

METHOD AND SYSTEM FOR SOFT FREQUENCY REUSE IN A DISTRIBUTED ANTENNA SYSTEM

SUMMARY OF THE INVENTION

5 **[0001]** The present invention generally relates to wireless communication systems employing Distributed Antenna Systems (DAS) as part of a distributed wireless network. More specifically, the present invention relates to a DAS utilizing Soft Frequency Reuse or Fractional Frequency Reuse techniques. In a particular embodiment, the present invention has been applied to the reuse of communications frequencies in central portions of adjacent DAS cells, improving
10 system data rates and performance. The methods and systems described herein are applicable to a variety of communications systems including systems utilizing various communications standards.

15 **[0002]** Numerous benefits are achieved by way of the present invention over conventional techniques. For instance, embodiments of the present invention control the amount of resources allocated to users located in different areas, thereby increasing the frequency efficiency and also improving the data rate for cell edge users. These and other embodiments of the invention along with many of its advantages and features are described in more detail in conjunction with the text below and attached figures.

BRIEF DESCRIPTION OF THE DRAWINGS

20 **[0003]** FIG. 1 illustrates different frequency reuse techniques according to an embodiment of the present invention;

25 **[0004]** FIG. 2 illustrates the structure of a Distributed Antenna System (DAS) according to an embodiment of the present invention;

30 **[0005]** FIG. 3 is a plot illustrating ergodic capacity versus the normalized distance from the DRU0 according to an embodiment of the present invention;

35 **[0006]** FIG. 4 is a plot illustrating ergodic capacity versus the normalized distance from the DRU0 according to another embodiment of the present invention;

[0007] FIG. 5 illustrates a capacity metric for a multiuser case versus the normalized distance from the DRU0 in eNB0(central cell) area according to an embodiment of the present invention;

[0008] FIG. 6 is a plot illustrating analytical ergodic capacity for edge cell and non-edge cell users versus α according to an embodiment of the present invention; and

5 [0009] FIG. 7 is a plot illustrating simulation capacity for edge cell and non-edge cell users versus α according to an embodiment of the present invention.

[0010] FIG. 8 is a simplified flowchart illustrating a method of implementing soft frequency reuse according to an embodiment of the present invention; and

[0011] FIG. 9 is a simplified flowchart illustrating a method of implementing fractional
10 frequency reuse according to an embodiment of the present invention. The method includes

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0012] Embodiments of the present invention provide a new cell architecture combining two inter-cell interference mitigation techniques, Distributed Antenna System and Soft Frequency
15 Reuse, to improve cell edge user's throughput when the system has full spectral efficiency.

[0013] Orthogonal Frequency Division Multiple Access (OFDMA) has been adopted as the transmission scheme for the next generation wireless communication systems. However, the downlink performance of cellular networks is known to be strongly limited by inter-cell interference in OFDMA based systems. In order to mitigate this interference, a number of
20 techniques have recently been proposed, e.g. the Soft Frequency Reuse (SFR) scheme and Distributed Antenna System (DAS). According to embodiments of the present invention, these two techniques are combined in a unique cell architecture, which can be referred to as DAS-SFR. In an implementation of this architecture, which is described herein, the antennas are distributed in a hexagonal cell such that the central antenna is responsible for serving a special area using
25 multiple frequency bands (e.g., all of the frequency bands) while the remaining antennas utilize only a subset of the frequency bands based on a frequency reuse factor. The inventors have analytically quantified the performance of the downlink multi-cell DAS-SFR in terms of the individual user's throughput under three different resource allocation scenarios. The results show that DAS-SFR reduces inter-cell interference in a multi-cell environment for users near the cell
30 boundaries as compared to a Hard Frequency Reuse (HFR) scheme with a frequency reuse factor

of 1. The results also show that DAS-SFR significantly increases the system capacity as compared to the HFR scheme with a frequency reuse factor of 3.

[0014] In DAS-SFR, by controlling the amount of resources allocated to users located in different areas, embodiments of the present invention increase the frequency efficiency and also improve the data rate for cell edge users. If the throughput requirement for the interior users is small, more resources can be assigned to the exterior users.

[0015] In the next generation wireless communication systems that use the 3GPP LTE (Long Term Evolution) standard, there is tremendous pressure to support a high data rate transmission. These systems are based on Orthogonal Frequency Division Multiple Access (OFDMA) to support the high data rate service and improve the Quality of Service (QoS), even for cell edge users as the main targets in the downlink.

[0016] The system bandwidth is divided into a number of sub-carriers in an OFDMA-based system such that each user utilizes a bandwidth smaller than the systems coherence bandwidth. Data from different users is transmitted in parallel on different sub-carriers. The orthogonality amongst the sub-carriers mitigates inter-carrier interference (ICI) while the resulting large OFDM symbol time and the narrow sub-carrier bandwidth reduces the effect of inter-symbol interference (ISI). Users located at the cell edge largely suffer from co-channel interference (CCI) or inter-cell interference from base stations (BS) of neighboring cells. Mobile 3GPP LTE adopts a frequency reuse factor of one, in which each cell serves users using the entire system bandwidth.

[0017] In order to reduce interference in cellular systems, several techniques have been incorporated in these standards. Advanced receiver techniques such as Maximum Likelihood (ML) Multiuser Detection (MUD), the MMSE Receiver MUD and Other-cell interference cancellation are three potential ways to reduce interference in cellular systems but these require a more complicated receiver. Advanced transmitter techniques such as Cooperative Encoding (CA), Closed-Loop MIMO Diversity Schemes (CLMD) and Beamforming are three other techniques to overcome the interference problem in cellular systems but CA requires very accurate channel state knowledge and real time inter-cell coordination, CLMD and Beamforming sacrifice spatial dimensions and require channel state knowledge.

[0018] One possible strategy to alleviate interference, both in the uplink and the downlink of cellular networks, is to reduce the overall transmit power by using a distributed antenna systems (DAS), which also has the additional advantage of improving capacity and coverage.

[0019] Other possible strategies include Frequency Reuse techniques, which effectively reduce inter-cell interference by geographically spacing the competing transmissions farther apart, which benefits users near the cell boundaries.

[0020] Distributed Antenna System (DAS) have been widely implemented in state-of-the art cellular communication systems to cover dead spots in wireless communications systems. As opposed to a conventional cellular system, where the antenna is centrally located, a DAS network consists of antenna modules that are geographically distributed to reduce access distance. These distributed antennas are connected to an eNodeB (eNB) LTE system by dedicated wires, fiber optics, or via a radio frequency link.

[0021] DAS has advantages including throughput improvement, coverage improvement, increased cellphone battery life, and a reduction in transmitter power. Recent research has shown benefits of using DAS in a cellular system for extending coverage, reducing call blocking rate and reducing inter-cell interference. An extension to a traditional DAS system is a Virtual DAS, wherein each remote has the added flexibility of independently transmitting preselected carriers.

[0022] Frequency reuse techniques are utilized herein to reduce inter-cell interference in cellular systems. This benefits users near the cell edges owing to simplicity and practicality. There are three major frequency reuse patterns illustrated in FIG. 1 for mitigating inter-cell interference: Hard Frequency Reuse, Fractional Frequency Reuse and Soft Frequency Reuse.

[0023] Hard Frequency Reuse (HFR) splits the system bandwidth into a number of distinct sub-bands according to a chosen reuse factor and lets neighboring cells transmit on different sub-bands. This inter-cell interference mitigation method is typically seen in GSM networks, when it comes to distribution of frequencies among the cells. When applied to LTE, the Resource Blocks (a group of sub-carriers) are divided into 3, 4 or 7 disjoint sets. These sets of Resource Blocks (RBs) are assigned to the individual eNBs in such a way that neighboring cells don't use the same set of frequencies, Fig 1 (c). This reduces the interference at the cell edge of any pair of cells significantly and can be considered the opposite extreme to Full Frequency Reuse in

matters of frequency partitioning techniques. While user interference at the cell edge is maximally reduced, the spectrum efficiency drops by a factor equal to the reuse factor. The inter-cell interference can be reduced with a frequency reuse factor of more than one, however, it may reduce the system capacity.

5 **[0024]** Fractional Frequency Reuse (FFR) has been proposed as an inter-cell interference mitigation technique in OFDMA based wireless networks. OFDMA provides the ability for each eNB to selectively allocate frequency sub-bands, data rates and power to the users depending on their location in the cell, according to some predefined frequency reuse pattern which may lead to significant capacity gains for the overall network. FFR splits the given bandwidth into an inner and an outer region, Fig. 1 (a). The spectrum allocated to the inner region is assigned to the nearby users (located close to the eNB in terms of path loss) applying a frequency reuse factor of one (i.e. the inner part is completely reused by all eNBs). While the spectrum allocated to the outer region, for users close to the cell edge (far users), is divided among the different eNBs as in hard frequency reuse techniques. This scheme is particularly useful to mitigate the inter-cell interference in the uplink, where severe interference situations can occur when the user is located close to a strong interferer from a neighbor cell.

20 **[0025]** Soft Frequency Reuse (SFR) has been proposed as an inter-cell interference mitigation technique in OFDMA based wireless networks. SFR shares the overall bandwidth by all eNBs (i.e. a reuse factor of one is applied), but for transmission on each group of RBs, the eNBs are restricted to a certain power bound. Fig. 1(b) illustrates the power and frequency assignments in the different cells of a system with SFR for a reuse factor of 3. It can be noticed in the frequency spectrum of Fig. 1(b) that there is a region of high-power transmissions and some regions of low-power transmissions. Using a similar strategy as in the previous method, resources in the high-power region are preferably assigned to UEs located at the cell edge, while cell-center UEs are typically assigned resources in the low-power regions.

30 **[0026]** HFR, though simple in implementation, suffers from a reduced spectral efficiency. On the other hand, both SFR and FFR have full spectral efficiency and are a strong mechanism for inter-cell interference mitigation. A coordinated resource allocation system can be impractical in realistic settings involving a large number of eNBs, random traffic and realistic path-loss models. However, an encouraging result is that by using even limited (yet practical) levels of coordination, significant performance benefits can still be obtained over a conventional cellular

architecture. Most of the recent publications have focused on investigating SINR advantages of DAS and analyzing its performance. On the other hand, there are no studies that combine DAS with SFR in order to reduce inter-cell interference. Some publications on DAS have focused on analyzing the uplink performance because of its analytical simplicity and there are few studies on the downlink performance of DAS although the demand for high-speed data rate will be dominant in the downlink path. There are also very few publications that consider the advantages of DAS in a multi-cell context. Recent research on FFR and SFR has focused on optimal system design utilizing advanced techniques such as graph theory and convex optimization to maximize network throughput. Additional works on FFR and SFR consider alternative schedulers and the authors determined the frequency partitions in a two-stage heuristic approach.

[0027] According to embodiments of the present invention, a new architecture is provided to suppress inter-cell interference. The architecture described herein combines DAS and SFR for an OFDMA system (e.g., LTE). Embodiments of the present invention provide benefits by using DAS-SFR in a multi-cell environment. The downlink advantages of DAS-SFR are described in terms of achievable ergodic capacity for three different frequency resource allocation scenarios. The results shows that a DAS-SFR architecture effectively addresses inter-cell interference in a multi-cell environment, especially at the cell boundaries when compared to a HFR cellular architecture and achieves a non-trivial capacity increase over a HFR cellular architecture with a frequency reuse factor of 3.

[0028] As described herein, an analytical framework has been developed to evaluate the ergodic capacity in a DAS-SFR architecture. This is an important metric to consider, especially for users at the cell-edge since modern cellular networks are increasingly required to provide users with high data-rate and a guaranteed quality-of-service, regardless of their geographic location, instead of simply a minimum user throughput which may be acceptable for applications like voice traffic. We present a strategy for optimally allocating frequency RBs to edge users for a DAS-SFR architecture, based on a chosen performance threshold T_p , which can be related to network traffic load. Finally we prepare a simulation scenario to compare the analytical results with the simulation results.

[0029] Referring to the spectral plots illustrated in FIG. 1, in the HFR system, the blue, orange, and green frequency bands occupy different frequency ranges and, in combination, fill the entire

spectrum. In HFR, cell 1 uses the lower frequencies, cell 2 uses the middle frequencies, and cell 3 uses the higher frequencies.

[0030] Referring to FIG. 2, the DAS includes a central cell referenced as eNB0, which includes DRU0 through DRU6, which can be considered to be cell 1 in FIG. 1A. eNB1, including a different set of DRUs, DRU0 through DRU6 can be considered to be cell 2 in FIG. 1A, etc. In FIG. 1C, cell 1 (e.g., DRU0 - DRU6 of eNB0) utilizes the blue frequency band and the other cells use different frequency bands as illustrated. For cells geographically separated from cell 1, for example, eNB7 could reuse the blue frequencies used in cell 1 (e.g., eNB0).

[0031] Referring once again to FIG. 1A, a set of frequencies represented by the gray frequency band in FIG. 1A and the Fraction Frequency Reuse spectrum, are reused in each of the cells (i.e., Cell 1, Cell 2, and Cell 3). Because this frequency band does not geographically overlap with adjacent cells (i.e., it is used at the central portion of the cell), overlap between adjacent cells is prevented and this frequency band can be reused in adjacent cells.

[0032] For fractional frequencies, because there is a spatial separation between the grey areas in Cell 1 and Cell 2 and Cell 3, as long as the spatial separation is significant enough, there will not be significant interference between the cells although the central portions of the cells are transmitting on the exact same frequencies. By keeping a separation and allocating the blue area in Cell 1 to specific frequencies, the orange area in Cell 2 to other specific frequencies, the green area in Cell 3 to still other specific frequencies, and the like for additional cells, embodiments of the present invention make efficient use of the given spectrum. Comparing the Fractional Frequency Reuse spectrum to the Hard Frequency Reuse spectrum, it is evident that FFR uses more of the available spectrum, which enables support for more users, operation at a higher data rate, combinations thereof, or the like. In the illustrated example, the fraction of the spectrum used has increased from about a third of the spectrum (HFR) to about half of the spectrum (FFR). Other implementations can utilize different fractions of the spectrum and the present invention is not limited to the particular example illustrated in FIG. 1.

[0033] To implement the fractional frequency reuse technique illustrated in FIG. 1A using the architecture illustrated in FIG. 2, DRU 1, 2, 3, 4, 5 and 6 of eNB0 would transmit and receive data using the blue frequencies and DRU0 of eNB0 would transmit and receive data using the grey frequencies. In an embodiment, the size of the area covered by DRU0 can be increased by increasing the transmit power associated with the central DRU (i.e., DRU0).

[0034] Referring to FIG. 1B, an architecture implementing Soft Frequency Reuse is illustrated and the matching spectrum illustrates the full use the spectrum by each of the adjacent cells. The blue geographical area in Cell 1 is associated with the outer DRUs in the communications unit illustrated as eNB0 in FIG. 2 (i.e., DRUs 1-6) and the grey geographical area in Cell 1 is associated with the central DRU in the communications unit illustrated as eNB0 in FIG. 2 (i.e., DRU0). As discussed above, the size of the grey circle can be increased/decreased by increasing/decreasing the power of utilized in conjunction with DRU0. As shown in the SFR spectrum for Cell 1, data is transmitted and received over the entire allocated spectrum, including portions of the spectrum that were unused for Cell 1 in the HFR example. The increase in spectrum provides increased data rate, increased capacity, combinations thereof, or the like.

[0035] Comparing FFR and SFR, the frequency bandwidth available for the peripheral DRUs (i.e., blue, orange, or green spectra) is increased for SFR in comparison to FFR. Additionally, the frequency bandwidth available for the central DRU (i.e., grey spectra) is also increased for SFR in comparison to FFR.

[0036] In an embodiment, fractional frequency reuse is implemented in a DAS system with a plurality of adjacent cells, each of the cells including a plurality of remote units. A first cell utilizes a first frequency bandwidth at a central portion of the cell (i.e., a central geographical area associated with a central DRU) and a second frequency bandwidth at peripheral portions of the cell (i.e., a peripheral geographical area associated with peripheral DRUs). A second cell utilizes a third frequency bandwidth at a central portion of the cell (i.e., a central geographical area associated with a central DRU) and the second frequency bandwidth at peripheral portions of the cell (i.e., a peripheral geographical area associated with peripheral DRUs).

[0037] In another embodiment, soft frequency reuse is implemented in a DAS system with a plurality of adjacent cells. A first cell utilizes a first frequency band at peripheral portions of the cell (i.e., a peripheral geographical area associated with peripheral DRUs) and a second frequency band (e.g., the remaining bandwidth) at a central portion of the cell (i.e., a central geographical area associated with a central DRU). A second cell utilizes a third frequency band at peripheral portions of the cell (i.e., a peripheral geographical area associated with peripheral DRUs) and a fourth frequency band, which may include multiple sub-bands (e.g., the remaining bandwidth) at a central portion of the cell (i.e., a central geographical area associated with a central DRU). The third frequency band may include frequencies in the second frequency band

and the multiple sub-bands of the fourth frequency band may include frequencies in the first frequency band as illustrated in FIG. 1.

[0038] As will be appreciated by one of skill in the art, operators utilize different spectrums and, in the examples illustrated in FIG. 1, they are contiguous. However, it should be noted that although contiguous spectra are illustrated in FIG. 1, this is not required by embodiments of the present invention and non-contiguous spectrums may be utilized in other embodiments. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0039] Although the embodiment illustrated in FIG. 1 utilizes three frequencies, embodiments of the present invention are not limited to this particular number and additional frequencies and frequency bands can be utilized, for example, additional frequency bands used in conjunction with additional cells. In a particular embodiment, seven frequency bands, twelve frequency bands, or the like can be utilized. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0040] System Architecture (DAS-SFR)

[0041] The general architecture of a Virtualized DAS in a multi-cell environment is shown in Fig. 2, where 7 Digital Remote Units (DRUs) are connected to an eNB via an optical fiber and a Digital Access Unit (DAU). The DAUs are interconnected and connected to multiple sectors. This capability enables the virtualization of the eNB resources at the independent DRUs. The eNBs are linked to a public switched telephone network or a mobile switching center. DRUs are sectorized such that each DRU allocated to a given eNB sector is simulcast. For the simulcasting operation, the access network between each eNB and its DRUs should have a multi-drop bus topology. The DAUs assign the RBs of the various sectors to the independent DRUs. In contrast, the same area (7 DRUs) is covered by only a high-power eNB in traditional cellular system. The proposed architecture divides the entire spectral bandwidth F into 3 parts (F_1, F_2, F_3). The idea is that the eNB assigns the full-reused frequency (all 3 parts) to the central DRU and the other 6 edge DRUs work on just 1 part based on a reuse factor of Δ in such a way that neighbor cell edge DRUs don't use the same frequency part.

[0042] The total transmit power of the n -th DRU of i -th cell in f -th frequency part is denoted $P_n^{(i,f)}$, where the central DRU of each cell is index by $n = 0$. Throughout this application, we assume that $P_n^{(i,f)} = P$.

[0043] We also consider the 2-tier cellular structure, where two continuous tiers of eighteen cells surround a given cell. Although this assumption of only 2-tiers of interfering cells is optimistic, a pessimistic assumption that all the DRUs and the eNB are transmitting full power all the time easily compensates.

5 [0044] Resource Allocation Scenarios:

[0045] In cellular DAS-SFR with multi users, there are several possible resource allocation scenarios using multiple DRUs. Much of the research on SFR system design has focused on how to determine the size of the frequency partition, for example, in a typical LTE system with a bandwidth of 5 MHz, 25 RBs may be available to serve users per each frequency part(

10 $F_i, i=1,2,3$).

[0046] For a typical central cell, let's assume the center DRU is assigned the full-reused frequency and the other six edge DRUs are assigned to F_1 . Now, we consider three resource allocation scenarios:

[0047] - **Scenario 1:** All F_1, F_2, F_3 RBs are assigned to all users in the cell. Note that in this
15 scenario, the very low SINR exterior users are inefficiently using the F_2 and F_3 RBs.

[0048] - **Scenario 2:** F_1 RBs are assigned to all users but F_2 and F_3 RBs are solely assigned to interior users. Note that in this scenario, the available RBs are fully assigned to the interior users, which leads to a big gap between the numbers of allocated RBs to the interior users as compared to the exterior users.

20 [0049] - **Scenario 3:** F_1 RBs are solely assigned to the exterior users, whereas the F_2 and F_3 RBs are assigned to the interior users. In this scenario, all RBs are more fairly assigned between all users, as compared to the previously mentioned scenario. Moreover, in this scenario the RBs are allocated to the users following a SINR-based approach, in which the edge users using the F_1 RBs, and the interior users using the F_2 and F_3 RBs have a high SINR.

25 [0050] We primarily assume a single user scenario, and further extend it to a uniformly distributed multiuser LTE system. In a multiuser scenario we investigate both the analytical and simulation results in order to verify the system's capacity improvement.

[0051] Channel Model and Received Signal

[0052] The downlink path of a DAS can be considered as an equivalent MIMO system with additive interference and noise. The received signal vector of the user in the 0th cell at frequency f can be expressed as:

$$\begin{aligned}
 y^{(0,f)} &= \text{signal} + \text{interference} + \text{noise} \\
 &= \mathbf{H}^{(0,f)} \mathbf{x}^{(0,f)} + \sum_{i=1}^{18} \mathbf{H}^{(i,f)} \mathbf{x}^{(i,f)} + \mathbf{n}
 \end{aligned} \tag{1}$$

where $\mathbf{H}^{(i,f)} \in \mathbb{C}^{1 \times 7}$, $i = 0, 1, \dots, 18$, denotes the channel matrix between the DRUs in the i -th cell and the user in the central (0th) cell, $\mathbf{x}^{(i,f)} = [x_0^{(i,f)}, x_1^{(i,f)}, \dots, x_6^{(i,f)}]^T \in \mathbb{C}^{7 \times 1}$, $i = 0, 1, \dots, 18$ is the transmitted signal vector of the DRUs in the i -th cell, $\mathbf{n}^{(f)} \in \mathbb{C}^{1 \times 1}$ denotes the white noise vector with distribution $\mathcal{CN}(0, \sigma_{n^{(f)}}^2 \mathbf{I}_1)$.

[0053] The distributed antenna power constraint is considered, we have

$$\mathbf{E} \left[\left| x_n^{(i,f)} \right|^2 \right] \leq P_n^{(i,f)}, n = 0, 1, \dots, 6, \quad i = 0, 1, \dots, 18, \tag{2}$$

where in DAS-SFR,

$$\begin{aligned}
 x_n^{(i,F_1)} &= 0, P_n^{(i,F_1)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 1, 2, \dots, 7, 9, 11, 13, 15, 17), \\
 x_n^{(i,F_2)} &= 0, P_n^{(i,F_2)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 0, 2, 4, 6, 7, 8, 10, 11, 12, 14, 15, 16, 18), \\
 x_n^{(i,F_3)} &= 0, P_n^{(i,F_3)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 0, 1, 3, 5, 8, 9, 10, 12, 13, 14, 16, 17, 18),
 \end{aligned}$$

in DAS-HFR3 (frequency reuse factor 3),

$$\begin{aligned}
 x_n^{(i,F_1)} &= 0, P_n^{(i,F_1)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 1, 2, \dots, 7, 9, 11, 13, 15, 17), \\
 x_n^{(i,F_2)} &= 0, P_n^{(i,F_2)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 0, 2, 4, 6, 7, 8, 10, 11, 12, 14, 15, 16, 18), \\
 x_n^{(i,F_3)} &= 0, P_n^{(i,F_3)} = 0 \quad \text{when } (n = 1, 2, \dots, 6 \quad \text{and} \quad i = 0, 1, 3, 5, 8, 9, 10, 12, 13, 14, 16, 17, 18),
 \end{aligned} \tag{3}$$

in DAS-HFR1 (frequency reuse factor 1),

$$x_n^{(i,f)} \neq 0, P_n^{(i,f)} \neq 0 \quad \text{when } (n = 0, 1, \dots, 6 \quad \text{and} \quad i = 0, 1, \dots, 18, \quad f = F_1, F_2, F_3),$$

in Conventional Cellular-HFR3 (frequency reuse factor 3),

$$\begin{aligned}
x_n^{(i,F_1)} = 0, P_n^{(i,F_1)} = 0 \quad & \text{when } (n=0,1,\dots,6 \text{ and } i=1,2,\dots,7,9,11,13,15,17) \text{ or} \\
& (n=1,2,\dots,6 \text{ and } i=0,8,10,12,14,16,18), \\
x_n^{(i,F_2)} = 0, P_n^{(i,F_2)} = 0 \quad & \text{when } (n=0,1,\dots,6 \text{ and } i=0,2,4,6,7,8,10,11,12,14,15,16,18) \text{ or} \\
& (n=1,2,\dots,6 \text{ and } i=1,3,5,9,13,17), \\
x_n^{(i,F_3)} = 0, P_n^{(i,F_3)} = 0 \quad & \text{when } (n=0,1,\dots,6 \text{ and } i=0,1,3,5,8,9,10,12,13,14,16,17,18) \text{ or} \\
& (n=1,2,\dots,6 \text{ and } i=2,4,6,7,11,15),
\end{aligned}$$

and in Conventional cellular-HFR1 (frequency reuse factor 1),

$$x_n^{(i,f)} = 0, P_n^{(i,f)} = 0 \quad \text{when } (n=1,\dots,6 \text{ and } i=0,1,\dots,18 \text{ and } f = F_1, F_2, F_3),$$

where $P_n^{(i,f)}$ denotes the power constraint of the n -th DRU in the i -th cell.

- 5 **[0054]** The composite fading channel matrix $\mathbf{H}^{(i,f)}$, $i=0,1,\dots,18$, encompasses not only small-scale fading but also large-scale fading, which is modeled as

$$\begin{aligned}
\mathbf{H}^{(i,f)} &= \mathbf{H}_w^{(i,f)} \mathbf{L}^{(i,f)} \\
&= [h_0^{(i,f)}, h_1^{(i,f)}, \dots, h_6^{(i,f)}] \cdot \text{diag}\{l_0^{(i,f)}, l_1^{(i,f)}, \dots, l_6^{(i,f)}\}
\end{aligned} \tag{3}$$

where $\mathbf{H}_w^{(i,f)}$ and $\mathbf{L}^{(i,f)}$ reflect the small-scale channel fading and the large-scale channel fading between the DRUs in the i -th cell and the user in the 0th cell, respectively.

- 10 $\{h_j^{(i,f)} | j=0,1,\dots,6; i=0,1,\dots,18; f=F_1, F_2, F_3\}$ are independent and identically distribute (*i.i.d*) circularly symmetric complex Gaussian variables with zero mean and unit variance, and $\{l_j^{(i,f)} | j=0,1,\dots,6; i=0,1,\dots,18; f=F_1, F_2, F_3\}$ can be modeled as

$$l_n^{(i,f)} = \sqrt{[D_n^{(i)}]^{-\gamma}} \chi_n^{(i,f)}, \quad n=0,1,\dots,6, \quad i=0,1,\dots,18 \tag{4}$$

- where $D_n^{(i)}$ and $\chi_n^{(i,f)}$ are independent random variables representing the distance and the shadowing between the user in the 0th cell and the n th DRU in the i -th cell, respectively, γ denotes the path loss exponent. $\{\chi_j^{(i,f)} | j=0,1,\dots,6; i=0,1,\dots,18; f=F_1, F_2, F_3\}$ are *i.i.d* random variables with probability density function (PDF)

$$f_\chi(\chi) = \frac{1}{\sqrt{2\pi}\lambda\sigma_\chi\chi} \exp\left(-\frac{(\ln \chi)^2}{2\lambda^2\sigma_\chi^2}\right), \quad \chi > 0, \tag{5}$$

where σ_χ is the shadowing standard deviation and $\lambda = \frac{\ln 10}{10}$.

[0055] Since the number of interfering source is sufficiently large and interfering source are independent with each other, the interference plus noise is assumed to be a complex Gaussian random vector as follows:

$$N^{(f)} = \sum_{i=1}^{18} \mathbf{H}^{(i,f)} \mathbf{x}^{(i,f)} + \mathbf{n}^{(f)} \quad (6)$$

5 The variance of N is derived by Central Limit Theorem as

$$\begin{aligned} \text{Var}(N^{(f)}) &= \left[\sum_{i=1}^{18} \sum_{n=0}^6 \left[I_n^{(i,f)} \right]^2 P_n^{(i,f)} + \sigma_{n^{(f)}}^2 \right] \mathbf{I}_1 \\ &= \left[\sigma^{(f)} \right]^2 \mathbf{I}_1 \end{aligned} \quad (7)$$

Therefore, the received signal at the mobile station at a given symbol duration is given by

$$\mathbf{y}^{(0)} = \mathbf{H}_w^{(0,f)} \mathbf{L}^{(0,f)} \mathbf{x}^{(0,f)} + N^{(f)} \quad (8)$$

[0056] Achievable capacity of distributed antenna network

10 **[0057]** If we assume the channel state information is known only at the receiver (CSIR) and the channel is ergodic, the ergodic Shannon capacity at a given location of the target mobile station can be calculated by

$$C^{(f)} = \mathbf{E}_{\mathbf{H}_w^{(0,f)}} \left[\log_2 \det \left(\mathbf{I}_1 + \frac{1}{\left[\sigma^{(f)} \right]^2} (\mathbf{H}_w^{(0,f)} \mathbf{L}^{(0,f)}) \mathbf{P}^{(0,f)} (\mathbf{H}_w^{(0,f)} \mathbf{L}^{(0,f)})^H \right) \right] \quad (9)$$

where $\mathbf{P}^{(0,f)}$ is the covariance matrix of the transmitted vector x and given by

15 $\text{diag}\{P_0^{(0,f)}, P_1^{(0,f)}, \dots, P_6^{(0,f)}\}$. If ergodicity of the channel is assumed, the ergodic capacity can be obtained as

$$\begin{aligned} C^{(f)} &= \mathbf{E}_{\mathbf{H}_w^{(0,f)}} \left[\log_2 \left(1 + \frac{1}{\left[\sigma^{(f)} \right]^2} \sum_{i=0}^6 |h_i^{(0,f)}|^2 \left[I_i^{(0,f)} \right]^2 P_i^{(0,f)} \right) \right] \\ &= \int_{\gamma_f=0}^{\infty} \log_2(1 + \gamma_f) f_{\gamma_f}(\gamma_f) d\gamma_f \end{aligned} \quad (10)$$

where $\gamma_f = \frac{1}{\left[\sigma^{(f)} \right]^2} \sum_{i=0}^6 |h_i^{(0,f)}|^2 \left[I_i^{(0,f)} \right]^2 P_i^{(0,f)}$ is a weighted chi-squared distributed random

variable with p.d.f given by

$$f_{\gamma_f}(\gamma_f) = \sum_{i=0}^6 \frac{[\sigma^{(f)}]^2 \pi_i}{[l_i^{(0,f)}]^2 P_i^{(0,f)}} \exp\left(-\frac{[\sigma^{(f)}]^2 \gamma_f}{[l_i^{(0,f)}]^2 P_i^{(0,f)}}\right), \quad (11)$$

where

$$\pi_i = \prod_{k=0, k \neq i}^6 \frac{[l_i^{(0,f)}]^2 P_i^{(0,f)}}{[l_i^{(0,f)}]^2 P_i^{(0,f)} - [l_i^{(0,f)}]^2 P_k^{(0,f)}}.$$

Then the ergodic capacity for MISO vector channel can be obtained in a simple form by

$$5 \quad C^{(f)} = -\frac{1}{\ln 2} \sum_{i=0}^6 \pi_i \exp\left(-\frac{[\sigma^{(f)}]^2}{[l_i^{(0,f)}]^2 P_i^{(0,f)}}\right) Ei\left(-\frac{[\sigma^{(f)}]^2}{[l_i^{(0,f)}]^2 P_i^{(0,f)}}\right), f = F_1, F_2, F_3 \quad (12)$$

where $Ei(t)$ is the exponential integral function ($Ei(t) = -\int_{-t}^{\infty} e^{-t} / t dt$) and can be easily calculated

with popular numerical tools such as MATLAB and MAPLE.

[0058] Since the derivation for this MISO vector channel is a generalization of a SISO channel, the ergodic capacity for SISO channel is given, respectively, by

$$10 \quad C^{(f)} = -\frac{1}{\ln 2} \exp\left(-\frac{[\sigma^{(f)}]^2}{[l_i^{(0,f)}]^2 P_i^{(0,f)}}\right) Ei\left(-\frac{[\sigma^{(f)}]^2}{[l_i^{(0,f)}]^2 P_i^{(0,f)}}\right), f = F_1, F_2, F_3 \quad (13)$$

[0059] Thus, the total ergodic capacity of the system can be obtained by adding the capacity of the individual carriers,

$$C_{total} = C^{(F_1)} + C^{(F_2)} + C^{(F_3)} \quad (14)$$

[0060] Analytical and Simulation Results

15 **[0061]** FIG. 3 and FIG. 4 represents the ergodic capacity of cellular DAS for different frequency reuse techniques versus the normalized distance from the eNB0 DRU0 in the direction of the worst case position X when the path loss exponent is 3.76. Each scenario is plotted for the individual capacities $C^{(F_1)}$, $C^{(F_2)}$, $C^{(F_3)}$, and also for the total capacity C_{total} .

[0062] The transmit power of each distributed antenna module is P whereas the transmit power of eNB in the conventional cellular system is $7P$. These figures show an interesting non-

20

monotonic relationship between capacity and the normalized distance from the base station. This is because the signal from a distributed antenna module becomes dominant around $0.6R$.

[0063] FIG. 3 compares the capacity performance of the two frequency reuse techniques, SFR and HFR3, for a particular central cell. Note that in the SFR technique, all 3 frequency bands are assigned, whereas, in the HFR3 method, only the F_1 band is used. The results show that the SFR method achieves the highest throughput, owing to use of more frequency bandwidth. More specifically, the total capacity achieved using the SFR method is the highest inside the normalized distance 0.5 .

[0064] A non-significant throughput reduction in the SFR technique is observed happening beyond a normalized distance 0.5 , due to the interference introduced from the neighboring central DRU cells. Note that there is no interference introduced from the DRU neighboring cells when the HFR3 method is applied. It is worth mentioning that the achieved throughput of the DAS-HFR3 is slightly lower than that of a conventional cellular (Con-HFR3) system near the eNB0 DRU0, due to the reduced transmit power.

[0065] FIG. 4 compares the capacity performance of the two frequency reuse techniques, SFR and HFR1, for a particular central cell. Note that in both SFR and HFR1 techniques, all 3 frequency bands are assigned. The achieved throughputs of the DAS-HFR1 and DAS-SFR are slightly lower than that of a conventional cellular (Con-HFR1) system near the eNB0 (DRU0), due to the reduced transmit power.

[0066] FIG. 4 illustrates that the HFR1 technique outperforms the SFR technique in terms of the achieved throughput inside the $(0, 0.5R)$ region, nevertheless, the SFR technique significantly improves the system performance by making up for the dead spots happening at the cell edges. Note that there is a significant amount of interference happening in the $(0.8R, R)$ region, creating dead-spots in the HFR1 technique.

[0067] Note that 80% of the users are located inside the $(0.5R, R)$ region, assuming a uniform distribution, while the other 20% are farther from the interfering cells. Therefore, it is more important to improve the system capacity inside the $(0.5R, R)$ region.

[0068] In multiuser systems, where all users are uniformly distributed in the cell, we need to consider different resource allocation scenarios which were defined above. Assuming that each

cell has radius R , we define parameter α ($0 < \alpha < 1$) such that the interior area is located in the $(0, \alpha R)$ region and the exterior area is located in the $(\alpha R, R)$ region.

[0069] In LTE systems, eNB distinguishes between the interior and exterior users based on their corresponding uplink power received at the central DRU. To implement this technique, we
 5 propose a threshold T_p as a parameter in eNB such that users with uplink power higher than T_p are assigned as interior users, and vice versa.

[0070] Note that

$$\begin{aligned} N_{\text{interior}} &= \alpha^2 N_{\text{users}}, \\ N_{\text{exterior}} &= (1 - \alpha^2) N_{\text{users}}, \end{aligned} \quad (15)$$

10 where N_{interior} represents the number of interior users, N_{exterior} represents the number of exterior users, and N_{users} represents the total number of users. We will consider the 3 different resource allocation scenarios mentioned above, where the number of RBs per users assigned in the different regions (interior or exterior) for different Scenarios can be expressed as in TABLE 1, where $N_{RB^{(F_i)}}, i=1,2,3$ represents the number of RBs for given frequency part F_i and $N_{RB^{(F_i)}}^{\text{tech}}$
 15 represent the number of RBs for given F_i for the different techniques.

[0071] Note that in all 3 scenarios we have applied the Round Robin scheduling technique.

[0072] If we consider the number of RBs which are assigned to the different regional users under the different scenarios, the capacity metric of the total system can be obtained by,

$$C_{\text{metric}}^{\text{total, tech}} = C_{\text{metric}}^{\text{(tech, } F_1)} + C_{\text{metric}}^{\text{(tech, } F_2)} + C_{\text{metric}}^{\text{(tech, } F_3)} \quad (16)$$

20 where

$$\begin{aligned} C_{\text{metric}}^{\text{(tech, } F_i)} &= N_{RB^{(F_i)}}^{\text{tech}} \cdot C^{(F_i)}, \quad i=1,2,3, \\ \text{tech} &\in \left\{ \text{DAS-SFR-SC1, DAS-SFR-SC2, DAS-SFR-SC3,} \right. \\ &\quad \left. \text{DAS-HFR3, Con-HFR3, DAS-HFR1, Con-HFR1} \right\}. \end{aligned}$$

[0073] In FIG. 5, the capacity metric is provided considering a uniform distribution of users and a Round Robin Scheduler. In this example, we assume α is 0.5. The achieved capacity of
 25 the DAS-SFR architecture with Scenario2 and Scenario3 is higher than that of DAS-SFR system with Scenario1, especially near the central DRU. This is due to the fact that the F_2 and F_3 RBs are

not assigned to the exterior users which have very low SINR and all F_2 and F_3 RBs assigned to interior users.

[0074] Comparing Scenario2 with Scenario3, we observe that the achievable capacity for interior users in DAS-SFR architecture with Scenario2 is slightly higher than that of scenario3 due to the full frequency reuse for the interior users in Scenario2. However, in Scenario3, only the F_2 and F_3 frequency bands are used by the interior users. Conversely, the achieved capacity for exterior users in a DAS-SFR architecture with Scenario3 is slightly higher than that of Scenario 2, due to the fact that all F_1 RBs are used by the exterior users, whereas in Scenario2 the F_1 RBs are partially used by the exterior users.

[0075] Note that FIG. 5 illustrates that the DAS-HFR1 technique outperforms other techniques in terms of the achieved throughput by majority of the interior users; nevertheless, SFR technique significantly improves the system performance by making up for the dead spots which appear at the cell edges. Note that there is a significant amount of interference happening in the $(0.8R, R)$ region, causing the dead spots in DAS-HFR1 technique.

[0076] In the established system environment, we evaluate the total system capacity for several cases for non-edge users (inside $(0, 0.8R)$ region) and edge users (inside $(0.8R, R)$). We assume α sweeps from 0.2 to 0.8. Remember that α manages the portion of resources allocated in Scenario2 and Scenario3.

[0077] FIG. 6 illustrates the analytical results for the non-edge users and edge users, where α varies between 0.2 and 0.8.

[0078] Note that as α changes, the number of RBs assigned to the users in Scenario2 and Scenario3 changes accordingly. However, in other techniques, with changing α , number of assigned RBs to the users remains unaltered. As α increases, the edge user's throughput increases in Scenario3, due to the fact that more RBs are assigned to those users. Specifically, as α increases, less users need to use F_1 RBs in Scenario3. However, in other techniques, edge users experience a constant throughput, due to the fact that the number of RBs allocated to the edge users remains constant as α changes. Specifically, regardless of the changes in α , all F_1 RBs are assigned to all users.

[0079] As α increases, non-edge users' throughput decreases, due to the fact that the total constant number of F_2 and F_3 RBs should be assigned to more number of users accordingly. Note that the rate of decrease in user throughput for non-edge users for Scenario3 is more than that of Scenario2, as α increases. The reason behind this is that the rate of decrease in number of RBs assigned to the non-edge users in Scenario3 is more than that of Scenario2. Specifically, as was previously mentioned, since no F_1 RBs are assigned to the non-edge users in Scenario3, non-edge users' throughput in Scenario3 is less than that of Scenario2.

[0080] The capacity of the above mentioned architectures is investigated through the system level simulation. We consider the two-ring hexagonal cellular system with nineteen eNBs, such that each cell has 7 DRUs, as in FIG. 2, where the eNBs distance is 500 meters. The 10 UEs are located in each DRU area, following a uniform distribution. An eNB allocates the available RBs to UEs by estimating the signaling and uplink power of UEs. We use the simulation parameters listed in TABLE 2.

[0081] At a TTI of simulation, the eNB in a cell gathers the CQI information of UEs and allocates the RBs to each UE using the Round Robin scheduling technique. The throughput of a UE is obtained based on the SINR of the UE in the assigned RB. In system level simulation, SINR is determined by the path loss and lognormal fading measured in RB. The throughput of a UE_m is estimated using the Shannon capacity as follows

$$C_m^{(f)} = W_{RB^{(f)}} \log(1 + SINR_m^{(f)}), \quad f = F_1, F_2, F_3 \quad (16)$$

where, $W_{RB^{(f)}}$ is the bandwidth of RBs assigned to a UE and $SINR_m^{(f)}$ is the SINR of a UE_m . The cell capacity in each region is total throughput of UEs in the corresponding region and is expressed as follows

$$C_{total} = \sum_{i=1}^3 \sum_{m=1}^M C_m^{(F_i)} \quad (17)$$

where M is the number of UEs in a group.

[0082] FIG. 7 illustrates the simulation results for the non-edge users and edge users, where α varies between 0.2 and 0.8. The results obtained through simulation corroborate the results provided by analytical methods.

[0083] The overall capacity increases by using the SFR technique, since the spectral efficiency in the interior region is higher than that in the exterior region when compared to HFR3

technique. The cell edge user's throughput increases by using the SFR technique, since the interference signal from neighbor cells is lower than that when we use HFR1 technique. In an embodiment using Scenario3 as a resource allocation strategy, the exterior user's throughput is increased.

5 **[0084]** FIG. 8 is a simplified flowchart illustrating a method of implementing soft frequency reuse according to an embodiment of the present invention. The method 800 includes transmitting and receiving data in a first geographical area and a first frequency band (810). The method also includes transmitting and receiving data in a second geographical area and a second frequency band (812). In an embodiment, the first geographical area is a central area of a cell including multiple DRUs and the second geographical area is a peripheral area of the cell. The method further includes transmitting and receiving data in a third geographical area and at least a portion of the first frequency band (814). At least a portion of the frequency band used for the third geographical area is thus reused in relation to the first geographical area. The method also includes transmitting and receiving data in a fourth geographical area and a third frequency band (816). In an embodiment, the third geographical area is a central area of a cell including multiple DRUs and the fourth geographical area is a peripheral area of the cell. The third frequency band may overlap with part of the first frequency band. Accordingly, multiple cells reuse the portions of the first frequency band, which may include multiple sub-bands that are contiguous or separated in frequency domain, in multiple adjacent cells.

20 **[0085]** It should be appreciated that the specific steps illustrated in FIG. 8 provide a particular method of implementing soft frequency reuse according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 8 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

30 **[0086]** FIG. 9 is a simplified flowchart illustrating a method of implementing fractional frequency reuse according to an embodiment of the present invention. The method 900 includes transmitting and receiving data in a first geographical area and a first frequency band (910) and

transmitting and receiving data in a second geographical area and a second frequency band (912). In an embodiment, the second geographical area surrounds the first geographical area. As an example, the first geographical area can be a central portion of a cell that is covered by a central DRU and the second geographical area can be a peripheral portion of the cell that is covered by a plurality of peripheral DRUs.

[0087] The method further includes transmitting and receiving data in a third geographical area and the first frequency band (914) and transmitting and receiving data in a fourth geographical area and a third frequency band (916). In an embodiment, the third geographical area surrounds the fourth geographical area. As an example, the third geographical area can be a central portion of another cell that is covered by a central DRU and the fourth geographical area can be a peripheral portion of the another cell that is covered by a plurality of peripheral DRUs. Thus, the frequency band used at the central portion of the first cell is reused at the central portion of the second cell. In embodiments, the frequency bands are not limited to contiguous blocks of frequencies, but can include sub-bands each including one or more frequency. The third frequency band can be different from the second frequency band, providing differing frequencies for the differing cells at adjacent geographical areas.

[0088] It should be appreciated that the specific steps illustrated in FIG. 9 provide a particular method of implementing fractional frequency reuse according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 9 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0089] It is also understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and scope of the appended claims.

TABLE 1. Number of RBs per user

	Interior region			Exterior region		
	F_1	F_2	F_3	F_1	F_2	F_3
$N_{RB^{(F)}}^{DAS-SFR-SC1}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	$\frac{N_{RB^{(F_2)}}}{N_{users}}$	$\frac{N_{RB^{(F_3)}}}{N_{users}}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	$\frac{N_{RB^{(F_2)}}}{N_{users}}$	$\frac{N_{RB^{(F_3)}}}{N_{users}}$
$N_{RB^{(F)}}^{DAS-SFR-SC2}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	$\frac{N_{RB^{(F_2)}}}{\alpha^2 N_{users}}$	$\frac{N_{RB^{(F_3)}}}{\alpha^2 N_{users}}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	0	0
$N_{RB^{(F)}}^{DAS-SFR-SC3}$	0	$\frac{N_{RB^{(F_2)}}}{\alpha^2 N_{users}}$	$\frac{N_{RB^{(F_3)}}}{\alpha^2 N_{users}}$	$\frac{N_{RB^{(F_1)}}}{(1-\alpha^2) N_{users}}$	0	0
$N_{RB^{(F)}}^{DAS-HFR3}, N_{RB^{(F)}}^{Con-HFR3}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	0	0	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	0	0
$N_{RB^{(F)}}^{DAS-HFR1}, N_{RB^{(F)}}^{Con-HFR1}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	$\frac{N_{RB^{(F_2)}}}{N_{users}}$	$\frac{N_{RB^{(F_3)}}}{N_{users}}$	$\frac{N_{RB^{(F_1)}}}{N_{users}}$	$\frac{N_{RB^{(F_2)}}}{N_{users}}$	$\frac{N_{RB^{(F_3)}}}{N_{users}}$

TABLE 2. Simulation Parameters

Parameters	Value
Channel Bandwidth for each Frequency Part	5 MHz
Carrier Frequency	2.14 GHz
FFT size	1024
Number of Resource Blocks for each Frequency Part	25
Subcarrier Spacing	15 kHz
Cellular Layout	Hexagonal grid, 19 sites
Inter-eNB Distance	500 meters
Log-normal Shadowing	8 dB
Propagation loss	$128.1 + 37.6 \log_{10}(R(km))$
White Noise Power Density	-174 dBm/Hz
Scheduling	Round Robin
TTI	1 ms

WHAT IS CLAIMED IS:

- 1 1. A method for routing and switching operator RF signals, the method
2 comprising:
3 providing one or more Digital Remote Units (DRUs), each configured to receive
4 one or more downlink radio frequencies and to transmit one or more uplink radio frequencies;
5 providing at least one Digital Access Unit (DAU) configured to communicate
6 with at least one of the one or more DRUs;
7 wherein a first DRU of a first cell is operable to communicate using a first set of
8 frequencies characterized by a first frequency band over a first geographic footprint;
9 wherein a plurality of additional DRUs of the first cell are operable to
10 communicate using a second set of frequencies characterized by a second frequency band
11 different from the first frequency band over a second geographic footprint surrounding the first
12 geographic footprint;
13 wherein a first DRU of a second cell is operable to communicate using the first
14 set of frequencies over a third geographical footprint; and
15 wherein a plurality of additional DRUs of the second cell are operable to
16 communication using a third set of frequencies characterized by a third frequency band different
17 from the first frequency band over a fourth geographic range surrounding the third geographic
18 range.
- 1 2. The method of claim 1 wherein the DRUs comprise remote radio units.
- 1 3. The method of claim 1 further comprising communicating between a
2 plurality of Base Transceiver Stations (BTS) coupled to the at least one DAU.
- 1 4. The method of claim 1 wherein one or more of the plurality of BTSs are
2 coupled to the DAU using a plurality of BTS sector RF connections.
- 1 5. The method of claim 1 further comprising transporting signals between
2 one or more DRUs and the at least one DAU.
- 3 6. A method of distributing communications frequencies, the method
4 providing:
5 providing a set of communications units in an array configuration;

6 transmitting and receiving, from a first communications unit of the set of
7 communications units,
8 a first set of frequencies characterized by a first frequency band and a first
9 geographic footprint; and
10 a second set of frequencies characterized by a second frequency band
11 different from the first frequency band and a second geographic range surrounding the first
12 geographic footprint; and
13 transmitting, and receiving, from a second communications unit of the set of
14 communications units,
15 a third set of frequencies including one or more frequencies in the first
16 frequency band and a third geographical footprint; and
17 a fourth set of frequencies including one or more frequencies in a third
18 frequency band and a fourth geographical footprint surrounding the third geographical footprint.

1 7. The method of claim 6 wherein the set of communications units include a
2 plurality of remote units in communication with a host unit.

1 8. The method of claim 6 wherein the first geographic footprint is centered
2 on the first communications unit.

1 9. The method of claim 6 wherein the second geographic footprint is a
2 peripheral footprint centered on the first communications unit.

1 10. The method of claim 6 wherein the third geographical footprint is centered
2 on the second communications unit.

1 11. The method of claim 6 wherein the fourth geographical footprint is a
2 peripheral footprint centered on the second communications unit.

1 12. The method of claim 6 wherein the second geographical footprint abuts
2 the fourth geographical footprint.

1 13. The method of claim 6 further comprising transmitting, and receiving,
2 from a third communications unit of the set of communications units,

3 a fifth set of frequencies including one or more frequencies in the first
4 frequency band and a fifth geographical footprint; and
5 a sixth set of frequencies in a fourth frequency band and a sixth
6 geographical footprint surrounding the fifth geographical footprint.

1 14. A communications system comprising:
2 a first communications unit operable to transmit and receive communications
3 using a first set of frequencies in a first frequency range and associated with a first geographical
4 footprint and a second set of frequencies in a second frequency range and associated with a
5 second geographical footprint; and
6 a second communications unit operable to transmit and receive communications
7 using one or more of the first set of frequencies in a region associated with a third geographical
8 footprint and one or more of the second set of frequencies in a region associated with a fourth
9 geographical footprint.

1 15. The communications system of claim 14 wherein the first communications
2 unit comprises a central DRU and a plurality of peripheral DRUs disposed adjacent the central
3 DRU.

1 16. The communications system of claim 15 further comprising a DAU
2 communicatively coupled to the central DRU and the plurality of peripheral DRUs.

1 17. The communications system of claim 15 further comprising a DAU
2 communicatively coupled to the central DRU.

1 18. The communications system of claim 17 further comprising a second
2 DAU communicatively coupled to the plurality of peripheral DRUs.

1 19. The communications system of claim 14 wherein the second geographical
2 footprint at least partially surrounds the first geographical footprint.

1 20. The communications system of claim 14 wherein the fourth geographical
2 footprint at least partially surrounds the third geographical footprint.

1 21. The communications system of claim 14 wherein the second geographical
2 footprint at least partially overlaps the fourth geographical footprint.

1 22. A frequency sharing system for a distributed antenna system, the
2 frequency sharing system comprising:
3 a first frequency band characterized by a first frequency range and associated with
4 a first geographic area associated with a first communications unit;
5 a second frequency band characterized by a second frequency range different
6 from the first frequency range and associated with a second geographic area at least partially
7 surrounding the first geographic area;
8 a third frequency band overlapping at least a portion of the second frequency band
9 and associated with a third geographic area associated with a second communications unit; and
10 a fourth frequency band overlapping at least a portion of the first frequency band
11 and associated with a fourth geographic area at least partially surrounding the third geographic
12 area.

1 23. The frequency sharing system of claim 22 wherein the first geographic
2 area is characterized by a first border and the second geographic area is characterized by a
3 second border, wherein a predetermined distance separates the first border and the second
4 border.

1 24. The frequency sharing system of claim 22 wherein the first frequency
2 band and the second frequency band are contiguous frequency bands.

1 25. The frequency sharing system of claim 22 wherein the first frequency
2 band comprises a first contiguous range of frequencies and the second frequency band comprises
3 a second contiguous range of frequencies adjacent the first frequency band.

1 26. A communications system comprising:
2 a first communications unit operable to transmit and receive communications
3 using a first set of frequencies over a first predetermined area; and
4 a second communications unit operable to transmit and receive communications
5 using a second set of frequencies over a second predetermined area;
6 wherein the first communications unit is operable to transmit and receive
7 communications using a third set of frequencies over a third predetermined area; and

8 wherein the second communications unit is operable to transmit and receive
9 communications using at least a portion of the third set of frequencies over a fourth
10 predetermined area.

1 27. The communications system of claim 26 wherein the first communications
2 unit comprises a plurality of DRUs, at least one of the plurality of DRUs being coupled to a
3 DAU.

1 28. The communications system of claim 26 wherein the third predetermined
2 area is at least partially surrounded by the first predetermined area.

1 29. The communications system of claim 26 wherein the fourth predetermined
2 area is at least partially surrounded by the second predetermined area.

1 30. The communications system of claim 26 wherein the first set of
2 frequencies, the second set of frequencies, and the third set of frequencies are distinct
3 frequencies.

1 31. The communications system of claim 26 wherein the first communications
2 unit and the second communications unit are disposed in an array configuration.

1 32. The communications system of claim 26 wherein the first predetermined
2 area overlaps at least a portion of the second predetermined area.

1 33. The communications system of claim 26 wherein the third predetermined
2 area includes a location of the first communications unit and the fourth predetermined area
3 includes a location of the second communications unit.

1 34. The communications system of claim 26 wherein the first communications
2 unit comprises a first plurality of digital remote units and the second communications unit
3 comprises a second plurality of digital remote units.

1 35. The communications system of claim 28 wherein the first set of
2 frequencies is associated with a first number of the first plurality of digital remote units and the
3 third set of frequencies is associated with another of the first plurality of digital remote units.

1 36. The communications system of claim 29 wherein the second set of
2 frequencies is associated with a first number of the second plurality of digital remote units and
3 the third set of frequencies is associated with another of the second plurality of digital remote
4 units.

ABSTRACT OF THE DISCLOSURE

A method for routing and switching operator RF signals includes providing one or more Digital Remote Units (DRUs), each configured to receive one or more downlink radio frequencies and to transmit one or more uplink radio frequencies and providing at least one Digital Access Unit (DAU) configured to communicate with at least one of the one or more DRUs. A first DRU of a first cell is operable to communicate using a first set of frequencies characterized by a first frequency band over a first geographic footprint and a plurality of additional DRUs of the first cell are operable to communicate using a second set of frequencies characterized by a second frequency band different from the first frequency band over a second geographic footprint surrounding the first geographic footprint. A first DRU of a second cell is operable to communicate using the first set of frequencies over a third geographical footprint and a plurality of additional DRUs of the second cell are operable to communication using a third set of frequencies characterized by a third frequency band different from the first frequency band over a fourth geographic range surrounding the third geographic range.

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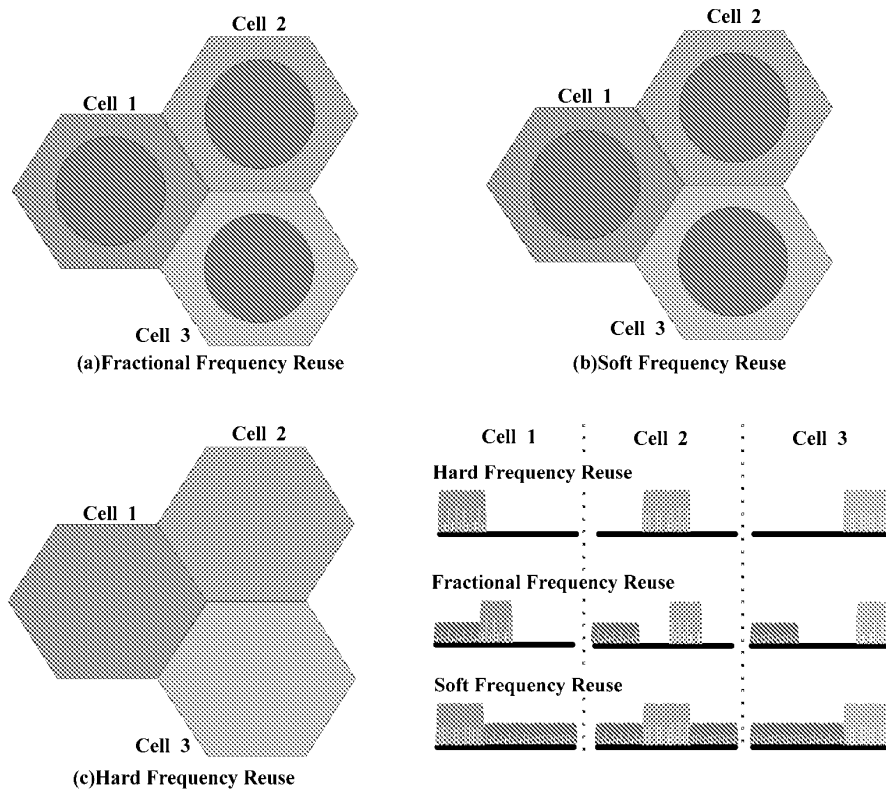


FIG. 1. Different Frequency Reuse Techniques

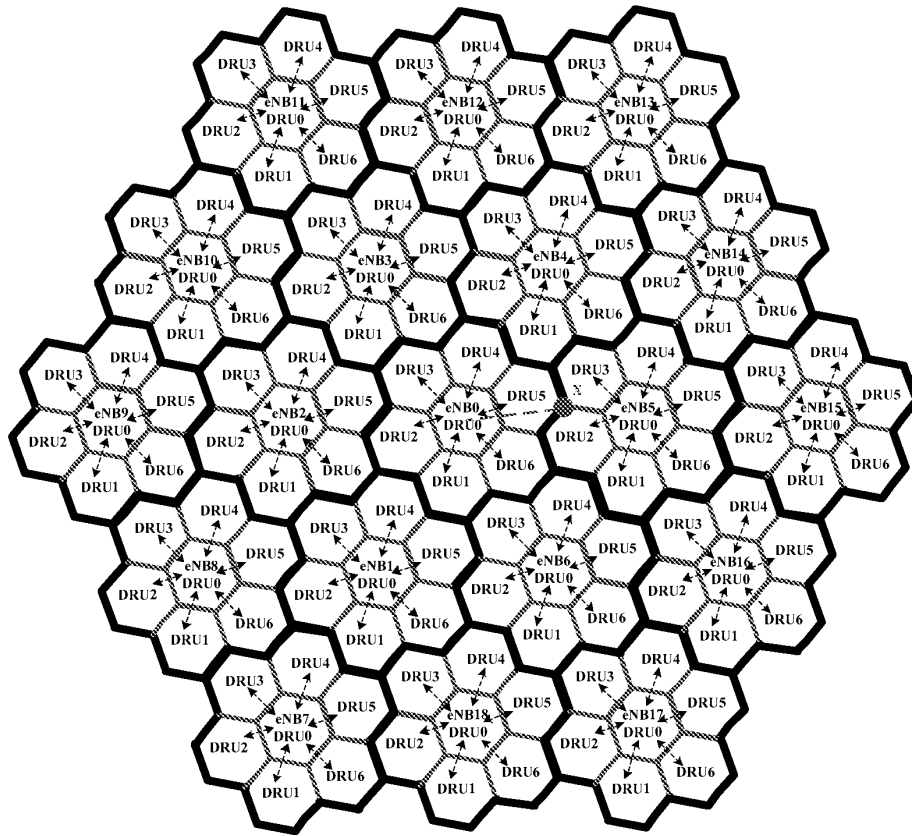


FIG. 2. Structure of a Distributed Antenna System

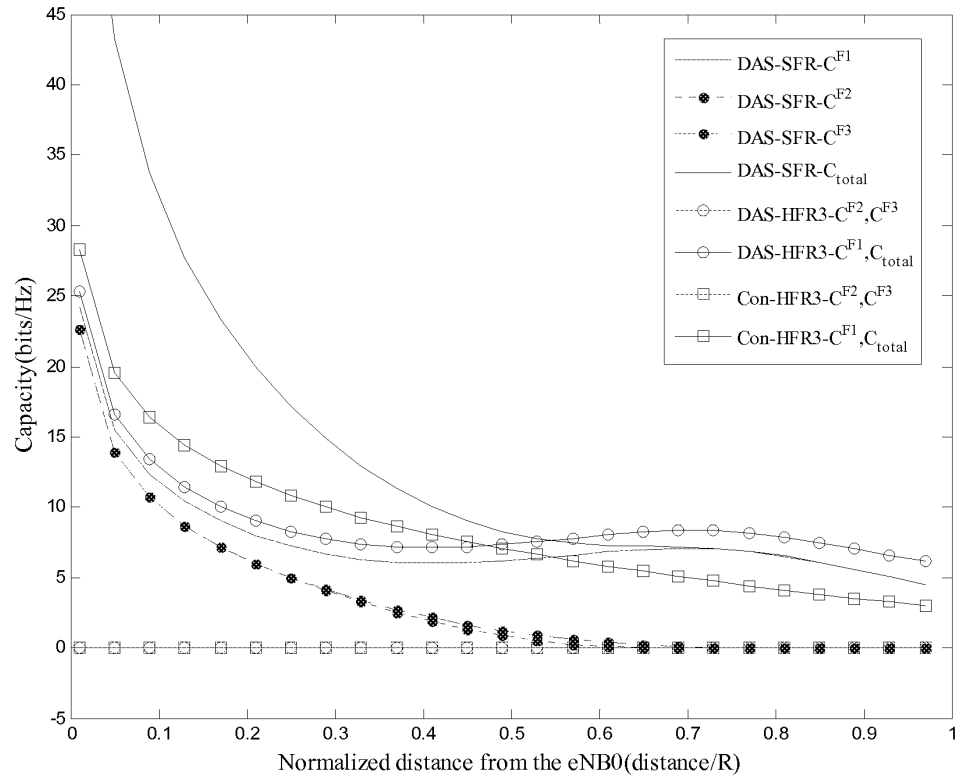


FIG. 3. Ergodic capacity versus the normalized distance from the DRU0

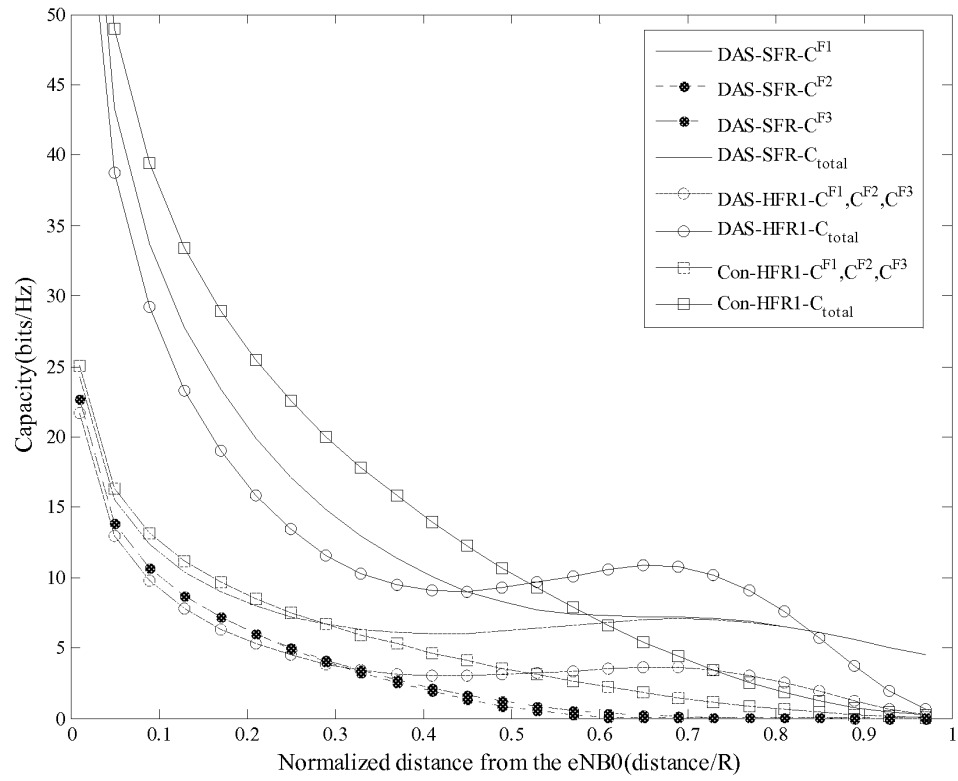


FIG. 4. Ergodic capacity versus the normalized distance from the DRU0

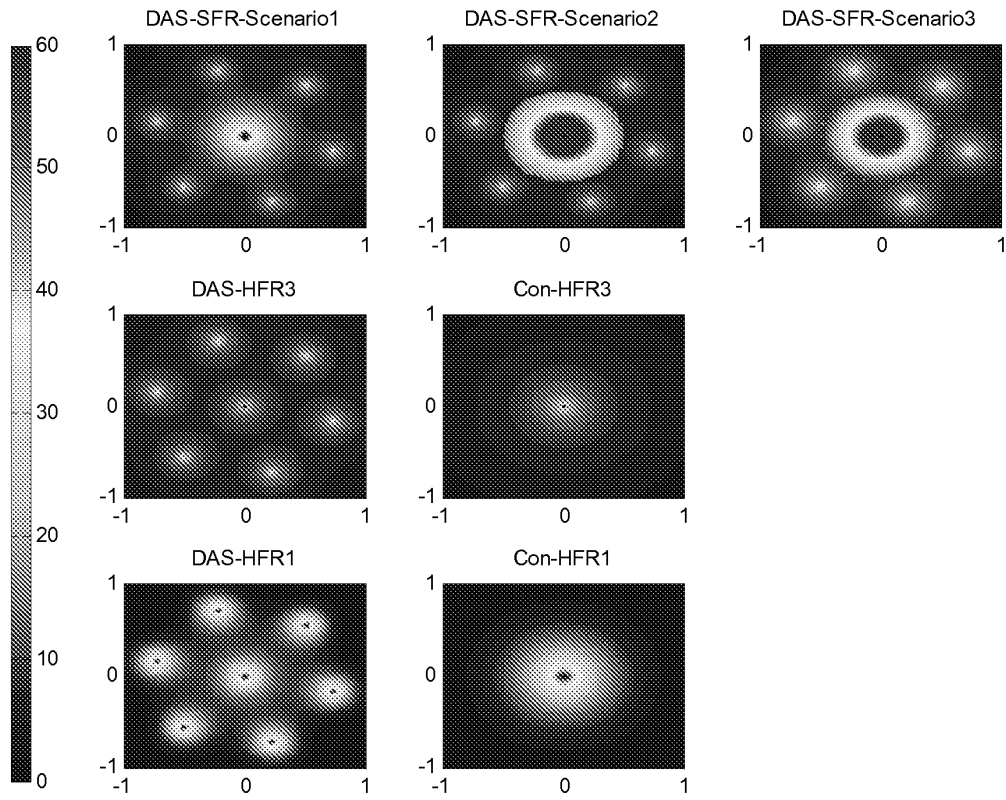


FIG. 5. Capacity metric for multiuser case versus the normalized distance from the DRU0 in eNB0(central cell) area

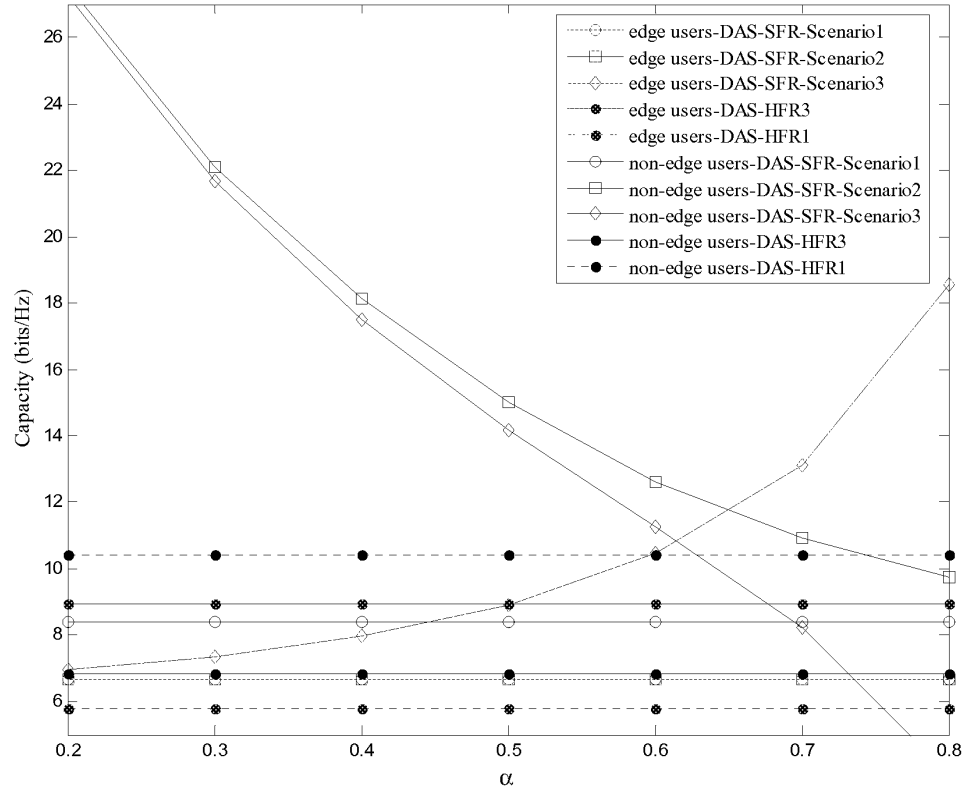


FIG. 6. Analytical ergodic capacity for edge cell and non-edge cell users versus α

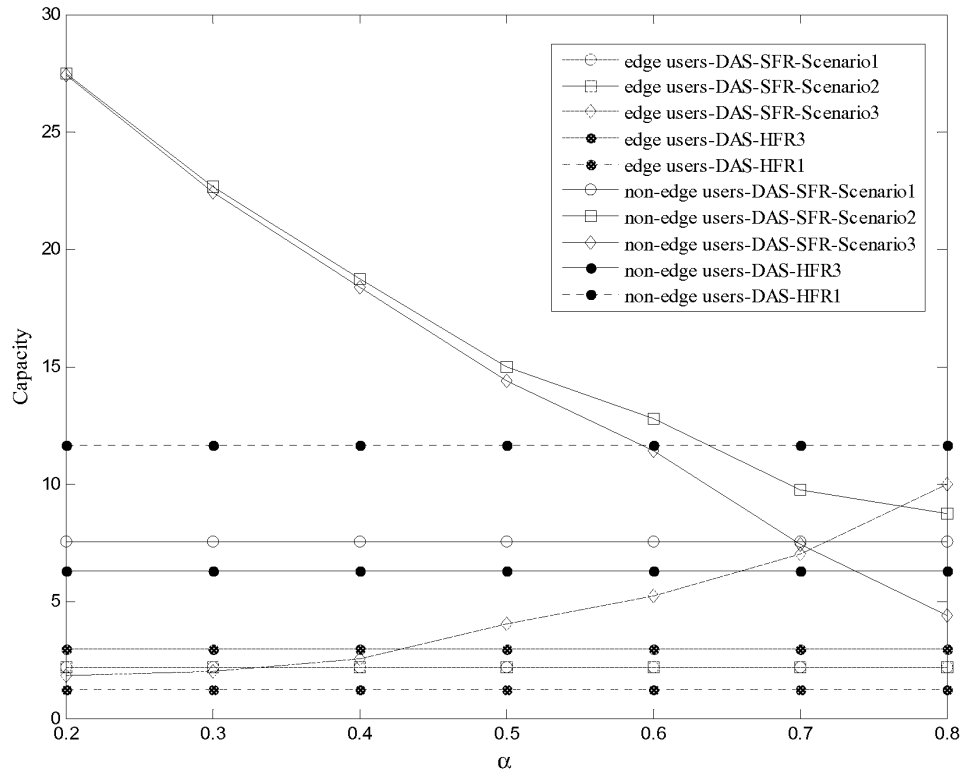


FIG. 7. Simulation capacity for edge cell and non-edge cell users versus α

800

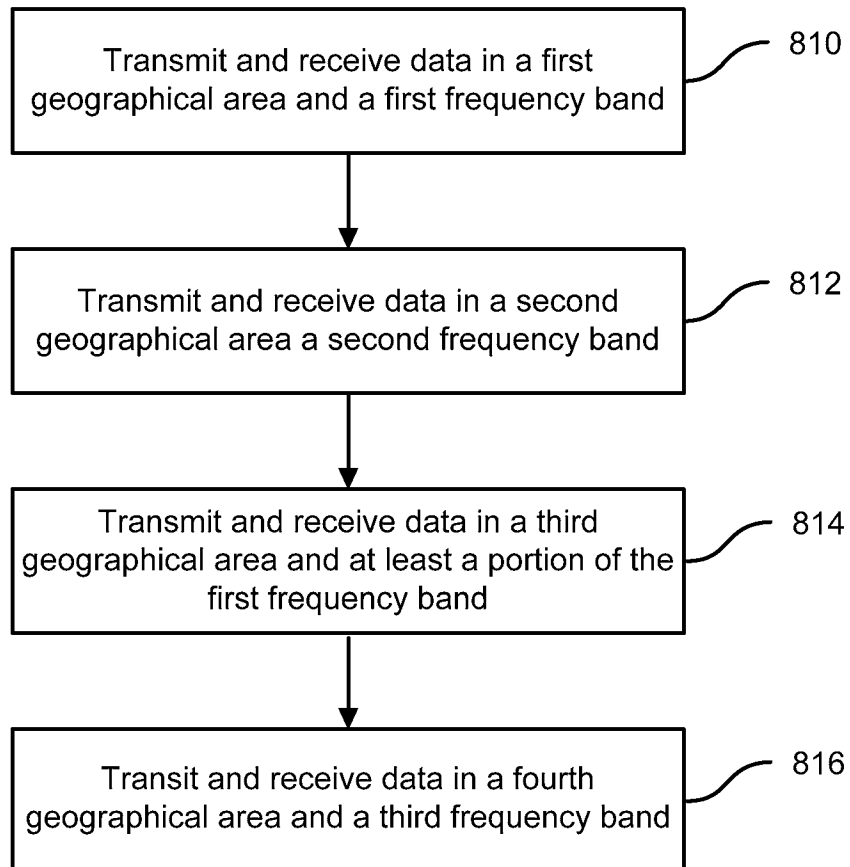


FIG. 8

900

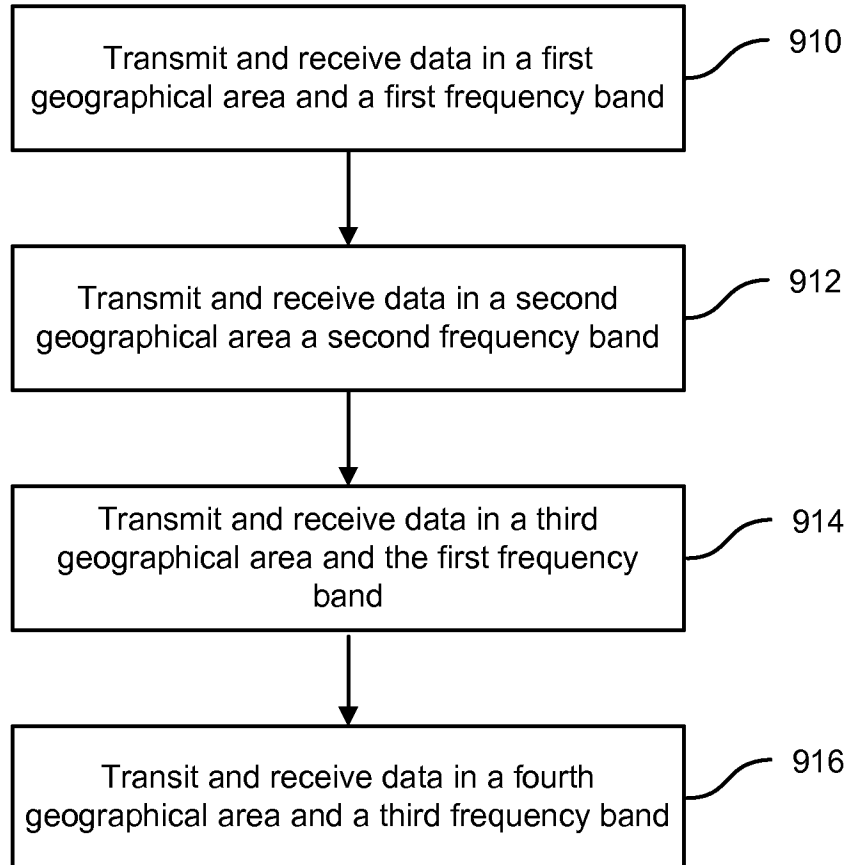


FIG. 9

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