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Graph-Based Dynamic Frequency Reuse in Cloud-RAN

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***Abstract*—This work aims to apply a new dynamic frequency reuse scheme based on fractional frequency reuse (FFR) in Cloud-RAN structure. FFR is one of the most efficient schemes to mitigate the inter-cell interference in OFDM system, while strict FFR in traditional cellular system is still facing some problems such as the inefficient use of spectrum. 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. We use a graph coloring method to allocate spectrum resource among different cell zones depending on different traffic demands as well as avoiding the inter-cell interference. With the application of our proposed scheme based on Cloud-RAN structure, we can not only improve the spectrum utilization, but also reduce the energy consumption through reducing the working number of BBUs. The simulation results show clearly that our new scheme in Cloud-RAN structure can achieve higher throughput and energy efficiency compared with the strict FFR in traditional cellular system.**

I. Introduction

The growing demands on wireless communication for higher data rate has driven the need to develop Orthogonal Frequency Division Multiple Access (OFDMA), which is a promising technique and has been included in several next generation cellular systems [1]. In a multi-cell OFDM system, users in different cells can share the same part of the spectrum in order to achieve higher communication speed with higher spectrum utilization. However, the inter-cell interference (ICI) would be an inevitable problem when users in adjacent cells share the same bandwidth.

Many interference mitigation schemes have been proposed. Among them, fractional frequency reuse (FFR) is considered as the most promising one, which has been included in fourth generation wireless standards [2]. In FFR, a cell is divided into center zone and edge zone, and the spectrum is also partitioned into two parts. Users in cell center zone can use the reuse-1 part, while another part of the spectrum is further divided into three sub-bands. Each sub-band will be allocated to a cell edge zone to ensure that any two adjacent cell edge zones would not use the same sub-bands so that the inter-cell interference could be effectively avoided. Whereas strict FFR is not perfect for the reason that only 2/3 of the spectrum provided by a baseband unit (BBU) is used effectively [3]. Furthermore, each zone of the cell can only use a fixed part of the spectrum without considering the varying traffic demands.

To overcome these shortages, we propose a new frequency reuse scheme based on a new cellular structure named Cloud-RAN. Cloud-RAN, or C-RAN, is composed of baseband units which are centralized to form a baseband resource pool and remote radio heads (RRH) [4]. The RRHs are connected with the baseband resource pool through high reliable optical fibers, and all RRHs can dynamically share the baseband resource provided by any BBU in the pool. 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 spectrum utilization. Similar structures have already been proposed and studied by many other works [5]–[7], but few of them focus on the frequency reuse problems.

In this paper, we present a load based graph coloring method to allocate spectrum resource to each cell dynamically as well as avoiding the inter-cell interference. In [8], graph approach had also been used to study the similar problems, but it only focused on avoiding inter-cell interference and neglected the traffic demands. Some other works consider the traffic demands in other forms, but each node in their graph just represents a single mobile station (MS) rather than a cell [9]. That would lead to a large-scale graph and make the problem more complex. In our graph coloring method, a node just represents a single cell, more precisely, a cell edge zone. Based on the different traffic demands of each cell, a node can be colored multiple times. With the application of our proposed scheme based on Cloud-RAN structure, we can have access to the whole bandwidth provided by each BBU to improve the spectrum utilization, as well as reducing the energy consumption through reducing the working number of BBUs. Simulation results show clearly that our scheme in Cloud-RAN structure can achieve higher spectrum utilization and energy efficiency to the system compared with the strict FFR scheme in traditional cellular system.

The rest of this paper is organized as follows: Section II describes how we apply the dynamic frequency reuse scheme in Cloud-RAN structure; The resource allocation scheme is proposed in Section III; The simulation results are shown in Section IV with careful analysis; Finally, Section V draws the conclusions.

II. System Modeling

Fig. 1 shows the strict FFR for a hexagonal grid modeled deployment with a cell-edge reuse factor of $\Delta = 3$, while cell center users can use common half of the bandwidth [10]. Each zone of the cell can only use a specified part of the

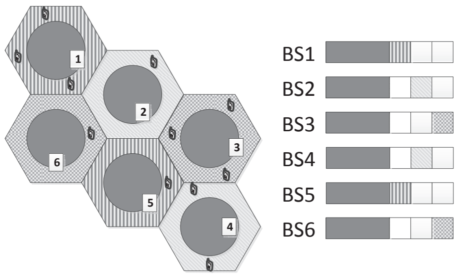

Fig. 1. FFR scheme deployments with Δ=3 reuse factor

bandwidth to avoid the inter-cell interference. Each BBU in a base station (BS) serves only one cell all the time. Due to the fixed structure, spectrum resources provided by a BBU can hardly be fully exploited, and each zone of a cell can only use a fixed part of the spectrum regardless of the different traffic demands, which would also result in a low spectrum utilization.

The application of our new dynamic frequency reuse scheme based on Cloud-RAN is shown in Fig. 2. Same as FFR, the spectrum is also divided into two parts to serve cell center zones and cell edge zones respectively. However, both parts of the spectrum in our scheme are further divided , each zone will use a flexible part of the spectrum based on traffic demands. Similar to all kinds of Cloud-RAN structures mentioned in other works, a baseband resource pool comprised of N BBUs is connected with M RRHs through reliable optical fibers to serve M cells. Generally, we have $N = M$. A switch of 10-Gb/s Ethernet has been placed in the structure to dynamically change the connections between BBUs and RRHs. The CPRI (Common Public Radio Interface) digital data are carried over the optical link [11].

In this paper, we consider an OFDM network across the whole band. Based on their own traffic demands, each cell demands different number of sub-carriers provided by the BBUs. So we can describe the time-varying traffic demands of each cell as a finite number of sub-carriers as done in [12]. A frequency band with a bandwidth of B is provided by each BBU. The baseband resource pool can easily get the information of traffic demands of cell center zones and cell edge zones, which are denoted by r_{ck} and r_{ek} respectively for cell k.

Fig. 2 gives a brief description of the whole system. Based on the different traffic demands of each cell, only 3 BBUs are needed. It should be noted that multiple signals received by different RRH that are to be processed by the same BBU should be frequency orthogonal to each other, so we need more BBUs to support users from different cells which use the same frequency. Cell 2, 5 and 6 are adjacent to each other, so they can by no means reuse a same part of bandwidth. Since cell 4 is not adjacent to cell 2 and 6, so it can use the same part of frequency with them. Meanwhile, the traffic demands in all cell center zones need to be satisfied with 3 BBUs, then the whole system could be supported by 3 BBUs in this traffic demands situation, rather than 6 BBUs in traditional cellular system. Clearly, the new structure can reduce energy consumption and improve the spectrum utilization.

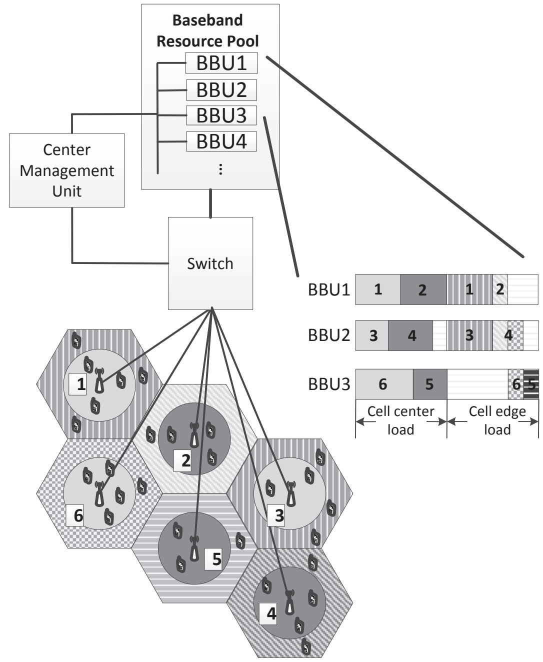

Fig. 2. Dynamic frequency reuse scheme in Cloud-RAN structure

To achieve the allocation result described above, we propose a dynamic frequency reuse scheme. It is a part of a switching scheme, which aims to reconfigure the topology of the connections between BBUs and RRHs. The switching scheme would be periodically applied to adapt to the time varying traffic demands of the whole Cloud-RAN system. We would just focus on the dynamic frequency reuse scheme in this paper. However, it is necessary to give a brief illustration of the working process of the switching scheme. Firstly, the baseband resource pool would gather the information of traffic demands of each cell zone. Then the information would be sent to a center management unit (CMU) as shown in Fig. 2. According to the traffic demands and location information of each cell, the CMU would generate a new topology structure about the connections between BBUs and RRHs based on our dynamic frequency reuse scheme. Then the CMU would send the information of new topology to the switch. Finally, the switch reconfigures the connections between the BBUs and RRHs to finish the whole switching process.

III. Proposed Dynamic Frequency Reuse Scheme

The new dynamic frequency reuse scheme aims to allocate spectrum resources among cell zones as well as avoiding the inter-cell interference while reducing the working number of BBUs. We divide our scheme into two parts, the main part is to allocate frequency resources to each cell edge zone, where the inter-cell interference needs to be considered and the graph model is used. The other part is to allocate spectrum

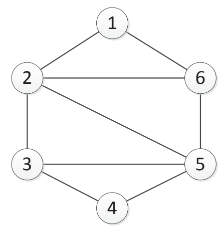

Fig. 3. Interference graph based on the cell location in Fig. 2

resources among cell center zones, which should depend on the allocation result of the first part.

A. Cell edge spectrum resource allocation scheme

To begin with, we need to construct an interference graph based on the deployment of cells, which is comprised of nodes representing cell edge zones and edges representing the interference relationship between two nodes. In the graph, two nodes connected by an edge means that the two nodes cannot be colored with the same color, i.e. the cell edge zones represented by the two nodes cannot reuse the same frequency. Each color indicates a certain part of spectrum, so coloring a node with a kind of color just means allocating a certain part of the spectrum to the cell edge zone represented by the node. According to the location of cells in Fig. 2, we can get the interference graph as Fig. 3 shows. The numbers marked on each node correspond to the cell number in Fig. 2. Let e_k be the load value of node k, which represents the traffic demands in edge zone of cell k, so we have $e_k = r_{ek}$. We use $c_{m,n}$ to indicate different colors, where we update the index m and n depending on the different generating methods. m indicates the index of a new color we introduce, and n indicates the index of a new color which is generated by spliting an existing color. We define $n = 1$ and update m to $m + 1$ when a new color is introduced. When we split an existing color to generate a new color, n needs to be updated to $n+1$ to indicate the new color. Based on the interference graph, the dynamic frequency reuse scheme can be elaborated on as the following steps.

Step 1: Select node k^* which has the maximum load value as the starting point to color the whole graph. If there are multiple nodes that have the maximum load value, choose the node with the maximum degree, i.e. the node which has the maximum number of edges incident to it. We color the chosen node k^* with color $c_{1,1}$, which has a load value, $l_{1,1}$, indicating the length of the spectrum corresponding to the color. For color $c_{1,1}$, we now have $l_{1,1} = e_{k^*}$.

Step 2: Choose the uncolored nodes adjacent to the colored ones to form a set $\mathbb{K}$. We define the available color set of node i as $\mathbb{C}_a(i)$. A node's available color set is comprised of colors existing in the graph which can be used to color the node. All nodes' available color sets would be updated after a node being colored in the graph. Choose node t which has the smallest available color set in set $\mathbb{K}$ as the target node. If there are multiple nodes meeting the aforementioned condition, choose the one with the maximum load value.

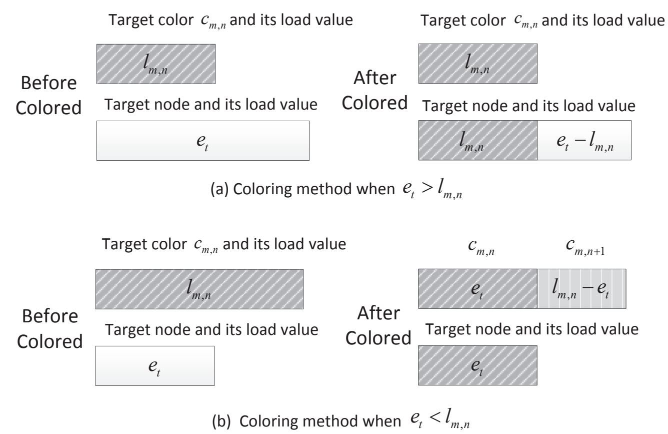

Fig. 4. Coloring method depends on differnet values of e_t and $l_{m,n}$

Step 3: Once determining the target node t, we can select a target color from the node's available color set $\mathbb{C}_a(t)$ to color it. If $\mathbb{C}_a(t)$ is empty, that means we cannot use any existing color to dye the target node. In this case, we need to introduce a new color $c_{m,1}$. Then we have $l_{m,1} = e_t$, and update all available color sets of uncolored nodes. Meanwhile, update set $\mathbb{K}$ by excluding node t from it.

If we have chance to choose an existing color from the target node's available color set, the color which has colored the least number of nodes would be preferred. Since each color stands for a certain part of spectrum, choosing the target color in this way may exploit the spectrum resource more efficiently. If there are multiple available colors, then the color whose load value is nearest to the target node's load value e_t would be selected.

Suppose color $c_{m,n}$ is selected as the target color, then different combinations of the load value $l_{m,n}$ of $c_{m,n}$ and the load value e_t of the target node t will lead to different results:

- $e_t > l_{m,n}$. Then the target node could be partially colored by $c_{m,n}$ as shown in Fig. 4(a). In practice, it means allocating a bandwidth of $l_{m,n}$ to node t, and keep it staying in set $\mathbb{K}$ to wait to be colored multiple times until its traffic demands are fully satisfied. After the node is partially colored with color $c_{m,n}$, its load value need to be updated to $e_t - l_{m,n}$.
- $e_t = l_{m,n}$. Then we just dye node t with color $c_{m,n}$ and exclude node t from set $\mathbb{K}$.
- $e_t < l_{m,n}$. Then we need to split color $c_{m,n}$ to generate a new color $c_{m,n+1}$ as shown in Fig. 4(b). The new color's load value $l_{m,n+1} = l_{m,n} - e_t$, and the load value of $c_{m,n}$ need to be updated as $l_{m,n} = e_t$. Then we can exclude node t from set $\mathbb{K}$. All the other nodes, except node t, which have already been colored by color $c_{m,n}$, are colored by at least two colors now.

After the target node is colored, we select the next target node in set $\mathbb{K}$ based on the rules mentioned in step 2 and repeat step 3, until set $\mathbb{K}$ becomes empty.

Step 4: Repeat step 2-3 until all nodes in graph are

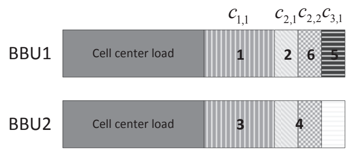

Fig. 5. Resource allocation result for cell edge users

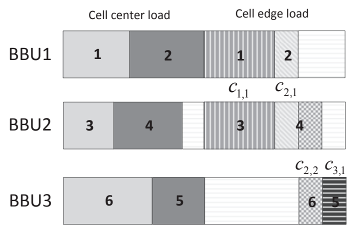

Fig. 6. Resource allocation result for all users

colored.Then we need to scale down the load value of each color. Let $\mathbb{C} = \{c_{1,1}, c_{1,2,}, \dots, c_{2,1}, \dots\}$ be the set of all colors used in graph, and $\mathbb{L} = \{l_{1,1}, l_{1,2}, \dots, l_{2,1}, \dots\}$ be the load value set of all colors, then $\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}$ is the length of spectrum to be assigned to cell edge users in each BBU. We limit the spectrum available for cell edge users to $B/2$. If $\frac{B/2}{\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}} < 1$, let $\delta = \frac{B/2}{\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}}$, and all $l_{i,j}$ need to be updated as $l_{i,j} = \delta \cdot l_{i,j}$. If $\frac{B/2}{\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}} > 1$, then this step can be skipped.

Step 5: Find whether there are available colors which can be used by some nodes. After all nodes in graph are examined and colored, the CMU can get information about the number of times $b_{m,n}$ that color $c_{m,n}$ being used to dye nodes for any color in $\mathbb{C}$. The times of each color used by nodes in graph just indicate the times of different part of spectrum reused by each cell edge zone. Then $b^* = \max\{b_{1,1}, b_{1,2}, \dots, b_{2,1}, \dots\}$ is just equal to the number of BBUs we need to support traffic demands of all cell edge zones. According to the traffic demands illustrated in Fig. 2, we may get the spectrum allocation result as shown in Fig. 5. We can see that all the other colors are used twice in the graph except color $c_{3,1}$. So we need two BBUs for all cell edge users. Cell 4 is colored by two colors: color $c_{2,1}$ and color $c_{2,2}$. Clearly, the whole frequency band is not fully used, and after step 4, the traffic demands of all cell edge zones may not be fully satisfied. Therefore, it's necessary to assign these unused spectrum to cell edge zones which need them.

For each node, if its available color set is not empty after the four steps above, we can choose colors from it to color the node. If color $c_{m,n}$ is in node's available color set, and $b_{m,n} < b^*$ (This limiting condition aims to reduce the number of working BBUs), then color $c_{m,n}$ is available now. We choose the color, whose load value is closest to the load value of target node, as the target color, with the purpose of avoiding wasting the spectrum resources. Repeat step 5 until all nodes in the graph have been checked.

After all steps mentioned above, the CMU would know the number of BBUs n_e which are needed to support the cell edge users. All the n_e BBUs form a set $\mathbb{N}_e$. In fact, attribute to the cellular structure, for a cellular system with M cells, we only need no more than $\frac{M}{3}$ BBUs for cell edge users, and more BBUs cannot improve the throughput. In our scheme, we always have $n_e \leq \frac{M}{3}$, but the total number n of BBUs to support all users would be finally decided after we get the number n_c of BBUs to support cell center users, while $n = \max\{n_c, n_e\}$.

TABLE I
RESOURCE ALLOCATION ALGORITHM FOR CELL CENTER USERS

1. Rank all RRHs which are assigned to one BBU in $\mathbb{N}_e$ based on the cell edge resource allocation scheme in descending order according to the different center traffic demands.
2. Choose the RRH with the maximun traffic demands as the target RRH. Find the BBUs which have enough spectrum resource to support this RRH to form a set $\mathbb{R}$(Connect the RRH to the BBU which has the most available spectrum resource, if no BBU has enough spare spectrum resource).
3. In $\mathbb{R}$, choose the BBU, which has the least spare resource after allocating spectrum resource to the target RRH, as the target BBU.
4. Choose the next RRH in the sequence, repeat 2-3 until all RRHs in this BBU have been allocated to certain BBUs.
5. Check the RRHs assigned to the next BBU in $\mathbb{N}_e$, repeat 1-4, until all BBUs in $\mathbb{N}_e$ are checked and all RRHs are assigned to certain BBUs.

B. Cell center spectrum resource allocation scheme

The resource allocation scheme for cell center zone would be much easier, for the reason that there is no need to consider inter-cell interference. According to the spectrum allocation result of the cell edge users, we can determine the available bandwidth for cell center users. if $\frac{B/2}{\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}} < 1$, then after scaling down the allocated spectrum resource of cell edge users, users in the cell center zones can only use the remaining half part of bandwidth of each BUU. If $\frac{B/2}{\sum_{l_{i,j} \in \mathbb{L}} l_{i,j}} \geq 1$, then the available bandwidth in each BBU for the cell center users is $B - \sum_{l_{i,j} \in \mathbb{L}} l_{i,j}$.

In our system, all users in one cell can only be allocated to one BBU. So as the allocation result for cell edge users shown in Fig. 5, RRHs in cell 1, 2, 5 and 6 are assigned to BBU1, and RRHs in cell 4 and cell 6 are assigned to BBU2. Then we need to use the method stated in Table I to decide how many BBUs we need actually to support them.

According to the cell center traffic demands in Fig. 2, the allocation result is shown in Fig. 6. The center zones of cell 1, 2, 5 and 6 are heavily loaded that they cannot be assigned to one BBU, so we need one more BBU to support them. As shown in Fig. 6, RRHs in cell 5 and 6 are assigned to BBU3, i.e. all users in cell 5 and 6 are served by BBU3. In the meantime, traffic demands in cell 3 and 4 could be satisfied by just one BBU. So the connections between all BBUs and RRHs could be determined, and we know that $n_c = 3$ BBUs are needed to serve cell center users. So finally, we need $n =$

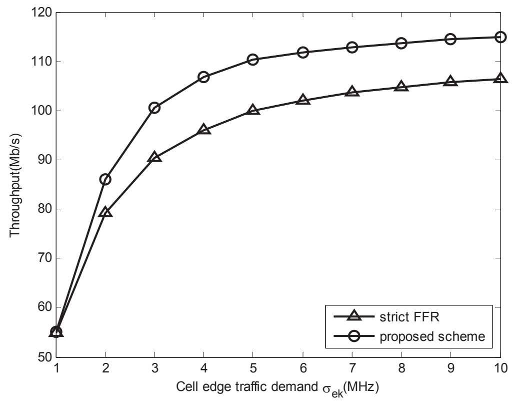

Fig. 7. Throughput of cell edge users

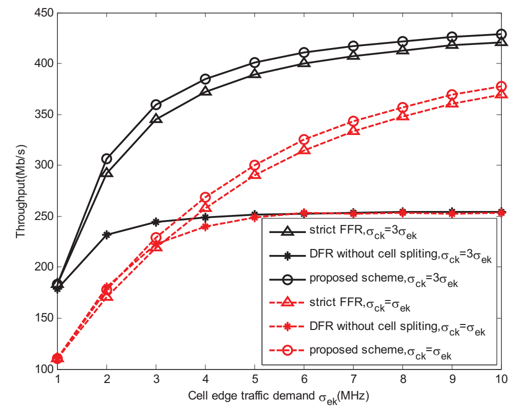

Fig. 8. Throughput of all users

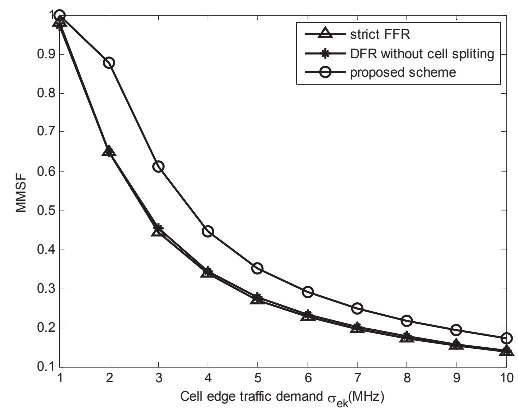

Fig. 9. MMSF of different schemes

3 BBUs to support the whole system in the traffic demands situation as shown in Fig. 2.

IV. Simulation Results

In this section, the performance of our scheme based on Cloud-RAN structure is evaluated. We use a scenario comprised of 9 cells to implement our simulation, and the bandwidth provided by a BBU is assumed to be $B = 20$ MHz. The average physical-layer spectral efficiency is set to 5.0 bit/s/Hz when interference are properly coordinated for throughput calculation. We suppose that the traffic demands yield a Gaussian random process with a non-traffic probability of P_{th} in each zone [13], the probability distribution function is given by

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

where we assume that $P_{th} = 0.25$. To change the traffic demands of different cell zones, we can just change the value of σ, for the reason that the mean traffic demands is $r = \sqrt{2\pi}\sigma Q^{-1}(1-2P_{th})$, where $Q^{-1}(\cdot)$ is the inverse error function. So in our simulation, we just change the value of σ to achieve different traffic demands. We use σ_{ck} and σ_{ek} to describe the bandwidth demands of center zone and edge zone respectively in cell k. The bandwidth requirement is supposed to be independent but identically distributed for all cells, i.e. $\sigma_{c1} = ... = \sigma_{cM}$, and $\sigma_{e1} = ... = \sigma_{eM}$.

Fig. 7 and Fig. 8 evaluate the throughput of users in each cell. Two other schemes are illustrated as contrast in the simulation. The contrast scheme 1 is the strict FFR in ordinary cellular structure, while the contrast scheme 2 is to apply our dynamic frequency reuse (DFR) scheme to all users without splitting the cell into two parts under Cloud-RAN structure. Fig. 7 focuses on the throughput of cell edge users, so we just compare our scheme with the strict FFR scheme in this figure. From the simulation result we can see clearly that our scheme can always achieve a higher throughput and is able to improve the throughput by 10% on average, for the reason that our scheme is flexible to allocate spectrum resource according to the time varying traffic demands of each cell edge zone.

Fig. 8 shows the total throughput of all the users in each cell, including those in cell edge zones and cell center zones. We set different value of σ_{ck}/σ_{ek}, to evaluate the performance of our scheme with respect to the different traffic demands distribution. The larger value of σ_{ck}/σ_{ek} means the heavier traffic demands in each cell center zone. From the figure we can see that no matter $\sigma_{ck}/\sigma_{ek} = 1$ or 3, our scheme can deal with it with an obvious improvement of throughput. It could be seen clearly that as the traffic demands increases in each cell, our scheme keeps a higher throughput than the other two. The throughput of DFR without cell spliting is much lower than the other two schemes, for the reason that it cannot fully exploit the whole spectrum resource.

Fig. 9 illustrates the mean value of minimal satisfaction factor (MMSF) of users in each cell. Here we define the satisfaction factor as the ratio of the allocated bandwidth to required bandwidth of a cell zone [14]. For each value of σ_{ek}, we calculate the MMSF for all users in each cell. It is clear that our scheme can effectively improve the performance of the users with heavy traffic demands that are hard to get enough spectrum resource, for the reason that all users can get a flexible part of frequency resource based on their traffic

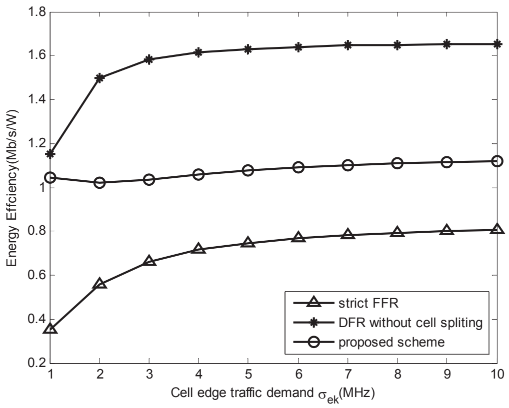

Fig. 10. Energy efficiency of the system in common traffic demands situation

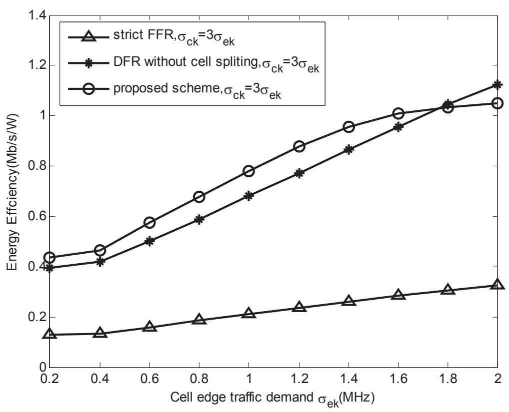

Fig. 11. Energy efficiency of the system in low traffic demands situation

demands in our scheme, rather than a fixed part in existing strict FFR scheme. To put it in another way, our scheme can improve the fairness for all users.

Fig. 10 shows the energy efficiency performance of the three different schemes in common traffic demands situation. We define the energy efficiency as the ratio of throughput of all users to the power of all working BBUs. So the unit of the energy efficiency we defined is Mb/s/W. The power of one working BBU is assumed to be 58W [15], and we set $\sigma_{ck}/\sigma_{ek} = 3$. From Fig. 10 we can see that the energy efficiency of strict FFR scheme in ordinary network structure is obviously lower than the other two schemes. The energy efficiency of DFR without cell spliting scheme is higher than our scheme, for the reason that it uses no more than $\frac{M}{3}$ BBUs, so it may achieve a lower energy cost. However, when there are fewer users in each cell, our proposed scheme will have a higher energy efficiency than other two schemes as Fig. 11 shows. In Fig. 11, we set $\sigma_{ck} = \sigma_{ek}$, and limit the value of σ_{ek} from 0.2 to 2. On this occasion, the BBUs used by our proposed scheme would be no more than the DFR without cell spliting, and our scheme can achieve a higher throughput as well, so a higher energy efficiency could also be achieved.

V. Conclusion

We propose a graph based dynamic frequency reuse scheme under Cloud-RAN structure in this work. We use graph coloring method to realize the frequency resource allocation among cell edge zones based on their different traffic demands dynamically, as well as avoiding the inter-cell interference. With the application of our proposed scheme based on Cloud-RAN structure, we can improve the utilization of frequency resource provided by each BBU, as well as reducing the energy consumption through reducing the number of working BBUs. The simulation results show clearly that our scheme with the Cloud-RAN structure can obviously improve the throughput and achieve higher energy efficiency than the state of art.

Acknowledgment

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