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A green radio resource allocation scheme for LTE-A downlink systems with CoMP transmission

Wen-Ching Chung · Chung-Ju Chang · Hsin-Ying Teng

Abstract In this paper, we propose a green radio resource allocation (GRRA) scheme for LTE-advanced downlink systems with coordinated multi-point (CoMP) transmission to support multimedia traffic. The GRRA scheme defines a green radio utility function, which is composed of the required transmission power, assigned modulation order, and the number of coordinated transmission nodes. By maximizing this utility function, the GRRA scheme can effectively save transmission power, enhance spectrum efficiency, and guarantee quality-of-service requirements. The simulation results show that when the traffic load intensity is greater than 0.7, the GRRA scheme can save transmission power by more than 33.9 and 40.1 %, as compared with the conventional adaptive radio resource allocation (ARRA) scheme (Tsai et al. in IEEE Trans Wireless Commun 7(5):1734–1743, 2008) with CoMP and the utility-based radio resource allocation (URRA) scheme (Katoozian et al. in IEEE Trans Wireless Commun 8(1):66–71, 2009) with CoMP, respectively. Besides, it enhances the system throughput by approximately 5.5 % and improves Jain's fairness index for best effort users by more than 155 % over these two ARRA and URRA schemes.

Keywords Green radio · Resource allocation · CoMP · LTE-A · QoS · Fairness

1 Introduction

Recently, the study of green radio communications has attracted considerable attention because of the high energy-efficiency demand in next-generation wireless systems [1–6]. When a base station (BS) is in an active mode, power supply, processing circuits, and air conditioning account for up to 60 % of the total energy consumption [1]. Therefore, reducing the energy consumption of the BS becomes an important issue. If the BS reduces its transmission power, the quality-of-service (QoS) experienced by users will be compromised. In green radio communications, one of the main design objectives is to reduce the amount of energy consumption while satisfying the QoS requirements [6].

Long term evolution-advanced (LTE-A) was introduced by the 3rd Generation Partnership Project (3GPP) to fulfill the requirements of IMT-Advanced for next-generation cellular systems [7–9]. In the LTE-A system, coordinated multi-point (CoMP) transmission is adopted to save the transmission power, increase the coverage of high data rates, enhance the cell-edge throughput, and/or increase the overall system throughput [10]. CoMP transmission indicates that the transmission is carried out among multiple geographically separated transmission nodes, which comprise a CoMP cooperating set. Therefore, the radio resource allocation (RRA) problem in the LTE-A system with CoMP transmission would involve multiple degrees of freedom in space, time, and frequency; thus, the RRA problem would become very challenging, particularly when the QoS requirement guarantee for multimedia traffic is considered.

The LTE-A downlink system adopts orthogonal frequency division multiple access (OFDMA) in the physical layer [8]. OFDMA can eliminate the intra-cell interference due to orthogonality between subcarriers. However, in a

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multi-cell OFDMA system with the frequency reuse factor being equal to one, a user would experience severe inter-cell interference with a resulting low signal-to-noise-and-interference ratio (SINR). CoMP transmission is an efficient technique to mitigate inter-cell interference for users. By allowing transmission nodes in neighbor cells to transmit the same signal on the same subcarrier, CoMP transmission transforms inter-cell interference into a valuable signal.

In the literature, two types of schemes have been presented to implement downlink CoMP transmission: coordinated scheduling/beamforming (CS/CB) and joint processing (JP) [11–13]. In the CS/CB scheme, the user scheduling/beamforming decisions are coordinated within the CoMP cooperating set [11]. By using beamforming weights, the interference to other users in different cells can be efficiently mitigated [12]. The JP scheme can also be categorized as joint transmission (JT) and dynamic cell selection (DCS) [13]. In the JT scheme, the data for the selected user is delivered simultaneously from multiple transmission nodes to improve the received signal quality and cancel the active interference for other users. However, in the DCS scheme, the data for the selected user is transmitted from only one transmission node at a time. The other nodes in the CoMP cooperating set are then muted to avoid generating the interference to the served user. In order to effectively utilize the radio resource and enhance the received signal quality, we consider that downlink CoMP transmission is implemented by the JT scheme in this paper.

The study of CoMP transmission has recently attracted considerable attention [14–17]. On the basis of a zero forcing beamforming technique, Tölli et al. [14] proposed an RRA method for cooperative MIMO–OFDM systems so as to implement the bit and power loading algorithms in practical systems. Gao et al. proposed a cooperating set construction algorithm [15] to determine the best groups of transmission nodes and coordinated users by evaluating channel orthogonality among users. Fodor et al. [16] studied the problems of setting SINR targets and allocating transmission powers for CoMP systems to obtain a better trade-off between the fairness and the multi-cell throughput performance. Moreover, Liu et al. [17] proposed a transmission scheme with the joint proportional fairness algorithm for CoMP-based systems. This scheme does not allocate the dedicated frequency band to cell-edge users and can obtain the best frequency diversity gain. However, these proposed schemes only considered a single service class. In modern mobile Internet systems, multimedia traffic support is an essential requirement.

On the other hand, the QoS requirement guarantee is an important performance consideration in the design of RRA schemes for wireless communication systems [18–21]. The QoS requirements contain the required bit error rate (BER), the minimum required transmission rate, the maximum packet delay tolerance, and the maximum packet dropping ratio. On the basis of the fixed priority for each traffic, Yu et al. [18] proposed a cross-layer design for MIMO–OFDMA systems to guarantee QoS requirements. Tsai et al. [19] proposed an adaptive radio resource allocation (ARRA) scheme for downlink OFDMA/SDMA systems. The ARRA scheme dynamically assigns a high priority value to the urgent user and allows a non-real time (NRT) user to be assigned a higher priority value than a real time (RT) user when an urgent need arises. In [20] and [21], utility-based radio resource allocation (URRA) schemes were proposed to maximize the utility function, which is designed on the basis of the QoS, rate, and fairness factors. However, these proposed schemes were designed for a single transmission node only. For multi-transmission nodes, the design of RRA schemes becomes more complicated given that they must determine the transmission nodes for users and consider the interference to/from other transmission nodes.

In this paper, we propose a green radio resource allocation (GRRA) scheme for LTE-A downlink systems with CoMP transmission to support multimedia traffic. The GRRA scheme first defines a service priority and a minimum number of transmission bits for each user on the basis of the degree of the user's urgency. According to a green radio utility function, it then assigns an appropriate CoMP transmission type, modulation order, and subchannel to users in a priority value sequence. By coordinating the transmission power of each transmission node, the GRRA scheme allows the transmission nodes to simultaneously serve multiple users at the same subchannel. Therefore, the proposed scheme can mitigate the interference, thus saving transmission power and increasing the system throughput, and can achieve a high Jain's fairness index [22] under the QoS requirement guarantee. The simulation results show that when the traffic load intensity is greater than 0.7, the GRRA scheme can save transmission power by more than 33.9 % as compared with the adaptive radio resource allocation (ARRA) scheme [19] and by more than 40.1 % as compared with the utility-based radio resource allocation (URRA) scheme [20]. Moreover, the GRRA scheme can achieve a Jain's fairness index for a best-effort (BE) service that is approximately 155 % greater and a system throughput that is approximately 5.5 % higher than both the ARRA and the URRA schemes.

The remainder of the paper is organized as follows. The system model is introduced in Sect. 2. Section 3 describes the design of the GRRA scheme. Section 4 presents the simulation results for the performance analysis of the GRRA scheme. Finally, Sect. 5 concludes the paper.

2 System model

In the LTE-A downlink system with CoMP transmission, each cell is partitioned into three sectors and one evolved Node B (eNB) is located at the center of the cell. As shown in Fig. 1, the eNB is equipped with a 120° directional antenna for each sector. Assume that the frequency reuse factor within the cell is 3, and the interference among sectors in the same cell is then ignored [23]. There are K pieces of single-antenna user equipment (UE) uniformly distributed in the sector. There are also two pieces of remote radio equipment (RRE) in each sector, denoted by RRE1 and RRE2, located at the cell edge of the sector with distance d to the eNB and distance $\frac{d}{2}$ to the sector boundary. Each RRE has a single omnidirectional antenna and is connected with eNB via an optical fiber. In the sector, the eNB and two RREs are operated at the same frequency band for the downlink CoMP transmission.

We adopt the JT scheme for CoMP transmission and define a CoMP cooperating set in the sector, denoted by Ω, which contains RRE1, RRE2, and eNB, numbered as nodes 1, 2, and 3, respectively. Thus, there are totally eight downlink CoMP transmission types in the LTE-A system. Table 1 lists the eight CoMP transmission types, where Ω_j is the set of transmission nodes for CoMP transmission type j, $0 \le j \le 7$. Transmission type 0 denotes that no transmission node is involved and thus implies no data transmission; transmission type 7 indicates that the data transmission has RRE1, RRE2, and eNB engaged.

Assume that each sector has N subchannels. In the LTE-A standard [24], each subchannel is composed of 12 subcarriers. Moreover, the frame time is defined as 10 ms and is divided into ten subframes. Each subframe consists of two slots, and each slot has seven OFDM symbols. The basic resource unit for allocation is one subchannel over one subframe. The channel state information (CSI) corresponding to the downlink channels from the eNB and RRE to the UE are reported by the UE to the eNB. The proposed green radio resource allocation (GRRA) scheme is carried out subframe by subframe at the eNB for each sector. In order to improve the spectrum efficiency for CoMP transmission, we consider that the CoMP transmission nodes can simultaneously serve at most three UEs at the same resource unit. The allocation decision and the user data are delivered from the eNB to the RREs by the optical fiber.

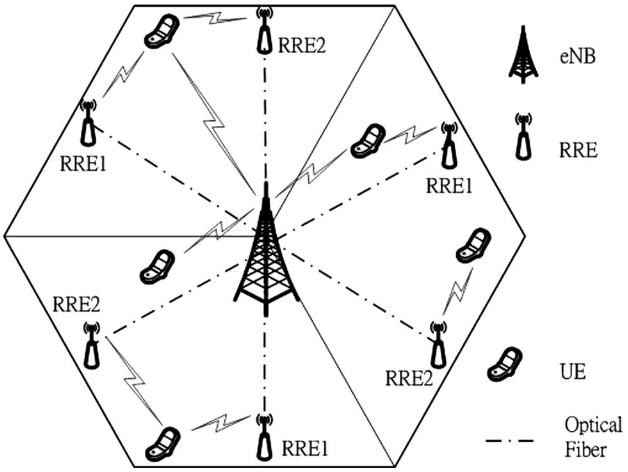

Fig. 1 The LTE-A downlink system with CoMP transmission

Let $h^i_{k,n}$ be the channel gain from transmission node i to UE k on subchannel n. Assume that the coherent time of the wireless channel is longer than the subframe duration. Therefore, the channel gain can be regarded as constant within a subframe. Denote the CoMP transmission type for UE k on subchannel n by $s_{k,n}$, thus $s_{k,n} \in \{0, 1, \ldots, 7\}$, and assume that the cooperative signals can be coherently combined at the UE [25]. Let Φ_n be the set of UE that multiplex on subchannel n. Thus, the received signal on subchannel n at UE k, denoted by $y_{k,n}$, is given by

$$y_{k,n} = \sum_{i\in\Omega_{s_{k,n}}} h^i_{k,n}\sqrt{p^i_{k,n}}x_{k,n} + \sum_{i'\in\Omega-\Omega_{s_{k,n}}} \sum_{k'\in\Phi_n,k'\neq k} h^{i'}_{k,n}\sqrt{p^{i'}_{k',n}}x_{k',n} + z_{k,n}, \qquad (1)$$

where $p^i_{k,n}$ is the allocated transmission power to UE k on subchannel n by node i, $x_{k,n}$ is the data symbol, $\Omega_{s_{k,n}}$ is the set of nodes of transmission type $s_{k,n}$, $\Omega - \Omega_{s_{k,n}}$ is the set containing elements that belong to Ω but not $\Omega_{s_{k,n}}$, and $z_{k,n}$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2. The first term on the right-hand side of (1) is the desired signal, whereas the second term is the interference signal from other transmission nodes to UE k on subchannel n in the same sector. Suppose that $p^i_{k,n}$ is designed in accordance with the pre-maximum-ratio-combining (pre-MRC) scheme [26, 27], which is given by

$$p^i_{k,n} = \frac{|h^i_{k,n}|^2}{\left(\sum_{i\in\Omega_{s_{k,n}}} |h^i_{k,n}|^2\right)^2} \times SINR^*_k \times \left(I_{k,n} + \sigma^2\right), \qquad (2)$$

Table 1 CoMP transmission types

Transmission type j	Transmission nodes	$\Omega_j = \{i \mid \text{node } i \text{ in type } j\}$
0	None	$\Omega_0 = \{\emptyset\}$
1	RRE1	$\Omega_1 = \{1\}$
2	RRE2	$\Omega_2 = \{2\}$
3	eNodeB	$\Omega_3 = \{3\}$
4	RRE1 & RRE2	$\Omega_4 = \{1, 2\}$
5	RRE1 & eNodeB	$\Omega_5 = \{1, 3\}$
6	RRE2 & eNodeB	$\Omega_6 = \{2, 3\}$
7	RRE1 & RRE2 & eNodeB	$\Omega_7 = \{1, 2, 3\}$

and

$$I_{k,n} = \sum_{i' \in \Omega - \Omega_{s_{k,n}}} \sum_{k' \in \Phi_n, k' \neq k} p^{i'}_{k',n} |h^{i'}_{k,n}|^2, \tag{3}$$

where $SINR_k^*$ is the minimum required SINR for UE k and $I_{k,n}$ is the interference power from other nodes on UE k at subchannel n. The $SINR_k^*$ with M-QAM modulation can be obtained by

$$SINR_k^* = -\frac{\ln(5BER_k^*)}{1.5}(M-1), \tag{4}$$

where BER_k^* is the BER requirement for UE k. Therefore, the total allocated power for UE k on subchannel n in the sector, denoted by $P_{k,n}$, is given by

$$P_{k,n} = \sum_{i \in \Omega_{s_{k,n}}} p^i_{k,n}. \tag{5}$$

Further, the LTE-A system can support three service classes: real-time (RT), non-real-time (NRT), and best-effort (BE) service classes. Each service class has different QoS requirements. For the RT service, the QoS requirements are the required BER, the maximum packet delay tolerance, and the maximum packet dropping ratio. For the NRT service, the QoS requirements include the required BER and the minimum required transmission rate. For the BE service, the QoS requirement is the required BER only. Let us denote R_k^*, D_k^*, and PD_k^* as the minimum required transmission rate, the maximum packet delay tolerance, and the maximum packet dropping ratio for UE k, respectively. There are four kinds of traffic types considered in the LTE-A system. The RT service has voice and video traffic; the NRT service has HTTP traffic; and the BE service has FTP traffic. Each traffic has one individual queue at the eNB. Suppose that the queue is large enough to store all the arriving packets. The traffic packet is stored in its own queue in a first-in first-out manner. Packet dropping occurs only when the packet delay time exceeds its maximum packet delay tolerance, but will not occur because of the overflow of buffer occupancy. Retransmission due to erroneous transmission is not considered in this study.

3 Green radio resource allocation (GRRA) scheme

The green radio resource allocation (GRRA) scheme first formulates the RRA problem of the LTE-A downlink system with CoMP transmission into utility-based optimization equations. Then, it employs a priority and bit assignment (PBA) algorithm and a priority-based resource allocation (PRA) algorithm to heuristically solve the optimization equations.

3.1 Problem formulation

Denote $m_{k,n}$ as the number of bits for UE k with M-QAM modulation on subchannel n, where $m_{k,n} = \log_2 M$ and $m_{k,n} = \{0, 2, 4, 6\}$, $1 \leq k \leq K$, $1 \leq n \leq N$. If $m_{k,n} = 0$, the implication is that subchannel n is not allocated to UE k in this subframe. If $m_{k,n} = 2$, 4, or 6, the implication is that subchannel n is assigned to UE k and the data are modulated in the modulation order of QPSK, 16-QAM, or 64-QAM, respectively. Thus the allocated transmission bits of UE k in this subframe, denoted by R_k, are given by

$$R_k = \sum_{n=1}^{N} q \cdot m_{k,n}, \tag{6}$$

where q is the number of OFDM symbols in one basic allocation unit (12 subcarries over 14 symbols), and $q = 168$.

Define the green radio utility function for UE k on subchannel n, denoted by $G_{k,n}$; a function of the modulation order index $m_{k,n}$ and the CoMP transmission type $s_{k,n}$. Denote $\mathbf{M}$ as the modulation order assignment vector, $\mathbf{M} = [m_{1,1}, \ldots, m_{1,N}, \ldots, m_{k,1}, \ldots, m_{k,N}, \ldots, m_{K,1}, \ldots, m_{K,N}]$, and $\mathbf{S}$ as the CoMP transmission type assignment vector, $\mathbf{S} = [s_{1,1}, \ldots, s_{1,N}, \ldots, s_{k,1}, \ldots, s_{k,N}, \ldots, s_{K,1}, \ldots, s_{K,N}]$. $\mathbf{M}$ and $\mathbf{S}$ will be the solution of the utility-based optimization equations for the LTE-A system with CoMP transmission. The GRRA scheme aims to enhance the system throughput and save the transmission power. Therefore, $G_{k,n}$ is designed as

$$G_{k,n} = \begin{cases} m_{k,n} + \frac{1}{\sqrt{|\Omega_{s_{k,n}}| \times P_{k,n}}}, & \text{if } P_{k,n} > 0, |\Omega_{s_{k,n}}| > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

where $|\Omega_{s_{k,n}}|$ is the number of elements in $\Omega_{s_{k,n}}$ and $P_{k,n}$ is in mW. When a transmission occurs, $P_{k,n} > 0$ and $|\Omega_{s_{k,n}}| > 0$, and we have $G_{k,n} > 0$. It can be seen in (7) that $m_{k,n}$ is the dominant term in $G_{k,n}$. A piece of UE with a higher modulation order will have a larger $G_{k,n}$ and thus a higher priority to be served. This implies that the objective of the system throughput enhancement can be achieved. Further, if there are some pieces of UE with the same modulation order, the piece of UE that needs fewer transmission nodes and less transmission power will be served earlier. This implies that the objective of transmission power saving can be attained. It should be noted that $G_{k,n}$ does not consider the QoS requirements of UE because we do not oversatisfy the QoS requirements of the UE.

Consequently, the utility-based optimization equations of the GRRA scheme for the LTE-A downlink system with CoMP transmission are formulated as follows:

$$(\mathbf{M}^*, \mathbf{S}^*) = \arg\max_{\mathbf{M},\mathbf{S}} \sum_{k=1}^{K} \sum_{n=1}^{N} G_{k,n}, \tag{8}$$

subject to the QoS requirement constraints:

(i) $D_k \le D_k^*$ if UE k is with RT service, and
(ii) $R_k \ge R_k^*$ if UE k is with NRT or BE service, $1 \le k \le K$;

and the system constraints:

$$\text{(i)}\quad \sum_{k=1}^{K} \operatorname{sgn}(m_{k,n}) \le 3, \forall n,$$

$$\text{(ii)}\quad \sum_{k=1}^{K}\sum_{n=1}^{N} p_{k,n}^{i} \le P_T^i, \forall i,$$

$$\text{(iii)}\quad I_{k,n} \le I_{th}, \forall k \in \Phi_n, n,$$

$$\text{(iv)}\quad R_k \le \left\lceil \frac{Q_k}{q} \right\rceil \times q, \forall k,$$

where D_k is the packet delay of UE k, $\operatorname{sgn}(\cdot)$ is the sign function, $\lceil x \rceil$ is the smallest integer greater than x, Q_k is the buffer occupancy of UE k, P_T^i is the maximum transmission power budget at node i, $I_{k,n}$ is the interference on UE k at the subchannel n given in (3), and I_{th} is the maximum allowed interference on the UE. The QoS requirement constraints are simply set to make the GRRA scheme fulfill the QoS requirement guarantee and achieve a high Jain's fairness index. The system constraint (i) is the *subchannel allocation constraint*; it is set because each subchannel in the same sector is assumed to be possibly allocated to at most three pieces of UEs. The system constraint (ii) is the *total power constraint*; it is set because the total power allocation for each OFDMA symbol has a limitation for downlink data transmission at each transmission node. The system constraint (iii) is the *interference limitation constraint*; it is set to reflect the co-channel interference limitation for resource allocation. In this study, we set $I_{th} = 0.1$ [28]. The system constraint (iv) is the *buffer occupancy constraint*; it is set because the allocated transmission bits to UE k should not be greater than its buffer occupancy.

However, it is complicated and intractable to obtain the optimal solution of the optimization equations given in (8) by an exhaustive search. The GRRA scheme is therefore designed to contain a priority and bit assignment (PBA) algorithm and a priority-based resource allocation (PRA) algorithm to heuristically determine the suboptimal set of assignment vectors ($\mathbf{M}^*$, $\mathbf{S}^*$) in (8).

3.2 Priority and bit assignment (PBA) algorithm

The PBA algorithm determines the service priority value and the minimum required number of transmission bits assigned to UE k, $1 \le k \le K$, according to its residual time before violating the QoS requirements.

Denote V_k as the residual lifetime of the head-of-line (HOL) packet of UE k, which indicates the number of subframes remaining for the HOL packet not to violate the QoS requirements. V_k is then designed as

$$V_k = \begin{cases} D_k^* - D_k, & \text{if UE } k \text{ is with the RT service,} \\ \left\lfloor \frac{B_k + B'_k}{R_k^*} - T_k \right\rfloor, & \text{if UE } k \text{ is with the NRT or BE service,} \end{cases} \tag{9}$$

where $\lfloor x \rfloor$ is the largest integer smaller than x, B_k is the number of residual bits in the HOL packet of UE k, T_k is the time duration that the packet has been buffered in the queue of UE k, and B'_k is the number of transmitted bits of UE k in T_k. The smaller the value of V_k, the more urgent UE k is. For the RT service, V_k is intuitively defined from its delay requirement. For the NRT service, the average transmission rate, denoted by $\bar{R}_k$, should be greater than or equal to the QoS requirement of the minimum transmission rate. Thus, V_k is derived from the inequality $(B_k + B'_k)/(V_k + T_k) \ge R_k^*$. On the other hand, for the BE service, we consider fairness to avoid the deprivation of BE UEs due to bad channel conditions. The R_k^* for the BE service is then set to the maximum average transmission rate among the BE UEs; that is, $R_k^* = \max_{k' \in \Phi_{BE}} \bar{R}_{k'}$, where Φ_{BE} is the set of UE with the BE service.

The priority value for UE k, denoted by u_k, is designed as

$$u_k = \begin{cases} \left(1 + \frac{D_k}{V_k + D_k}\right) \times \alpha_k, & \text{if } V_k > 0, \\ 2 \times \alpha_k, & \text{otherwise,} \end{cases} \tag{10}$$

where α_k is the default priority constant for UE k. We set $\alpha_k = 3, 2,$ or 1 for UE k with the RT, NRT, or BE service, respectively, given that the RT service, which has a strict delay requirement, should have the highest priority value and the BE service, which is background traffic, should have the lowest priority value. It can be seen from (10) that the more urgent (less V_k) UE k is, the higher is the priority value of UE k.

Subsequently, the minimum required number of transmission bits allocated to UE k at the current subframe to avoid violating QoS requirements, denoted by $\hat{R}_k$, is given as

$$\hat{R}_k = \begin{cases} \left\lceil \frac{B_k}{V_k \times q} \right\rceil \times q, & \text{if } V_k \ge V_{th}, \\ \left\lceil \frac{B_k}{q} \right\rceil \times q, & \text{otherwise,} \end{cases} \tag{11}$$

where V_{th} is the threshold for V_k. If V_k is below V_{th}, it means that UE k is very urgent and its HOL packet should be completely transmitted at the current subframe. Therefore, we set $\hat{R}_k = \lceil \frac{B_k}{q} \rceil \times q$. Otherwise, the HOL packet should be equally delivered over the next V_k subframes, and we set $\hat{R}_k = \lceil \frac{B_k}{V_k \times q} \rceil \times q$. If the value of V_{th} is set to 1, the entire HOL packet should be delivered within the current subframe. In order to release the system load, in this study, we set $V_{th} = 3$.

3.3 Priority-based resource allocation (PRA) algorithm

The PRA algorithm allocates an appropriate CoMP transmission type, modulation order, subchannel, and transmission power to the UE with the highest priority value to maximize the green radio utility function.

In order to guarantee the QoS requirements, the PRA algorithm serves the hightest-priority UE first. Let Φ_c be the set of backlogged UE with the highest priority and having bits to be transmitted at the current subframe and N_f be the set of free subchannels. The highest-priority UE with its best-condition channel, denoted by (k^*, n^*), is obtained by

$$(k^*, n^*) = \arg \max_{k \in \Phi_c, n \in N_f} G_{k,n}. \qquad (12)$$

It should be noted that when the maximal G_{k^*,n^*} is found, the CoMP transmission type s_{k^*,n^*}, the modulation order m_{k^*,n^*}, and the subchannel n^* are determined for UE k^*. Here, the assigned modulation order m_{k^*,n^*} should satisfy the system constraint (iv). Before the radio resource is allocated to UE k^*, the system constraints (ii) and (iii) are checked. If the power budget at the transmission node i, $i \in \Omega_{s_{k^*,n^*}}$, is sufficient for delivering the packet to UE k^* on subchannel n^* and the interference to the other selected UE on subchannel n^* is less than I_{th}, the radio resource is allocated to UE k^* at this subframe. The set of the used transmission nodes on the subchannel n^*, denoted by Ω_{u,n^*}, is then updated by $\Omega_{u,n^*} = \Omega_{u,n^*} + \{i | i \in \Omega_{s_{k^*,n^*}}\}$. If $|\Omega_{u,n^*}| = 3$, subchannel n^* is removed from N_f because of the system constraint (i). Moreover, the queue length of UE k^* and the consumed power at transmission node i, denoted by P_k^*, are updated after this allocation. The PRA algorithm is repeated until all radio resources are allocated to all the pieces of UE or no candidate UE exists. The pseudocode of this PRA algorithm is shown in the "Appendix".

4 Simulation results

4.1 Simulation environment

We use Matlab as the simulation tool. In this simulation, the parameters of the considered LTE-A downlink system are set to be compatible with the 3GPP Evolved Universal Terrestrial Radio Access (E-UTRA) standards [24]. The system bandwidth in each sector is 5 MHz. The maximum system transmission rate for eNB or RRE is equal to 25.2 Mbps, which is obtained when each subchannel delivers data with the highest modulation order of 64-QAM. The path loss from RRE is modeled as $36.7\log(d_R) + 132.8 + 26\log(f_c)$ dB, where d_R is the distance between RRE and UE in kilometers and f_c is the carrier frequency in gigahertz [10]. The shadowing from RRE is assumed to be lognormal with zero mean and a standard deviation of 10 dB. The path loss from the eNB is modeled as $39.09\log(d_B) + 130.8 + 20\log(f_c)$ dB, where d_B is the distance between the eNB and the UE in kilometers. The shadowing from the eNB is lognormal with zero mean and a standard deviation of 6 dB. Moreover, the multipath channel is assumed to be a six-tap Rayleigh-faded path with an exponential power delay profile [29]. The other parameters of the LTE-A system are listed in Table 2 [25].

The LTE-A system can accommodate four traffic types: voice traffic of the RT service, video traffic of the RT service, HTTP traffic of the NRT service, and FTP traffic of the BE service. The voice traffic is modeled as an ON–OFF model [30]. The video traffic is composed of a sequence of streaming video frames [31]. Each video frame is composed of eight slices (packets). The HTTP traffic is modeled as a sequence of page downloads [31]. Both the main and the embedded object sizes follow a truncated lognormal distribution. The FTP traffic is modeled as a sequence of file downloads [31], where the file size follows a truncated lognormal distribution. The distribution parameters for voice, video, HTTP, and FTP traffic can be found in [30] and [31], and thus details are omitted here. The QoS requirements for each traffic type are listed in Table 3 [30].

4.2 Performance evaluation

The proposed GRRA scheme will be compared with the conventional adaptive radio resource allocation (ARRA) scheme [19] and the utility-based radio resource allocation (URRA) scheme [20]. Here, the ARRA and URRA schemes with CoMP transmission are also considered,

Table 2 Parameters of the LTE-A system

Parameters	Assumption
Cell radius	1,000 m
Carrier frequency, f_c	2 GHz
Number of subchannels, N	25
Total eNB Tx power, P_T^3	43 dBm
Total RRE Tx power, P_T^1 (P_T^2)	30 dBm
Antenna pattern	$A_H(\phi) = -\min(12(\phi/\phi_{3dB})^2, A_m)$ $\phi_{3dB} = 70°$, $A_m = 25$ dB
Antenna gain	14 dBi
Thermal noise density	−174 dBm/Hz

where only the transmission node with the largest channel gain is chosen for CoMP transmission. In the ARRA scheme, user priority is defined as the minimum number of bits required to transmit at the current subframe so as to guarantee QoS requirements. Because the NRT packet size is greater than the RT packet size, the NRT UE might have a higher priority than the RT UE when it is urgent. In the URRA scheme, the utility value is designed according to the QoS, rate, and fairness factors. For the URRA scheme to have the best performance on QoS measurements and system throughput, the fairness factor is set to one. The QoS factor for the NRT UE k is modified to be $\left(1+\frac{R_k^*}{R_k^*+\bar{R}_k}\right)$ such that the NRT service has a higher QoS factor than the BE service. In the following figures, the traffic load intensity of the system is defined as

$$\text{Traffic Load Intensity} = \frac{\text{total average arrival rates of all traffics}}{\text{maximum system transmission rate}}, \tag{13}$$

and the traffic load intensity is varied from 0.1 to 0.9. Further, assume that each traffic type has the same number of pieces of UE.

Figure 2 shows the average transmission power consumed versus the traffic load intensity. It is found that when the traffic load intensity is greater than 0.7, the GRRA scheme can save transmission power by more than 33.9 and 40.1 % as compared with the ARRA and URRA schemes with CoMP, respectively. Moreover, the ARRA (URRA) scheme with CoMP saves transmission power by more than 57.8 % (56.6 %) as compared with the original ARRA (URRA) scheme without CoMP. The reasons for this are as follows. The ARRA (URRA) scheme with CoMP transforms inter-cell interference into more valuable signals and thus consumes less transmission power to achieve the required SINR than the original ARRA (URRA) scheme without CoMP. By using the green radio utility function of (7), the GRRA scheme selects the UE with a higher modulation order and less transmission power. Moreover, it allows three transmission nodes to serve one piece of UE by the system constraint (i) and considers the interference among transmission nodes by the system constraint (iii). Thus, it can most efficiently mitigate inter-cell interference and consume the lowest average transmission power. On the other hand, the URRA and ARRA schemes with CoMP are assumed to choose only the transmission node with the largest channel gain to deliver packets. This might cause some interference to the other pieces of UE on the same subchannel and then more transmission power might be needed to achieve the required SINR.

Table 3 The QoS requirements for each traffic type

	Voice (RT)	Video (RT)	HTTP (NRT)	FTP (BE)
Required BER	10^{-3}	10^{-4}	10^{-6}	10^{-6}
Maximum packet delay tolerance	40 ms	10 ms	N/A	N/A
Maximum packet dropping ratio	1 %	1 %	N/A	N/A
Minimum required transmission rate	N/A	N/A	100 kbps	N/A

N/A not applicable

Figure 3 depicts the system throughput versus the traffic load intensity. It can be seen that the RRA schemes with CoMP can enhance the system throughput by more than 80 % as compared with those without CoMP. Although the GRRA scheme and the URRA and ARRA schemes with CoMP have almost similar system throughput, the GRRA scheme has a 5.5 % higher system throughput than the other two schemes. The reasons for this are as follows. As pieces of RRE are established, the maximum system transmission rate for the LTE-A system is increased. Thus, the GRRA scheme and the URRA and ARRA schemes with CoMP have a higher system throughput than the URRA and ARRA schemes without CoMP. Although the GRRA scheme considers fairness for the BE service in the priority value assignment by (9) and (10), it mitigates some co-channel interference among the pieces of UE by the system constraint (iii) so as to increase the received SINR. Further, it allocates the subchannel with the highest modulation order to the UE by (12). Hence, the GRRA scheme can enhance the system throughput. On the other hand, the URRA and ARRA schemes with CoMP only choose the transmission mode with the largest channel gain. This might increase interference among the pieces of UE and then reduce the

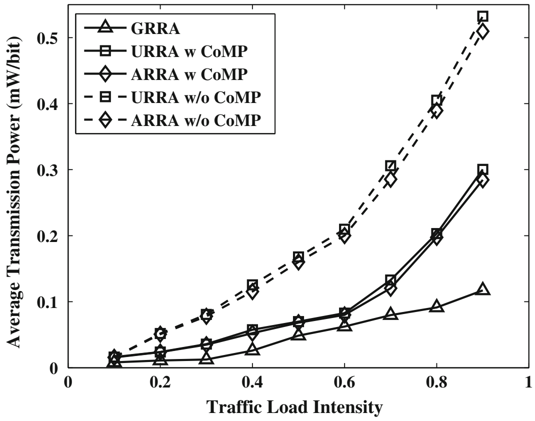

Fig. 2 Average transmission power

system throughput. From the simulation results of Figs. 2 and 3, it can be seen that the proposed GRRA scheme can efficiently save transmission power and enhance the system throughput for the LTE-A system with multimedia traffic.

Figure 4 depicts the packet dropping ratio of voice and video traffic. The GRRA and URRA with CoMP schemes can guarantee the dropping ratio requirement for voice traffic for a traffic load intensity up to 0.9 and for video traffic for a traffic load intensity up to 0.8. The ARRA with CoMP scheme has the largest voice and video packet dropping ratios. The phenomena are explained below. Voice traffic has a larger delay tolerance than video traffic, and the number of packets for video traffic is greater than that for voice traffic. Therefore, the dropping ratio requirement for voice traffic can be fulfilled more easily than that for video traffic. In the GRRA and the URRA with CoMP schemes, the RT traffic always has the highest priority value as given in (10) and can be served first. However, the ARRA with CoMP scheme allows the NRT traffic to have a higher priority than the RT traffic when the former becomes urgent, and then the NRT traffic can be first served. Thus, as the number of NRT packets increases, the RT packets cannot be delivered within the delay requirement, and the ARRA with CoMP scheme has the largest RT-service packet drop ratio among the three compared schemes.

Figure 5 presents the mean packet delay of voice and video traffic. All three schemes satisfy the packet delay requirements of voice and video traffic. It can be found that the ARRA (URRA) with CoMP scheme has the largest (smallest) mean packet delay, and the GRRA scheme lies in the middle. The reasons for this are the same as those given in Fig. 4. In the GRRA scheme, the HOL packet for the UE is equally delivered over the next residual subframes by (11) as it is not urgent. However, in the URRA scheme, the entire HOL packet is delivered to the UE as it is served. Therefore, the GRRA scheme has a larger RT-service packet delay than the URRA scheme.

Figure 6 shows the average transmission rate of HTTP traffic. The ARRA scheme with CoMP has the highest transmission rate of HTTP traffic. The GRRA and the URRA with CoMP schemes can guarantee the minimum transmission rate requirement for HTTP traffic up to a traffic load intensity of 0.81. The reason for this is as follows. In the GRRA and the URRA with CoMP schemes, the NRT service always has a smaller priority value than the RT service. Therefore, as the traffic load is heavy, there is not enough radio resource for HTTP traffic to attain its minimum transmission rate requirement as given in (10). On the other hand, in the ARRA with CoMP scheme, the user priority is defined as the minimum number of bits required to transmit at the current subframe. Given that the NRT packet size is greater than the RT packet size, the NRT service has a higher priority than the RT service when it becomes urgent. Therefore, the ARRA with CoMP scheme has the largest NRT-service transmission rate.

Figure 7 presents Jain's fairness index for FTP traffic. Jain's fairness index is defined as [22]

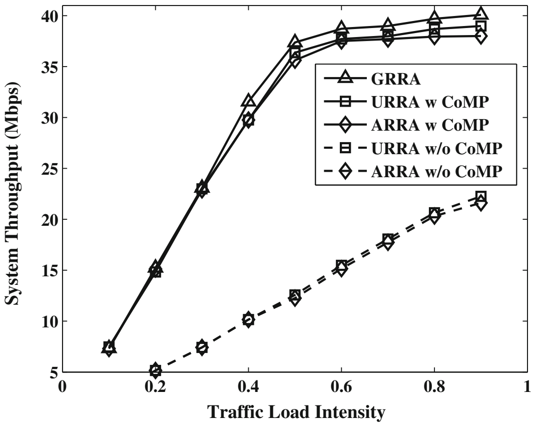

Fig. 3 System throughput

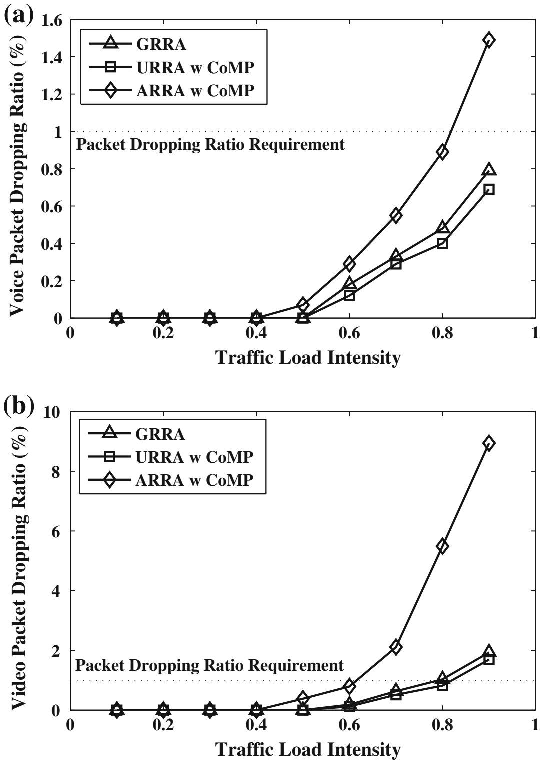

Fig. 4 Packet dropping ratio of **a** voice traffic and **b** video traffic

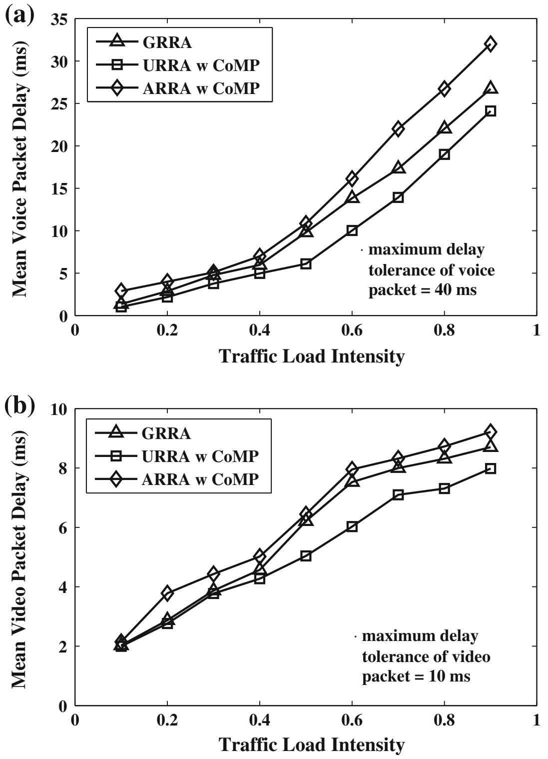

Fig. 5 Mean packet delay of **a** voice traffic and **b** video traffic

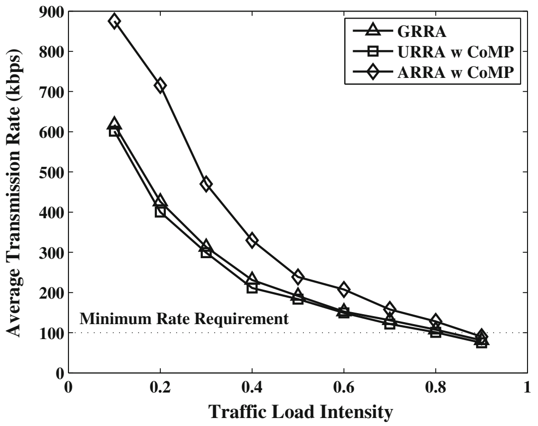

Fig. 6 Average transmission rate of HTTP traffic

$$\text{Jain Fairness Index} = \frac{\left(\sum \bar{R}_k\right)^2}{K \sum \bar{R}_k^2}. \tag{14}$$

The GRRA scheme improves Jain's fairness index for FTP traffic by more than 155 % as compared with the URRA and ARRA schemes with CoMP. This is because the GRRA scheme assigns higher priority values to BE UE with lower transmission rates by (9) and (10) so as to attain a higher Jain's fairness index. On the other hand, the URRA and ARRA schemes with CoMP allocate more radio resources to BE UE with better channel conditions such that BE UE with worse channel conditions cannot obtain enough radio resource.

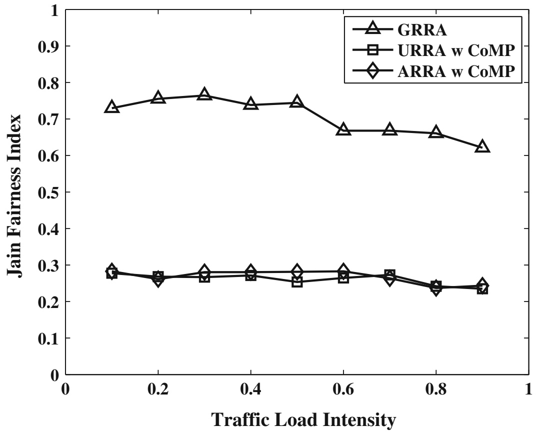

Fig. 7 Jain's fairness index for FTP traffic

5 Conclusions

In this paper, we propose a green radio resource allocation (GRRA) scheme for LTE-A downlink systems with CoMP transmission to support multimedia traffic. The objective of the GRAA scheme is to maximize the green radio utility value, which comprises system transmission power, modulation order, and the number of coordinated transmission nodes. By coordinating the transmission power of each transmission node, it allows transmission nodes to simultaneously serve multiple users at the same subchannel. The GRAA scheme employs a priority and bit assignment (PBA) algorithm and a priority-based resource allocation (PRA) algorithm. The PBA algorithm defines the service priority value and the minimum number of transmission bits for each piece of UE according to the degree of the UE's urgency. According to the green radio utility function, the PRA algorithm allocates the radio resource to UE in the priority value order. Therefore, the GRRA scheme can mitigate the interference, thus saving transmission power and increasing the system throughput, and can achieve a high Jain's fairness index under the QoS requirement guarantee. The simulation results show that when the traffic load intensity is greater than 0.7, the GRRA scheme can save transmission power by more than 33.9 % as compared with the conventional adaptive radio resource allocation (ARRA) scheme [19] with CoMP and by more than 40.1 % as compared with the conventional utility-based radio resource allocation (URRA) scheme [20] with CoMP. Moreover, the GRRA scheme can improve Jain's fairness index for FTP traffic by more than

155 % as compared with the URRA and ARRA schemes with CoMP.

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Appendix

The pseudocode of the PRA algorithm is shown below.

```
[PRA Algorithm]
Receive $\{(u_k, \hat{R}_k), 1 \le k \le K\}$ from the PBA algorithm.
Set $\mathbf{M} = 0, \mathbf{S} = 0$, $P_u^i = 0, 1 \le i \le 3$.
Set $N_f = \{n | 1 \le n \le N\}$, $\Phi = \{k | Q_k > 0, 1 \le k \le K\}$.
Set $\tilde{m}_{k,n} = \min\{\frac{Q_k}{q}, 3\}$, $k \in \Phi$, $n \in N_f$.
while $|\Phi| > 0$ and $|N_f| > 0$
    Set $\Phi_c = \{k' | u_{k'} = \max u_k$ and $\hat{R}_k > 0, k \in \Phi\}$.
    Set $\tilde{s}_{k,n} = \arg\max_{0 \le j \le 7} G_{k,n}(\tilde{m}_{k,n}, j)$, $k \in \Phi_c$, $n \in N_f$.
    Find $(k^*, n^*) = \arg\max_{k \in \Phi_c, n \in N_f} G_{k,n}(\tilde{m}_{k,n}, \tilde{s}_{k,n})$.
    if $P_u^i + p_{k^*,n^*}^i \le P_T^i$, $i \in \Omega_{s_{k^*,n^*}}$ and $I_{k,n^*} \le I_{th}$, $k \in \Phi_{n^*} + \{k^*\}$, then
        Set $m_{k^*,n^*} = \tilde{m}_{k^*,n^*}$, $s_{k^*,n^*} = \tilde{s}_{k^*,n^*}$.
        Set $\Phi_{n^*} = \Phi_{n^*} + \{k^*\}$, $\Omega_{u,n^*} = \Omega_{u,n^*} + \{i | i \in \Omega_{s_{k^*,n^*}}\}$.
        Set $P_u^i = P_u^i + p_{k^*,n^*}^i$, $i \in \Omega_{s_{k^*,n^*}}$.
        Set $Q_{k^*} = \max\{Q_{k^*} - q \cdot m_{k^*,n^*}, 0\}$.
        Set $\hat{R}_{k^*} = \max\{\hat{R}_{k^*} - q \cdot m_{k^*,n^*}, 0\}$.
        if $Q_{k^*} = 0$ then
            Set $\Phi = \Phi - \{k^*\}$.
        end if
        if $|\Omega_{u,n^*}| = 3$ then
            Set $N_f = N_f - \{n^*\}$.
        end if
    else
        if $\tilde{m}_{k^*,n^*} > 1$ then
            Set $\tilde{m}_{k^*,n^*} = \tilde{m}_{k^*,n^*} - 1$.
        else
            Set $u_{k^*} = 0$.
        end if
    end if
end while
```

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