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Traffic-Aware Graph-Based Dynamic Frequency Reuse for Heterogeneous Cloud-RAN

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***Abstract*—In order to allocate frequency resource among users in heterogeneous Cloud-RAN (Het-Cloud-RAN) as well as avoid the co-channel interference, we propose a traffic-aware graph-based dynamic frequency reuse scheme. Cloud-RAN is a new network structure comprised of baseband units (BBU) and remote radio heads (RRH), which has the ability to reduce the energy costs of network. Two kinds of RRHs, including macro RRHs and pico RRHs, are considered to form the two tiers of the Het-Cloud-RAN. We construct the interference graph where the vertices represent different RRHs in the network, and then apply our proposed scheme in it. We use a graph coloring method to allocate different length of bandwidth to cells in different tiers based on their traffic demands. Our scheme also considers the time varying traffic and can adjust the frequency allocation based on the change of traffic demands in each cell without re-performing the whole scheme. With the application of our scheme in Het-Cloud-RAN, we can not only improve the spectrum utilization and efficiency, but also reduce the energy consumption through reducing the number of working BBUs. The system level simulation results show clearly that our new scheme in Het-Cloud-RAN outperforms the existing frequency allocation scheme based on traditional cellular system in many ways including throughput and energy efficiency.**

I. Introduction

With the fast-growing mobile data traffic, Orthogonal Frequency Division Multiple Access (OFDMA) has become a widely used access technique and has been included in several next generation cellular systems [1]. In an OFDM system, the co-channel interference can be mitigated effectively through assigning orthogonal sub-channels to different users. Meanwhile, the concept of heterogeneous network (Het-Net) with macrocells and picocells is currently under extensive discussion within 3GPP as an effective solution to improve network performance [2]. With the application of OFDM in Het-Net, users in different tiers can reuse the same frequency to improve the spectrum utilization. But how to mitigate the interference of cross-tier and same-tier and allocate the spectrum more effectively is of great significance.

Many researchers have studied the frequency reuse schemes based on Het-Net. In [3] and [4], the spectrum is allocated to macrocells with reuse factor $\Delta = 3$ and fractional frequency reuse scheme respectively, and users in different tier can exploit the rest spectrum different from the macrocells where they are located in. But the inflexible frequency allocation schemes may cause a low spectrum utilization. A dynamic frequency allocation strategy is proposed in [5] with power control, but they only consider a simple scene of only one macrocell with several femtocells. [6] used a graph method to realize the spectrum allocation among cells in different tiers, yet the different traffic demands in different cells are not considered. Besides, most of the existing papers just discuss their schemes based on the traditional Het-Net. However, traditional Het-Net is still facing some problems such as relatively low baseband resource utilization and energy efficiency, due to its inflexible structure where a base station is fixedly served by one baseband unit (BBU).

In the meantime, a new cellular structure named Cloud-RAN is proposed by the industry and has been studied by several researchers. Cloud-RAN, or C-RAN, is composed of baseband units (BBU) which are centralized to form a baseband resource pool (BSP) and remote radio heads (RRH) where radio function is located [7]. The RRHs are connected with the BSP through high reliable optical fibers, and all RRHs can dynamically share the baseband resource provided by any BBU in BSP. Through a switch, multiple RRHs can be served by one BBU at the same time, so users from different cells can use the spectrum provided by one BBU to improve the baseband resource utilization. Therefore, a Cloud-RAN combined with heterogeneous structure would be a promising one from the view point of energy-efficiency and high baseband resource utilization with high data rate as the next generation network.

In this paper, we apply a traffic-aware graph-based dynamic frequency reuse scheme based on Het-Cloud-RAN. With the combination of Cloud-RAN and heterogeneous structure, the pico cells with relatively low traffic demands may have chance to exploit the baseband resource holes remain by macro users in each BBU to further improve the baseband resource utilization. We use a graph coloring method to allocate frequency resources to each cell based on our previous work in [8], which focused on fractional frequency reuse (FFR) in homogeneous networks. Different from other existing similar graph-based methods [9]–[11], our graph coloring method considers the different traffic demands of different cells in two tiers as well as views a cell as a single vertex in the graph, and it can deal with the time varying traffic demands through simple adjustment without re-performing the whole scheme. Comparing with the existing graph-based frequency allocation schemes in traditional Het-Net, applying a graph-based scheme in a cloud based network would be more practical owing to the centralized processing structure. With the application

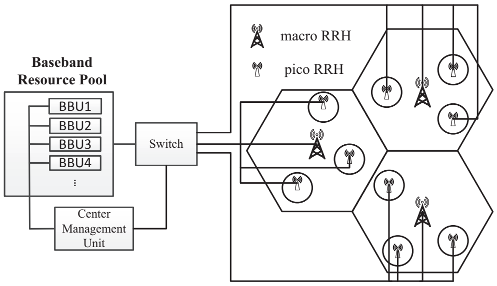

Fig. 1. The structure of Het-Cloud-RAN

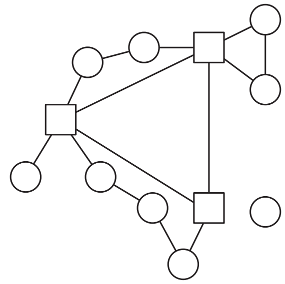

Fig. 2. Interference graph based on the deployment of RRHs in Fig. 1

of our proposed scheme in Het-Cloud-RAN, we can have access to the whole bandwidth provided by each BBU in the BSP to improve the baseband resource utilization, as well as reduce the energy consumption through reducing the number of working BBUs. The system level simulation results show clearly that our scheme with the new structure outperforms the existing schemes in traditional Het-Net in many ways including energy efficiency and spectrum utilization.

The rest of this paper is organized as follows: Section II introduces the Het-Cloud-RAN and describes how we construct the interference graph; A traffic-aware graph-based dynamic frequency reuse scheme is proposed in Section III; Section IV shows the simulation results with detailed analysis; Finally, Section V gives the conclusion.

II. System Model and Interference Analysis

A. Heterogeneous Cloud-RAN

Consider the structure of Het-Cloud-RAN as shown in Fig. 1 where the RRHs of both macrocells and picocells are connected to the BSP through a switch of 10-Gb/s Ethernet [12]. A number of N_m macro RRHs are regularly deployed to form N_m ordinary hexagonal macrocells, and N_p pico RRHs in total are randomly deployed in each macrocell. The switch can dynamically change the connections between BBUs and RRHs under the control of the center management unit (CMU). Owing to the centralized structure, the CMU can easily get the comprehensive information of the whole system, e.g. the geographic position of each RRH and the traffic demands in each cell with low cost, to make decisions on resource allocation.

Considering an OFDM system, we assume each BBU may process the signal over the whole bandwidth B MHz which is divided into N_R resource blocks (RB). Each RB is the combination of several sub-channels and has a certain bandwidth. One user may occupy a resource block (RB) in a time slot to transmit data. So we define the time-varying traffic demands of each RRH as a finite number of RBs in each certain time. Since we suppose that one user could occupy only one RB at most in a time slot, the traffic demands r_k of RRH k is just equal to the number of users served by RRH k, where k is the index of all RRHs, including macro RRHs and pico RRHs. With the adaptive switching, each RRH may exploit any part of spectrum provided by any BBU. However, it should be noted that multiple signals received by different RRHs that are to be processed by the same BBU must be frequency orthogonal to each other. So we need multiple BBUs to support users from different cells which use the same frequency.

B. Interference Graph Construction

We use a graph coloring method to realize the spectrum allocation for all cells, so we should firstly construct the interference graph. In Het-Cloud-RAN, the interference graph is constructed by the CMU, and it is comprised of the vertices representing the RRHs and the edges representing the interference relationship between each two RRHs. The two vertices connected by an edge cannot be dyed the same color, which means that the RRHs represented by the two vertices cannot be allocated with the same frequency, or else serious inter-cell interference would occur. Fig. 2 shows a possible interference graph corresponding to the deployment of RRHs in Fig. 1. The squares represent the macro RRHs and the circles represent the pico RRHs. Considering the macro RRHs and the pico RRHs together, the total number of vertices N_v is just equal to $N_m + N_p$.

The RRHs of both macrocells and picocells work with the omni-directional antennas. Due to the regular deployment of the macro RRHs, the interference relationships among them are easily defined. The interference between two neighboring macro RRHs is intolerable and others could be ignored. However, due to the randomness of macro-pico distance and pico-pico distance, the corresponding interference should be judged by SIR measurement. Here we only consider the downlink interference. The transmit power per RB of the macro RRHs and the pico RRHs, denoted as P^m and P^p respectively, are assumed to be constant. To judge whether a pair of pico RRHs i and j can reuse the same frequency, we need to consider the SIR of a pico user which could receive both signals from the two pico RRHs. The SIR of the pico user k on a specific RB can be expressed as

$$\gamma_k^{pp} = \frac{P^p \cdot G_{ik}(d_{ik})}{P^p \cdot G_{jk}(d_{jk})} \tag{1}$$

where $G_{ik}(d_{ik})$ and $G_{jk}(d_{jk})$ are the distance-dependent path-loss from pico RRH i and pico RRH j to pico user k separately, d_{ik} and d_{jk} are the distance from pico user k to pico RRH i and pico RRH j. We set a SIR threshold Γ^{pp} to ensure that the co-channel interference from other picocells on pico users is tolerable. With the SIR expression above and Γ^{pp} as well as the radius of picocell R_p, we can easily get a distance threshold R_{th}^{pp}, through the way similar to [5]. The interference from pico RRH j to any pico users served by pico RRH i can be ignored if the distance between the two RRHs is longer than R_{th}^{pp}. Any two pico RRHs can not be allocated with the same frequency if the distance between them are closer than R_{th}^{pp}, which means we need to connect the two corresponding vertices with an edge in the interference graph. Similarly, we can also get the distance threshold R_{th}^{mp} between macro RRHs and pico RRHs with the macro to pico SIR threshold Γ^{mp}. With these distance thresholds and the geographic location information of all RRHs in the network, the CMU can easily construct the interference graph.

III. Traffic-Aware Graph-Based Dynamic Frequency Reuse Scheme

A. Traffic-Aware Graph Coloring Method

The traffic-aware dynamic frequency reuse scheme we propose for Het-Cloud-RAN is based on the graph coloring method. Different from other existing graph-based frequency reuse schemes, our scheme consider the different traffic demands of each cell. We define a load value e_n for each vertex n in our interference graph. The load value of a vertex is just equal to the bandwidth demands of the RRH represented by the vertex. We also define the load value of each color, which indicates a certain length of bandwidth represented by the color. So dyeing a vertex a color just means allocating a part of the bandwidth to the RRH represented by the vertex. Besides, in our proposed scheme, a vertex can be colored multiple times with different colors, which means that the RRH represented by the vertex can be allocated with different parts of the frequency which are orthogonal to each other. Let c_i be the color we used to color the vertices and the load value of it is assumed to be $l(c_i)$. We define the available color vector $\mathbf{c}_k^a = [c_{k,1}^a, c_{k,2}^a, \dots]^T$ and the used color vector $\mathbf{c}_k^u = [c_{k,1}^u, c_{k,2}^u, \dots]^T$ for vertex k where $c_{k,i}^a = 1$ means vertex k is able to but not yet dyed in color c_i and $c_{k,i}^a = 0$ for vice versa, and $c_{k,i}^u = 1$ means vertex k is already dyed in color c_i and $c_{k,i}^u = 0$ for vice versa. We also define the load value vector $\mathbf{l} = [l(c_1), l(c_2), ...]$. During the coloring process, the CMU needs to generate new colors depending on the traffic demands and update available color vectors and used color vectors for all vertices in real time. Based on the interference graph we construct in Section II, the traffic-aware graph coloring method can be elaborated on as the following steps:

Step 1: Choose the vertex which has the maximum load value as the target vertex. If there are multiple vertices, choose the one with largest degree. Suppose the target vertex is vertex k^*, the CMU generates the first color c_1 and dyes vertex k^*, so we have $l(c_1) = e_{k^*}$.

Step 2: Select all the uncolored vertices adjacent to the already colored one as the target vertices to form a set $\mathbb{K}$. If there are no uncolored vertex adjacent to the already colored one, the CMU needs to search the whole graph for an

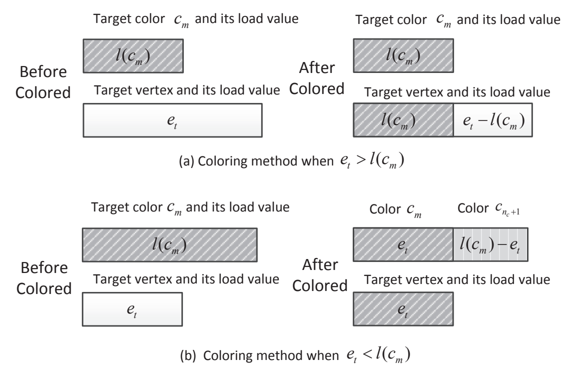

Fig. 3. Coloring method depends on different values of e_t and $l(c_m)$

uncolored vertex with the maximum load value to form the set $\mathbb{K}$.

Step 3: Select vertex t which has the maximum load value in set $\mathbb{K}$ as the target vertex, then a target color needs to be chosen to dye the vertex. If $\sum_{i=1}^{n_c} c_{t,i}^a = 0$ where n_c is the total number of the colors at present, the vertex t can not be dyed in any existing color. Then the CMU needs to generate a new color c_{n_c+1}. Let $l(c_{n_c+1}) = e_t$ and update available color vectors and used color vectors for all the vertices. Meanwhile, exclude vertex t from set $\mathbb{K}$ and update n_c to $n_c + 1$.

if $\sum_{i=1}^{n_c} c_{t,i}^a > 0$ which means the CMU can choose an existing color to dye vertex t, the color c_m which has dyed the least number of vertex with the condition $c_{t,m}^a = 1$ will be chosen as the target color. Since the CMU has decided the target vector and the target color, the different combinations of the load value e_t and $l(c_m)$ will lead to different results:

- $e_t > l(c_m)$. The target vertex could be partially colored by c_m as shown in Fig. 3(a) and keep it staying in set $\mathbb{K}$ to wait to be colored multiple times until its traffic demands are fully satisfied. In practice, it means allocating a bandwidth of $l(c_m)$ to vertex t. After that, its load value e_t needs to be updated to $e_t - l(c_m)$.
- $e_t = l(c_m)$. The CMU just dyes vertex t in color c_m and exclude it from set $\mathbb{K}$.
- $e_t < l(c_m)$. The CMU needs to split color $l(c_m)$ to generate a new color c_{n_c+1} as shown in Fig. 3(b). The new color's load value $l_{c_{n_c+1}} = l(c_m) - e_t$, and the load value of c_m needs to be updated as $l(c_m) = e_t$. Then we can exclude vertex t from set $\mathbb{K}$. After updating the used color vectors and available color vectors, all the other vertices which have already been dyed in color c_m, except vertex t, are colored with at least two colors c_m and c_{n_c+1} now.

Repeat this step until set $\mathbb{K}$ becomes empty.

Step 4:Repeat step 2-3, until all vertices are dyed in at least one color. Then the CMU needs to calculate the value of $\sum_{i=1}^{N_c} l(c_i)$, where N_c is the total number of different used colors. If $\sum_{i=1}^{N_c} l(c_i) > N_R$, that means the band requirements need to be provided by one BBU are overloaded. Then the load value of each color needs to be scaled down. Let $\delta =$

TABLE I
ALGORITHM TO GENERATE TOPOLOGY MATRIX $\mathbf{S}$

```
Initialize with S = o_{N_B*N_v};
for i = 1 to N_B
    v_i = (c_k^u)^T, ∀ vertex k ∈ 𝕍;
    for j = 1 to N_v
        if v_i · c_j^u = 0
            v_i = v_i + (c_j^u)^T;
            remove vertex j from 𝕍;
            S(i, j) = 1;
        end
    end
    if 𝕍 = ∅ break;
end
```

$N_R \,/\, \sum_{i=1}^{N_c} l(c_i)$, and update all $l(c_i)$ as $l(c_i) = \lfloor \delta \cdot l(c_i) \rfloor$. If $\sum_{i=1}^{N_c} l(c_i) \le N_R$, the load value of each color will not be changed.

Step 5: Find whether there are available colors which still can be used to dye some vertices. For any vertex i, if $\sum_{i=1}^{N_c} c_{k,i}^a > 0$, that means we still can choose existing colors to dye it. After all vertices are dyed in at least one color in the aforementioned four steps, the CMU can get the information about the number of times each color used by vertices. The times of each color used by vertices in graph just indicate the times of different part of spectrum reused by each cell. The number of times $b(c_i)$ color c_i used can be expressed as $b(c_i) = \sum_{k=1}^{N_v} c_{k,i}^u$, and $b^* = max\{b(c_1), b(c_2), \dots, b(c_{N_c})\}$ is just equal to the number N_B of BBUs we need to support traffic demands in the network. The CMU needs to check each color c_i with the limiting condition that $b(c_i) < N_B$ (This limiting condition aims to reduce the number of working BBUs) to find their best target vector t^* ($t^* \in [1, 2, \dots, N_v]$) satisfying the following conditions:

$$\begin{gathered} r_{t^*} > \mathbf{l} \cdot \mathbf{c}_{t^*}^u, \mathbf{c}_{t^*,i}^a = 1, \\ \min_{t^*} |l(c_i) - (r_{t^*} - \mathbf{l} \cdot \mathbf{c}_{t^*}^u)|, \\ \max_{t^*} \{\min(l(c_i), (r_{t^*} - \mathbf{l} \cdot \mathbf{c}_{t^*}^u))\} \end{gathered} \tag{2}$$

which aims to exploit more spectrum resource with less waste based on the traffic demands r_{t^*} of RRH t^*. Then we will have $c_{t^*,i}^{u^*} = 1$ and finally obtain the $\mathbf{c}_{t^*}^{u^*}$, which is the additional used color vector of each vertex. For each $\mathbf{c}_i^{u^*}$ we get for any vertex i, update $\mathbf{c}_i^u$ as $\mathbf{c}_i^u = \mathbf{c}_i^u + \mathbf{c}_i^{u^*}$.

After all steps mentioned above, the CMU needs to generate the topology of connections between RRHs and BBUs based on the coloring result. Only the RRHs that have non-overlapping bandwidth could be connected to one BBU. Let all vertices form a set $\mathbb{V}$, and the target is to get a topology matrix $\mathbf{S}_{N_B*N_v}$, where $\mathbf{S}(i,j) = 1$ means there should be a physical connection between BBU i and RRH j. The algorithm is summarized in Table I. Then the CMU will send $\mathbf{S}$ to the switch, and the switch can reconfigure the connection between BBUs and RRHs based on $\mathbf{S}$.

TABLE II
ADJUSTMENT METHOD WHEN USER NUMBER INCREASE IN ONE CELL

1) If $\sum_{i=1}^{N_c} c_{k,i}^a > 0$, the CMU will find the color c_i with the condition $c_{k,i}^a = 1$ to dye vertex k, then update e_k as $e_k = e_k - l(c_i)$ and update $\mathbf{c}_k^u$. Repeat this until the color c_{i^*} which meet the condition that if $c_{k,i^*}^u = 1$, $\mathbf{l} \cdot \mathbf{c}_k^u > r_k^*$, otherwise $\mathbf{l} \cdot \mathbf{c}_k^u < r_k^*$ is selected. Let $c_{k,i^*}^u = 1$. If color $c_{i^{**}}$ with the condition that if $c_{k,i^{**}}^u = 1$, $\mathbf{l} \cdot \mathbf{c}_k^u = r_k^*$ is found, then the adjustment could be finished with $c_{k,i^{**}}^u = 1$.
2) Split color c_{i^*} to generate a new color c_{N_c+1}. The load value of c_{N_c+1} is $l(c_{N_c+1}) = \mathbf{l} \cdot \mathbf{c}_k^u - r_k^*$. Then update the load value of c_{i^*} as $l(c_{i^*}) = l(c_{i^*}) - l(c_{N_c+1})$. Next, update N_c to $N_c + 1$, and update all used and available color vectors of all vertices to finish the adjustment.
3) If $\sum_{i=1}^{N_c} c_{k,i}^a = 0$ with $e_k > 0$, which means that the CMU can not find the color c_{i^*} mentioned above. Then the CMU will generate a new color c_{N_c+1} to color vertex k, $l(c_{N_c+1}) = r_k^* - \mathbf{l} \cdot \mathbf{c}_k^u$. Then update all available color vectors for all vertices in graph and update N_c to $N_c + 1$.
4) Calculate the value of $\sum_{i=1}^{N_c} l(c_i)$. If $\sum_{i=1}^{N_c} l(c_i) > N_R$, the load values of all colors need to be scaled down by multiplying a factor δ, where $\delta = N_R \,/\, \sum_{i=1}^{N_c} l(c_i)$.
5) Check if color c_{N_c} can be used by other vertices, then finish the adjustment, and update all used and available color vectors of all vertices.

B. Adjustment Method for Time Varying Traffic Load

The majority of the existing graph-based frequency reuse schemes in other works are statistic that they always ignore the time varying traffic demands in each cell. Once the number of users change in one cell, usually the whole schemes need to be re-performed and the entire interference graph need to be traversed. In our scheme, we propose a method to adjust the frequency reuse result based on the time varying traffic demands in different cells without re-performing the whole scheme. The adjustment method just focus on the vertex with changing traffic demands to avoid traversing the whole graph, so it can reduce the complexity of the whole method effectively.

When the CMU detects that the number of users changed in one cell covered by a RRH in the network, it needs to change the load value of corresponding vertex. Suppose the number of users changes in the cell covered by RRH k, and the load value of it change from r_k to r_k^*. The load value of vertex k needs to be updated as $e_k = |r_k^* - r_k|$. Then with the different situations, different methods will be performed based on the frequency allocation in the previous moment. The adjustment method expressed in Table II is adapt to the situation when $r_k^* > r_k$, i.e. the number of users served by RRH k increased. The method in Table III is adapt to the situation when $r_k^* < r_k$. Based on the new updated used color vector $\mathbf{c}_k^u$, the CMU can generate the new topology matrix for switch to change the connections between BBUs and RRHs with the algorithm proposed above if necessary.

IV. Simulation Results and Performance Analysis

We use system level simulation to verify the performance of our graph-based scheme in a scenario of 7 macrocells with 4 pico RRHs in each macrocell. The simulation parameters

TABLE III
ADJUSTMENT METHOD WHEN USER NUMBER DECREASE IN ONE CELL

1) For vertex k, find the color c_i which has the maximum load value with the condition $c^u_{k,i} = 1$, let $c^u_{k,i} = 0$ and update e_k as $e_k = e_k - l(c_i)$. Repeat this step until the color $c_i{}^*$ which meet the conditions that if $c^u_{k,i^*} = 1$, $\mathbf{l} \cdot \mathbf{c}^u_k > r^*_k$, otherwise $\mathbf{l} \cdot \mathbf{c}^u_k < r^*_k$ is selected. Keep $c^u_{k,i^*} = 1$. If color $c_{i^{**}}$ with the condition that if $c^u_{k,i^{**}} = 1$, $\mathbf{l} \cdot \mathbf{c}^u_k = r^*_k$ is found, then the adjustment could be finished with $c^u_{k,i^{**}} = 1$.
2) Split color c_{i^*} to generate a new color c_{N_c+1}. The load value of c_{N_c+1} is $l(c_{N_c+1}) = \mathbf{l} \cdot \mathbf{c}^u_k - r^*_k$, Update the load value of c_{i^*} as $l(c_{i^*}) = l(c_{i^*}) - l(c_{N_c+1})$, then update N_c to $N_c + 1$, and update all used and available color vectors of all vertices to finish the adjustment.

from [6] and [13] are listed in Table IV. We suppose that the traffic demands yield a Gaussian random process with a non-traffic probability of p_{th} in each zone [14], the probability distribution function is given by

$$f_r(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp[-\frac{1}{2\sigma^2}(x - \sqrt{2\pi}\sigma Q^{-1}(1-2p_{th}))^2] \quad (3)$$

where we assume that $p_{th} = 0.25$. The average bandwidth requirements can be reached as $r_{ave} = \sqrt{2\pi}\sigma Q^{-1}(1-2p_{th})$. Since we suppose that one user can only occupy one RB at most in a time slot, the number of users can be expressed as $n_{UE} = \lfloor r_{ave}/b \rfloor$, where b is the length of bandwidth per RB. So we can change the number of users through adjusting the value of σ. The number of users is supposed to be independent but identically distributed for all macrocells. In the simulation, we firstly generate a set number of users randomly in the network, then decide whether a user is served by a macro RRH or a pico RRH based on the location of each user. We use a CQI mapping table according to [15] to get the throughput of each user based on their SINR in the simulation.

Two other schemes are compared with our proposed scheme in the simulation. In R1 scheme, all users including macro users and pico users have access to all bandwidth based on a typical cellular system without considering the inter-cell interference coordination, i.e. the reuse factor $\Delta = 1$. The FR3 scheme is also applied in a Het-Cloud-RAN, but the frequency reuse factor of macro users is fixed by $\Delta = 3$, and 2/3 of the bandwidth provided by each BBU is allocated to pico users according to [3]. Since there is few other graph based frequency reuse schemes which consider the different traffic demands in each cell as well as view a cell as a single vertex in the graph, we choose these two schemes as the comparisons. We change the value of σ to generate different number of users r_{ave} located in each macrocell, in order to evaluate the performance of our scheme in different traffic situations. For each value of n_{UE}, we realize the simulation for 100 times to evaluate the average performance. In our proposed scheme, we use the traffic-aware graph coloring method to realize the frequency allocation for the first time, then we use the adjustment method for time varying traffic demands to adjust the frequency allocation in the following 99 times based on the changed number of users in each cell.

TABLE IV
SIMULATION PARAMETERS

Parameter	**Value**
System Bandwidth B	20MHz
Number of RBs N_R	100
Bandwidth per RB b	180kHz
Macrocell Inter-site Distance	500m
Picocell Radius R_p	30m
Distance-dependent Path Loss From Macro to User	$128.1 + 37.6 * \lg(R)$, R in kilometers
Distance-dependent Path Loss From Pico to User	$140.7 + 36.7 * \lg(R)$, R in kilometers
Multipath Fading	3GPP TU channel
Log-normal Shadowing	-8dB
Penetration Loss	-20dB
macro RRH Transmit Power	46dBm
pico RRH Transmit Power	30dBm
Noise Power Density	-174dBm/Hz
SIR Threshold Γ^{pp}, Γ^{mp}	6dB, 8dB

Fig. 4 gives the throughput of all users in the network. We can see clearly that our scheme outperforms the other two in throughput clearly by about 6% and 30% respectively, for the reason that our dynamic scheme can improve the spectrum utilization through allocating different length of bandwidth to different cells based on their traffic demands, and improve the spectrum efficiency through mitigating the inter-cell interference as well. In FR3 scheme, the macro users can only use 1/3 of the bandwidth to mitigate inter-cell interference, so the traffic demands in each cell may not be fully satisfied. In R1 scheme, all users can use the whole band, but may suffer from serious inter-cell interference.

Fig. 5 illustrates the mean value of minimal satisfaction factor (MMSF) of all cells in the network. Here we define the satisfaction factor as the ratio of the allocated bandwidth to required bandwidth of a cell [16]. Clearly, the MMSF is a factor which can indicate the fairness of different schemes. Here we compare our scheme with FR3, which is also an interference coordination schemes. In FR3 scheme, cells with heavy traffic demands are hard to get enough bandwidth resource for the reason that each macrocell can only use 1/3 of the whole bandwidth fixedly. Comparing with the FR3 scheme, our proposed scheme can effectively improve the MMSF, which means that our scheme can improve the network fairness.

Fig. 6 shows the energy efficiency performance of three schemes in different kinds of networks. We define the energy efficiency as the ratio of throughput of all users to the power of all working BBUs with transmit power of RRHs based on the number of users. The power of one working BBU is assumed to be 58W [17]. The R1 scheme is performed in traditional cellular structure that each macrocell needs to be supported by one BBU fixedly and all BBUs need to keep on working, so it suffers the lowest energy efficiency. With the reduction of number of working BBUs and the improvement of throughput,

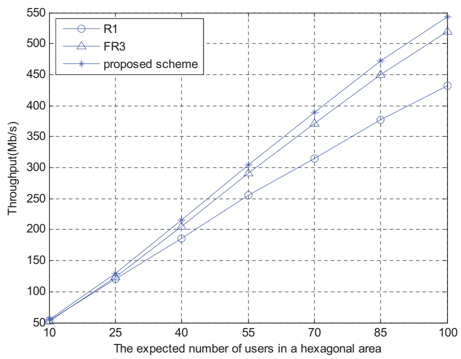

Fig. 4. Throughput of all users

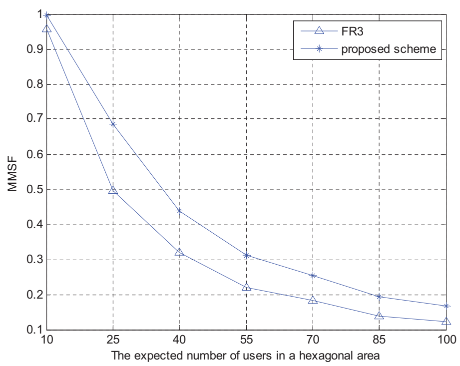

Fig. 5. MMSF of different schemes

our proposed scheme can achieve a significantly higher energy efficiency than the other two schemes.

V. Conclusion

In this paper, we propose a traffic-aware graph-based dynamic frequency reuse scheme and apply it in heterogeneous Cloud-RAN. A graph coloring method is applied to allocate frequency resource to different cells in both two tiers based on their different traffic demands. The frequency reuse scheme also consider the time varying traffic and can adjust the frequency allocation based on the changing traffic and the frequency allocation of previous moment without re-performing the whole scheme. With the application of our scheme in Het-Cloud-RAN, we can not only improve the spectrum utilization and efficiency, but also reduce the energy consumption through reducing the number of working BBUs. The system level simulation results show clearly that our scheme in the Het-Cloud-RAN can obviously improve the performance including user throughput and network energy efficiency compared with the state of art.

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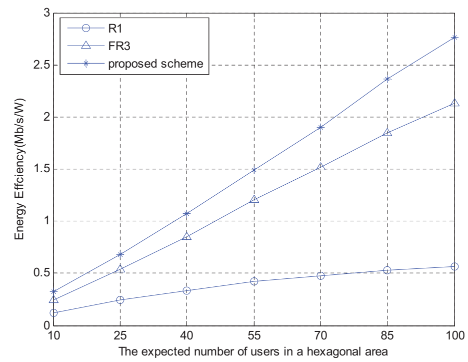

Fig. 6. Energy efficiency of different schemes

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