total number of the detected *ref-eNBs*. These form a sub-set of all eNBs, whose locations are denoted by the set $\mathcal{A}$ (i.e., $\mathcal{R} \subset \mathcal{A}$).
2) *UA-eNBs*: Defined by the set $\mathcal{U} = \{u_i^j : j = 0, 1, \ldots, J-1\}$, where i is the index of the associated *ref-eNB*$_i$ (from $\mathcal{R}$) and j is the index of the underlying searching zone.
3) *ref-UEs*: Defined by the set of UEs that are associated with *ref-eNB*$_i$, $\mathcal{G}_Q^i = \{ue_q^i : q = 1, 2, \ldots, Q\}$, where Q is the total number of associated UEs. For example, if *ref-eNB*$_3$ has a total of 100 associated UEs, then $\mathcal{G}_{100}^3 = \{ue_1^3, ue_2^3, \ldots, ue_{100}^3\}$.
4) *UA-UEs*: These are the set of UEs that are associated with the ith *UA-eNB* within zone j (i.e., u_i^j). We call this set $\mathcal{S}_P^j = \{ue_p^j : p = 1, 2, \ldots, P\}$, where P is the total number of associated UEs within zone index j. For example, suppose that a *UA-eNB* has associated with *ref-eNB*$_5$. While screening the zone with index 2, the u_5^2 has detected 20 UEs. Then, the set of these UEs is identified as $\mathcal{S}_{20}^2 = \{ue_1^2, ue_2^2, \ldots, ue_{20}^2\}$.
5) *X-UEs*: Defined by the number of unreachable UEs (i.e., no RFC available) within the RoI, denoted $\mathcal{X}$.
6) *SZs*: Defined by divided areas surrounding *ref-eNB*$_i$, $\mathcal{Z}_i^J = \{z_i^j : j = 0, 1, \ldots, J-1\}$, where J is the total number of the defined *SZs*; e.g., if *ref-eNB*$_2$ has 12 surrounding *SZs*, then $\mathcal{Z}_2^{12} = \{z_2^0, z_2^1, \ldots, z_2^{11}\}$. This set, $\mathcal{Z}_i^J$, surrounds the cell edge (around the cell border) of the corresponding *ref-eNB*$_i$, where there are $\mathcal{X}$ UEs left without RFC.

V. *UA-eNBs* Searching Procedures

Basically, the *UA-eNBs* perform two essential searching procedures. First, it should find a *ref-eNB* to obtain the required RRM. Second, and after association with a *ref-eNB*, the *UA-eNBs* start searching for surviving UEs, which are starving for a serving cell. In this context and because both *UA-eNBs* and

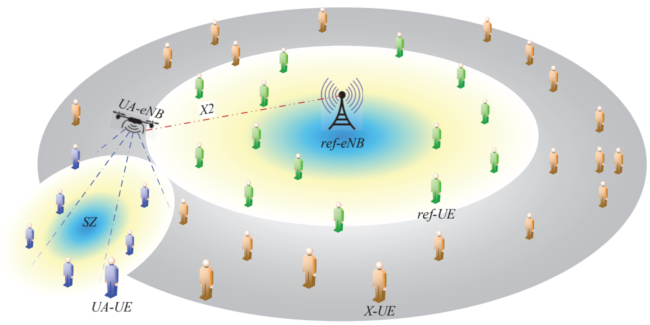

Fig. 1. Illustrative example showing the SARO entities

UEs are battery-power limited, the following concerns arise: 1) the *UA-eNBs* should find a *ref-eNB* as quickly as possible to save their battery capacity; 2) the *X-UEs* (in brown in Fig. 1) should be reached (found and located within a reasonable time of delay) by the searching *UA-eNBs* before many of the *X-UEs* run out of battery power (race against time). These concerns involve time-critical requirements. Thus, the search schemes must be time efficient, as described in the following.

A. Search Procedure for Finding ref-eNBs

To locate *ref-eNBs*, the *UA-eNBs* can scan the whole RoI or use some prediction algorithm (or probability distribution functions), but under the above requirements, such searching schemes are inefficient (e.g., time-consuming). To facilitate the searching efforts and develop time-efficient strategies, we start from the following:

1) Typically, the *eNBs* (i.e., $\mathcal{A}$) are already deployed according to a predefined plan (network topology)—that is, all the eNBs ($\mathcal{A}$) are distributed based on where the RFC is most needed (e.g., hot spots and crowded areas). We exploit the known location distributions to find the best candidate locations to search for survivors.
2) Based on the above, the location definitions in $\mathcal{A}$ (also defined by their Physical Cell Identifications (PCIs)) are known to the *UA-eNBs*, $\mathcal{U}$. But initially, the *UA-eNBs* do not know about the working status of $\mathcal{A}$; where are the *ref-eNBs*, $\mathcal{R}$, located? (get the RRM; see Section IV-A).

To facilitate the searching efforts, we propose the following scheme, in which the *UA-eNBs* conduct simultaneous localization (for $\mathcal{R}$) with low computation overhead; we call this scheme ***Cluster Centroid-based Search (CCBS)***:

1) We divide the RoI based on the location set $\mathcal{A}$ into T groups (or clusters) by using well-known partitioning algorithms, such as *k-means++* [17]. This is a simple and fast (relatively low overhead) way to find points that serve as centroids for each partition subset of $\mathcal{A}$, to serve as initial searching points for *UA-eNBs*. These initial points are defined by the set $\mathcal{K} = \{(x_k^{\text{ua}}, y_k^{\text{ua}}) : k = 1, 2, 3, \dots, K\}$, where K is the total number of cluster centroids. If we assume that for each defined cluster k there is one searching *UA-eNB*, K will be equal to the total number of the searching *UA-eNBs*, assuming there is at least one *ref-eNB* for each cluster k; see Fig. 2.

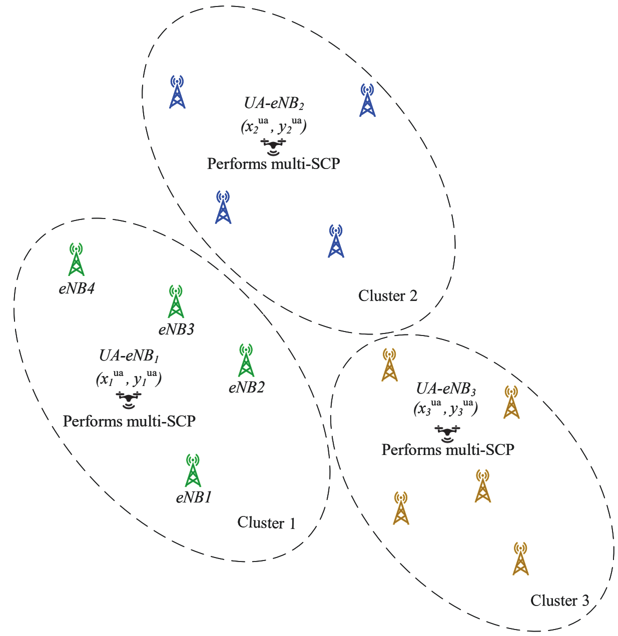

Fig. 2. *UA-eNBs* center at cluster centroids

2) In the *CCBS* scheme, for each cluster centroid, there is one *UA-eNB* centering initially at $(x_k^{\text{ua}}, y_k^{\text{ua}})$; K *UA-eNBs* are assigned, one each, to all K cluster centroids in $\mathcal{K}$. It is worth mentioning here that deploying *UA-eNBs* at low altitude, they receive (more likely) Line-of-Sight (LoS) signaling from multiple potential *ref-eNBs*; they might receive better RSRP levels than ground UEs. Also, deployment of low altitude *UA-eNBs* ensures that the ground UEs would receive good levels of RSRP while getting screened by these *UA-eNBs* (this is to reduce the PathLoss (**PL**) effect); see Section V-B. Considering this case, we assume that both *UA-eNBs* and their *ref-eNBs* have the same height, denoted by $\mathbf{h_{UA}}$ and $\mathbf{h_{ref}}$, respectively. The LoS distance is denoted by $\mathbf{r}$.
3) While centering at its allocated location (i.e., at centroid $(x_k^{\text{ua}}, y_k^{\text{ua}})$), *UA-eNB$_k$* performs multi-cell search (i.e., SCP). Once *UA-eNB$_k$* detects a serving cell, the PCI of the decoded cell is identified (i.e., a *ref-eNB* found), and hence its location, $(x_i^{\text{ref}}, y_i^{\text{ref}})$, becomes known. In this case, *UA-eNB$_k$* associates with its *ref-eNB$_i$* for exchanging the necessary information (i.e., RRM).
4) The associated *UA-eNB$_k$* has to search specifically for *X-UEs*, which are mostly located at the cell edge of *ref-eNB$_i$* (see Figs. 1 and 4), assuming the in-cell UEs, $\mathcal{G}_Q^i$, have already associated with *ref-eNB$_i$*. To do so, *UA-eNB$_k$* should adjust its initial distance ($\mathbf{r}$) from *ref-eNB$_i$*, such that it can search the required area, which is $\mathcal{Z}_i^J$, circulating around the cell edge. The initial distance is calculated as below:

$$\mathbf{r} = \sqrt{(x_i^{\text{ref}} - x_k^{\text{ua}})^2 + (y_i^{\text{ref}} - y_k^{\text{ua}})^2}, \tag{1}$$

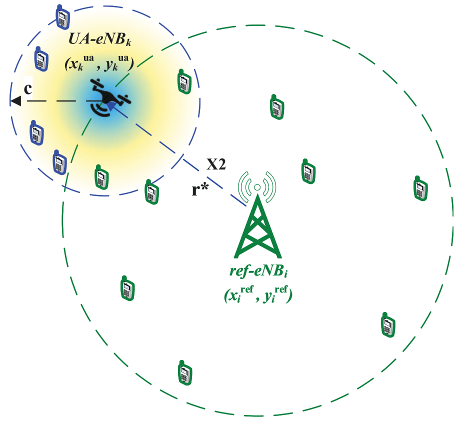

Fig. 3. Maximum distance as defined in (3)

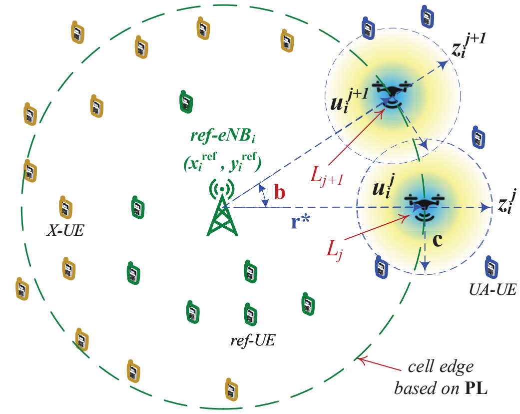

Fig. 4. *UA-eNB* screening locations

where $(x_i^{\text{ref}}, y_i^{\text{ref}})$ and $(x_k^{\text{ua}}, y_k^{\text{ua}})$ are defined in $\mathcal{R}$ and $\mathcal{K}$, respectively. To locate the *ref-eNB$_i$* cell edge, we use **PL** to calculate a maximum distance, called $\mathbf{r}^*$, in which the **PL** does not exceed a predefined value $\mathbf{PL}_{\text{threshold}}$. This also required to maintain the communication link between them (X2). We consider the following **PL** formula, which is widely used in the literature (for urban and suburban areas) for system-level simulations [18]:

$$\begin{aligned}\mathbf{PL}(\mathbf{r}) &= 40 \cdot (1 - 4 \cdot 10^{-3} \cdot \mathbf{h_{ref}}) \cdot \log_{10}(\mathbf{r}) \\ &\quad - 18 \cdot \log_{10}(\mathbf{h_{ref}}) + 21 \cdot \log_{10}(f) + 80\ dB,\end{aligned} \tag{2}$$

where $\mathbf{r}$ is the distance (in kilometers) between the *ref-eNB$_i$* and *UA-eNB$_k$*, f is the carrier frequency in MHz, and $\mathbf{h_{ref}}$ is the *ref-eNB$_i$* antenna height (in meters), measured from the average rooftop level.

5) Now we calculate the maximum distance ($\mathbf{r}^*$), which is the solution to the following optimization problem.

$$\begin{aligned}\mathbf{r}^* &= \arg\max_{\mathbf{r}} \mathbf{PL}(\mathbf{r}) \\ &\text{subject to } \mathbf{PL}(\mathbf{r}) \le \mathbf{PL}_{\text{threshold}}.\end{aligned} \tag{3}$$

After solving (3), *UA-eNB$_k$* will be placed at distance $\mathbf{r}^*$ from its *ref-eNB$_i$*, screening around the cell edge, as shown in Fig. 3. This will help the uncovered UEs, $\mathcal{X}$, to get associated with *UA-eNB$_k$* while screening its *SZs* (i.e., $\mathcal{Z}_i^J$); the associated UEs are defined in $\mathcal{S}_P^j$.

B. Search Procedure for Finding X-UEs

After finding $\mathbf{r}^*$, the associated *UA-eNB$_k$* will follow a path around the cell edge (according to the **PL**, the distance $\mathbf{r}^*$ changes accordingly). Here and for ease of presentation, we assume that the cell edge is a circular boundary; the searching model is detailed in Fig. 4. As stated before, there are *SZs* around *ref-eNB$_i$*, called z_i^j (Section VI), in which *UA-eNB$_k$* searches for *X-UEs*. Specifically, *ref-eNB$_i$* assigns its *SZs* to the associated *UA-eNB$_k$*, which is defined by $\mathcal{U}$ (Section IV-B) to represent its location with respect to each *SZ*, z_i^j. For example, when screening a particular z_i^j, the corresponding u_i^j refers to the current location of *UA-eNB$_k$*. The following steps elaborate on the screening procedure:

1) In each z_i^j, when *X-UEs* are exposed to the RFC of *UA-eNB$_k$* (at location u_i^j), they initiate the CSP. Hence, *UA-eNB$_k$* becomes the serving cell for all the detected UEs.
2) All *X-UEs* in z_i^j that are found (by *UA-eNB$_k$*) will be registered as *UA-UEs* (to differentiate them from those that are already associated with the corresponding *ref-eNB$_i$*). As stated in Section IV-B, item 4, the number of these UEs (*UA-UEs*) is defined by $\mathcal{S}_P^j$—that is, for each z_i^j, there is a corresponding $\mathcal{S}_P^j$.
3) The context information of the *UA-UEs* (see [19] for more detail) in $\mathcal{S}_P^j$ will be stored in *UA-eNB$_k$*. To detect as many *X-UEs* as possible, *UA-eNB$_k$* may circulate around the cell edge multiple times. In this case, every time *UA-eNB$_k$* makes a new round, it does not need to re-register the already detected UEs (i.e., *UA-UEs*). More specifically, after association, *UA-eNB$_k$* broadcasts control messages to the corresponding *UA-UEs* to change their RRM status to the IDLE state [20]. Also, these control messages may include what is called "barred cell," on which the *UA-UEs* are not allowed to camp [21]—this is to prevent these *UA-UEs* from making multi-access attempts on the neighboring *ref-eNB$_i$*. Such arrangements will save more power in the battery-limited UEs and provide lightweight signaling overhead (save bandwidth).

VI. *UA-eNB* Location Setup for *SZs*

Now, we detail how *UA-eNB$_k$* moves around the cell edge within the radius $\mathbf{r}^*$ (see Fig. 4). Recall the set $\mathcal{U} = \{u_i^j : j = 0, 1, \ldots, J-1\}$, where i is the index of the associated *ref-eNB$_i$* and j is the index of a particular zone under screening, z_i^j. Also, u_i^j represents a particular location of *UA-eNB$_k$* related to *SZ* j. In other words, each value of j corresponds to a specific location of *UA-eNB$_k$* on the cell edge path—that is, j represents location coordinates on that path. So, we need to find these locations for each value of j, where *UA-eNB$_k$* is located. We explain how to find these coordinates for each value of j. When screening *SZ* j, *UA-eNB$_k$* should be located at L_j, which is defined (in polar) as:

$$L_j = \mathbf{r}^* \underline{/j.\mathbf{b}} \quad , \; j = 0, 1, \ldots, J-1, \tag{4}$$

where $L_0 = \mathbf{r}^* \underline{/0}$ is the initial location and J is the total number of the *SZs* around *ref-eNB*$_i$ (calculated below). Now, we calculate the angle $\mathbf{b}$ as follows. After completing the screening process, *UA-eNB*$_k$ should move to the next *SZ* at L_{j+1} such that the distance between its previous and next positions, denoted by $d(L_j, L_{j+1})$, is approximately twice of its RFC radius, the quantity labeled $\mathbf{c}$ in Fig. 4. This is to keep each *SZ* separated from each other and minimize the overlapping between the corresponding RFC, as Fig. 4 illustrates. Note that even when RFC overlapping occurs, there is no confusion among the detected UEs (to which *SZ* they belong); this is because *UA-eNB*$_k$ registers the detected UEs (i.e., *UA-UEs*) such that each *SZ* has its own UEs, which means that $\mathcal{S}^j_{p1} \cap \mathcal{S}^{j+1}_{p2} = \emptyset$, where the subscripts $p1$ and $p2$ are the total number of the detected UEs (i.e., *UA-UEs*) in *SZ* index j and $j+1$, respectively.

From above, we have $d(L_j, L_{j+1}) \approx \mathbf{2c}$. To simplify the calculation, assume that the arc length between L_j and L_{j+1} is equal to $\mathbf{2c}$, and hence we write the following expression:

$$\mathbf{b} \approx 360 \cdot \mathbf{c}/(\pi \cdot \mathbf{r}^*) \quad \text{degrees.} \tag{5}$$

So, the resulting total number of *SZs* is $J = \lceil 360/\mathbf{b} \rceil$, and hence j should range between 0 and $J-1$. It should now be clear how *UA-eNB*$_k$ circulates around *ref-eNB*$_i$, searching for survivor *X-UEs*. Once the whole screening process is complete, each *UA-eNB*$_k$ generates an information table, as detailed in Table I. This table will be shared with the corresponding *ref-eNB*; the latter will process the incoming information in conjunction with its own association table (see Table II) to generate the necessary *UEBCM*—that is, each *ref-eNB* will have its own *UEBCM*, as we detail next.

VII. Generating Crisis Map, *UEBCM*

After aggregating all the necessary data (as in Table I) from the associated *UA-eNB*$_k$, each *ref-eNB*$_i$ will generate its own *UEBCM* for the area around its cell edge and beyond (including the in-cell area), having the necessary information about how the surviving UEs are distributed. The generated *UEBCM* should give sufficient situational awareness to the corresponding PSAs such that they have enough knowledge about where the most survivors are collected, prioritizing the SAROs in a quick way (the time is critical). To elaborate on the *UEBCM*, we detail in the following.

A. Illustrative Scenario Setup

For the purpose of clarity and brevity, we consider one *ref-eNB*$_i$ with its associated *UA-eNB*$_k$ to generate the corresponding *UEBCM*. Also, to use the searching procedure of Section V-B, we set the necessary parameters as follows. We assume $\mathbf{c} = 40m$ and $\mathbf{r}^* = 100m$ (cell radius of *UA-eNB* and *ref-eNB*, respectively), resulting in $\mathbf{b} = 45.83°$ (see formula (5)), and $J = 8$ (i.e., $\mathcal{U} = \{u^j_i : j = 0, 1, \ldots, 7\}$). After completing the searching process, Fig. 5 is produced, illustrating the attached UEs corresponding each *SZ*, including the in-cell UEs (i.e., *ref-UEs*). In this example, the solid blue circles refer to centers of the *SZs* (as described in Fig. 4), denoted by L_j. The UEs around each L_j are associated with the corresponding *SZ* (i.e., where they are screened and discovered); each *SZ*, z^j_i, has its own UEs as shown in multi-colored circles. To make that clear and based on the SAROs system model (Section IV-B), we write the corresponding entities as follows (for Fig. 5). The number of *ref-UEs* is equal to $\mathcal{G}^i_{63} = \{ue^i_1, ue^i_2, \ldots, ue^i_{63}\}$. The number of *UA-UEs* within the *SZ* z^0_i is equal to $\mathcal{S}^0_{45} = \{ue^0_1, ue^0_2, \ldots, ue^0_{45}\}$. Similarly, the number of *UA-UEs* within z^1_i is equal to $\mathcal{S}^1_9 = \{ue^1_1, ue^1_2, \ldots, ue^1_9\}$, and so on for the others z^j_i—this represents individual densities in each specific *SZ*, which is defined by $\mathcal{Z}^8_i = \{z^0_i, z^1_i, \ldots, z^7_i\}$.

B. Illustrative Scenario Findings

Based on the preceding information, the corresponding *ref-eNB*$_i$ generates immediate *UEBCM* for the impacted area, giving visual information about the potential survivor distributions to the corresponding PSAs. Specifically, all the surviving UEs (i.e., *ref/UA-UEs*) in our design (i.e., *UE-based SAROs*) have become human sensors for the survivors in the RoI. Accordingly, the *ref-eNB*$_i$ will generate the intended *UEBCM* (detailed in Fig. 6). This map is generated based on the received RSRP levels, which have been received during the screening procedure—these RSRPs are normally sent by the associated UEs. We can observe from this map that some UEs receive high RSRP levels (approximately −50 to −70 *dBm*), especially in the yellowish (and yellowish-green) areas. These levels are (likely) associated with outdoor UEs. Likewise, we can see areas in dark blue in Fig. 6, representing low levels of RSRP. These levels are (likely) received from indoor UEs (experiencing high **PL**); they might be stranded inside buildings and need immediate help—this gives the PSAs better awareness on the disaster victim locations. It is obvious that the above vital information can be easily/quickly extracted from the generated maps (i.e., *UEBCMs*), enabling the cor-

TABLE I

Information table for each *ref-eNB*$_i$–*UA-eNB*$_k$ pair

$\mathcal{Z}^J_i$	*UA-eNB locations (polar)*	*Density (UE/SZ)*	*Average RSRP (dBm)*
z^0_i	L_0	$\mathcal{S}^0_{p1}$	RxLev#0
z^1_i	L_1	$\mathcal{S}^1_{p2}$	RxLev#1
.	.	.	.
.	.	.	.
z^{J-1}_i	L_{J-1}	$\mathcal{S}^{J-1}_{pn}$	RxLev#J-1

TABLE II

Association table for each *ref-eNB*$_i$

$\mathcal{R}$	*ref-eNB*$_i$	$\mathcal{G}^i_Q$*, total no. of ref-UEs*	*Average RSRP (dBm)*
(x^{ref}_1, y^{ref}_1)	1	$\mathcal{G}^1_{Q1}$	RxLev#1
(x^{ref}_2, y^{ref}_2)	2	$\mathcal{G}^2_{Q2}$	RxLev#2
.	.	.	.
.	.	.	.
(x^{ref}_I, y^{ref}_I)	I	$\mathcal{G}^I_{Qn}$	RxLev#I

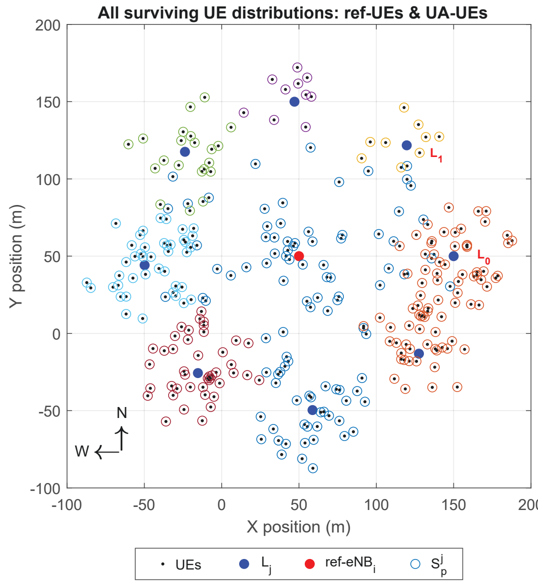

Fig. 5. Attached UEs corresponding to each *SZ*

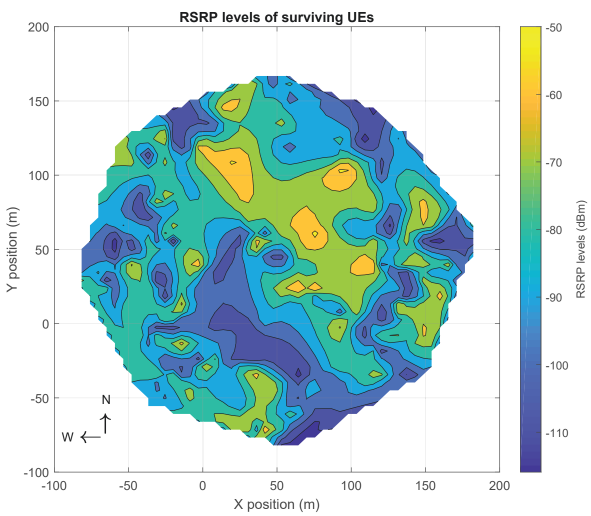

Fig. 6. RSRP levels of the attached UEs

responding PSAs to provide *SAROs* for the largest number of survivors in a prioritized way.

VIII. Conclusion

In this paper, we have proposed a new framework for SAROs (called *UE-based SAROs*) post-disaster to find and locate survivors based on the idea that most individuals have their own UEs—potentially, they are still alive and need to be rescued. This framework provides vital information to the PSAs to prioritize their SAROs and manage the available resources. By considering the surviving UEs as human-based sensors distributed in the RoI and are able to exchange signaling messages without active user participation, the *UE-based SARO* achieves the following task: Right after disasters, it generates immediate visual crisis maps, *UECBMs*, providing quick vital information about which region contains the majority of the potential survivors. Finally, *UE-based SAROs* provide PSAs with situational awareness about the disaster-impacted area quickly and even before they arrive at the scene.

Acknowledgment

The first author was supported by the Iraqi Ministry of Higher Education and Scientific Research through scholarship under Grant 4650/11/16/2014. This work was supported in part by the National Science Foundation under grant CMMI-1638284.

References

[1] O. Safecom, "Land Mobile Radio (LMR) 101 part 1: Educating decision-makers on LMR technologies," Tech. Rep. https://www.dhs.gov/sites/default/files/publications/LMR 101_508FINAL.pdf

[2] M. Zarri, "Network 2020: Mission critical communications," GSMA, Tech. Rep., 2017. https://www.gsma.com/network2020

[3] Nokia, "LTE networks for public safety services," 2015. https://networks.nokia.com

[4] AT&T Newsroom, "All 50 U.S. states, 2 Territories and the District of Columbia opt-in to FirstNet," dec 2017. http://www.5gamericas.org/en/newsroom/member-news/all-50-us-states-2-territories-and-district-columbia-opt-firstnet/

[5] 3GPP TS 24.334 V15.2.0, "Proximity-services (ProSe) User Equipment (UE) to ProSe function protocol aspects; Stage 3 (release 15)," 2018. http://portal.3gpp.org

[6] Y. Heisler, "A huge 4G milestone: LTE is now available for 98% of Americans," Tech. Rep., 2015. http://bgr.com/2015/03/23/lte-coverage-map-united-states/

[7] Public Safety and Homeland Security, "2017 Atlantic hurricane season impact on communications," Tech. Rep., 2018. https://docs.fcc.gov/public/attachments/DOC-353805A1.pdf

[8] 3GPP TS 36.213 V15.2.0, "Physical layer procedures (release 15)," 2018. https://portal.3gpp.org

[9] 3GPP TS 36.422 v15.0.0, "X2 signaling transport (release 15)," 2018. https://portal.3gpp.org

[10] A. Merwaday and I. Guvenc, "UAV assisted heterogeneous networks for public safety communications," in *2015 IEEE Wirel. Commun. Netw. Conf. Work.* IEEE, mar 2015, pp. 329–334.

[11] M. Deruyck, J. Wyckmans, W. Joseph, and L. Martens, "Designing UAV-aided emergency networks for large-scale disaster scenarios," *EURASIP J. Wirel. Commun. Netw.*, vol. 2018, no. 1, p. 79, dec 2018. https://doi.org/10.1186/s13638-018-1091-8

[12] Google.org, "https://google.org/crisismap/weather_and_events."

[13] 3GPP TS 36.133 V14.5.0, "Requirements for support of radio resource management," 2017. http://www.etsi.org/standards-search

[14] A. A. R. Alsaeedy and E. K. P. Chong, "Mobility management for 5G IoT devices: Improving power consumption with lightweight signaling overhead," *IEEE Internet Things J.*, jun 2019. https://doi.org/10.1109/JIOT.2019.2920628

[15] Fujitsu Network Communications Inc., "High-capacity indoor wireless solutions: Picocell or Femtocell?" Tech. Rep., 2013. https://www.fujitsu.com/us/Images/High-Capacity-Indoor-Wireless.pdf

[16] 3GPP TS 36.331 V14.3.0, "Radio Resource Control (RRC); Protocol specification (release 14)," 2017. https://portal.3gpp.org

[17] D. Arthur, D. Arthur, and S. Vassilvitskii, "K-means++: the advantages of careful seeding," *Proc. 18TH Annu. ACM-SIAM Symp. Discret. ALGORITHMS*, 2007. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.360.7427

[18] 3GPP TS 36.942 V15.0.0, "Radio Frequency (RF) system scenarios (release 15)," 2018. http://portal.3gpp.org

[19] 3GPP TS 23.401 v14.4.0, "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (release 14)," 2017. https://portal.3gpp.org

[20] A. A. R. Alsaeedy and E. K. P. Chong, "Tracking area update and paging in 5G networks: A survey of problems and solutions," *Mob. Networks Appl.*, vol. 24, no. 2, pp. 578–595, apr 2019. https://doi.org/10.1007/s11036-018-1160-6

[21] 3GPP TS 36.304 V14.3.0, "User Equipment (UE) procedures in idle mode (release 8)," 2017. http://portal.3gpp.org