(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
2 February 2017 (02.02.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/019121 A1

(51) International Patent Classification:
H04W 72/08 (2009.01) *H04W 88/06* (2009.01)

(21) International Application Number:
PCT/US2015/067148

(22) International Filing Date:
21 December 2015 (21.12.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/199,040 30 July 2015 (30.07.2015) US

(71) Applicant: **INTEL CORPORATION** [US/US]; 2200 Mission College Boulevard, Santa Clara, California 95054 (US).

(72) Inventors: **ARYAFAR, Ehsan**; 2200 Mission College Blvd, Santa Clara, California 95054 (US). **SINGH, Sarabjot**; 4507 Carlyle Court, Apt 121, Santa Clara, California 95054 (US). **HIMAYAT, Nageen**; 44609 Parkmeadow Dr., Fremont, California 94539 (US). **TALWAR, Shilpa**; 10606 Creston Drive, Los Altos, California 94024 (US).

(74) Agent: **JOHNSON, R. Whitney**; STOEL RIVES LLP, 201 South Main, Suite 1100, Salt Lake City, Utah 84111 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

(54) **Title**: SYSTEMS AND METHODS FOR DISTRIBUTED FAIR RESOURCE ALLOCATION IN MULTI RADIO ACCESS TECHNOLOGY BASED HETEROGENEOUS NETWORKS

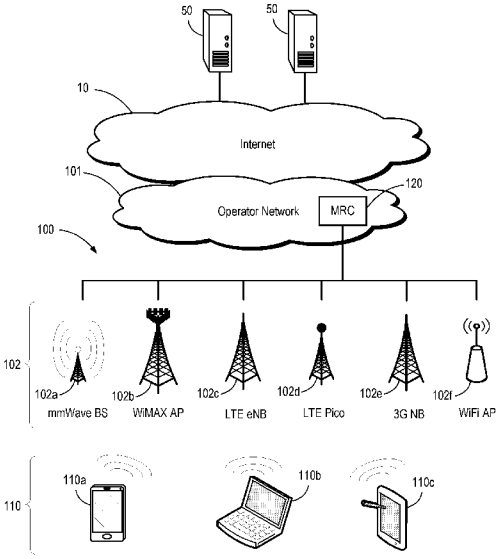


FIG. 1

(57) **Abstract**: Systems and methods provide embodiments for fast and fair distributed resource allocation for bearer splitting in HetNets. A distributed fair resource allocation can be performed by each base stations of a HetNet in an independent manner. A centralized resource allocation modification can be performed at a centralized network entity to enhance a result of the distributed fair resource allocation embodiments or other distributed resource allocation approaches.

WO 2017/019121 A1

SYSTEMS AND METHODS FOR DISTRIBUTED FAIR RESOURCE ALLOCATION IN MULTI RADIO ACCESS TECHNOLOGY BASED HETEROGENEOUS NETWORKS

Related Applications

[0001] This application is an international filing based on U.S. Provisional Patent Application No. 62/199,040, titled FAST AND FAIR DISTRIBUTED BEARER SPLITTING IN HETNETS, filed July 30, 2015, which is hereby incorporated herein by reference in its entirety.

Technical Field

[0002] The present disclosure generally relates to wireless communications over heterogeneous wireless communication systems.

Brief Description of the Drawings

[0003] FIG. 1 is an example heterogeneous network with varying radio access technologies at various base stations within the network.

[0004] FIG. 2 is a flow diagram of a distributed fair resource allocation process, according to one embodiment of the present disclosure.

[0005] FIG. 3 is a flow diagram of a centralized resource allocation modification process, according to one embodiment.

[0006] FIG. 4 illustrates, for one embodiment, example components of a user equipment device.

[0007] FIG. 5 is a block diagram illustrating electronic device circuitry 500 that may be eNB circuitry, UE circuitry, network node circuitry, or some other type of circuitry in accordance with various embodiments

Detailed Description of Preferred Embodiments

[0008] Wireless mobile communication technology uses various standards and protocols to transmit data between a base station and a wireless communication device. Wireless wide area network (WWAN) communication system standards and protocols can include, for example, the 3rd Generation Partnership Project (3GPP) long term evolution (LTE), and the Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard, which is commonly known to industry groups as worldwide

interoperability for microwave access (WiMAX). Wireless local area network (WLAN) can include, for example, the IEEE 802.11 standard, which is commonly known to industry groups as WiFi. Other WWAN and WLAN standards and protocols are also known.

[0009] In 3GPP radio access networks (RANs) in LTE systems, a base station may include Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Node Bs (also commonly denoted as evolved Node Bs, enhanced Node Bs, eNodeBs, or eNBs) and/or Radio Network Controllers (RNCs) in an E-UTRAN, which communicate with a wireless communication device, known as user equipment (UE). In LTE networks, an E-UTRAN may include a plurality of eNBs and may communicate with a plurality of UEs. An evolved packet core (EPC) may communicatively couple the E-UTRAN to an external network, such as the Internet. LTE networks include radio access technologies (RATs) and core radio network architecture that can provide high data rate, low latency, packet optimization, and improved system capacity and coverage.

[0010] In homogeneous networks, a node, also called a macro node or macro cell, may provide basic wireless coverage to wireless devices in a cell. The cell may be the area in which the wireless devices are operable to communicate with the macro node. Heterogeneous networks (HetNets) may be used to handle the increased traffic loads on the macro nodes due to increased usage and functionality of wireless devices. HetNets may include a layer of planned high power macro nodes (macro-eNBs or macro cells) overlaid with layers of lower power nodes (small cells, small-eNBs, micro-eNBs, pico-eNBs, femto-eNBs, or home eNBs [HeNBs]) that may be deployed in a less well-planned or even entirely uncoordinated manner within the coverage area (cell) of a macro node. The lower power nodes may generally be referred to as “small cells,” small nodes, or low power nodes. HetNets may also include various types of nodes utilizing varying types of RATs, such as LTE eNBs, 3G NodeBs, WiFi APs, and WiMAX base stations.

[0011] As used herein, the terms “node” and “cell” are both intended to be synonymous and refer to a wireless transmission point operable to communicate with multiple wireless mobile devices, such as a UE, or another base station. Furthermore, cells or nodes may also be WiFi access points (APs), or multi-radio cells with both WiFi/ cellular or additional RATs. For example, nodes or cells may

include various technologies such that cells operating on different RATs are integrated in one unified HetNet.

[0012] Considerable effort has been directed to selecting the best RAT or base station for clients or user equipment (UE) through which all of the UE's traffic is subsequently delivered. This is largely because the network architectures have not supported the traffic splitting feature until now.

[0013] Traffic splitting, however, could play a crucial role in load balancing in emerging multi-radio access technology (RAT) based HetNets. Recent developments like the ongoing standardization of the "3GPP RAN anchored WLAN" network architecture for LTE-WLAN aggregation (LWA) by 3GPP RAN working group 2 & 3 for Release 13 may support algorithms for traffic splitting. In this architecture, the 3GPP interface is used as the control and mobility anchor for the WLAN link, which serves as an additional "carrier" within the 3GPP network and is used for data offload. 3GPP has agreed to a below PDCP offload solution for WLAN aggregation, wherein PDCP packets are sent to the WLAN termination point (which could be an access point (AP) or an Access Controller-AP) via the Xw interface (e.g., GTP-U). There is also a proposal to make WLAN offload transparent to the WLAN AP (e.g., no AP impact) by sending above or below PDCP IP or PDCP data over an IP/IP-sec tunnel between the eNB and the UE. Here bearer traffic may be entirely offloaded to WLAN or the bearer is potentially split over both WLAN and LTE links. One of the key design questions is on how the traffic should be split across these different RATs for each UE so as to maximize the system performance.

[0014] Various architectural frameworks have been proposed for LWA bearer splitting for the 3GPP anchored WLAN architecture. General architectures applicable to several different protocol aggregation solutions have been proposed, such as "push" and "pull" models of bearer splitting. Many of the key principles of these architectures can operate effectively across both collocated and non-collocated WLAN deployments and across uplink and downlink bearer splitting, and can support various protocol aggregation solutions that are presently available. To leverage the capabilities of these architectures, bearer splitting algorithms have also been proposed to minimize the maximum delay observed by a typical user in the network. However, in the presently available bearer splitting algorithms, the network wide fairness is not considered.

[0015] The present disclosure provides embodiments for fast and fair distributed resource allocation for bearer splitting in HetNets. A distributed fair resource allocation can be performed by each of the base stations of a HetNet in an independent manner. A centralized resource allocation modification can be performed at a centralized network entity to enhance a result of the distributed fair resource allocation embodiments or other distributed resource allocation approaches.

[0016] In certain embodiments of the present disclosure, a distributed fair resource allocation may be performed. Each client (e.g., UE) may share information regarding its physical layer (PHY) rate and achieved total service rate (e.g., total throughput) to all base stations (e.g., LTE eNB, 3G NodeB, WiFi AP, and WiMAX base station) to which the client has a non-zero PHY rate. The base stations then distributedly and independently calculate the resources (e.g., time resource fractions) that should be allocated to each client in a manner that the overall fairness across all clients is increased.

[0017] In certain embodiments of the present disclosure, a centralized resource allocation modification may be performed. Base stations may share information regarding the clients connected to them, their service rate, and/or PHY rate to a centralized controller. The centralized controller can then opportunistically enhance the outcome of a distributed resource allocation, such as the disclosed distributed fair resource allocation embodiments disclosed herein.

[0018] Generally, legacy architectures, and discussions and literature regarding the same, assume presence of a centralized network entity. However, such a centralized architecture design may require real-time signal sharing between base stations and the central entity which can become a bottleneck with large network size, with high network dynamics, or when low latency links between base stations and the central entity do not exist.

[0019] The distributed fair resource allocation of presently disclosed embodiments may be performed autonomously by each base station and is a fully distributed solution. The centralized resource allocation modification of presently disclosed embodiments may be performed independent of the distributed fair resource allocation, such as with other distributed resource allocation approaches. A hybrid approach of the presently disclosed embodiments may utilize the distributed fair resource allocation disclosed herein and also the centralized resource allocation

modification disclosed herein. The hybrid approach may utilize opportunistic centralized network supervision and may have tunable computational complexity. This makes the hybrid design adaptable to network dynamics as well as varied delays between base stations and the central entity.

[0020] More specifically, certain embodiments herein may provide bearer splitting across multiple RATs that are disposed at separate and distinct nodes (e.g., an eNB providing WWAN service and a WiFi AP providing WLAN service) within the HetNet. The radio links may include a WLAN link, an LTE link (or other WWAN link), a millimeter wave link, and/or the like. For the bearer splitting, a proportion of traffic to be sent on each link (or via each base station) may need to be determined (e.g., bearer split control). The bearer split decisions may account for link quality and traffic quality of service (QoS) requirements across users. The present disclosure provides embodiments for fast and fair distributed bearer splitting using distributed fair resource allocation. The decisions regarding how to split bearer traffic, or allocate resources in splitting bearer traffic, can be performed by each of the base stations of a HetNet in an independent manner. A centralized resource allocation modification can be performed at a centralized network entity to enhance a result of the distributed fair resource allocation.

[0021] FIG. 1 is an example heterogeneous network (HetNet) 100, which may include and/or couple to an operator network 101 and provide varying radio access technologies at various base stations 102, including for example an mmWave base station 102a, a WiMAX base station 102b, an LTE eNB 102c, an LTE pico cell 102d, a 3G NodeB 102e, and a WiFi AP 102f (individually and collectively 102). The HetNet 100 provides or otherwise enables wireless communications by one or more clients or user equipment device (UE) 110, such as a smart phone 110a, a laptop computer 110b, a tablet computing device 110c, or the like. The operator network 101 may be coupled to an Internet 10, or similar publicly accessible computer network, that includes one or more IP application servers 50. The operator network may also include a centralized controller, such as a multiple rack controller (MRC) 120, that has some backbone connection to the different bases stations 102. The MRC 120 may direct bearer traffic to the various base stations 102. The HetNet 100 provides bearer traffic through the base stations 102 to a plurality of UEs 110. The HetNet 100 enables bearer traffic splitting, such as over two or more base stations 102, potentially using different RAT. In other words, a UE 110 may transmit and/or

receive content of a single source content provider, over multiple RATs, which may also be via multiple base stations 102.

[0022] Where an operator is primarily providing LTE or LTE advanced wireless communication services, the HetNet 100 may include a plurality of eNBs 102c (macro cells), a plurality of LTE pico cells 102d, and/or a plurality of 3G NodeBs 102e. The HetNet 100 may optionally include one or more additional RATs in different base stations 102, such as illustrated in FIG. 1, to supplement the primary LTE RAT.

[0023] Each base station 102 has a limited transmission range and thus the set of UEs 110 each base station 102 serves is limited to the UEs 110 within the range of the base station 102. Neighboring base stations 102 may overlap in their coverage. While determining which base station 102 a UE 110 should associate with among same technology base stations 102 (e.g., choosing the optimal WiFi base station if a client has a WiFi RAT), the present disclosure can assume there exists a rule to pre-determine client RAT-BS association, for example, based on the maximum received signal strength, or any load balancing algorithm.

[0024] Also, each UE 110 may include multiple RATs and therefore can have access to multiple base stations 102. The present disclosure assumes that each base station 102 splits bearer traffic to each UE 110 over multiple base stations 102 using multiple RATs. A design consideration in a HetNet 100 that splits bearer traffic to a UE 110 over multiple base stations 102 using multiple RATs is how the traffic should be split across these different base stations 102 so as to maximize performance.

[0025] The present disclosure provides systems and methods that perform fast and fair distributed resource allocation for bearer splitting in the HetNet 100. A distributed fair resource allocation can be performed by each of the base stations 102 in an independent manner. Each client UE 110 may share information regarding its PHY rate and total service rate (e.g., total throughput) to all base stations 102 to which the client UE 110 has a non-zero PHY rate. The base stations 102 then distributedly and independently calculate the resources (e.g., time resource fractions) that should be allocated to each UE 110 in a manner that the overall fairness across all UEs 110 is increased.

[0026] The present disclosures also provides for centralized resource allocation modification of a distributed resource allocation. The HetNet 100 may include a

centralized resource allocation modification that may be performed at a centralized network controller, such as the MRC 120. Base stations 102 may share information with the centralized network controller 120 regarding which UEs 110 are connected to the base station 102, the resource allocation to each UE 110, and a PHY rate achieved at each UE 110. The centralized controller 120 can then opportunistically enhance the outcome of a distributed resource allocation performed by the base stations 102.

[0027] As can be appreciated, the systems and methods disclosed herein can be deployed in any of a variety of HetNet architectures that provide wireless communication to UEs.

[0028] FIG. 2 is flow diagram of a distributed fair resource allocation process 200, according to one embodiment of the present disclosure. The process 200 may be implemented by a system that includes HetNet wireless network deployment that includes a set of base stations M = {1 … M}, and a set of clients N = {1…N} (e.g., UEs). FIG. 1 shows an example of such a system with a HetNet of M base stations 102 and N UEs 110. The system may be a multi-rate system and use $R_{i,j}$ to denote the PHY rate of a UE *i* from base station *j*. Since each base station *j* serves more than one client *i*, the clients may share resources such as time and frequency slots (e.g., in 3/4G) or transmission opportunities (e.g., in WiFi). The PHY rate $R_{i,j}$ experienced by a client *i* from a base station *j* thus depends on the load of the base station *j* and will therefore be a fraction of $R_{i,j}$. In certain embodiments, each base station *j* may employ a time division multiple access (TDMA) throughput sharing model and $\lambda_{i,j}$ can denote the fraction of time allocated to client *i* by base station *j*. Hence, the throughput achieved by client *i* from base station *j* is equal to $\lambda_{i,j}R_{i,j}$ and its total throughput would be the sum of throughputs achieved across all base stations.

[0029] A performance metric in the embodiments of the present disclosure is referred to as service rate and can be denoted by h_i, which is a generic term that is a notion of quality of service (QoS) or performance achieved by client *i*, and encompasses metrics such as, "throughput," "weighted throughput," and other metrics. Certain embodiments are generic and encompass and apply to any definition of h_i, as long as in the proposed definition h_i is an increasing function of $R_{i,j}$ and $\lambda_{i,j}$. Two example service rate h_i definitions are:

$$\begin{cases} h_i = \text{Total Throughput} = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j} \\ h_i = \dfrac{\text{Total Throughput}}{\text{User Specific Weight}} = \dfrac{\sum_{j=1}^{M} \lambda_{i,j} R_{i,j}}{\omega_i} \end{cases}$$

[0030] The process 200 of FIG. 2 includes a generic distributed resource allocation algorithm that is implemented in a HetNet by each base station. Each client *i* reports its current service rate h_i,and its achieved or otherwise observed PHY rate to all base stations to which it has a non-zero PHY rate. In return, each base station tries to locally equalize the service rates across all its plurality of clients. The process 200 of FIG. 2 can equalize service rates and increase fairness across the plurality of clients by (i) sorting by service rates: the plurality of clients are sorted based on their total received service rates from other base stations; and (ii) equalizing service rates: shifting resources from high service rate clients to lower ones. The process 200 enables the base station to locally enhance fairness across its plurality of clients.

[0031] An indication of a service rate h_i is received 202 from each client *i* of the plurality of clients. The indication of the service rate h_i may depend on how the service rate h_i is defined. In certain embodiments, the indication received 202 may include an aggregation of a link service rate achieved at the client from one or more other base stations, other than the instant base station *j*. In certain embodiment, the indication may be received 202 in the form of a total throughput h_i, in a form such as defined above. The indication may also be received 202 as an aggregation of the PHY rate $R_{i,j}$ achieved according to a current allocation of resources, including a current time resource fraction $\lambda_{i,j}$ from only one or more other base stations, excluding the instant base station *j*.

[0032] The plurality of clients of the base station are sorted 204 according to the service rate achieved by each client. The sorting 204 may be based on the service rate achieved from other base stations h'_i, such that $h'_1 \leq \cdots \leq h'_k \leq h'_{k+1} \leq \cdots \leq h'_n$.

[0033] A new allocation of resources is determined 206 that would enhance equalization of the service rates across the plurality of clients. The new allocation of resources may be referred to as a more equalized service rate across the plurality of

clients. Equalization may be a trend toward a fairness objective. The fairness objective may be determined by, or otherwise dependent on, the definition of service rate and a definition of fairness. Fairness is not limited to equal distribution of resources, equal service rates, and/or equal PHY rates. A fairness objective may broadly encompass any objective of enhancing overall effectiveness, efficiency, and/or performance of a system. For example, in a system including a first UE with 3G and WiFi capability and a second UE with LTE, 3G, and WiFi capability, a fairness objective may be such that the second UE achieves a much higher total throughput (simply because of the faster PHY rate available through the additional LTE RAT) than the first UE.

[0034] In certain embodiments, in which the service h_i is defined as a weighted total throughput, the new allocation of resources achieves a more equalized service rate h''_i for each UE such that:

$$h''_1 = h''_2 = \ldots = h''_k = \gamma \mid \lambda'_{1,j} > 0, \sum_{i=1}^{k} \lambda'_{i,j} = 1$$

$$h''_{k+1}, \ldots, h''_{n'} \geq \gamma \text{ and } \lambda_{i,j} = 0,$$

where γ is a client group service rate, updated resource fraction $\lambda'_{i,j}$ is an update to time resource fraction $\lambda_{i,j}$ to achieve h''_i, and h''_i is a total service rate that is a more equalized service rate achieved by UE *i* after the new allocation of resources by the base station. The new allocation resources may be determined so as to achieve more equalized service rates h''_i of the plurality of UEs by determining updated resource fractions $\lambda'_{i,j}$, client index *k,* and client group service rate γ such that:

$$h'_1 + \frac{\lambda'_{1,j} R_{1,j}}{\omega_1} = h'_2 + \frac{\lambda'_{2,j} R_{2,j}}{\omega_2} = \cdots \leq h'_k + \frac{\lambda'_{k,j} R_{k,j}}{\omega_k} = \gamma$$

$$h'_k < \gamma \leq h'_{k+1}$$

$$\sum_{i=1}^{k} \lambda'_{i,j} = 1, \quad \lambda'_{i,j} > 0,$$

where ω_i is a weighting for UE *i* of the plurality of UEs.

[0035] The client index *k* can be determined, for example, by checking the following inequalities:

$$\text{if} \quad \frac{(h'_2 - h'_1)\omega_1}{R_{1,j}} > 1 \Rightarrow k = 1, \quad \text{else}$$

$$\text{if} \quad \frac{(h'_3 - h'_1)\omega_1}{R_{1,j}} + \frac{(h'_3 - h'_2)\omega_2}{R_{2,j}} > 1 \Rightarrow k = 2, \quad \text{else}$$

$$\ldots$$

if $\frac{(h'_n - h'_1)\omega_1}{R_{1,j}} + \cdots \frac{(h'_n - h'_{n-1})\omega_{n'-1}}{R_{2,j}} > 1 \Rightarrow k = n' - 1,$ else

$$k = n'.$$

[0036] The client group service rate γ can be determined by:

$$\sum_{i=1}^{k} \frac{(\gamma - h'_i)\omega_i}{R_{i,j}} = 1.$$

[0037] With client index *k,* and client group service rate γ determined, updated resource fractions $\lambda'_{i,j}$ can easily be determined by solving the equation:

$$h'_1 + \frac{\lambda'_{1,j}R_{1,j}}{\omega_1} = h'_2 + \frac{\lambda'_{2,j}R_{2,j}}{\omega_2} = \cdots \leq h'_k + \frac{\lambda'_{k,j}R_{k,j}}{\omega_k} = \gamma$$

[0038] A randomization parameter pj may be introduced in order to avoid concurrent adaptation of a single client by multiple base stations.

[0039] The foregoing example of an algorithm for determining a fair allocation of resources in a distributed manner can be summarized in the following pseudo code for a distributed fair resource allocation algorithm, according to one embodiment:

Algorithm DFRA: Distributed Fair Resource Allocation
Input: h_i , $R_{i,j}$, and $\lambda_{i,j}$ $\forall$ client *i* for which $R_{i,j} > 0$
randomization parameter p_j
Output: Updated $\lambda_{i,j}$
1. Let *n'* denote the number of clients *s.t.* $R_{i,j} > 0$
2. Sort clients based on their total achieved service rates from **other** BSs, *i.e.*,
$h'_1 \leq \ldots \leq h'_k \leq h'_{k+1} \leq \ldots \leq h'_{n'}$
3. Equalize service rates, *i.e.*, find *k*, *γ*, and $\lambda'_{i,j}$ *s.t.*
$h''_1 = h''_2 = \ldots = h''_k = \gamma \mid \lambda'_{i,j} > 0$, $\sum_{i=1}^{k} \lambda'_{i,j} = 1$
$h''_{k+1}, \ldots, h''_{n'} \geq \gamma$ *and* $\lambda'_{i,j} = 0$
4. **if** $(rand < p_j^{mj+1})$ **then**
5. *Update* $\lambda_{i,j}$
6. **if** concurrent adaptation **then** increment m_j
7. **else** reset m_j to *0*
8. **end**

[0040] Certain algorithms for determining a fair allocation of resources may reach stability or equilibrium, such that additional equalizations may have nominal impact. At a state of equilibrium, processing to determine a new allocation of resources and/or transmittal of the new allocation of resources may be costly relative to any benefit. Accordingly, techniques can be introduced to reduce processing and/or transmittal as the process 200 approaches and/or reaches a state of equilibrium.

[0041] In certain embodiments, whether or not the updated resource fractions $\lambda'_{i,j}$ are included in a new allocation of resources may depend on whether the equalized service rate h''_i would represent an increase over a current minimum service rate min h_i by a multiplicative factor (1+*d*). Specifically, if $h''_i \geq \min h_i (1+d)$, then the new allocation of resources is transmitted to each UE; and if $h''_i < \min h_i (1+d)$, then the new allocation of resources is not transmitted to each UE and the base station communicates with the plurality of UEs according to a current allocation of resources.

[0042] A centralized intervention process may also enhance performance despite, or beyond, an equalization state, such as will be described below with reference to FIG. 3.

[0043] The new allocation of resources for each client of the plurality of clients is transmitted 208 or otherwise communicated to the plurality of clients. For example, an updated resource fraction $\lambda'_{i,j}$ may be transmitted to each client *i*. Each client may utilize new allocation of resources, or relevant portion thereof, to configure communication with the base station *j* according to the new allocation of resources.

[0044] The base station can then communicate 210 with each client of the plurality of clients according to the new allocation of resources.

[0045] The distributed fair resource allocation process 200 of FIG. 2 can operate effectively in a distributed manner, without any centralized control, to enhance performance of a HetNet with respect to a fairness objective.

[0046] In other embodiments, centralized intervention can improve efficiency of the distributed fair resource allocation process 200 of FIG. 2, and of other distributed resource allocation processes. In such hybrid embodiments, both a distributed resource allocation process and a centralized intervention process are utilized. One example of a centralized intervention process is described below with reference to FIG. 3. A centralized intervention process may be implemented through or by a

network controller (NC) that has information about a set of clients linked to each base station of the network and the PHY rates of those sets of clients.

[0047] In practical HetNet deployments, a central entity would have different communication links (with different delays, capacity, etc.) to different base stations. This, coupled with the extent of network dynamics (e.g., client mobility), poses a limit on how frequent resource allocation needs to be recalculated and, therefore, how much processing can be done in the NC.

[0048] For example, in a static (low mobility) network in which base stations have high capacity links to the NC, the resource allocation problem can be solved in a fully centralized manner. In contrast, when a central controller does not exist (e.g., when different base stations belong to different network operators) or in a highly dynamic network with low capacity BS-NC links, the problem can only be solved in a fully distributed manner.

[0049] The disclosed hybrid embodiments provide a middle ground architecture that divides processing and/or computation into two parts: distributed computation by each base station followed by tunable (in terms of computation time) and opportunistic centralized supervision that enhances the outcome of the distributed solution.

[0050] FIG. 3 is flow diagram of a centralized resource allocation modification process 300, according to one embodiment. A network controller (NC) is assumed, or a base station or other network component operating as a centralized entity with backbone connection to other base stations is assumed. The process 300 may identify cyclic shifts across base stations and modifies their resource fractions (e.g., time resource fraction $\lambda_{i,j}$) such that the outcome has a higher maximum-minimum fair allocation than the starting point. The process 300 can centrally modify a resource allocation by (i) constructing a directed graph representation of the HetNet; (ii) determining an appropriate shift in resources for each edge; and (iii) for a pre-determined number of iterations (a) finding a directed cycle in the graph (e.g., by using Depth First Search method) and (b) finding the optimal value of shifted resource fractions and modifying the base station resources accordingly.

[0051] PHY rates $R_{i,j}$ are received 302 from a plurality of base stations for tracking or compilation in a PHY rate matrix $[R_{i,j}]_{NxM}$ and time resource fractions $\lambda_{i,j}$ are also received 302 for a resource allocation matrix $[\lambda_{i,j}]_{NxM}$, where N is a number

of the UEs, M is a number of the base stations, $R_{i,j}$ is a PHY rate achieved at UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*.

[0052] A graph G = (V, E) is constructed 304, where V is a set of vertices and E is a set of edges between the vertices. Each vertex *j* in V corresponds to base station *j*. There is a directed edge *e* in E from *j* to *j'* where $R_{i,j} < R_{i,j'}$ and $\lambda_{i,j} > 0$.

[0053] An appropriate shift in time resource fractions $\lambda_{i,j}$ is determined 306 for each edge *e*. Determining an appropriate shift ε in time resource fractions $\lambda_{i,j}$ for each directed edge *e* of E may include defining $\varepsilon_{j,j'} = max_i \lambda_{i,j}$ and $i^{j,j'} = \arg max_i \lambda_{i,j}$ for each UE *i* where $R_{i,j} < R_{i,j'}$ and $\lambda_{i,j} > 0$.

[0054] A tuning variable T is received 308 specifying a number of iterations for tuning computation time. A computation time of an apparatus implementing the process 300 may be tunable by adjusting the iterations *T*.

[0055] For a predetermined number of iterations *T*: a directed cycle in the graph G is identified 310, an optimal value of shift in time resource fractions $\lambda_{i,j}$ is determined 312, and the optimal value of shift in time resource fractions $\lambda_{i,j}$ is communicated 314 to the corresponding base station *j*.

[0056] The directed cycle in the graph G may be determined 312 using a depth first search method.

[0057] An optimal value of shift ε in time resource fractions $\lambda_{i,j}$ may be determined 312 by setting $\varepsilon = \min\{\varepsilon_{j'1,j'2}, \varepsilon_{j'2,j'3}, \ldots, \varepsilon_{j'k,j'1}\}$ and for each edge *e* = (j', j'') that is in *c*: setting $i' = i^{j',j''}$; setting $\lambda_{i',j'} = \lambda_{i',j'} - \varepsilon$; setting $\lambda_{i',j''} = \lambda_{i',j''} + \varepsilon$; removing *e* from E, if $\lambda_{i',j'} = 0$; and updating $\varepsilon_{j',j''}$ and $i^{j',j''}$.

[0058] The foregoing example of an algorithm for centralized intervention can be summarized in the following pseudo code for a centralized resource allocation modification algorithm, according to one embodiment:

Algorithm CRAM: Centralized Resource Allocation Modification
Input: PHY rate matrix $[R_{ij}]_{N\times M}$
Resource allocation matrix $[\lambda_{ij}]_{N\times M}$
Number of iterations T
Output: Updated resource allocation matrix $[\lambda_{ij}]_{N\times M}$
1. Construct a directed Graph $G = (V, E)$ with M vertices
Each vertex $j \in V$ corresponds to the BS $j \in M$
$\exists$ a directed edge $e \in E$ from j to j' (*i.e.*, $e = (j,j')$) if for some client i, $R_{ij} < R_{ij'}$ and $\lambda_{ij} > 0$
2. $\forall e = (j,j')$, let $\varepsilon_{ij'} = max_i \lambda_{ij}$ and $i^{(j,j')} = arg\ max_i \lambda_{ij}$ be defined over those clients i for which $R_{ij} < R_{ij'}$ and $\lambda_{ij} > 0$
3. **for** t = 1:T
4. Let $c = j'_1 \rightarrow j'_2 \rightarrow \ldots \rightarrow j'_k \rightarrow j'_1$ denote a directed cycle in G
5. **if** c = {} **break**
6. Let $\varepsilon = min\ \{\varepsilon_{j'1,j'2}, \varepsilon_{j'2,j'3}, \ldots, \varepsilon_{j'k,j'1}\}$
7. $\forall e = (j',j'') \in$ c **do**
8. let $i' = i^{(j',j'')}$ (as defined in Line 2)
9. $\lambda_{i'j'} = \lambda_{i'j'} - \varepsilon$
10. $\lambda_{i'j''} = \lambda_{i'j''} + \varepsilon$
11. **if** $\lambda_{i'j'} = 0$ remove e from E
12. update $\varepsilon_{i'j''}$ and $i^{j',j''}$
13. **end**

[0059] Additional policies can be used to reduce the convergence time of the distributed fair resource allocation process 200 of FIG. 2 and the centralized resource modification process 300 of FIG. 3. First, note that since the distributed fair resource allocation process 200 operates on real numbers, the time to convergence in theory can be unbounded. This problem can be easily solved by defining a discretization factor on service rates or time fractions. In particular, we can avoid this issue by defining the following property or policy: During service rate equalization by a base station in performing the distributed fair resource allocation process 200, the local minimum service rate must increase by at least a multiplicative factor equal to 1+d, as described above.

[0060] An additional policy can be used that defines an order on when base stations execute distributed fair resource allocation process 200 and guarantees a linear bound on convergence time: A base station that serves the client with lowest service rate across all clients has a higher priority for service rate equalization. This second policy can be easily implemented in the distributed fair resource allocation process 200 by making the base station randomization parameter pj proportional to the service rates. Further, in networks in which a wired backbone exists (e.g., enterprise networks), each base station can broadcast its minimum service rate to other base stations, and therefore base stations can distributedly determine an order (or adjust their pjs) based on other base stations' minimum service rates.

[0061] Embodiments described herein may be implemented into a system using any suitably configured hardware and/or software. FIG. 4 illustrates, for one embodiment, example components of a UE device 400. In some embodiments, the UE device 400 may include application circuitry 402, baseband circuitry 404, Radio Frequency (RF) circuitry 406, front-end module (FEM) circuitry 408 and one or more antennas 410, coupled together at least as shown.

[0062] The application circuitry 402 may include one or more application processors. For example, the application circuitry 402 may include circuitry such as, but not limited to, one or more single-core or multi-core processors. The processor(s) may include any combination of general-purpose processors and dedicated processors (e.g., graphics processors, application processors, etc.). The processors may be coupled with and/or may include memory/storage and may be configured to execute instructions stored in the memory/storage to enable various applications and/or operating systems to run on the system.

[0063] The baseband circuitry 404 may include circuitry such as, but not limited to, one or more single-core or multi-core processors. The baseband circuitry 404 may include one or more baseband processors and/or control logic to process baseband signals received from a receive signal path of the RF circuitry 406 and to generate baseband signals for a transmit signal path of the RF circuitry 406. The baseband processing circuitry 404 may interface with the application circuitry 402 for generation and processing of the baseband signals and for controlling operations of the RF circuitry 406. For example, in some embodiments, the baseband circuitry 404 may include a second generation (2G) baseband processor 404a, third generation (3G) baseband processor 404b, fourth generation (4G) baseband processor 404c,

and/or other baseband processor(s) 404d for other existing generations or generations in development or to be developed in the future (e.g., fifth generation (5G), sixth generation (6G), etc.). The baseband circuitry 404 (e.g., one or more of baseband processors 404a-d) may handle various radio control functions that enable communication with one or more radio networks via the RF circuitry 406. The radio control functions may include, but are not limited to, signal modulation/demodulation, encoding/decoding, radio frequency shifting, etc. In some embodiments, modulation/demodulation circuitry of the baseband circuitry 404 may include Fast-Fourier Transform (FFT), precoding, and/or constellation mapping/demapping functionality. In some embodiments, encoding/decoding circuitry of the baseband circuitry 404 may include convolution, tail-biting convolution, turbo, Viterbi, and/or Low Density Parity Check (LDPC) encoder/decoder functionality. Embodiments of modulation/demodulation and encoder/decoder functionality are not limited to these examples and may include other suitable functionality in other embodiments.

[0064] In some embodiments, the baseband circuitry 404 may include elements of a protocol stack such as, for example, elements of an evolved universal terrestrial radio access network (E-UTRAN) protocol including, for example, physical (PHY), media access control (MAC), radio link control (RLC), packet data convergence protocol (PDCP), and/or radio resource control (RRC) elements. A central processing unit (CPU) 404e of the baseband circuitry 404 may be configured to run elements of the protocol stack for signaling of the PHY, MAC, RLC, PDCP, and/or RRC layers. In some embodiments, the baseband circuitry 404 may include one or more audio digital signal processor(s) (DSP) 404f. The audio DSP(s) 404f may include elements for compression/decompression and echo cancellation and may include other suitable processing elements in other embodiments. Components of the baseband circuitry 404 may be suitably combined in a single chip or single chipset, or disposed on a same circuit board in some embodiments. In some embodiments, some or all of the constituent components of the baseband circuitry 404 and the application circuitry 402 may be implemented together, such as, for example, on a system on a chip (SOC).

[0065] In some embodiments, the baseband circuitry 404 may provide for communication compatible with one or more radio technologies. For example, in some embodiments, the baseband circuitry 404 may support communication with an

evolved universal terrestrial radio access network (E-UTRAN) and/or other wireless metropolitan area network (WMAN), a wireless local area network (WLAN), or a wireless personal area network (WPAN). Embodiments in which the baseband circuitry 404 is configured to support radio communications of more than one wireless protocol may be referred to as multi-mode baseband circuitry.

[0066] The RF circuitry 406 may enable communication with wireless networks using modulated electromagnetic radiation through a non-solid medium. In various embodiments, the RF circuitry 406 may include switches, filters, amplifiers, etc. to facilitate the communication with the wireless network. The RF circuitry 406 may include a receive signal path, which may include circuitry to down-convert RF signals received from the FEM circuitry 408 and provide baseband signals to the baseband circuitry 404. The RF circuitry 406 may also include a transmit signal path, which may include circuitry to up-convert baseband signals provided by the baseband circuitry 404 and provide RF output signals to the FEM circuitry 408 for transmission.

[0067] In some embodiments, the receive signal path of the RF circuitry 406 may include mixer circuitry 406a, amplifier circuitry 406b, and filter circuitry 406c. The transmit signal path of the RF circuitry 406 may include filter circuitry 406c and mixer circuitry 406a. The RF circuitry 406 may also include synthesizer circuitry 406d for synthesizing a frequency for use by the mixer circuitry 406a of the receive signal path and the transmit signal path. In some embodiments, the mixer circuitry 406a of the receive signal path may be configured to down-convert RF signals received from the FEM circuitry 408 based on the synthesized frequency provided by the synthesizer circuitry 406d. The amplifier circuitry 406b may be configured to amplify the down-converted signals, and the filter circuitry 406c may be a low-pass filter (LPF) or band-pass filter (BPF) configured to remove unwanted signals from the down-converted signals to generate output baseband signals. Output baseband signals may be provided to the baseband circuitry 404 for further processing. In some embodiments, the output baseband signals may be zero-frequency baseband signals, although this is not a requirement. In some embodiments, the mixer circuitry 406a of the receive signal path may comprise passive mixers, although the scope of the embodiments is not limited in this respect.

[0068] In some embodiments, the mixer circuitry 406a of the transmit signal path may be configured to up-convert input baseband signals based on the synthesized frequency provided by the synthesizer circuitry 406d to generate RF output signals

for the FEM circuitry 408. The baseband signals may be provided by the baseband circuitry 404 and may be filtered by the filter circuitry 406c. The filter circuitry 406c may include a low-pass filter (LPF), although the scope of the embodiments is not limited in this respect.

[0069] In some embodiments, the mixer circuitry 406a of the receive signal path and the mixer circuitry 406a of the transmit signal path may include two or more mixers and may be arranged for quadrature downconversion and/or upconversion respectively. In some embodiments, the mixer circuitry 406a of the receive signal path and the mixer circuitry 406a of the transmit signal path may include two or more mixers and may be arranged for image rejection (e.g., Hartley image rejection). In some embodiments, the mixer circuitry 406a of the receive signal path and the mixer circuitry 406a of the transmit signal path may be arranged for direct downconversion and/or direct upconversion, respectively. In some embodiments, the mixer circuitry 406a of the receive signal path and the mixer circuitry 406a of the transmit signal path may be configured for super-heterodyne operation.

[0070] In some embodiments, the output baseband signals and the input baseband signals may be analog baseband signals, although the scope of the embodiments is not limited in this respect. In some alternative embodiments, the output baseband signals and the input baseband signals may be digital baseband signals. In these alternative embodiments, the RF circuitry 406 may include analog-to-digital converter (ADC) and digital-to-analog converter (DAC) circuitry, and the baseband circuitry 404 may include a digital baseband interface to communicate with the RF circuitry 406.

[0071] In some dual-mode embodiments, a separate radio IC circuitry may be provided for processing signals for each spectrum, although the scope of the embodiments is not limited in this respect.

[0072] In some embodiments, the synthesizer circuitry 406d may be a fractional-N synthesizer or a fractional N/N+1 synthesizer, although the scope of the embodiments is not limited in this respect, as other types of frequency synthesizers may be suitable. For example, the synthesizer circuitry 406d may be a delta-sigma synthesizer, a frequency multiplier, or a synthesizer comprising a phase-locked loop with a frequency divider.

[0073] The synthesizer circuitry 406d may be configured to synthesize an output frequency for use by the mixer circuitry 406a of the RF circuitry 406 based on a

frequency input and a divider control input. In some embodiments, the synthesizer circuitry 406d may be a fractional N/N+1 synthesizer.

[0074] In some embodiments, frequency input may be provided by a voltage controlled oscillator (VCO), although that is not a requirement. Divider control input may be provided by either the baseband circuitry 404 or the application circuitry 402, depending on the desired output frequency. In some embodiments, a divider control input (e.g., N) may be determined from a look-up table based on a channel indicated by the application circuitry 402.

[0075] The synthesizer circuitry 406d of the RF circuitry 406 may include a divider, a delay-locked loop (DLL), a multiplexer, and a phase accumulator. In some embodiments, the divider may be a dual modulus divider (DMD), and the phase accumulator may be a digital phase accumulator (DPA). In some embodiments, the DMD may be configured to divide the input signal by either N or N+1 (e.g., based on a carry-out) to provide a fractional division ratio. In some example embodiments, the DLL may include a set of cascaded, tunable, and delay elements; a phase detector; a charge pump; and a D-type flip-flop. In these embodiments, the delay elements may be configured to break up a VCO period into Nd equal packets of phase, where Nd is the number of delay elements in the delay line. In this way, the DLL provides negative feedback to help ensure that the total delay through the delay line is one VCO cycle.

[0076] In some embodiments, the synthesizer circuitry 406d may be configured to generate a carrier frequency as the output frequency, while in other embodiments, the output frequency may be a multiple of the carrier frequency (e.g., twice the carrier frequency, four times the carrier frequency, etc.) and used in conjunction with quadrature generator and divider circuitry to generate multiple signals at the carrier frequency with multiple different phases with respect to each other. In some embodiments, the output frequency may be an LO frequency (fLO). In some embodiments, the RF circuitry 406 may include an IQ/polar converter.

[0077] The FEM circuitry 408 may include a receive signal path, which may include circuitry configured to operate on RF signals received from one or more antennas 410, amplify the received signals, and provide the amplified versions of the received signals to the RF circuitry 406 for further processing. The FEM circuitry 408 may also include a transmit signal path, which may include circuitry configured to

amplify signals for transmission provided by the RF circuitry 406 for transmission by one or more of the one or more antennas 410.

[0078] In some embodiments, the FEM circuitry 408 may include a TX/RX switch to switch between transmit mode and receive mode operation. The receive signal path of the FEM circuitry 408 may include a low-noise amplifier (LNA) to amplify received RF signals and provide the amplified received RF signals as an output (e.g., to the RF circuitry 406). The transmit signal path of the FEM circuitry 408 may include a power amplifier (PA) to amplify input RF signals (e.g., provided by the RF circuitry 406), and one or more filters to generate RF signals for subsequent transmission (e.g., by one or more of the one or more antennas 410).

[0079] In some embodiments, the UE device 400 may include additional elements, such as, for example, memory/storage, a display, a camera, a sensor, and/or an input/output (I/O) interface.

[0080] FIG. 5 is a block diagram illustrating electronic device circuitry 500 that may be eNB (or other base station) circuitry, UE circuitry, network controller circuitry, network node circuitry, or some other type of circuitry in accordance with various embodiments. In embodiments, the electronic device circuitry 500 may be, or may be incorporated into or otherwise a part of, an eNB, a UE, a network node, or some other type of electronic device. In embodiments, the electronic device circuitry 500 may include radio transmit circuitry 510 and receive circuitry 512 coupled to control circuitry 514. In embodiments, the transmit circuitry 510 and/or receive circuitry 512 may be elements or modules of transceiver circuitry, as shown. The electronic device circuitry 500 may be coupled with one or more plurality of antenna elements 516 of one or more antennas. The electronic device circuitry 500 may include or otherwise have access to one or more memory 518 or computer-readable storage media. The electronic device circuitry 500 and/or the components of the electronic device circuitry 500 may be configured to perform operations similar to those described elsewhere in this disclosure.

[0081] In embodiments where the electronic device circuitry 500 is or is incorporated into or otherwise part of a UE (or other client), the receive circuitry 512 may be to receive, from an evolved NodeB (eNB) of a long term evolution (LTE) network (or other base station), an allocation of resources, such as a time resource fraction of a PHY rate at which bearer traffic can be expected to be received. The control circuitry 514 may be to determine a service rate provided by the receive

circuitry 512 and transmit circuitry 510. The transmit circuitry 510 may be to transmit, to the eNB (or other base station), an indication of the service rate achieved and bearer traffic according to the allocation of resources.

[0082] In embodiments where the electronic device circuitry 500 is an eNB and/or a network node, or is incorporated into or is otherwise part of an eNB and/or a network node, the receive circuitry 512 may be to receive, from the UE (or other client), an indication of the service rate achieved at the UE from all base stations. The control circuitry 514 may be to distributedly and independently calculate the resources (e.g., time resource fractions) that should be allocated to the UE and other UEs in a manner that the overall fairness across all UEs is increased. The transmit circuitry 510 may be to transmit to a user equipment (UE) of a long term evolution (LTE) network the new allocation of resources.

[0083] In certain embodiments, the electronic device circuitry 500 shown in FIG. 5 is operable to perform one or more methods or processes, such as the processes shown in FIGS. 2 and 3. In particular, the control circuitry 514 when included in a base station is operable to perform the process of FIG. 2. The control circuitry 514, when included in a network controller (multiple rack controller), a centralized base station or other centralized network node, is operable to perform the process of FIG. 3.

[0084] As used herein, the term "circuitry" may refer to, be part of, or include an Application Specific Integrated Circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group), and/or memory (shared, dedicated, or group) that executes one or more software or firmware programs, a combinational logic circuit, and/or other suitable hardware components that provide the described functionality. In some embodiments, the circuitry may be implemented in, or functions associated with the circuitry may be implemented by, one or more software or firmware modules. In some embodiments, circuitry may include logic, at least partially operable in hardware.

Examples

[0085] The following examples pertain to further embodiments.

[0086] Example 1 is a base station to operate in a radio access network (RAN) based heterogeneous network. The base station includes a wireless interface and one or more processors. The wireless interface includes transmit circuitry and receive circuitry, and communicates with a variety of user equipments (UEs)

according to an allocation of resources. The receive circuitry receives from each UE an indication of a service rate achieved at the UE from one or more other base stations. The processors sort the UEs according to the service rate achieved at each UE from one or more other base stations. The processors determine a new allocation of resources that would enhance equalization of the service rates of the UEs, transmit to each of the UEs, via the wireless interface, the new allocation of resources which organize the UEs to communicate with the base station according to the new allocation of resources, and communicate with the UEs, via the wireless interface, according to the new allocation of resources.

[0087] Example 2 includes the base station of Example 1, where the wireless interface communicates with the UEs using a radio access technology (RAT), and where one or more other base stations communicate with the UEs using a different RAT.

[0088] Example 3 includes a base station of any of Examples 1-2, where the wireless interface communicates with the UEs using a radio access technology (RAT), and where one or more other base stations communicate with the UEs using the same RAT.

[0089] Example 4 includes the base station of any of Examples 1-3, where the indication of the service rate achieved at the UE contains total throughput h_i, which is an aggregation of service rates achieved from all base stations, including the base station and one or more other base stations, such that

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j},$$

where M is a number of base stations in a set of base stations that includes the base station, $R_{i,j}$ is the PHY rate of the UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j.*

[0090] Example 5 includes the base station of any of Examples 1-4, where the indication of the service rate achieved at the UE contains an aggregation of the service rate achieved from only one or more other base stations, and excludes the base station.

[0091] Example 6 includes the base station of Example 1, where the indication of the service rate contains h'_i, which is a portion of a total service rate h_i that is achieved from other base stations.

[0092] Example 7 includes the base station of Example 6, where

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j},$$

$\lambda_{i,j}$ is a resource fraction, and

$R_{i,j}$ is a PHY rate of the UE *i* from base station *j*,

where one or more processors of base station *j* sort the UEs in order of h'_i as follows:

$$h'_1 \leq \cdots \leq h'_k \leq h'_{k+1} \leq \cdots \leq h'_{n'},$$

where the new allocation of resources achieves a more equalized service rate h''_i for each UE is such that

$$h''_1 = h''_2 = \ldots = h''_k = \gamma \mid \lambda'_{1,j} > 0, \sum_{i=1}^{k} \lambda'_{i,j} = 1$$

$$h''_{k+1}, \ldots, h''_{n'} \geq \gamma \text{ and } \lambda_{i,j} = 0,$$

and where γ is a client group service rate and updated resource fraction $\lambda'_{i,j}$ is an update to $\lambda_{i,j}$ to achieve h''_i.

[0093] Example 8 includes the base station of Example 7, where the more equalized service rate h''_i is a total service rate that is a more equalized service rate achieved by UE *i* after the new allocation of resources by the base station.

[0094] Example 9 includes the base station of Example 7, where one or more processors determine the new allocation of resources to achieve more equalized the service rates h''_i of the UEs by determining updated resource fractions $\lambda'_{i,j}$, client index *k,* and client group service rate γ such that

$$h'_1 + \frac{\lambda'_{1,j} R_{1,j}}{\omega_1} = h'_2 + \frac{\lambda'_{2,j} R_{2,j}}{\omega_2} = \cdots \leq h'_k + \frac{\lambda'_{k,j} R_{k,j}}{\omega_k} = \gamma$$

$$h'_k < \gamma \leq h'_{k+1}$$

$$\sum_{i=1}^{k} \lambda'_{i,j} = 1, \quad \lambda'_{i,j} > 0,$$

and where ω_i is a weighting for UE *i* of the UEs.

[0095] Example 10 includes the base station of Example 9, where one or more processors determine client index *k* by checking the following inequalities

$$\text{if} \quad \frac{(h'_2 - h'_1)\omega_1}{R_{1,j}} > 1 \Rightarrow k = 1, \quad \text{else}$$

$$\text{if} \quad \frac{(h'_3 - h'_1)\omega_1}{R_{1,j}} + \frac{(h'_3 - h'_2)\omega_2}{R_{2,j}} > 1 \Rightarrow k = 2, \quad \text{else}$$

$$\cdots$$

$$\text{if} \quad \frac{(h'_n - h'_1)\omega_1}{R_{1,j}} + \cdots \frac{(h'_n - h'_{n-1})\omega_{n'-1}}{R_{2,j}} > 1 \Rightarrow k = n' - 1, \quad \text{else}$$

$$k = n'.$$

[0096] Example 11 includes the base station of Example 10, where the client group service rate γ can be determined by

$$\sum_{i=1}^{k} \frac{(\gamma - h'_i)\omega_i}{R_{i,j}} = 1.$$

[0097] Example 12 includes the base station of any of Examples 1-11, where one or more processors further determine if the equalized service rate h''_i would represent an increase over a current minimum service rate $\min h_i$ by a multiplicative factor (1+*d*), such that

if

$$h''_i \geq min\ h_i\,(1+d),$$

then the new allocation of resources is transmitted to each UE, and

if

$$h''_i < \min h_i\,(1+d),$$

then the new allocation of resources is not transmitted to each UE and the base station communicates with the UEs according to a current allocation of resources.

[0098] Example 13 includes the base station of any of Examples 1-12, where, if the base station serves a UE with a lowest service rate of all UEs, then the base station has a higher priority for service rate equalization than the one or more other base stations.

[0099] Example 14 includes the base station of Example 13, where a randomization parameter p_j is set proportional to the service rates for each UE to facilitate determining a prioritization order.

[00100] Example 15 includes the base station of any of Examples 1-14, where one or more processors receive a lowest service rate for each of the other base stations, determine a prioritization order for service rate equalization, and in accordance with the prioritization order, initiate service rate equalization by sorting the plurality of UEs.

[00101] Example 16 includes the base station of any of Examples 1-15, where the new allocation of resources is determined by one or more processors to improve the service rate of all of the UEs.

[00102] Example 17 includes the base station of any of Examples 1-16, where the new grant of resources is determined by one or more processors to improve the service rate of all of the UEs.

[00103] Example 18 includes the base station of any of Examples 1-17, where the base stations are base stations with which the UE has a non-zero PHY rate.

[00104] Example 19 includes the base station of any of Examples 1-18, further containing a network interface to communicate with an operator network. The network interface receives from the operator network packets of data to be transmitted to the UEs, and also sends to the operator network packets of data to be received from the UEs.

[00105] Example 20 includes the base station of Example 19, where the network interface communicates a new allocation of resources, such that the network controller (e.g., MRC) can split bearer traffic to the base stations according to the new allocation of resources.

[00106] Example 21 includes the base station of any of Examples 1-20, which contains an eNodeB operating based on a long term evolution (LTE) standard.

[00107] Example 22 includes the base station of any of Examples 1-21, which contains a WiFi access point operating in a wireless local area network.

[00108] Example 23 includes the base station of any of Examples 1-22, which comprises a Worldwide Interoperability for Microwave Access (WiMAX) base station.

[00109] Example 24 is an apparatus for wireless communication over a radio access network (RAN) based heterogeneous network. The apparatus contains a wireless interface including transmit circuitry and receive circuitry, one or more processors, and a computer-readable storage medium. The wireless interface communicates with the variety of user equipments (UEs) according to an allocation of resources. A computer-readable storage medium contains instructions that, when executed by one or more processors, cause the apparatus to perform operations to receive, via the receive circuitry of the wireless interface, from each of the UEs indication of a service rate achieved at the UE from one or more base stations. These instructions also sort the UEs according to the service rate achieved at each UE from one or more other base stations, determine a new allocation of resources

for a given based station that would enhance equalization of the service rates of the UEs, transmit, via the transmit circuitry of the wireless interface, to each of the UEs the new allocation of resources to arrange the UEs to communicate with the given base station according to the new allocation of resources, and communicate with the UEs, via the wireless interface, according to the new allocation of resources.

[00110] Example 25 is a computer-readable storage medium. The computer-readable storage medium contains instructions that, when executed by one or more processors, cause the apparatus to perform operations. The operations include receiving, via the receive circuitry of the wireless interface, from each of the UEs an indication of a service rate achieved at the UE from one or more other base stations, sorting the UEs according to the service rate achieved at each UE, determining a new allocation of resources that would enhance equalization of the service rates of the UEs, transmitting, via the transmit circuitry of the wireless interface, to each of the UEs the new allocation of resources to organize the UEs to communicate with the base station according to the new allocation of resources, and finally, communicate with the UEs, via the wireless interface, according to the new allocation of resources.

[00111] Example 26 is an apparatus of a radio access network (RAN) based heterogeneous network for wireless communication with a variety of user equipments (UEs). The apparatus contains one or more processors and a computer-readable storage medium. The computer-readable storage medium contains instructions that, when executed by one or processors, cause the apparatus to perform operations. These operations include receiving from each of the UEs an indication of a service rate achieved at the UE from one or more base stations, sorting the UEs according to the service rate achieved at each UE, determining an allocation of resources for a given base station of one or more base stations that would enhance equalization of the service rates of the UEs, transmitting to each of the UEs the new allocation of resources to arrange the UEs to communicate with the given base station according to the new allocation of resources, so that the given base station can communicate with the UEs according to the new allocation of resources.

[00112] Example 27 is an apparatus of a radio access network (RAN) based heterogeneous network for wireless communication. The apparatus contains one or more network interfaces to provide electronic communications with base stations of

the heterogeneous network that provide wireless communication with user equipments (UEs) and one or more processors. The network interfaces provide electronic communications with base stations of the heterogeneous network that provide wireless communication with user equipments (UEs). The processors receive from the base stations physical layer (PHY) rates $R_{i,j}$ for a PHY rate matrix $[R_{i,j}]_{NxM}$ and time resource fractions $\lambda_{i,j}$ for a resource allocation matrix $[\lambda_{i,j}]_{NxM}$, where N is a number of the UEs, M is a number of the base stations, $R_{i,j}$ is a PHY rate achieved at UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*. The processors construct a graph G = (V, E), where V is a set of vertices and E is a set of edges between the vertices, where each vertex *j* in V corresponds to base station *j* and there is a directed edge *e* in E from *j* to *j'* where $R_{i,j} < R_{i,j'}$ and $\lambda_{i,j} > 0$, determine an appropriate shift in time resource fractions $\lambda_{i,j}$ for each edge *e* for a predetermined number of iterations *T*, identify a directed cycle in the graph G, determine an optimal value of shift in time resource fractions $\lambda_{i,j}$, and communicate the optimal value of shift in time resource fractions $\lambda_{i,j}$ to the corresponding base station *j*.

[00113] Example 28 includes the apparatus of Example 27, where the directed cycle in the graph G is determined using a depth first search method.

[00114] Example 29 includes the apparatus of any of Examples 27-28, where determining an appropriate shift ε in time resource fractions $\lambda_{i,j}$ for each directed edge *e* of E includes defining $\varepsilon_{j,j'} = max_i \lambda_{i,j}$ and $i^{j,j'} = \arg max_i \lambda_{i,j}$ for each UE *i* where $R_{i,j} < R_{i,j'}$ and $\lambda_{i,j} > 0$.

[00115] Example 30 includes the apparatus of Example 29, where $c = j'_1 \rightarrow j'_2 \rightarrow \ldots \rightarrow j'_k \rightarrow j'_1$ denotes the directed cycle in graph G and if $c = \{\}$ the iterations T break, and where determining an optimal value of shift ε in time resource fractions $\lambda_{i,j}$ includes setting $\varepsilon = \min\{\varepsilon_{j'_1,j'_2}, \varepsilon_{j'_2,j'_3}, \ldots, \varepsilon_{j'_k,j'_1}\}$, for each edge *e* = (j', j'') that is in *c*, setting $i' = i^{j',j''}$, setting $\lambda_{i',j'} = \lambda_{i',j'} - \varepsilon$, setting $\lambda_{i',j''} = \lambda_{i',j''} + \varepsilon$, removing *e* from E, if $\lambda_{i',j'} = 0$, and updating $\varepsilon_{j',j''}$ and $i^{j',j''}$.

[00116] Example 31 includes the apparatus of any of Examples 27-30, where a computation time of the apparatus is tunable by adjusting the iterations T.

[00117] Example 32 includes the apparatus of any of Examples 27-31, where the apparatus contains a network controller.

[00118] Example 33 includes the apparatus of any of Examples 27-32, where the apparatus comprises a base station of the heterogeneous network.

[00119] Example 34 includes the apparatus of Example 33, where, using a distributed algorithm, the processors further equalize the service rates for a set of UEs for which each UE in the set of UEs has a service rate from the apparatus that is greater than zero, the distributed algorithm to determine a new allocation of resources to achieve equalized service rates, and includes updated time resource fractions from the new allocation of resources in the resource allocation matrix $[\lambda_{i,j}]_{NxM}$.

[00120] Example 35 includes the apparatus of Example 34, where the processors equalize the service rates by sorting the set of UEs according to the service rate achieved at each UE, determining new time resource fractions $\lambda_{i,j}$ that would enhance equalization of the service rates of the set of UEs, transmitting to each of the UEs a corresponding new time resource fraction to arrange the set of UEs to communicate with the apparatus according to a new allocation of resources so that the given base station can communicate with the UEs according to the new allocation of resources.

[00121] Example 36 is a computer-readable storage medium. The computer-readable storage medium contains instructions that, when executed by the one or processors, cause the apparatus to perform operations. These operations include receiving from the base stations physical layer (PHY) service rates $R_{i,j}$ for a PHY service rate matrix $[R_{i,j}]_{NxM}$ and time resource fractions $\lambda_{i,j}$ for a resource allocation matrix $[\lambda_{i,j}]_{NxM}$, where N is a number of the UEs, M is a number of the base stations, $R_{i,j}$ is a PHY service rate achieved at UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*; constructing a graph G = (V, E), where V is a set of vertices and E is a set of edges between the vertices, where each vertex *j* in V corresponds to base station *j* and there is a directed edge *e* in E from *j* to *j'* where $R_{i,j} < R_{i,j'}$ and $\lambda_{i,j} > 0$; determining an appropriate shift in time resource fractions $\lambda_{i,j}$ for each edge *e*, for a predetermined number of iterations *T*; identifying a directed cycle in the graph G; determining an optimal value of shift in time resource

fractions $\lambda_{i,j}$; and communicating the optimal value of shift in time resource fractions $\lambda_{i,j}$ to the corresponding base station *j*.

[00122] Example 37 is a user equipment (UE). The UE contains a first wireless interface to communicate with a first base station, a second wireless interface to communicate with a second base station, and one or more processors. The processors determine a service rate provided via the first wireless interface and the second wireless interface. generate a message to report the service rate to the first base station and to the second base station, transmit the message via the first wireless interface and the second wireless interface, receive, in response to the message, a new grant of resources from one or more of the first base station and the second base station, and configure the UE to communicate with the first base station and the second base station according to the new grant of resources.

[00123] Example 38 includes the UE of Example 37, where the first wireless interface communicates with the first base station using a first radio access technology (RAT), and the second wireless interface communicates with the second BS using a second RAT different from the first RAT.

[00124] Example 39 includes the UE of any of Examples 37-38, where the first wireless interface communicates with the first base station using a given RAT, and the second wireless interface communicates with the second base station using the same given RAT.

[00125] Example 40 includes the UE of any of Examples 37-39, where the new grant of resources is determined by the base station to improve the service rate of the UE.

[00126] Example 41 includes the UE of any of Examples 37-40, where the new grant of resources is determined by the base station to improve the service rate of another UE.

[00127] Example 42 includes UE of any of Examples 37-41, where the new grant of resources is determined by the base station to improve service rates of a set of UEs, which includes the UE.

[00128] Example 43 includes the UE of any of Examples 37-42, where the service rate is a total service rate provided via the first wireless interface and the second wireless interface in aggregate.

[00129] Example 44 includes the UE of Example 37, where the service rate comprises a first service rate for the first wireless interface and a second service rate for the second wireless interface.

[00130] Example 45 includes the UE of any of Examples 37-44, where the service rate includes one or more of uplink service rates and a downlink service rate.

[00131] Example 46 includes the UE of any of Examples 37-45, where the service rate comprises a total throughput achieved by the UE.

[00132] Example 47 includes the UE of any of Examples 37-46, where the service rate comprises a total throughput h_i achieved by the UE *i*, where

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j}$$

where M is a number of base stations in a set of base stations that includes the first base station and the second base station, $R_{i,j}$ is a physical layer (PHY) rate of the UE *i* to base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*.

[00133] Example 48 includes the UE of any of Examples 37-47, where the service rate contains a total throughput h_i achieved by the UE *i*, where

$$h_i = \frac{\sum_{j=1}^{M} \lambda_{i,j} R_{i,j}}{\omega_i}$$

where M is a number of base stations in a set of base stations that includes the first base station and the second base station, $R_{i,j}$ is a physical rate of the UE *i* to base station *j*, $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*, and ω_i is a weight for UE *i*.

[00134] Example 49 includes the UE of any of Examples 37-48, where the first wireless interface and the second wireless interface comprises one or more of radio frequency (RF) circuitry, front-end module (FEM) circuitry, and an antenna.

[00135] Example 50 is a user equipment (UE). The UE includes a variety of wireless interfaces each using radio access technology (RAT) to communicate with a base station of a variety of base stations, and one or more processors. The processors determine a service rate provided via the variety of wireless interfaces, generate a message to report the service rate to each base station , receive, in response to the message, a new grant of resources from one or more base stations, and configure the UE to communicate via wireless interfaces according to a reallocation of resources.

[00136] Example 51 includes the user equipment of Example 50, where each wireless interface communicates with a corresponding base station using a unique radio access technology (RAT) that is different from any RAT used by any other wireless interface,

[00137] Example 52 includes the user equipment of any of Examples 50-51, where the reallocation of resources is to enhance the service rate.

[00138] Example 53 includes the user equipment of any of Examples 50-52, where the reallocation of resources is determined by one or more of the base stations based on the service rate, and one or more received services rates of other UEs communicating with the base stations.

[00139] Example 54 is a base station to operate in a radio access network (RAN) based heterogeneous network. The base station includes a wireless interface and one or more processors. The wireless interface includes transmit circuitry and receive circuitry which communicates with the (UEs) according to an allocation of resources. The receive circuitry receives from each UE an indication of a service rate achieved at the UE from one or more other base stations. The processors sort the plurality UEs according to the service rate achieved at each UE from the base stations, determine a new allocation of resources that would enhance equalization of the service rates of the UEsm and if the equalized service rate h''_i of a UE *i* would represent an increase over a current minimum service rate min h_i by a multiplicative factor (1+*d*), such that $h''_i \geq \min h_i (1 + d)$, then the processors would transmit, via the wireless interface, to each of the UEs the new allocation of resources to cause the UEs to communicate with the base station according to the new allocation of resources, and communicate with the UEs, via the wireless interface, according to the new allocation of resources.

[00140] Example 55 includes the base station of Example 54, where the processors further receive a lowest service rate for each of the base stations, determine a prioritization order for service rate equalization, and in accordance with the prioritization order, initiate service rate equalization by sorting the variety of UEs.

[00141] Example 56 includes the base station to operate in a radio access network (RAN) based heterogeneous network. The base station includes a wireless interface and one or more processors. The wireless interface includes transmit circuitry and receive circuitry, and communicates with the UEs according to an allocation of

resources. The receive circuitry receives from each UE the indication of a service rate achieved at the UE from one or more other base stations. The processors receive a lowest service rate for each of the other base stations, determine a prioritization order for service rate equalization, and in accordance with the prioritization order, perform service rate equalization by sorting the UEs according to the service rate achieved at each UE from the base stations, determine a new allocation of resources that would enhance equalization of the service rates of the plurality of UEs, transmit, via the wireless interface, to each of the UEs the new allocation of resources to cause the UEs to communicate with the base station according to the new allocation of resources, and communicate with the UEs, via the wireless interface, according to the new allocation of resources.

[00142] Example 57. An apparatus for a user equipment (UE) comprising: logic, at least a portion of which includes circuitry, to: determine a service rate provided via a first wireless interface and a second wireless interface; generate a message to report the service rate to a first base station and to a second base station; transmit the message via the first wireless interface and the second wireless interface; receive, in response to the message, a new grant of resources from one or more of the first base station and the second base station; and configure the UE to communicate with the first base station and the second base station according to the new grant of resources.

[00143] Example 58. An apparatus of a base station to operate in a radio access network (RAN) based heterogeneous network, comprising: logic, at least a portion of which comprises includes, to: communicate with a plurality of user equipments (UEs) according to an allocation of resources, via a wireless interface, receive from each UE of a plurality of UEs indication of a service rate achieved at the UE from one or more other base stations; sort the plurality of UEs according to the service rate achieved at each UE from the one or more other base stations; determine a new allocation of resources that would enhance equalization of the service rates of the plurality of UEs; transmit, via the wireless interface, to each UE of the plurality of UEs the new allocation of resources to configure the plurality of UEs to communicate with the base station according to the new allocation of resources; and communicate with the plurality of UEs, via the wireless interface, according to the new allocation of resources.

[00144] Various techniques, or certain aspects or portions thereof, may take the form of program code (i.e., instructions) embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, a non-transitory computer-readable storage medium, or any other machine-readable storage medium wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the various techniques. In the case of program code execution on programmable computers, the computing device may include a processor, a storage medium readable by the processor (including volatile and non-volatile memory and/or storage elements), at least one input device, and at least one output device. The volatile and non-volatile memory and/or storage elements may be a RAM, an EPROM, a flash drive, an optical drive, a magnetic hard drive, or another medium for storing electronic data. The eNB (or other base station) and UE (or other mobile station) may also include a transceiver component, a counter component, a processing component, and/or a clock component or timer component. One or more programs that may implement or utilize the various techniques described herein may use an application programming interface (API), reusable controls, and the like. Such programs may be implemented in a high-level procedural or an object-oriented programming language to communicate with a computer system. However, the program(s) may be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or an interpreted language, and combined with hardware implementations.

[00145] It should be understood that many of the functional units described in this specification may be implemented as one or more components, which is a term used to more particularly emphasize their implementation independence. For example, a component may be implemented as a hardware circuit comprising custom very large scale integration (VLSI) circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A component may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices, or the like.

[00146] Components may also be implemented in software for execution by various types of processors. An identified component of executable code may, for instance, comprise one or more physical or logical blocks of computer instructions, which may, for instance, be organized as an object, a procedure, or a function. Nevertheless, the executables of an identified component need not be physically

located together, but may comprise disparate instructions stored in different locations that, when joined logically together, comprise the component and achieve the stated purpose for the component.

[00147] Indeed, a component of executable code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within components, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different storage devices, and may exist, at least partially, merely as electronic signals on a system or network. The components may be passive or active, including agents operable to perform desired functions.

[00148] Reference throughout this specification to “an example” means that a particular feature, structure, or characteristic described in connection with the example is included in at least one embodiment of the present disclosure. Thus, appearances of the phrase “in an example” in various places throughout this specification are not necessarily all referring to the same embodiment.

[00149] As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de facto equivalent of any other member of the same list solely based on its presentation in a common group without indications to the contrary. In addition, various embodiments and examples of the present disclosure may be referred to herein along with alternatives for the various components thereof. It is understood that such embodiments, examples, and alternatives are not to be construed as de facto equivalents of one another, but are to be considered as separate and autonomous representations of the present disclosure.

[00150] Although the foregoing has been described in some detail for purposes of clarity, it will be apparent that certain changes and modifications may be made without departing from the principles thereof. It should be noted that there are many alternative ways of implementing both the processes and apparatuses described

herein. Accordingly, the present embodiments are to be considered illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

[00151] It will be understood by those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined only by the following claims.

What is claimed is:

Claims

1. A base station to operate in a radio access network (RAN) based heterogeneous network, the base station comprising:

a wireless interface including transmit circuitry and receive circuitry, the wireless interface to communicate with the plurality of user equipments (UEs) according to an allocation of resources, the receive circuitry of the wireless interface to receive from each UE of the plurality of UEs indication of a service rate achieved at the UE from one or more other base stations; and

one or more processors to:

sort the plurality of UEs according to the service rate achieved at each UE from the one or more other base stations;

determine a new allocation of resources that would enhance equalization of the service rates of the plurality of UEs;

provide, for transmission via the wireless interface, to each UE of the plurality of UEs the new allocation of resources to configure the plurality of UEs to communicate with the base station according to the new allocation of resources; and

communicate with the plurality of UEs, via the wireless interface, according to the new allocation of resources.

2. The base station of claim 1, wherein the wireless interface communicates with the plurality of UEs using a radio access technology (RAT), and

wherein the one or more other base stations communicate with the plurality of UEs using a different RAT.

3. The base station of claim 1, wherein the wireless interface communicates with the plurality of UEs using a radio access technology (RAT), and

wherein the one or more other base stations communicate with the plurality of UEs using the same RAT.

4. The base station of any of claims 1-3, wherein the indication of the service rate achieved at the UE comprises total throughput h_i, which is an

aggregation of service rates achieved from all base stations, including the base station and the one or more other base stations, such that:

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j},$$

where M is a number of base stations in a set of base stations that includes the base station, $R_{i,j}$ is the PHY rate of the UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*.

5. The base station of any of claims 1-3, wherein the indication of the service rate achieved at the UE comprises an aggregation of the service rate achieved from only the one or more other base stations, and excludes the base station.

6. The base station of claim 1, wherein the indication of the service rate comprises h'_i, which is a portion of a total service rate h_i that is achieved from other base stations.

7. The base station of claim 6, wherein

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j},$$

$\lambda_{i,j}$ is a resource fraction, and

$R_{i,j}$ is a PHY rate of the UE *i* from base station *j*,

wherein, the one or more processors of base station *j* sort the plurality of UEs in order of h'_i as follows:

$$h'_1 \leq \cdots \leq h'_k \leq h'_{k+1} \leq \cdots \leq h'_{n'},$$

wherein the new allocation of resources achieves a more equalized service rate h''_i for each UE such that:

$$h''_1 = h''_2 = \ldots = h''_k = \gamma \mid \lambda'_{1,j} > 0, \sum_{i=1}^{k} \lambda'_{i,j} = 1$$

$$h''_{k+1}, \ldots, h''_{n'} \geq \gamma \text{ and } \lambda_{i,j} = 0,$$

where γ is a client group service rate and updated resource fraction $\lambda'_{i,j}$ is an update to $\lambda_{i,j}$ to achieve h''_i.

8. The base station of claim 7, wherein the more equalized service rate h''_i is a total service rate that is a more equalized service rate achieved by UE *i* after the new allocation of resources by the base station.

9. The base station of claim 7, wherein the one or more processors determine the new allocation of resources to achieve more equalized service rates h''_i of the plurality of UEs by determining updated resource fractions $\lambda'_{i,j}$, client index *k,* and client group service rate γ such that:

$$h'_1 + \frac{\lambda'_{1,j}R_{1,j}}{\omega_1} = h'_2 + \frac{\lambda'_{2,j}R_{2,j}}{\omega_2} = \cdots \leq h'_k + \frac{\lambda'_{k,j}R_{k,j}}{\omega_k} = \gamma$$

$$h'_k < \gamma \leq h'_{k+1}$$

$$\sum_{i=1}^{k} \lambda'_{i,j} = 1, \quad \lambda'_{i,j} > 0,$$

where ω_i is a weighting for UE *i* of the plurality of UEs.

10. The base station of claim 9, wherein the one or more processors determine client index *k* by checking the following inequalities:

$$\text{if} \quad \frac{(h'_2 - h'_1)\omega_1}{R_{1,j}} > 1 \Rightarrow k = 1, \quad \text{else}$$

$$\text{if} \quad \frac{(h'_3 - h'_1)\omega_1}{R_{1,j}} + \frac{(h'_3 - h'_2)\omega_2}{R_{2,j}} > 1 \Rightarrow k = 2, \quad \text{else}$$

$$\cdots$$

$$\text{if} \quad \frac{(h'_n - h'_1)\omega_1}{R_{1,j}} + \cdots \frac{(h'_n - h'_{n-1})\omega_{n'-1}}{R_{2,j}} > 1 \Rightarrow k = n' - 1, \quad \text{else}$$

$$k = n'.$$

11. The base station of claim 10, wherein the client group service rate γ can be determined by:

$$\sum_{i=1}^{k} \frac{(\gamma - h'_i)\omega_i}{R_{i,j}} = 1.$$

12. The base station of any of claims 1-3, wherein the one or more processors are further to determine if the minimum equalized service rate h''_i would represent an increase over a current service rate h_i by a multiplicative factor (1+*d*), such that

if

$$h''_i \geq min\, h_i\,(1+d),$$

then the new allocation of resources is transmitted to each UE, and

if

$$h''_i < \min h_i\,(1+d),$$

then the new allocation of resources is not transmitted to each UE and the base station communicates with the plurality of UEs according to a current allocation of resources.

13. The base station of claim 1, wherein, if the base station serves a UE with a lowest service rate of all UEs of the plurality of UEs, then the base station has a higher priority for service rate equalization than the one or more other base stations.

14. The base station of claim 13, wherein a randomization parameter p_j is set proportional to the service rates for each UE of the plurality of UEs to facilitate determining a prioritization order.

15. The base station of claim 1, wherein the one or more processors are further to:

receive a lowest service rate for each of the one or more other base stations;

determine a prioritization order for service rate equalization; and

in accordance with the prioritization order, initiate service rate equalization by sorting the plurality of UEs.

16. The base station of claim 1, wherein the new allocation of resources is determined by the one or more processors to improve the service rate of one or more UEs of the plurality of UEs.

17. A computer-readable storage medium having stored thereon instructions that, when executed by one or processors, cause the apparatus to perform operations to:

receive, via the receive circuitry of the wireless interface, from each UE of the plurality of UEs indication of a service rate achieved at the UE from one or more other base stations;

sort the plurality of UEs according to the service rate achieved at each UE;

determine a new allocation of resources that would enhance equalization of the service rates of the plurality of UEs;

transmit, via the transmit circuitry of the wireless interface, to each UE of the plurality of UEs the new allocation of resources to configure the plurality of UEs to communicate with the base station according to the new allocation of resources; and

communicate with the plurality of UEs, via the wireless interface, according to the new allocation of resources.

18. The computer-readable storage medium of claim 17, wherein the wireless interface communicates with the plurality of UEs using a radio access technology (RAT), and

wherein the one or more other base stations communicate with the plurality of UEs using a different RAT.

19. The computer-readable storage medium of any of claims 17-18, wherein the indication of the service rate achieved at the UE comprises total throughput h_i, which is an aggregation of service rates achieved from all base stations, including the base station and the one or more other base stations, such that:

$$h_i = \sum_{j=1}^{M} \lambda_{i,j} R_{i,j},$$

where M is a number of base stations in a set of base stations that includes the base station, $R_{i,j}$ is the PHY rate of the UE *i* from base station *j*, and $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*.

20. A user equipment (UE) comprising:

a first wireless interface to communicate with a first base station;

a second wireless interface to communicate with a second base station; and

one or more processors to:

determine a service rate provided via the first wireless interface and the second wireless interface;

generate a message to report the service rate to the first base station and to the second base station;

provide the message for transmission via the first wireless interface and the second wireless interface;

receive, in response to the message, a new grant of resources from one or more of the first base station and the second base station; and

configure the UE to communicate with the first base station and the second base station according to the new grant of resources.

21. The UE of claim 20, wherein the first wireless interface communicates with the first base station using a first radio access technology (RAT) and the second wireless interface communicates with the second BS using a second RAT different from the first RAT.

22. The UE of claim 20, wherein the first wireless interface communicates with the first base station using a given RAT and the second wireless interface communicates with the second base station using the same given RAT.

23. The UE of claim 20, wherein the new grant of resources is determined by the base station to improve the service rate of the UE.

24. The UE of claim 20, wherein the new grant of resources is determined by the base station to improve service rates of a set of UEs, which includes the UE.

25. The UE of any of claims 20-24, wherein the service rate comprises a total throughput h_i achieved by the UE i, wherein

$$h_i = \frac{\sum_{j=1}^{M} \lambda_{i,j} R_{i,j}}{\omega_i}$$

where M is a number of base stations in a set of base stations that includes the first base station and the second base station, $R_{i,j}$ is a physical rate of the UE *i* to base station *j*, $\lambda_{i,j}$ is a time resource fraction of UE *i* by base station *j*, and ω_i is a weight for UE *i*.

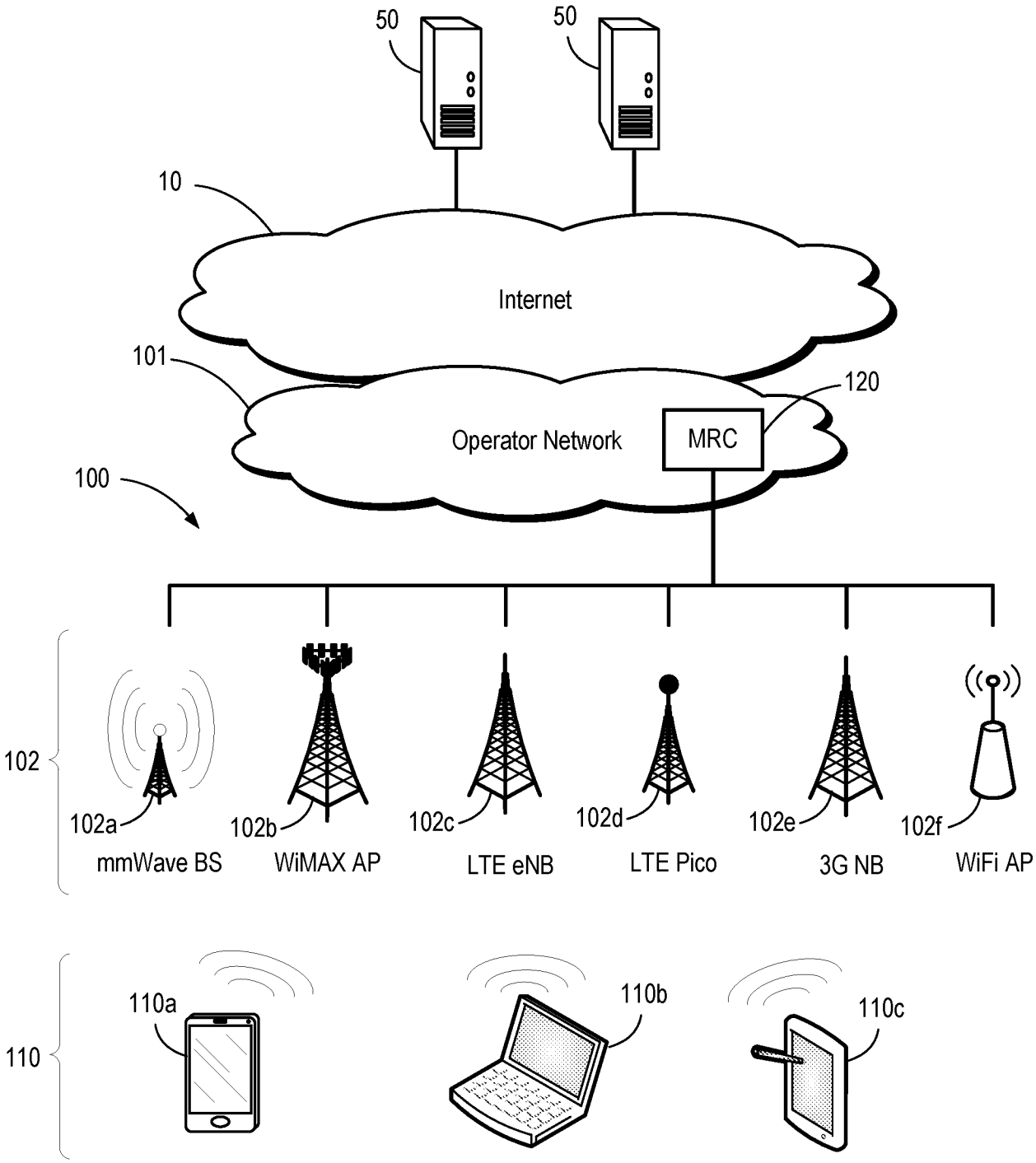

50
50
10
Internet
101
120
Operator Network
MRC
100
102
102a
mmWave BS
102b
WiMAX AP
102c
LTE eNB
102d
LTE Pico
102e
3G NB
102f
WiFi AP
110
110a
110b
110c

FIG. 1

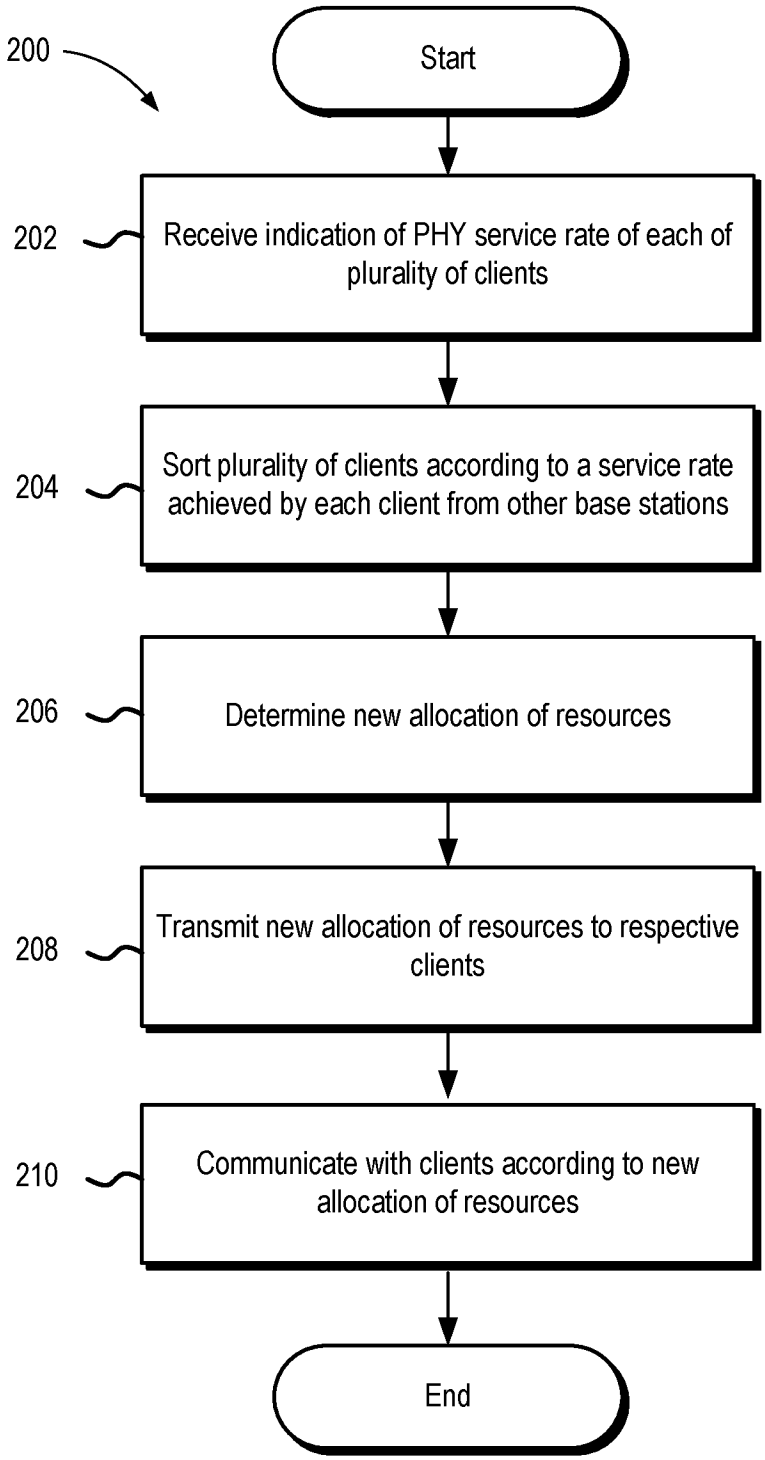

200
Start
202
Receive indication of PHY service rate of each of plurality of clients
204
Sort plurality of clients according to a service rate achieved by each client from other base stations
206
Determine new allocation of resources
208
Transmit new allocation of resources to respective clients
210
Communicate with clients according to new allocation of resources
End

FIG. 2

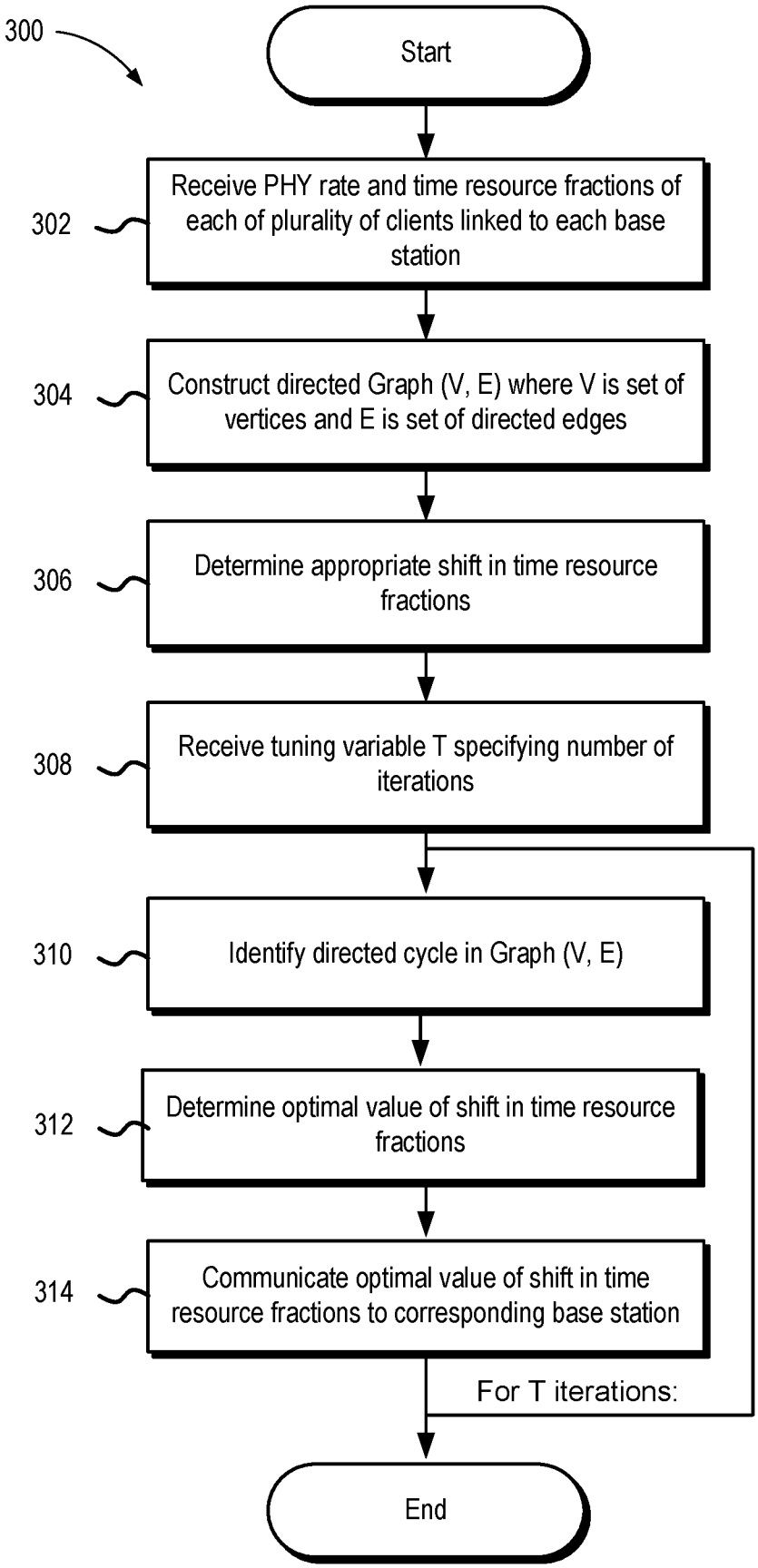

300
Start
302
Receive PHY rate and time resource fractions of each of plurality of clients linked to each base station
304
Construct directed Graph (V, E) where V is set of vertices and E is set of directed edges
306
Determine appropriate shift in time resource fractions
308
Receive tuning variable T specifying number of iterations
310
Identify directed cycle in Graph (V, E)
312
Determine optimal value of shift in time resource fractions
314
Communicate optimal value of shift in time resource fractions to corresponding base station
For T iterations:
End

FIG. 3

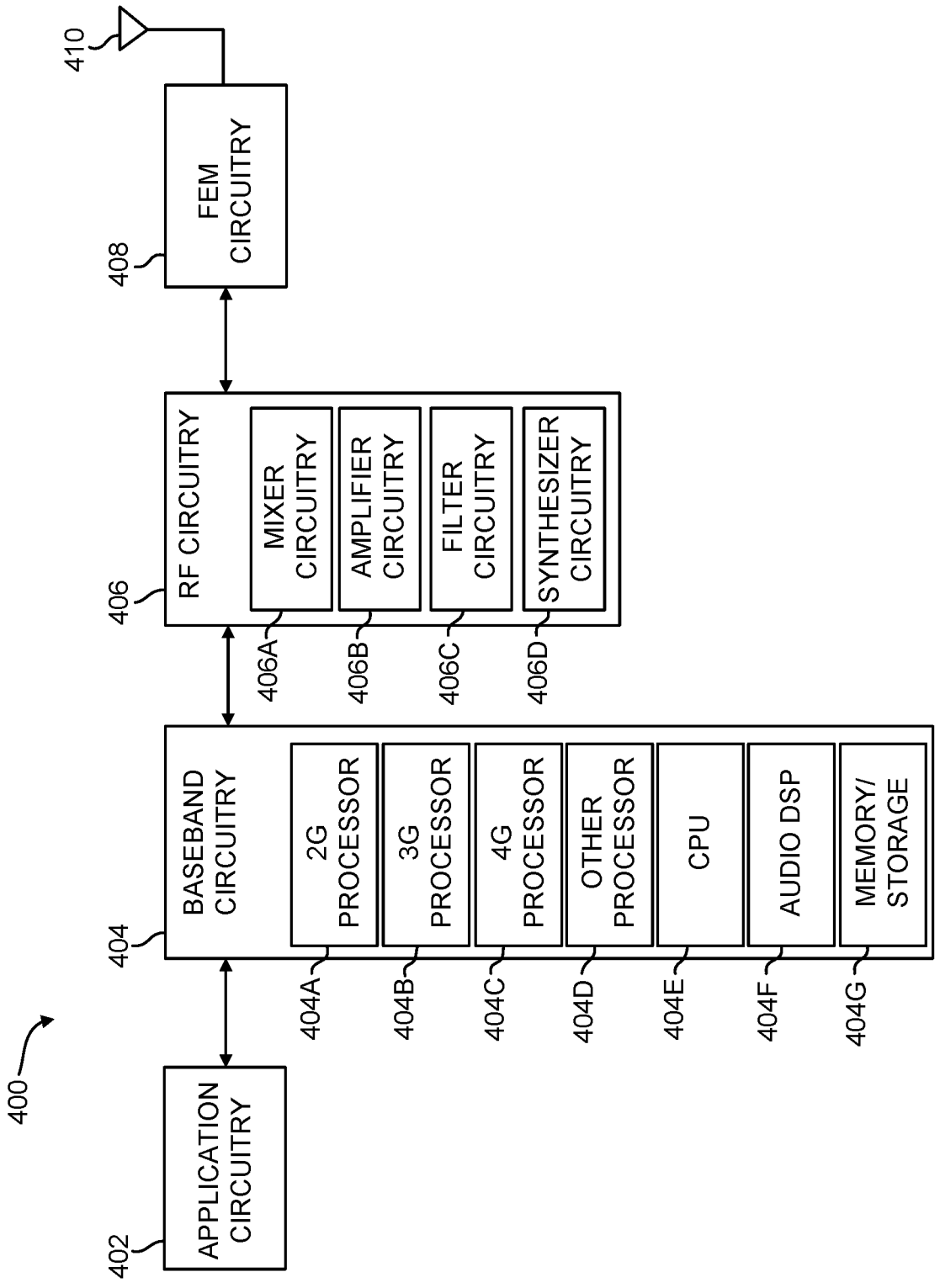

400
402
APPLICATION CIRCUITRY
404
BASEBAND CIRCUITRY
404A
2G PROCESSOR
404B
3G PROCESSOR
404C
4G PROCESSOR
404D
OTHER PROCESSOR
404E
CPU
404F
AUDIO DSP
404G
MEMORY/ STORAGE
406
RF CIRCUITRY
406A
MIXER CIRCUITRY
406B
AMPLIFIER CIRCUITRY
406C
FILTER CIRCUITRY
406D
SYNTHESIZER CIRCUITRY
408
FEM CIRCUITRY
410

FIG. 4

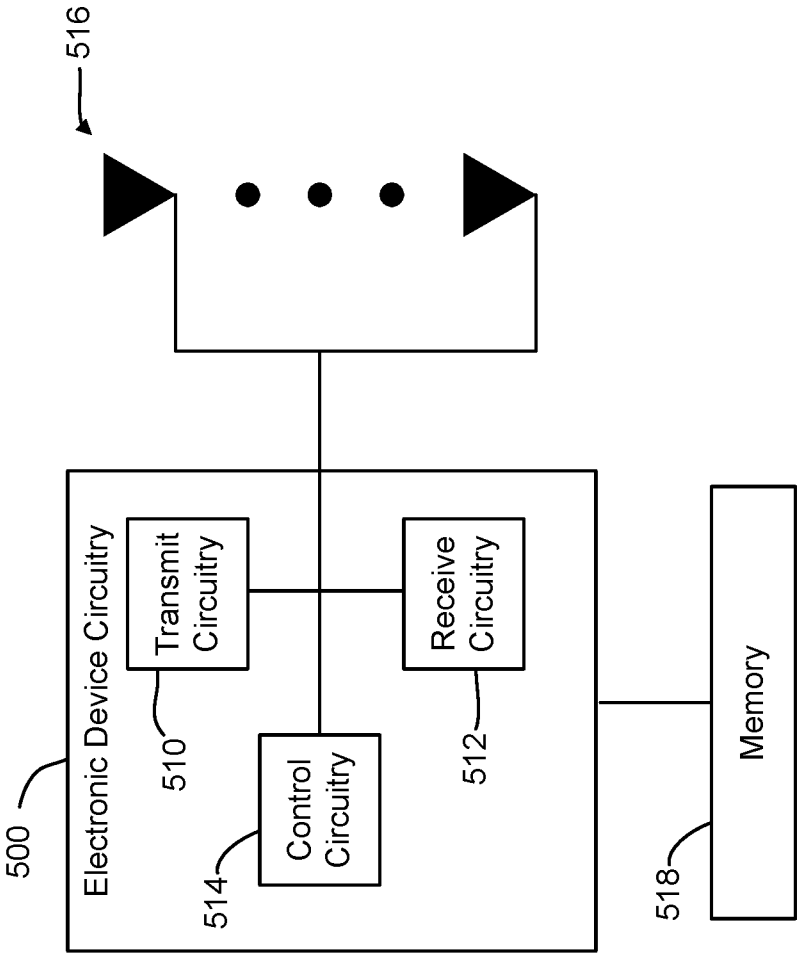

516
Electronic Device Circuitry
Transmit Circuitry
Receive Circuitry
Control Circuitry
Memory
500
510
512
514
518

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/067148

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04W72/08 H04W88/06
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/213310 A1 (YEH SHU-PING [US] ET AL) 31 July 2014 (2014-07-31) figures 4-6 paragraph [0026] - paragraph [0040] -----	1-25
X	US 2015/092573 A1 (ZHANG XIAOXIA [US] ET AL) 2 April 2015 (2015-04-02) abstract paragraph [0006] - paragraph [0043] paragraph [0071] - paragraph [0079] paragraph [0100] - paragraph [0156] -----	1-25
A	US 2011/249642 A1 (SONG OSOK [US] ET AL) 13 October 2011 (2011-10-13) the whole document -----	1-25

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 March 2016	23/03/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Frantzeskakis, D

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/067148

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2015/117362 A1 (LUO TAO [US] ET AL) 30 April 2015 (2015-04-30) the whole document	1-25
A	EP 1 968 332 A1 (SIEMENS NETWORKS S P A [IT]) 10 September 2008 (2008-09-10) the whole document	1-25

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2015/067148

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014213310 A1	31-07-2014	CN 104904253 A	09-09-2015
		EP 2952032 A1	09-12-2015
		US 2014213310 A1	31-07-2014
		WO 2014120863 A1	07-08-2014
US 2015092573 A1	02-04-2015	US 2015092573 A1	02-04-2015
		WO 2015047869 A1	02-04-2015
US 2011249642 A1	13-10-2011	CN 102907135 A	30-01-2013
		EP 2559291 A1	20-02-2013
		ES 2534640 T3	27-04-2015
		JP 5766785 B2	19-08-2015
		JP 2013524737 A	17-06-2013
		JP 2015136134 A	27-07-2015
		KR 20130025399 A	11-03-2013
		US 2011249642 A1	13-10-2011
		WO 2011130438 A1	20-10-2011
US 2015117362 A1	30-04-2015	US 2015117362 A1	30-04-2015
		WO 2015065724 A1	07-05-2015
EP 1968332 A1	10-09-2008	EP 1968332 A1	10-09-2008
		US 2010080180 A1	01-04-2010
		WO 2008110500 A1	18-09-2008