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High Availability Optimization in Heterogeneous Cellular Networks

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***Abstract*—The exponential growth in data traffic and dramatic capacity demand in fifth generation (5G) has inspired the move from traditional single-tier cellular networks towards heterogeneous cellular networks (HetNets). To face the coming trend in 5G, the high availability requirement in new applications, needs to be satisfied to achieve low latency service. Usually, these applications require a temporal availability of six nines or even higher. In this work, we present a tractable multi-tier multi-band availability model to examine the high availability in carrier aggregation (CA)-enabled HetNets. We first derive a closed-form expression for the availability in CA-enabled HetNets based on the signal-to-interference-plus-noise model. By doing so, we formulate the joint subcarrier and power allocation problem, to maximize the availability under the power constraint. The optimization problem is non-convex problem, which is challenging to solve. To cope with it, the genetic algorithm (GA) is proposed to optimize availability through joint subcarrier and power allocation. The average availability in CA-enabled HetNets improves with decreasing the number of UEs, and increasing the power budget ratio interestingly. Increasing the maximum number of aggregated carriers can not guarantee substantial improvements in average availability.**

I. Introduction

In the past, the target of wireless technologies has mainly focused on achieving higher data rates and data volumes. However, high average rate and high total data are not the only performance indicators that guarantee the ubiquitous connectivity in next generation wireless networks. The target of next generation wireless networks has extended to realize high availability and low latency, in order to support the upcoming new applications under the context of Internet of Things (IoT), such as haptic communication [1], or vehicular communication. The temporal availability requirement of these applications is six nines or higher. A detailed analysis on future application as well as high availability requirement can be found in [2].

The rapid growth of wireless data traffic, fueled by an ever increasing availability requirement of smart mobile computing devices, imposes a huge challenge to current cellular networks. Deploying more macro base stations (BSs) is no longer a sustainable solution to handle the traffic load. Whereas, deploying inexpensive, small-scale, low-power nodes in conventional macro cells becomes a cost-effective solution, which is the so called Heterogeneous cellular networks (HetNets) [3]. These low power nodes can be pico and femto BSs. With the irresistible demand to support the aforementioned new applications in HetNets, the modeling, characterization and optimization of availability in HetNets becomes extremely important.

According to reliability theory [4], generally, there are two feasible methods to achieve high availability in a system. The first method is to substitute or improve some unreliable sub-components to make the system more reliable. The other method is to incorporate redundancy in order to improve the system reliability, through utilizing multiple sub-components in parallel. With multiple less reliable links connected to BSs in parallel boost equivalent availability as that a single more reliable link with higher transmit power or more robust coding.

CA and Coordinated Multi-Point (CoMP) are two techniques that enable multiple less reliable links in parallel to boost availability. As specified by 3GPP in [5], CA, which enables the concurrent utilization of multiple carriers in the physical layer, was originally proposed to increase bit rate and capacity. In [6], the CA was proposed to improve peak data rate in multi-band HetNets. Coordinated Multi-Point (CoMP) is another well-known technique originally proposed in [7] to increase the spectral efficiency through coordinating transmissions and scheduling decisions among several BSs. In [8], the CoMP was applied to achieve a chosen target capacity coverage.

The CA and CoMP have recently been applied to enhance the availability. In [9], carrier aggregation is applied to guarantee high availability by a joint transmission over various links at different carrier frequencies. However, their work is limited to Rayleigh-fading links. The model in [9] was extended to [10] by including selection combining and maximal ratio combining over Nakagami-m fading. It is revealed in [9] and [10] that it is more beneficial in terms of power to utilize multiple links in parallel rather than boosting the power of a single link. In [11], CoMP was studied to reduce outage probability. More recently, in [12], macro- as well as micro-diversity was applied, to derive an analytical model for achieving high availability. Nevertheless, all of the aforementioned works have neglected path loss in the availability model and interference in each carrier.

Due to the different achievable capacity of each link and cumulative interference caused by all the simultaneously transmitting nodes, nearby or faraway, simply considering the received power from the desired transmitter may not accurately capture the availability characteristics. A more appropriate model taking into account the interference statistics is the signal-to-interference-plus-noise ratio (SINR) model, which is also the main element determining the shannon capacity. Assuming the shadowing fading as a random variable, [13] studied the high availability in wireless networks with different transmit power at the BS based on SINR model. However, modeling and analyzing the availability in HetNets based on SINR model can be computationally and analytically challenging.

Unlike existing works, the aim of this work is to propose a joint subcarrier and power allocation mechanism to optimize the availability in HetNets. The main contributions of this paper are summarized as follows:

- We present an analytical model for availability in HetNets based on SINR model. Unlike [14] and [15], where a UE connects to one BS offering the highest instantaneous SINR, we assume each UE connects to multiple BSs simultaneously. This results in a novel approach to model and analyze availability with multiple connections.
- We derive an exact closed-form expression for the availability of a random UE in HetNets, this availability highly dependents on the subcarrier and power allocation.
- We formulate an optimization problem to maximize the average availability under the BS power constraint. This optimization problem is NP-hard in nature.
- We propose a genetic algorithm (GA) based optimization algorithm to solve the joint subcarrier and power allocation problem. The average availability in CA-enabled HetNets improves with decreasing the number of UEs, and increasing the power budget ratio interestingly. To the best of our knowledge, this is the first work using GA for availability optimization in HetNets.

II. System Model

We consider HetNets with $\mathcal{K} = \{1, ..., K\}$ denoting the set of K tiers which may include macro-cells, pico-cells and femtocells. We focus on the downlink transmission and assume open access for all the small cells.

We denote the set of UEs as $\mathcal{N} = \{1, 2, ..., N\}$ and the set of BSs as $\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_2 \cup ... \cup \mathcal{B}_K = \{1, 2, ..., S\}$, where $\mathcal{B}_k$ represents the set of BSs in tier k. To achieve high availability via multiple links, each UE is allowed to be connected with multiple BSs simultaneously. We denote the set of UEs associated with the sth BS as $\mathcal{N}_s$, and thus $\mathcal{N} = \mathcal{N}_1 \cup \mathcal{N}_2 \cup ... \cup \mathcal{N}_S$. We assume that each BS has maximum Q available bands (e.g., 800MHz, 2.4GHz, ...), each spectrum band contains F subcarriers. We denote the set of bands in each BS as $\mathcal{Q} = \{1, 2, ..., Q\}$, and the set of subcarriers at each BS as $\mathcal{M} = \{\underbrace{1, \ldots, F}_{band_1}, ..., \underbrace{(Q-1)F + 1, \ldots, QF}_{band_Q}\}$.

We assume the maximum subcarrier transmit power at the mth subcarrier of the sth BS is $P_{s,m}^{\max}$, and the maximum transmit power of the sth BS is $P_s^{\max}$. We consider the discrete power allocation at the mth subcarrier of the sth BS with integer level $l_{s,m}$, where

$$l_{s,m} \begin{cases} \in [1, L], \text{If UE occupied } m\text{th subcarrier of } s\text{th BS}, \\ = 0, \text{If no UE occupied } m\text{th subcarrier of } s\text{th BS}, \end{cases} \tag{1}$$

and L is the maximum integer level. Thus, the transmit power allocated to each subcarrier of a BS belongs to the set $\{0, \frac{1}{L}P_{s,m}^{\max}, \frac{2}{L}P_{s,m}^{\max}, \cdots, \frac{l_{s,m}}{L}P_{s,m}^{\max}, \cdots, P_{s,m}^{\max}\}$.

To specify the UE association and the resource assignment, we denote $v_{s,n}^m$ as the resource-allocation indicator binary variable. If $v_{s,n}^m = 1$, it indicates that subcarrier m of the sth BS $(s \in \mathcal{B})$ is allocated to the nth UE $(n \in \mathcal{N})$, and $v_{s,n}^m = 0$ $(m \in \mathcal{M})$ if otherwise.

We assume the following resource assignment constraint, subcarrier aggregation constraint, and per BS power constraint need to be satisfied:

1) Variable $v_{s,n}^m$ must satisfy that each subcarrier for a BS can only be occupied by at most one UE.

2) The total number of assigned subcarriers for each UE should be at most ρ, due to hardware constraints.

3) The total power consumption at each BS over all its subcarriers $\sum_{m \in \mathcal{M}} \frac{l_{s,m}}{L} P_{s,m}^{\max}$ should not exceed a power budget $\theta P_s^{\max}$ with the power budget ratio θ.

We focus on the network-centric resource allocation, and use different path loss exponents for different bands to capture the possible large differences in propagation characteristics associated with each band's carrier frequency. We formulate the SINR of the nth UE associated with the mth subcarrier of the sth BS as

$$SINR_{s,n}^m = \frac{\frac{l_{s,m}}{L} P_{s,m}^{\max} H_{s,n} C_q d_{s,n}^{-\alpha_q} v_{s,n}^m}{\underbrace{\sum_{i \in \mathcal{B} \setminus s} \frac{l_{i,m}}{L} P_{i,m}^{\max} H_{i,n} C_q d_{i,n}^{-\alpha_q}}_{I_{s,n}^m} + N_0}, \tag{2}$$

where $q = \lceil m/F \rceil$, and $\lceil \cdot \rceil$ is the ceiling function. For instance, if $m = 15$, $F = 10$, we have $q = 2$. In (2), $I_{s,n}^m$ is the aggregate interference at the nth UE from all the other BSs over the mth subcarrier, α_q is the path loss exponent of the qth band, $H_{s,n}$ is the random variable capturing the fading effects of the subcarrier between the sth BS and the nth UE, $d_{s,n}$ is the distance between the sth BS and the nth UE, N_0 is the noise power, and C_q is the constant depends strongly on carrier frequency with $C_q = (\frac{\mu_q}{4\pi})^2$ for the wavelength μ_q. For simplicity, we ignore shadowing and consider Rayleigh fading only with $H_{s,n} \sim exp(1)$.

The signal cannot be successfully received if the $SINR_{s,n}^m$ is below a certain threshold τ. Hence the availability of the nth UE associated with the mth subcarrier of the sth BS is characterized as

$$A_{s,n}^m = \mathcal{P}\left(SINR_{s,n}^m > \tau\right). \quad (3)$$

Generally, $A_{s,n}^m$ is given in the form $1-10^{-x}$, where x indicates the number of nines. Based on this definition, the availability of the nth UE connected to multiple BSs is derived in the following theorem.

Theorem 1. *The availability of the nth UE connected to multiple BSs in HetNets is derived as*

$$A_n = 1 - \prod_{s\in\mathcal{B}, m\in\mathcal{M}} \left(1 - A_{s,n}^m\right), \forall n \in \mathcal{N}, \quad (4)$$

where $A_{s,n}^m$ is the availability of the nth UE associated with the mth subcarrier of the sth BS

$$A_{s,n}^m = \begin{cases} 0 & \text{if } v_{s,n}^m = 0 \\ \exp\left(-\lambda_s \tau N_0\right) & \text{if } v_{s,n}^m = 1, I_{s,n}^m = 0 \\ \prod\limits_{i=1}^{S} \lambda_i \sum\limits_{j=1, j\neq s}^{S} \frac{\exp(-N_0\lambda_s\tau)}{\lambda_s(\lambda_j+\lambda_s\tau)\prod\limits_{k=1,k\neq s,j}^{S}(\lambda_k-\lambda_j)} & \\ & \text{if } v_{s,n}^m = 1, I_{s,n}^m \neq 0 \end{cases} \quad (5)$$

with

$$\lambda_s = L\big/(l_{s,m} P_{s,m}^{\max} C_q d_{s,n}^{-\alpha_q}). \quad (6)$$

Proof. For $v_{s,n}^m = 0$, we can directly obtain $A_{s,n}^m = 0$.

For $v_{s,n}^m = 1$ with no interference (i.e., $I_{s,n}^m = 0$), we have

$$\begin{aligned} A_{s,n}^m &= \mathcal{P}\left(SINR_{s,n}^m > \tau\right) \\ &= \mathcal{P}\left(\frac{l_{s,m}}{L} P_{s,m}^{\max} H_{s,n} C_q d_{s,n}^{-\alpha_q} \geq \tau N_0\right) \\ &\overset{(a)}{=} \exp(-\lambda_s \tau N_0), \end{aligned} \quad (7)$$

where (a) is performed based on $H_{s,n} \sim Exp(1)$, and λ_s is given in (6).

For $v_{s,n}^m = 1$ and $I_{s,n}^m \neq 0$, we apply the change of variables $x = I_{s,n}^m + N_0$, $y = \frac{l_{s,m}}{L} P_{s,m}^{\max} H_{s,n} C_q d_{s,n}^{-\alpha_q}$, and $z = y/x$ to obtain

$$\begin{aligned} A_{s,n}^m &= \mathcal{P}\left(z > \tau\right) \\ &= \int_\tau^\infty f_z\left(z\right) dz \\ &= \int_\tau^\infty \int_0^\infty x f_x\left(x\right) f_y\left(xz\right) dx dz. \end{aligned} \quad (8)$$

By plugging $y = xz$ into (7), we obtain

$$f_y\left(xz\right) = \lambda_s \exp\left(-\lambda_s xz\right). \quad (9)$$

Next, we focus on computing $f_x\left(x\right)$. Employing $t_i = \frac{l_{i,m}}{L} P_{i,m}^{\max} H_{i,n} C_m d_{i,n}^{-\alpha_q}$ and $t = I_{s,n}^m$, we can rewrite t as

$$t = \sum\nolimits_{i\in B\backslash s} t_i, \quad (10)$$

with

$$f_{t_i}\left(x\right) \sim \lambda_i exp\left(-\lambda_i x\right), \quad (11)$$

where

$$\lambda_i = L\big/(l_{i,m} P_{i,m}^{\max} C_m d_{i,n}^{-\alpha_q}). \quad (12)$$

In order to obtain the probability density function (PDF) of $\sum_{i\in B\backslash s} t_i$, we apply the following lemma [32].

Lemma 1. *Let $(X_i)_{i=1\ldots n}$, $n \geq 2$, be independent exponential random variables with pairwise distinct respective parameters λ_i. Then the PDF of their sum is*

$$f_{X_1+X_2+\ldots+X_n}\left(X\right) = \left[\prod_{i=1}^{n} \lambda_i\right] \sum_{j=1}^{n} \frac{e^{-\lambda_j x}}{\prod\limits_{k=1,k\neq j}^{n} (\lambda_k - \lambda_j)}. \quad (13)$$

Based on Lemma 1, the PDF of $\sum_{i\in B\backslash s} t_i$ is derived as

$$\begin{aligned} f_t\left(t\right) &= f_t\left(x - N_0\right) \\ &= \prod_{i=1,i\neq s}^{S} \lambda_i \sum_{j=1,j\neq s}^{S} \frac{e^{\lambda_j N_0}}{\prod\limits_{k=1,k\neq s,j}^{S} (\lambda_k - \lambda_j)} e^{-\lambda_j x}. \end{aligned} \quad (14)$$

Combining (8), (9) and (14), we obtain

$$\begin{aligned} &A_{s,n}^m = \\ &= \int_\tau^\infty \int_{N_0}^\infty x \prod_{i=1,i\neq s}^{S} \lambda_i \sum_{j=1,j\neq s}^{S} \frac{e^{\lambda_j N_0} e^{-\lambda_j x} \lambda_s e^{-\lambda_s xz}}{\prod\limits_{k=1,k\neq s,j}^{B} (\lambda_k - \lambda_j)} dx dz \\ &= \prod_{i=1}^{S} \lambda_i \sum_{j=1,j\neq s}^{S} \frac{e^{\lambda_j N_0}}{\prod\limits_{k=1,k\neq s,j}^{B} (\lambda_k - \lambda_j)} Z\left(\tau, N_0, \lambda_j + \lambda_s z\right). \end{aligned} \quad (15)$$

where

$$\begin{aligned} &Z\left(\tau, N_0, \lambda_j + \lambda_s z\right) \\ &= \int_\tau^\infty \int_{N_0}^\infty x e^{-(\lambda_j+\lambda_s z)x} dx dz \\ &= \int_\tau^\infty \left(\frac{N_0 \mathrm{e}^{-N_0(\lambda_j+\lambda_s z)}}{(\lambda_j+\lambda_s z)} + \frac{\mathrm{e}^{-N_0(\lambda_j+\lambda_s z)}}{(\lambda_j+\lambda_s z)^2}\right) dz. \end{aligned} \quad (16)$$

Employing a change of variable of $u = N_0\left(\lambda_j + \lambda_s z\right)$, we obtain

$$Z(\tau, N_0, \lambda_j + \lambda_s z) = \int_{N_0(\lambda_j+\lambda_s\tau)}^{\infty} \left(\frac{N_0}{\lambda_s} \frac{\mathrm{e}^{-u}}{u} + \frac{N_0}{\lambda_s} \frac{\mathrm{e}^{-u}}{u^2} \right) du = \frac{\mathrm{e}^{-N_0(\lambda_j+\lambda_s\tau)}}{\lambda_s(\lambda_j+\lambda_s\tau)}. \tag{17}$$

Combining (15) and (17), we obtain $A_{s,n}^m$ with $v_{s,n}^m = 1$ and $I_{s,n}^m \neq 0$ as

$$A_{s,n}^m = \prod_{i=1}^{S} \lambda_i \sum_{j=1, j\neq s}^{S} \frac{e^{-N_0\lambda_s\tau}}{\lambda_s(\lambda_j+\lambda_s\tau) \prod\limits_{k=1,k\neq s,j}^{B} (\lambda_k - \lambda_j)}. \tag{18}$$

□

III. Problem Formulation

The target is to maximize average availability over all UEs in HetNets, which can be achieved by searching the optimal UE association, resource assignment, and power allocation. This availability optimization problem is formulated as follows:

$$\max \ \frac{\sum_{n\in\mathcal{N}} A_n}{N} \tag{19}$$

$$\text{s.t. } l_{s,m} \leq L, \forall s \in \mathcal{B}, \forall m \in \mathcal{M} \tag{19a}$$

$$\sum\nolimits_{m\in\mathcal{M}} l_{s,m} \frac{P_{s,m}^{\max}}{L} \leq \theta P_s^{\max}, \forall s \in \mathcal{B} \tag{19b}$$

$$\sum\nolimits_{n\in\mathcal{N}} v_{s,n}^m \leq 1, \forall s \in \mathcal{B}, \forall m \in \mathcal{M} \tag{19c}$$

$$\sum\nolimits_{s\in\mathcal{B}} \sum\nolimits_{m\in\mathcal{M}} v_{s,n}^m \leq \rho, \forall n \in \mathcal{N}, \tag{19d}$$

The constraints (19a)-(19d) are divided into four categories: power level constraint in (19a), per-BS power constraint in (19b), resource assignment constraint in (19c) and subcarrier aggregation constraint in (19d). The *power level constraint* in (19a) represents the maximum discrete transmit power level of each subcarrier is L. The *per-BS power constraint* in (19b) represents that the maximum transmit power at each BS is limited by its total power budget. The *resource assignment constraint* in (19c) represents each subcarrier of each BS can be allocated to at most one UE. The *subcarrier aggregation constraint* in (19d) implies that the maximum number of aggregated subcarriers must satisfy the hardware constraints.

Instinctively, the optimization problem discussed above is in the form of mixed integer non-linear programming (MINLP) problem, which is generally NP-hard and cannot be solved by traditional optimization methods. In the next section, we will develop bio-inspired GAs to solve the optimization problem.

IV. Genetic Algorithm Approach

To solve the optimization problem, we present a joint resource and power allocation mechanism based on genetic algorithm (GA). GA is inherently an evolutionary process that involves individual encoding, fitness function depiction, selection, crossover and mutation operations [16].

A. Individual Encoding

To reflect the subcarrier assignment and power allocation, we propose an integer-based encoding scheme. We generate the initial population $\mathcal{R} = \{1, ..., R\}$ consists of R different individuals. Each individual consists of two integer-based matrices. These matrices should satisfy the subcarrier assignment constraint, the subcarrier aggregation constraint, and the per-BS power constraint during initialization to accelerate the convergence process. We represent the two integer-based matrices in the rth individual in the following.

1) One is a subcarrier assignment matrix Γ^r

$$\Gamma^r = \begin{bmatrix} \gamma_{1,1}^r, & \cdots, & \gamma_{1,M}^r \\ \gamma_{2,1}^r, & \cdots, & \gamma_{2,M}^r \\ \vdots & \vdots & \vdots \\ \gamma_{S,1}^r, & \cdots, & \gamma_{S,M}^r \end{bmatrix}, \tag{20}$$

where the matrix elements $\gamma_{s,m}^r$ $(1 \leq s \leq S, 1 \leq m \leq M, 1 \leq r \leq R)$ indicates the $\gamma_{s,m}$th UE associated with the mth subcarrier of the sth BS. For instance, $\gamma_{s,m} = n$ indicates $v_{s,n}^m = 1$, and $\gamma_{s,m} = 0$ indicates no UE associated with the mth subcarrier of the sth BS (i.e., $\sum_{n\in\mathcal{N}} v_{s,n}^m = 0$, $\forall m \in \mathcal{M}$).

Note that subcarrier assignment matrix Γ^r always satisfy the resource assignment constraint. According to the population initialization in **Algorithm 1**, we count the number of assigned subcarriers for each UE to satisfy the subcarrier aggregation constraint ρ.

2) The other one is a power allocation matrix L^r

$$L^r = \begin{bmatrix} l_{1,1}^r, & \cdots, & l_{1,M}^r \\ l_{2,1}^r, & \cdots, & l_{2,M}^r \\ \vdots & \vdots & \vdots \\ l_{S,1}^r, & \cdots, & l_{S,M}^r \end{bmatrix}, \tag{21}$$

where $l_{s,m}^r$ represents the power level allocated to the mth subcarrier of the sth BS .

To satisfy the per BS power constraint, the matrix element $l_{s,m}^r$ is initialized in sequence with subcarriers. According to the population initialization in **Algorithm 1**, we compare the maximum subcarrier transmit power $P_{s,m}^{max}$ with the remaining power p_s^{rest} at the sth BS, where $p_s^{rest} = \theta P_s^{\max} - p_s^{assign}$, with p_s^{assign} representing the power consumed for the allocated subcarriers. If $p_s^{rest} \geq P_{s,m}^{\max}$, the transmit power allocated to the mth subcarrier can be randomly selected from $[1, L]$, thus $l_{s,m}^r = randi(L)$. Otherwise we set $l_{s,m}^r = randi(\left\lceil \frac{L}{P_{s,m}^{\max}} p_s^{rest} \right\rceil)$, to guarantee that the assigned power cannot be larger than the maximum transmit power at the sth BS, where $\lceil \cdot \rceil$ is the ceiling function.

Algorithm 1 Population initialization

set $r=1$, $c_n=0$, $p_s^{assign}=0$, $p_s^{rest}=\theta P_s^{\max}$, the set of assignable UEs $\mathcal{N}_f=\mathcal{N}$
while $r \le R$ **do**
  for BS s=1 to S **do**
    for subcarrier m=1 to M **do**
      if $\mathcal{N}_f \ne \Phi$ **then**
        randomly select a UE $n \in \mathcal{N}$
        $\gamma_{s,m}^r = n$
        $c_n = c_n + 1$
        if $c_n \ge \rho$ **then**
          $\mathcal{N}_f = \mathcal{N}_f \backslash n$
        end if
        $p_s^{assign} = p_s^{assign} + \frac{l_{s,m}^r}{L} P_{s,m}^{\max}$
        $p_s^{rest} = \theta P_s^{\max} - p_s^{assign}$
        if $p_s^{rest} \ge P_{s,m}^{\max}$ **then**
          $l_{s,m}^r = randi(L)$
        else $l_{s,m}^r = randi(\left\lceil \frac{L}{P_{s,m}^{\max}} p_s^{rest} \right\rceil)$
        end if
      else $\gamma_{s,m}^r = 0$, $l_{s,m}^r = 0$
      end if
    end for
  end for
  $r = r + 1$
  $c_n = 0$
  $p_s^{assign} = 0$
  $p_s^{rest} = \theta P_s^{\max}$
  $\mathcal{N}_f = \mathcal{N}$
end while

B. Fitness Function and Selection

In GA, selection operation is applied to choose individuals to participate in reproduction, which has a significant influence on driving the search towards a promising trend and finding optimal solutions in a short time. We adopt the famous roulette wheel selection method, where the selection probability of an individual is proportional to its fitness-evaluation function. The selection probability of the rth individual is defined as

$$q_r = \frac{f(r)}{\sum_{r \in \mathcal{R}} f(r)} \tag{22}$$

where $f(r)$ is the fitness function of individual r. The quality of the individual is judged by the fitness function.

Due to that all the constraints are met during initialization, we directly take the objective function as the fitness function, which is given by

$$f(r) = \frac{\sum_{n \in \mathcal{N}} A_n}{N}. \tag{23}$$

The set of individuals are filtered based on its selection probability in each generation.

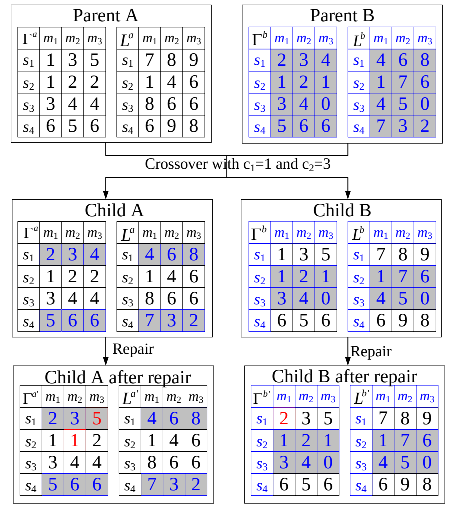


Fig. 1: Two point crossover and individual repair

1) Crossover and Mutation: The crossover operation is used to mix between the individuals to increase their fitness. In this paper, two-point crossover is performed to produce new solutions. In order to avoid scrambling the per-BS power constraint, we limit the crossover operation between arbitrary row of the matrices of one individual and that of another individual. Every elements between the two points are swapped between the parent individuals to produce two child individuals. The subcarrier aggregation constraint may be violated after crossover operation, some elements of subcarrier assignment matrix need to be repaired by allocating to other UEs.

We illustrate an example of two point crossover and individual repair operation in Fig. 1 with 4 BSs and 6 UEs deployed in HetNets, where each BS has 3 subcarriers and each UE can associate at most 2 subcarriers. We set $P_s^{\max} = 40\ W$, $P_{s,m}^{\max} = 16\ W$, and $L = 16$. The randomly generated two crossover points are $c_1 = 1$ and $c_2 = 3$. The crossover between parent A and parent B is performed by switching the rows of the 1th BS and the 4th BS in both matrices of parent A with that of parent B. After crossover, the assigned subcarriers for the 2th UE and the 4th UE violate the subcarrier aggregation constraint $\rho = 2$ in child A. As such, we repair $\gamma_{1,3}$ and $\gamma_{2,2}$ in child A using randomly generated number 5 and 1 to obtain the child A$'$.

In the mutation operation, the elements in both matrices of each individual are randomly altered to diversify the population after the crossover operation, which will pave the way towards global optima. 1) For the mutation occuring at the arbitrary element of the subcarrier assignament matrix, repair operation may be required to satisfy the subcarrier aggregation constraint to speed up the convergence; 2) For the mutation occuring at the arbitrary element $l_{s,m}$ of the power allocation matrix, repair

TABLE II: SIMULATION PARAMETERS

Parameter	Value
The number of macro-BS	1
The number of pico-BS	$1 \sim 9$
The number of UEs	$2 \sim 20$
Maximum transmit power of macro-BS	46dBm (40W)
Maximum transmit power of pico-BS	30dBm (1W)
Maximum connections for each UE	$1 \sim 10$
800MHz band's wavelength μ_1	0.375
2.5GHz band's wavelength μ_2	0.125
800MHz band's path loss exponent α_1	3
2.5GHz band's path loss exponent α_2	4
The number of subcarriers in each band	10
Maximum integer power level	16
Maximum subcarrier transmit power of macro-BS	$40W/10$
Maximum subcarrier transmit power of pico-BS	$1W/10$
Noise PSD	-174dBm
SINR threshold τ	1
Population size	20
Crossover probability	0.95
Mutation probability	0.01
Maximum generation	2000

TABLE III: Average availability for various number of UEs after 2000 generations

N	4	8	12	16	20
Availability	10 nines	7 nines	5 nines	3 nines	3 nines

operation will be performed using

$$l_{s,m} = \text{randi} \left[\min\left\{\left(P_s^{\max} - \sum_{i=1,i\neq m}^{M} l_{s,i}\frac{P_{s,i}^{\max}}{L}\right), P_{s,m}^{\max}\right\}\frac{L}{P_{s,m}^{\max}}\right], \quad (24)$$

to satisfy the power level constraint and per-BS power constraint.

By performing the crossover and mutation operation over the parent individuals, the worst parent individuals are replaced by their children in the next generation.

V. Numerical Results

In this section, we provide numerical results to illustrate the performance of the proposed algorithm. We consider CA-based HetNets consisting of 2 tiers (marco and pico) and 2 bands (800MHZ and 2.5GHZ). The set-up is a circle area A of size $(\pi 500^2)m^2$, where the macro BS is located at the center, the pico BSs and UEs are randomly distributed in A. The specific parameters used are summarized in Table I unless otherwise specified. All the results are obtained by averaging 100 Monte Carlo simulations.

Fig. 2 plots the convergence behaviour of the proposed algorithm with the maximum number of aggregated subcarriers $\rho = 5$ and the power budget ratio $\theta = 1$. We first observe that the average availability converge after approximately 500 number of generations for various number of UEs. Importantly, the GA achieves 60% more average availability compared with that of the random resource allocation at the initialization. It is

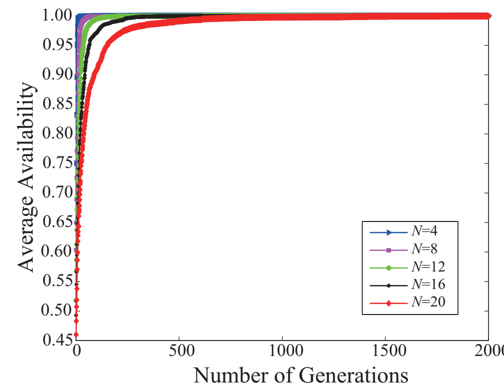


Fig. 2: Convergence behavior versus the number of generations

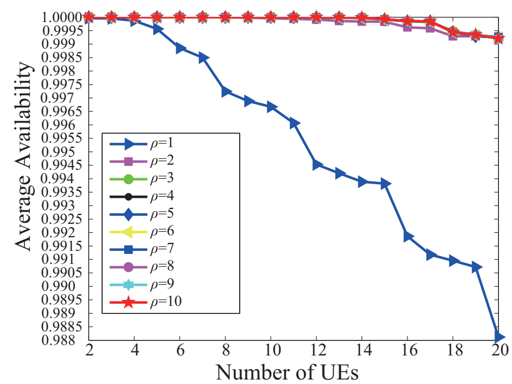
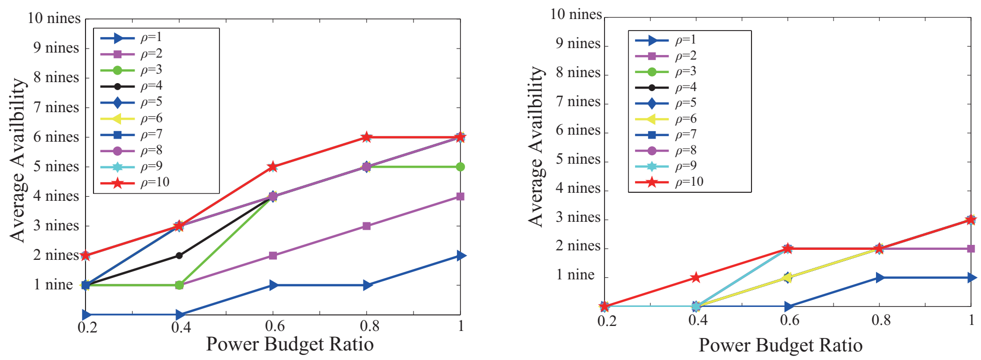


Fig. 3: Availability versus the number of UEs

revealed that the converage speed can be substantially increased with reduced number of UEs in HetNets. As shown in Table II, applying the proposed GA results in the average availability of 10 nines for HetNets with 4 UEs, and the average availability of 3 nines for HetNets with 20 UEs.

Fig. 3 plots the availability versus the number of UEs for various subcarrier aggregation contraint ρ. We observe that the average availability decreses with increasing the number of UEs. This can be explained by the fact that the transmit power allocated to the UE decreases and the interference from the same subcarrier at other BSs increases with increasing the number of UEs. More importantly, the average availability can be improved by relaxing the maximum number of aggregated subcarriers. The substantial improvement of average availability is achieved from single subcarrier constraint to two aggregated subcarriers constraint, however further increasing the maximum number of aggregated subcarriers can not achieve much improvement. This indicates that increasing the maximum number of aggregated subcarriers may not guarantee substantial improvement of average availability.

In Fig. 4, we plot the average availabilty versus vairous power budget ratio θ for various maximum number of aggre-



(a) Average availability of 10 UEs

(b) Average availability of 20 UEs

Fig. 4: Average availability versus different power budget ratios

TABLE IV: Average availability versus various maximum number of aggregated subcarriers

$\theta = 1$	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4 \sim 10$
$N = 10$	2 nines	4 nines	5 nines	6 nines
$N = 20$	1 nine	2 nines	3 nines	3 nines

gated subcarriers ρ. It is shown that the average availability increases with increasing θ for same ρ, which results from the increased received power. The six nines of average availability can be achieved for HetNets with 10 UEs for $\rho = 4 \sim 10$ and $\theta = 1$ as shown in Table III, these availability values are sufficient for the requirement of many real-time applications. However, the average availability of 6 nines is not achievable in HetNets with 20 UEs even with $\theta = 1$ and $\rho = 10$. Similar as the observation in Fig. 3, increasing the maximum number of aggregated subcarriers can not guarantee subtantial improvement in the average availability.

VI. CONCLUSIONS

In this paper, we have presented the theoretical model and optimization algorithm to achieve high availability in CA-enabled HetNets. We have developed a novel availability model under the SINR model. We have also derived a closed-form expression for the availability in CA-enabled HetNets. We have formulated the optimization problem for the average availability. To solve the non-convex optimization problem, we have proposed an efficient GA-based algorithm for the joint resource and power allocation. The average availability in CA-enabled HetNets can be improved by increasing the number of aggregated subcarriers or the power budget ratio, or decreasing the number of UEs. The substantial improvement of average availability may not be achieved via increasing the maximum number of aggregated carriers.

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