Exploiting LTE-Advanced HetNets and FeICIC for UAV-assisted Public Safety Communications

Abhaykumar Kumbhar\textsuperscript{1,2}, Ismail Güvenç\textsuperscript{3}, Simran Singh\textsuperscript{3}, and Adem Tuncer\textsuperscript{4}
\textsuperscript{1}Department of Electrical and Computer Engineering, Florida International University, Miami, FL 33174
\textsuperscript{2}Motorola Solutions, Inc., Plantation, FL 33322 USA
\textsuperscript{3}North Carolina State University, 890 Oval Dr, Raleigh, NC 27606, USA
\textsuperscript{4}Yalova University, Çınarcık Yolu Üzeri, 77200 Merkez/Yalova, Turkey

Abstract—Ensuring ubiquitous mission-critical public safety communications (PSC) to all the first responders in the public safety network (PSN) is crucial at an emergency site. Recently, the use of unmanned aerial vehicles (UAVs) has received extensive interest for PSC to fill the coverage holes and establish reliable connectivity. The UAVs can be deployed as unmanned aerial base stations (UABSs) as part of a heterogeneous network (HetNet) PSC infrastructure. In this article, we address the inter-cell interference limiting factor in LTE-Advanced HetNets by applying 3GPP Release-11 further-enhanced inter-cell interference coordination (FeICIC) and cell range expansion (CRE) to enhance the system-wide spectral efficiency (SE). Through simulation with different path-loss models, we compare the system-wide 5th percentile SE when UABSs are deployed in a hexagonal grid and when their locations are optimized using a genetic algorithm, while also jointly optimizing the CRE and the FeICIC parameters. Our results show that at optimized UABS locations, the 3GPP Release-11 FeICIC with reduced power subframes can provide considerably better 5th percentile SE than the 3GPP Release-11 with almost blank subframes.

Index Terms—Cell range expansion, eICIC, FeICIC, First-Net, genetic algorithm, interference management, Okumura-Hata model, public safety, UAV, UAVBS.

I. INTRODUCTION

Public safety communications (PSC) is considered to be the cornerstone of public safety response system and plays a critical role in saving lives, property, and national infrastructure during a natural or man-made emergency. To further enhance the capabilities of next generation PSC networks, countries such as the United States, the United Kingdom, and Canada are building a 4G Long Term Evolution (LTE) based broadband public safety network \cite{1}–\cite{3}. In particular, 4G mobile networks have great potential to revolutionize PSC during emergency situations by providing much needed high-speed real-time data, video, and multimedia services along with mission-critical communication. However, given the limited spectrum allocation for LTE-based PSC, the usage of such services would need improved channel capacity quality, and spectral efficiency (SE) \cite{1}, \cite{4}.

An additional challenge in designing an LTE-based PSC network is to achieve seamless and ubiquitous coverage by minimizing coverage holes. However, this coverage criteria will be difficult to achieve using only the dedicated cell towers. For example, the first responders network authority (FirstNet) in the United States is designing a PSC network, which is required to minimize coverage gaps and attain at least 95\% coverage of the geographical area and human population \cite{5}.

To this end, the deployment of LTE-Advanced small cells is increasingly becoming popular to provide improved spectral capacity and extend network coverage \cite{6}–\cite{8}. Moreover, recent practices in small cell deployment include the usage of ad-hoc and air-borne small cells such as the unmanned aerial base stations (UABSs). With minimum interdependencies and at low cost, these UABSs can be deployed at an emergency site for restoration and temporary expansion of PSC network \cite{9}. This can improve overall network spectral capacity and provides virtually omnipresent coverage which is essential for first-responders to be efficient and save lives. On the other hand, the deployment of these UABSs can also introduce significant inter-cell interference with the ground network and limit the overall PSC network SE \cite{10}–\cite{13}.

In this paper, for a suburban environment, we study the performance of inter-cell interference coordination (ICIC) and cell range expansion (CRE) techniques for an LTE band class 14 PSC network \cite{1} as shown in Fig. 1. By randomly removing macro base stations (MBSs), we simulate a mock emergency situation to study the impact of interference and CRE when the UABSs are deployed. The simulation model considers Rayleigh fading and simplified path loss model and Okumura-Hata model for calculating the propagation losses. Subsequently, we explore potential gains in 5th percentile SE (5pSE) from the use of Release-10/11 ICIC techniques for a UABS-based PSC HetNet. Furthermore, we jointly optimize the UAVBS locations, CRE parameter of the UABSs, and ICIC

![Fig. 1. The PSC scenario with MBS and UABSs constituting an air/ground HetNet infrastructure. The MBS can use inter-cell interference coordination techniques defined in LTE-Advanced. The UABSs can dynamically change their position to maintain good coverage and can utilize range expansion bias to take over MBS UEs.](image-url)
parameters for both MBSs and UABSs.

The rest of this paper is organized as follows. Section II provides a brief literature review of related work, Section III introduces the UABS-based HetNet model, different path-loss models, and the definition of 5pSE as a function of network parameters. The UABSs deployment and ICIC parameter configurations using the genetic algorithm and hexagonal grid UABS model are described in Section IV. In Section V, we analyze and compare the 5pSE of the HetNet using extensive computer simulations for various ICIC techniques, and finally, the last section provides some concluding remarks. Table I lists the notations and symbols used throughout the paper.

II. LITERATURE REVIEW

LTE based HetNets are a well-researched topic, and numerous studies have been carried to enhance the network performance, improve coverage, and mitigate network interference. In [14], a fractional frequency reuse method is used to mitigate interference in a fixed HetNet, improve the indoor coverage, and maximize the network SE by minimizing the UE’s outage probability to cell-edge UEs in an OFDMA-based LTE HetNet. However, [14] did not consider any of the 3GPP Release-10 and Release-11 inter-cell interference coordination (ICIC) techniques for fixed HetNet deployments.

3GPP Release-10 eICIC and Release-11 FeICIC techniques have been studied in [12], [15], [16] for HetNets. For example, [15] proposes algorithms that jointly optimize the eICIC parameters, UE cell association rules, and the spectrum resources shared between the macro and fixed small cells. Nevertheless, 3GPP Release-11 FeICIC technique for better resource utilization and CRE for offloading a larger number of UEs to small cells was not considered in [15]. The effectiveness of 3GPP Release-10 and Release-11 ICIC techniques with ICIC parameter optimization have been studied in [12], without considering any mobility for small cells.

Recent advancements in UAV technology has enabled the possibility of deploying small cells as UABSs mounted with a communication system. UABSs such as balloons, quadcopters, and gliders equipped with LTE-Advanced capabilities can be utilized to further enhance the capabilities of LTE-based HetNets. The ability of UABSs to dynamically reposition in a HetNet environment can improve the overall SE of the network by filling the coverage gaps and offloading UEs in high-traffic regions. Hence, it is of critical nature to optimize the locations of UABSs in a UAV-based HetNet to optimize SE gains.

Recent studies [17]–[22] are mainly focused on finding an optimal location of UAV in the geographical area of interest to meet traffic demands. Moreover, in [17]–[20], the UAV location optimization was not designed for a HetNet environment, and interference mitigation was not explicit. Whereas in [11], [23] the use of CRE for offloading users from a macrocell to UABSs has been explored without considering ICIC. To maximize the 5pSE of the HetNet, a brute force method is used to find the optimal UAV locations in [23], while the genetic algorithm is used for optimizing UAV locations in [11].

The effect of interference in a UAV-based network is investigated in [24]. By calculating the optimal distance between the two interfering UAVs, each UAV is positioned at fixed height to maximize the coverage area. However, this UAV-based network is not designed for LTE-Advanced HetNets. A priority-based UE offloading and UE association with mobile small cells for PSC is studied in [25]. To improve the overall system throughput, 3GPP Release-10 eICIC and CRE is taken into account. However, using almost blank subframes (ABS) at an MBS results in under-utilization of radio resources when compared to the use of reduced power FeICIC.

To the best of our knowledge, the use of inter-cell interference coordination techniques in UAV based HetNets has not been adequately studied in the literature. The contribution of our study is to address this challenge of interference mitigation by using and optimizing FeICIC and CRE techniques and at the same time, optimize the UAV locations using the genetic algorithm to achieve maximum SE.
with intensities $\lambda_{\text{mbs}}$ and $\lambda_{\text{ue}}$, respectively [12], [26]. The UABSs are deployed either at fixed locations in a hexagonal grid, or the locations are optimized using the genetic algorithm.

We assume that the MBSs and the UABSs share a common transmission bandwidth, round robin scheduling is used in all downlink transmissions, and full buffer traffic is used in every cell. The transmit power of the MBS and UABS are $P_{\text{mbs}}$ and $P_{\text{uabs}}$, respectively, while $K$ and $K'$ are the attenuation factors due to geometrical parameters of antennas for the MBS and the UABS, respectively. Then, the effective transmit power of the MBS is $P'_{\text{mbs}} = KP_{\text{mbs}}$, while the effective transmit power of the UABS is $P'_{\text{uabs}} = K'P_{\text{uabs}}$.

An arbitrary UE $n$ is always assumed to connect to the nearest MBS or UABS, where $n \in \{1, 2, \ldots, N_{\text{ue}}\}$. Then, for the $n$th UE the reference symbol received power (RSRP) from the macro-cell of interest (MOI) and the UAV-cell of interest (UOI) are given by [12]

$$S_{\text{mbs}}(d_{mn}) = \frac{P'_{\text{mbs}}H}{10^{\varphi/10}}, \quad S_{\text{uabs}}(d_{un}) = \frac{P'_{\text{uabs}}H}{10^{\varphi'/10}},$$

where the random variable $H \sim \text{Exp}(1)$ accounts for Rayleigh fading, $\varphi$ is the path-loss observed from MBS in dB, $\varphi'$ is the path-loss observed from UABS in dB, $d_{mn}$ is the distance from the nearest MOI, and $d_{un}$ is the distance from the nearest UOI.

### A. Path Loss Model

Given the complexity of signal propagation, an accurate path-loss modeling would require complex ray tracing models and empirical measurements. To measure the path-loss observed by the $n$th UE, we use the simplified path loss model (SPLM), which is an approximation to the real propagation channel. However, for more accurate analysis of the signal reliability requirements in PSC networks, we also implement the suburban Okumura-Hata path loss model (OHPLM) with LTE band class 14 frequency [1], [27].

#### 1) Simplified Path Loss Model: The SPLM gives a coarse analysis of signal propagation and is a function of path loss exponent and the distance between the serving base station and the $n$th UE [28]. Based on the SPLM, the path-loss (in dB) observed by the $n$th UE from $m$th MOI and $n$th UOI is given by

$$\varphi = 10\log_{10}(d_{mn}^\delta), \quad \varphi' = 10\log_{10}(d_{un}^\delta),$$

where $\delta$ is the path-loss exponent, and $d_{un}$ depends on the locations of the UABSs that will be dynamically optimized.

Fig. 3(a) shows the empirical path-loss cumulative distribution functions (CDFs), calculated for all the distances between base stations ($X_{\text{mbs}}$ and $X_{\text{uabs}}$) and UEs ($X_{\text{ue}}$) using (2). For the path-loss exponent value defined in Table II, we plot the CDFs for the cases when 50% and 97.5% of the MBSs are destroyed. Inspection of Fig. 3(a) reveals the variation in CDFs is minimum for the different number of UABSs deployed and for a different number of the MBSs destroyed. This is because the SPLM does not consider external terrestrial factors. Nevertheless, the maximum allowable path-loss for the system is 160 dB.
where $f_c$ is the carrier frequency in MHz, $h_{bs}$ is the height of the base station in meter, and $a(h_{ue})$ is the correction factor for the UE antenna height $h_{ue}$ in meter, which is defined as

$$a(h_{ue}) = 1.1\log(f_c) - 0.7h_{ue} - 1.56\log(f_c) - 0.8.$$  

(8)

Furthermore, OHPLM assumes the carrier frequency ($f_c$) to be between 150 MHz to 1500 MHz, the height of the base station ($h_{bs}$) between 30 m to 200 m, UE antenna height ($h_{ue}$) between 1 m to 10 m, and the distances $d_{mn}$ and $d_{un}$ between 1 km to 10 km [32], [33]. Nevertheless, the simulation values considered for OHPLM are defined in Table II.

In Fig. 3(b), we plot the empirical path-loss CDFs using (3)–(8) and the OHPLM parameters in Table II. Moreover, we plot the OHPLM path-loss CDFs for the cases when 50% and 97.5% of the MBS are destroyed. Inspection of Fig. 3(b) reveals a step-wise distribution of path-loss in the CDFs. This behavior is due to the variation in the height of base-stations, i.e., UABSs are deployed at the height of 100 m (larger path loss) while the height of MBSSs is 30 m (smaller path loss). With 50% of the MBS destroyed, it can be seen that most UEs are connected to the MBSs, while with 97.5% of the MBS destroyed most UEs are served by the UABSs. Regardless, the maximum allowable path-loss when 50% and 97.5% of the MBSs are destroyed is 225 dB as shown in Fig. 3(b).

B. 3GPP Release-10/11 Inter-Cell Interference Coordination

Due to their low transmission power, the UABSs are unable to associate a larger number of UEs compared to that of MBSSs. However, by using the cell range expansion (CRE) technique defined in 3GPP Release-8, UABSs can associate a large number of UEs by offloading traffic from the MBSSs. A negative side effect of CRE includes increased interference in the downlink on cell-edge UEs or the UEs in CRE region of the UABS, which is addressed by using ICIC techniques in LTE and LTE-Advanced [34]–[36].

3GPP Release-10 introduced a time-domain based enhanced ICIC (eICIC) technique to address interference problems. In particular, it uses ABSs which require the MBS to completely blank the transmit power on the physical downlink shared channel (PDSCH) resource elements as shown in Fig. 4(a). This separates the radio frames into coordinated subframes (CSF) and uncoordinated subframes (USF). On the other hand, 3GPP Release-11 defines further-enhanced ICIC (FeICIC), where the data on PDSCH is still transmitted but at a reduced power level as shown in Fig. 4(b).

The MBSSs can schedule their UEs either in USF or in CSF based on the scheduling threshold $\rho$. Similarly, the UABSs can schedule their UEs either in USF or in CSF based on the scheduling threshold $\rho'$. Let $\beta$ denote the USF duty cycle, defined as the ratio of number of USF subframes to the total number of subframes in a radio frame. Then, the duty cycle of CSFS is $(1 - \beta)$. For ease of simulation, in this paper, we consider that the USF duty cycle $\beta$ is fixed at 0.5 for all the MBSSs, which is shown in [12] to have limited effect on system performance when $\rho$ and $\rho'$ are optimized. Finally, let $0 \leq \alpha \leq 1$ denote the power reduction factor in coordinated subframes of the MBS for the FeICIC technique; $\alpha = 0$ corresponds to...
where in [12] for a HetNet scenario, the signal-to-interference as in LTE Release-8.

Fig. 4. LTE-Advanced frame structures for time-domain ICIC.

Given the eICIC and FeICIC framework in 3GPP LTE-Advanced as in Fig. 4, and following an approach similar to that in [12] for a HetNet scenario, the signal-to-interference ratio (SIR) experienced by an arbitrary UE can be defined for CSFs and USFs for the MOI and the UOI as follows:

\[
\begin{align*}
\Gamma &= \frac{S_{\text{mbs}}(d_{m})}{S_{\text{usf}}(d_{u}) + Z} \rightarrow \text{USF SIR from MOI} \\
\Gamma_{\text{csf}} &= \frac{\alpha S_{\text{mbs}}(d_{m})}{S_{\text{csf}}(d_{u}) + Z} \rightarrow \text{CSF SIR from MOI}, \\
\Gamma' &= \frac{S_{\text{usf}}(d_{u})}{\alpha S_{\text{mbs}}(d_{m}) + Z} \rightarrow \text{USF SIR from UOI}, \\
\Gamma'_{\text{csf}} &= \frac{S_{\text{csf}}(d_{u})}{\alpha S_{\text{mbs}}(d_{m}) + Z} \rightarrow \text{CSF SIR from UOI},
\end{align*}
\]

where \( Z \) is the total interference power at a UE during USF or CSF from all the MBSs and UABSs, excluding the MOI and the UOI. In hexagonal grid UABS deployment model (and in [12]), locations of the UABSs (and small cells) are fixed. To maximize the 5pSE of the network, in this paper we actively consider the SIRs in (9)-(12) while optimizing the locations of the UABSs using the genetic algorithm.

C. UE Association and Scheduling

The cell selection process relies on \( \Gamma \) and \( \Gamma' \) in (9) and (11), respectively, for the MOI and UOI SIRs, as well as the CRE \( \tau \). If \( \tau' \) is less than \( \Gamma \), then the UE is associated with the MOI; otherwise, it is associated with the UOI. After cell selection, the MBS-UE (MUE) and UABS-UE (UUE) can be scheduled either in USF or in CSF radio subframes as:

\[
\begin{align*}
\text{If } \Gamma > \tau & \quad \text{and } \Gamma \leq \rho \rightarrow \text{USF-MUE}, \\
\text{If } \Gamma > \tau & \quad \text{and } \Gamma > \rho \rightarrow \text{CSF-MUE}, \\
\text{If } \Gamma \leq \tau & \quad \text{and } \Gamma' > \rho' \rightarrow \text{USF-UUE}, \\
\text{If } \Gamma \leq \tau & \quad \text{and } \Gamma' \leq \rho' \rightarrow \text{CSF-UUE}.
\end{align*}
\]

Once a UE is assigned to an MOI/UOI, and it is scheduled within a USF/CSF, then the SE for this UE can be expressed for the four different scenarios in (13)-(16) as follows:

\[
\begin{align*}
C_{\text{mbs}}^{\text{usf}} &= \frac{\beta \log_{2}(1 + \Gamma)}{N_{\text{mbs}}^{\text{usf}}}, \\
C_{\text{mbs}}^{\text{csf}} &= \frac{(1 - \beta) \log_{2}(1 + \Gamma_{\text{csf}})}{N_{\text{mbs}}^{\text{csf}}}, \\
C_{\text{usf}}^{\text{usf}} &= \frac{\log_{2}(1 + \Gamma')}{N_{\text{usf}}^{\text{usf}}}, \\
C_{\text{usf}}^{\text{csf}} &= \frac{\log_{2}(1 + \Gamma'_{\text{csf}})}{N_{\text{usf}}^{\text{csf}}}.
\end{align*}
\]

where \( N_{\text{mbs}}^{\text{usf}}, N_{\text{mbs}}^{\text{csf}}, N_{\text{usf}}^{\text{usf}}, \) and \( N_{\text{usf}}^{\text{csf}} \) are the number of MUEs and UUEs scheduled in USF and CSF radio subframes, and \( \Gamma, \Gamma_{\text{csf}}, \Gamma', \Gamma'_{\text{csf}} \) are as in (9)-(12).

In this paper, we consider the use of 5pSE which corresponds to the worst fifth percentile UE capacity among the capacities of all the \( \text{N}_{\text{ue}} \) UEs (calculated based on (17)-(20)) within the simulation area. We believe it is a critical metric particularly for PSC scenarios to maintain a minimum QoS level at all the UEs in the environment. We define the dependency of the 5pSE to UABS locations and ICIC parameters as

\[
C_{5\text{th}}(X_{\text{uabs}}, S_{\text{ICIC}}^{\text{mbs}}, S_{\text{ICIC}}^{\text{uabs}}), \quad (21)
\]

where \( X_{\text{uabs}} \in \mathbb{R}_{N_{\text{uabs}}}^{N_{\text{mbs}}^{\times 3}} \) captures the UABS locations as defined earlier, \( S_{\text{ICIC}}^{\text{mbs}} = [\alpha, \rho] \in \mathbb{R}_{N_{\text{mbs}}}^{N_{\text{mbs}}^{\times 2}} \) is a matrix that captures individual ICIC parameters for each MBS, while \( S_{\text{ICIC}}^{\text{uabs}} = [\tau, \rho'] \in \mathbb{R}_{N_{\text{uabs}}}^{N_{\text{uabs}}^{\times 2}} \) is a matrix that captures individual ICIC parameters for each UABS. In particular,

\[
\alpha = [\alpha_{1}, ..., \alpha_{N_{\text{mbs}}}]^{T}, \quad \rho = [\rho_{1}, ..., \rho_{N_{\text{mbs}}}]^{T}
\]

are \( N_{\text{mbs}} \times 1 \) vectors that include the power reduction factor and MUE scheduling threshold parameters for each MBS. On the other hand,

\[
\tau = [\tau_{1}, ..., \tau_{N_{\text{uabs}}}]^{T}, \quad \rho' = [\rho'_{1}, ..., \rho'_{N_{\text{uabs}}}]^{T}
\]

are \( N_{\text{uabs}} \times 1 \) vectors that involve the CRE bias and UUE scheduling threshold at each UABS. As noted in Section III-B, the duty cycle \( \beta \) of ABS and reduced power subframes is assumed to be set to 0.5 at all MBSs to reduce search space and complexity.

Considering that the optimum values of the vectors \( \alpha, \rho, \rho' \), and \( \tau \) are to be searched over a multi-dimensional space, computational complexity of finding the optimum parameters is prohibitively high. Hence, to reduce the system complexity (and simulation runtime) significantly, we consider the same ICIC parameters are used for all MBSs and for all UABSs. In particular, we consider that for \( i = 1, ..., N_{\text{uabs}} \) we have \( \alpha_{i} = \alpha \) and \( \rho_{i} = \rho \), while for \( j = 1, ..., N_{\text{uabs}} \) we have \( \tau_{j} = \tau \) and \( \rho'_{j} = \rho' \). Therefore, the dependence of the 5pSE on the UABS locations and ICIC parameters can be simplified as

\[
C_{5\text{th}}(X_{\text{uabs}}, \alpha, \rho, \tau, \rho'), \quad (24)
\]

which we will seek ways to maximize in the next section. We leave the problem of individually optimizing ICIC parameters
Fig. 5. An example of a chromosome for FeICIC simulation, where the UABS locations, ICIC parameter $\tau$, $\alpha$, $\rho$, and $\rho'$ are optimized. The ICIC parameter $\beta$ is not optimized and is fixed at 50% duty cycle.

for the MBSs and UABSs as a future work due to the high computational complexity of the problem.

IV. UABS DEPLOYMENT OPTIMIZATION

In this section, we discuss the UABS deployment using the genetic algorithm (GA) and the hexagonal grid model, where we use the 5pSE as an optimization metric to maximize for both scenarios.

Listing 1. Steps for optimizing population using GA.

```
Input: set of UABS locations and ICIC parameters
FITNESS function: 5pSE of the network
Output: Arg: Best individuals of ICIC parameters and highest 5pSE
Method: NewPopulation <- empty set
StopCondition: Number of iterations
SELECTION: Roulette wheel selection method
while (! StopCondition) {
  for i = 1 to Size do {
    Parent1 <- SELECTION(NewPopulation, FITNESS function)
    Parent2 <- SELECTION(NewPopulation, FITNESS function)
    Child <- Reproduce(Parent1, Parent2)
    if (small random probability) {
      child <- MUTATE(Child)
      add child to NewPopulation
    }
  }
  EVALUATE(NewPopulation, FITNESS function);
  Args <- GetBestSolution(NewPopulation)
  Population <- Replace(Population, NewPopulation)
}
```

A. Genetic Algorithm based UABS Deployment Optimization

The GA is a population-based optimization technique that can search a large environment simultaneously to reach an optimal solution [11]. In this paper, the UABS coordinates and the ICIC parameters constitute the GA population, and a subsequent chromosome is illustrated in Fig. 5. Listing 1 describes the main steps used to optimize the UABS locations and ICIC parameters while computing the 5pSE.

We apply the GA to simultaneously optimize the UABS locations and ICIC parameters in order to maximize the 5pSE of the network over a given geographical area of interest. The location of each UABS within a rectangular simulation area is given by $(x_i, y_i)$ where $i \in \{1, 2, ..., N_{uabs}\}$. The UABS locations and the ICIC parameters that maximize the 5pSE objective function can be calculated as

$$\hat{X}_{uabs}, \hat{\alpha}, \hat{\rho}, \hat{\rho}' = \arg\max_{X_{uabs}, \alpha, \rho, \tau, \rho'} C_{5th}(X_{uabs}, \alpha, \rho, \tau, \rho'). \quad (25)$$

Since searching for optimal $X_{uabs}$ and ICIC parameters through a brute force approach is computationally intensive, in this paper we use the GA to find optimum UABS locations and the best-fit ICIC parameters $\tau$, $\alpha$, $\rho$, and $\rho'$.

Listing 2. Steps for computing 5pSE for hexagonal grid deployment.

```
Input: set of UABS locations and ICIC parameters
Output: SE: 5pSE for the network
Method: StopCondition: Number of iterations
while (! StopCondition) {
  Generate UABS locations for $t = 1$ to ICICParms.tau do {
    for $a = 1$ to ICICParms.alpha[a] do {
      for $r = 1$ to ICICParms.rho[r] do {
        for $p = 1$ to ICICParms.rhoprime[p] do {
          SE = Calc5thPercentileSE(nodal locations, nodal Tx powers, path-loss, tau, beta, alpha, rho, rhoprime)
        }
      }
    }
  }
}
```

For the MBS locations shown in Fig. 2(b), an example outcome of UABS locations using the GA is shown in Fig. 6. Given the mobility and agility of UABSs, using the GA, the UAV positions can be dynamically rearranged to optimized locations to achieve the best network performance at the site of an emergency.

Fig. 6. PSC network after a disaster with UABS locations optimized using the GA (UAV height: 100 m).
Fig. 7. PSC network after a disaster with UABS deployed on a fixed hexagonal grid (UAV height: 100 m).

B. UABS Deployment in a Hexagonal Grid

As a lower complexity alternative to optimizing UABS locations, we consider deploying the UABSs on a hexagonal grid, where the position of the UABSs are deterministic. We assume that the UABSs are placed within the rectangular simulation area regardless of the existing MBS locations. The 5pSE for this network is determined by using a brute force technique as described in the pseudo-code 2 which only considers optimization of the ICIC parameters captured through the matrix $S_{ICIC}$. In particular, the ICIC parameters that maximize the 5pSE can then be calculated as:

$$\left[\hat{\alpha}, \hat{\rho}, \hat{\tau}, \hat{\rho}'\right] = \arg \max_{\alpha, \rho, \tau, \rho'} C_{5th}(X_{uabs}^{(hex)}),$$  \hspace{0.5cm} (26)

where $X_{uabs}^{(hex)}$ are the fixed and known hexagonal locations of the deployed UABSs within the simulation area.

For the MBS locations shown in Fig. 2(b), an example outcome of UABS locations using the hexagonal grid deployment is shown in Fig. 7. In the case of loss in PSC network infrastructure, UABSs can be deployed rapidly on a fixed hexagonal grid as a primary deployment strategy to form new small cells and consequently improve the network coverage.

V. SIMULATION RESULTS

In this section, using extensive computer simulations, we compare the 5pSE of a UABS assisted PSC HetNet with and without ICIC techniques while considering different UABS deployment strategies and path loss models. Unless otherwise specified, the system parameters for the simulations are set to the values in Table II.

A. 5pSE with UABSs Deployed on a Hexagonal Grid

In the following we will discuss the key 5pSE observations when the UABSs are deployed on a hexagonal grid and utilizing optimized ICIC parameters (see (26) and Listing 2). In Fig. 8 and Fig. 9, we plot the variations in 5pSE with respect to CRE while using SPLM and OHPLM, respectively.

1) 5pSE with Simplified Path Loss model: In Fig. 8(a), we plot the 5pSE variation with respect to CRE for no-ICIC mechanism (NIM). In the case of NIM, all the base stations (MBSs and UABSs) always transmit at full power ($P_{mbs}$ and $P_{uabs}$). The close evaluation of Fig. 8(a), shows that the peak value of 5pSE for NIM is observed at around 0 dB CRE. This is because, with no CRE, the number of UEs associated with the UABSs and the interference experienced by these UEs is minimal. Moreover, as the CRE increases, the number of UEs associated with the UABSs increases and so does the interference experienced by these UEs. Hence, with NIM the 5pSE decreases with increasing CRE as seen in Fig. 8(a).

The performance of 3GPP Release-10 and Release-11 ICIC techniques in terms of 5pSE and the variation in CRE are plotted in Fig. 8(b) and Fig. 8(c). As noted in Section III-B, the transmission power during blank subframes at the MBSs for eICIC is 0, and power reduction of the CSFs at the MBSs for FeICIC is $\alpha P_{mbs}$. Using this understanding, the analysis Fig. 8(b) and Fig. 8(c) shows that the 5pSE for ICIC techniques at 0 dB CRE are relatively lower. On the other hand, the ICIC techniques observe improvement in 5pSE performance with increasing CRE and the peak values of the 5pSE for the ICIC techniques is observed when the CRE is between 6 – 9 dB. This influence of CRE on the 5pSE for NIM and 3GPP Release-10 and Release-11 ICIC techniques are summarized in Fig. 10.

2) 5pSE with Okumura-Hata Path Loss Model: In Fig. 9(a), we plot the 5pSE variation with respect to CRE for NIM. In the case of NIM, all the base stations (MBSs and UABSs) always transmit at full power ($P_{mbs}$ and $P_{uabs}$). The peak value of 5pSE for NIM is observed at around 3 dB CRE when 50% of the MBSs are destroyed. On the other hand, when 97.5% of the MBSs are destroyed, even though the number of existing MBSs are small and the interference is minimal, the higher path-loss presents higher probability for a cell-edge UE to fall out of coverage area. Moreover, in the absence of any ICIC, using CRE can magnify the impact of interference. Hence, the 5pSE gains with NIM are close to zero.

In Fig. 9(b) and Fig. 9(c), we plot the variation of 5pSE with respect to CRE for 3GPP Release-10/11 ICIC techniques. The analysis of Fig. 9(b) and Fig. 9(c) shows that the ICIC

| Parameter                          | Value                  |
|-----------------------------------|------------------------|
| MBS and UE intensity              | 4 per km² and 100 per km² |
| MBS and UABS transmit powers      | 46 dBm and 30 dBm       |
| Path-loss exponent                | 4                      |
| Altitude of UABSs                 | 100 m                  |
| Simulation area                   | $10 \times 10$ km²     |
| GA population size and generation number | 60 and 100               |
| GA crossover and mutation probabilities | 0.7 and 0.1             |
| Cell range expansion ($\gamma$) in dB | 0 to 15 dB            |
| Power reduction factor for MBS during ($\alpha$) | 0 to 1     |
| Duty cycle for the transmission of USF ($\beta$) | 0.5 or 50%           |
| Scheduling threshold for UUEs ($\rho$) | 20 dB to 40 dB       |
| Scheduling threshold for MUEs ($\rho'$) | $-20$ dB to $-5$ dB |
| MBS destroyed sequence            | 50% and 97.5%          |
| PSC LTE Band 14 center frequency  | 763 MHz for downlink and 793 MHz for uplink |
| Height of MBS                     | 30 m                   |
| Height of UE                      | 3 m                    |
techniques observe improvement in 5pSE performance with increasing CRE. When 50% MBS are destroyed, the 5pSE peak values for the eICIC and FeICIC are observed when the CRE is between $6 - 9$ dB and $3 - 6$ dB, respectively. When $97.5\%$ of the MBSs are destroyed, even though the cell-edge UEs observe higher path loss, using the 3GPP Release-10/11 ICIC techniques along with CRE can decrease the probability of cell-edge UE going out of coverage. Thus sustaining the 5pSE of the network as seen in Fig. 9(b) and Fig. 9(c). Further analysis show that the FeICIC technique observes significant
improvement in SE performance when compared to NIM and eICIC. This influence of CRE on the 5pSE for NIM and 3GPP Release-10/11 ICIC techniques is summarized in Fig. 11.

On comparison of Fig. 10 and Fig. 11, we observe modest deviation in peak values of 5pSE between NIM, eICIC, and FeICIC with SPLM. This is because UEs experience better SIR with lower path-losses. Whereas, with OHPLM we observe significant deviation in the peak values of 5pSE due to higher path-losses. However, the higher path-losses in OHPLM can be compensated by using modest/higher CRE values and 3GPP Release-10/11 ICIC techniques.

Overall, with hexagonal grid deployment for both the path-loss models, the 5pSE for the network is higher when larger numbers of UABSs are deployed and when fewer MBSs are destroyed. Also, the 5pSE decreases with the increasing number of destroyed MBSs as seen in Fig. 8 and Fig. 9.

B. 5pSE with GA Based UABS Deployment Optimization

In the following, we will discuss the key 5pSE observations, when UABS locations and ICIC parameters optimized through the GA as in (25) and Listing 1. In Fig. 12 and Fig. 13, we plot the peak 5pSE for the network using the GA, versus the optimized CRE value while using SPLM and OHPLM, respectively. In the GA based simulations, the optimum CRE value is directly related to the locations of the UABSs with respect to the MBSs, the number of UEs offloaded to the UABSs, and the amount of interference observed by the UEs.

1) 5pSE with Simplified Path Loss Model: In Fig. 12(a) and Fig. 12(b), we plot the peak 5pSE with respect to the optimized CRE value for eICIC and FeICIC, respectively, for SPLM. Inspection of Fig. 12(a) and Fig. 12(b) shows higher values of CRE when 50% of the MBSs are destroyed and implies the presence of substantial interference from these large number of MBSs. Hence, offloading a large number of UEs from MBSs to UABSs with higher values of CRE is necessary for achieving better 5pSE gains.

On the other hand, when most of the infrastructure is destroyed (i.e., when 97.5% of the MBSs destroyed), the interference observed from the MBSs is limited, and a larger number of UEs need to be served by the UABSs. Therefore, with fewer UABSs deployed, higher CRE are required to serve a larger number of UEs and achieve better 5pSE. On the other hand, when a larger number of UABSs are deployed, smaller values of CRE will result in better 5pSE gains. We record these behavior in Fig. 12(a) and Fig. 12(b) for eICIC and FeICIC, respectively.

2) 5pSE with Okumura-Hata Path Loss model: Using (9)–(12), we plot the SIR in Fig. 14 for 3GPP Release-10/11 ICIC techniques for OHPLM. As noted in Fig. 3(a), the higher path-loss observed with OHPLM results in lower SIR as seen in Fig. 14. Using this understanding, we inspect the peak 5pSE values plot with respect to the optimized CRE value for eICIC and FeICIC techniques as shown in Fig. 13(a) and Fig. 13(b), respectively.

With 3GPP Release-10 ABS, higher values of CRE are required for UABSs to compensate for the high path-loss factor and under-utilization of radio resources by the MBSs in CSF radio subframes. When 50% and 97.5% of the MBSs are destroyed, the peak 5pSE values for eICIC are achieved with minimal SIR values and by offloading a large number of UEs from MBSs to UABSs as seen in Fig. 13(a).

On the other hand, with 3GPP Release-11 reduced power subframes, MBSs can establish and maintain the connection with sufficient number of cell-edge MUEs, while offloading the out-of-coverage UEs to UABSs for better QoS. When 50% and 97.5% of the MBSs are destroyed, the peak 5pSE values
for FeICIC with minimal SIR values and moderate CRE as shown in Fig. 13(b).

Overall, using GA for both path-loss models, FeICIC in Release-11 is seen to outperform Release-10 eICIC with terms of overall 5pSE of the network. When larger numbers of UABSs are deployed and when fewer MBSs are destroyed 5pSE of the network is higher. Also, the 5pSE decreases with the increasing number of destroyed MBSs as seen in Fig. 13.

C. Performance Comparison Between Fixed (Hexagonal) and Optimized UABS Deployment with eICIC and FeICIC

We summarize our key results from earlier simulations in Fig. 15 and Fig. 16 for both path-loss models and compare the key trade-offs between fixed (hexagonal) deployment and GA based deployment of UABSs.

1) Influence of SPLM on 5pSE: In Fig. 15, we compare the 5pSE observations with SPLM shown in Fig. 8 and Fig. 12. The comparative analysis reveals that UABSs deployment with optimized CRE and optimized location provides a better 5pSE than the UABSs deployed on a fixed hexagonal grid. Furthermore, Fig. 15 shows that the 5pSE gains from the optimization of UABS locations are more significant when 50% of the MBSs are destroyed and less significant when 97.5% of the MBSs are destroyed. When 50% MBSs are destroyed, there are still a large number of MBSs present which causes substantial interference. Hence, in such interference driven scenario it is important to optimize the locations of the UABSs, and use of larger number of UABSs to provide significant gains in the 5pSE.

On the other hand, with 97.5% of the MBSs destroyed, the interference from the MBSs is small, and deploying the UABSs on a hexagonal grid will perform close to optimum UABS deployment.

2) Influence of OHPLM on 5pSE: In Fig. 16, we compare the 5pSE observations with OHPLM shown in Fig. 9 and Fig. 13. The comparative analysis reveals that UABSs deployment with optimized CRE and optimized location provides a better 5pSE than the UABSs that are deployed on a fixed hexagonal grid.
With eICIC in Release-10, when 50% and 97.5% of the MBSs are destroyed, the 5pSE gains from the optimized UABS locations are significant as shown in Fig. 16(a). On the other hand, with FeICIC in Release-11, the 5pSE gains from the optimized UABS locations are more significant when 50% of the MBSs are destroyed as seen in Fig. 16(b). However, the difference between the hexagonal deployment and optimized deployment is especially small since the power reduction factor $\alpha$ in the MBS CSFs provides an additional optimization dimension for improving the 5pSE. Use of a larger number of UABSs when 97.5% of the MBSs are destroyed is shown to provide modest gains in the 5pSE, in contrast to significant gains in the 5pSE when 50% of the MBSs are destroyed.

D. Comparison of Computation Times for Different UABS Deployment Algorithms

In this subsection, we compare the computation times for the GA and hexagonal grid deployment techniques with ICIC optimization. Using an Intel Core i7-4810, central processing unit operating at 2.8 GHz, 24 GB of random access memory, and Monte-Carlo experimental approach, we calculate the mean runtime for the Matlab simulations. In Fig. 17, we plot the mean runtime required for calculating the optimal ICIC parameters and optimized UABS locations using (25), Listing 1, and the simulation values defined in Table II. Inspection of Fig. 17 reveals FeICIC technique requires similar computational time when compared to the eICIC technique for GA based optimization. The main reason for this is that the large search space for UABS locations, which are common in both FeICIC and eICIC based approaches, dominates the computation time when compared with the optimization of ICIC parameters.

On the other hand, in Fig. 18, we plot the mean runtime required for UABS deployment on a hexagonal grid using (26), the simulation values defined in Table II, and with fixed step size for the ICIC parameters. Inspection of Fig. 18 reveals FeICIC technique requires significantly higher computational time when compared to the eICIC technique. The main reason for this behavior is due to additional computation required for optimizing the power reduction factor $\alpha$ for the FeICIC approach. In general, with the GA and the hexagonal grid deployment, when larger number of UABSs are deployed, and larger number of the MBSs are present, the mean runtime is the largest. On the other hand, the mean runtime decreases with smaller number of UABSs deployed and when a smaller number of MBSs are present. Moreover, the comparative analysis of Fig. 17 and Fig. 18 reveals that optimization (ICIC parameters and UABS locations) using GA requires significantly more computational time when compared to UABSs deployment on a hexagonal grid.

VI. CONCLUDING REMARKS

In this article, we show that the mission-critical communications could be maintained and restored by deploying UABSs in the event of any damage to the public safety infrastructure. Through simulations, we compare and analyze the 5pSE of the network for different path-loss models and different UABS deployment strategies. With SPLM, our analysis shows that deployment of the UABSs on a hexagonal grid is close to optimal when the observed interference is limited. In the presence of substantial interference, the GA approach is more effective for deploying UABSs. On the other hand, with OHPLM, the network observes high path-loss when compared to SPLM. To subdue the effects of high path-loss, the GA approach is shown to be more effective. Our simulation shows that optimizing UABSs locations and ICIC parameters using GA yields significant improvement when compared to the deployment of the UABSs on a hexagonal grid.

Finally, we observe that the HetNets with reduced power subframes (FeICIC) yield better 5pSE than that with almost blank subframes (eICIC). In a simulated network with SPLM and when 60 UABS locations are optimized using the GA, the FeICIC observes a modest improvement over eICIC: approximately 17% and 15% when 50% and 97.5% of the MBSs are destroyed, respectively. On the other hand, with OHPLM and when 60 UABS locations are optimized using the GA, the FeICIC yields a significant improvement over eICIC: approximately 66% and 51% when 50% and 97.5% of the MBSs are destroyed, respectively.
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