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Resource allocation algorithm with limited feedback for multicast single frequency networks*

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Abstract: The single frequency network (SFN) can provide a multimedia broadcast multicast service over a large coverage area. However, the application of SFN is still restricted by a large amount of feedback. Therefore, we propose a multicast resource allocation scheme based on limited feedback to maximize the total rate while guaranteeing the quality of service (QoS) requirement of real-time services. In this scheme, we design a user feedback control algorithm to effectively reduce feedback load. The algorithm determines to which base stations the users should report channel state information. We then formulate a joint subcarrier and power allocation issue and find that it has high complexity. Hence, we first distribute subcarriers under the assumption of equal power and develop a proportional allocation strategy to achieve a tradeoff between fairness and QoS. Next, an iterative water-filling power allocation is proposed to fully utilize the limited power. To further decrease complexity, a power iterative scheme is introduced. Simulation results show that the proposed scheme significantly improves system performance while reducing 68% of the feedback overhead. In addition, the power iterative strategy is suitable in practice due to low complexity.

Key words: Multicast, Single frequency networks (SFN), Orthogonal frequency division multiplexing access (OFDMA), Resource allocation
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1 Introduction

To use limited resources more efficiently, the 3rd Generation Partnership Project (3GPP) has proposed the multimedia broadcast multicast service (MBMS) (3GPP TS 22.146:2006), which can efficiently deliver the same data to a large number of users, and which has attracted attention from both academia and industry. Nevertheless, the rate of each multicast stream is limited by the worst user. Thus, effective resource allocation is necessary.

Over the past decade, the resource allocation issue has been extensively investigated for multicast systems (Kwack *et al.*, 2007; Liu *et al.*, 2008; Ngo *et al.*, 2009). The performance improvement is limited, because in these works the advantages provided by cooperative diversity were not exploited. Recently, cooperation has been introduced into multicast networks, since it can achieve a high transmission rate (Laneman *et al.*, 2004). Research on cooperative multicast can be roughly classified as three types: network coding-based cooperation (Jin and Li, 2009; Li and Chen, 2009), space-time coded cooperation (Alay *et al.*, 2009; Zhang *et al.*, 2010), and power efficient cooperation (Li and Chen, 2008; Gong *et al.*, 2011). The aforementioned studies consider only single cell MBMS scenarios.

In the 4G network, a higher multicast rate requirement has been proposed, which can hardly be achieved through the single cell MBMS. Therefore, multi-cell cooperation MBMS based on single frequency networks (SFN) has received more and more

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attention, as it provides broadcast services over a large coverage area (Kurjenniemi and Vartiainen, 2008; Pitaval *et al.*, 2010) and significantly increases the multicast rate. Moreover, in SFN, each base station (BS) transmits common multicast data via the same time-frequency resource. Therefore, handoff is not required when users roam to an adjacent service area. However, in the current stage, the application of SFN for MBMS provisioning has the following issues:

1. Uplink feedback overhead. Each multicast user needs to report channel state information (CSI) not only to the serving BS, but also to other cooperative BSs.
2. Computational complexity of resource allocation. Multiple BSs should jointly distribute resource to the multicast service involving users of different CSI and quality-of-service (QoS) requirements.

The research on SFN is still in its early stage. Some performance evaluations of MBMS through SFN were provided in Morimoto *et al.* (2009) and Rong *et al.* (2011). As one of the first works on resource allocation in SFN, Kwon and Lee (2009) proposed an optimal power allocation scheme for the heterogeneous modulation and coding scheme case (OPA-HE), where iterative water-filling is used. However, the complexity of the scheme increases exponentially with more users and more subcarriers. Moreover, it is assumed in this scheme that all CSI is available at the resource manager, which requires a lot of uplink feedback, and which may not be suitable in practical implementation. In addition, Kwon and Lee (2009) assumed that all multicast groups have the same service and demand. However, future broadband wireless networks should support a wide variety of communication services with diverse QoS requirements.

In this paper, we investigate the multicast resource allocation issue in SFN, where real-time (RT) and quasi-real-time (QRT) services are supported simultaneously. The aim is to maximize the total data rate while guaranteeing the QoS requirements of RT multicast services. We design a user feedback control (UFC) algorithm and then develop a proportional subcarrier allocation strategy, where the subcarriers are distributed to different groups, proportional to their channel gains and QoS requirements. To effectively use the limited power, the iterative water-filling power allocation strategy and the power iterative strategy with QoS constraints are proposed. In addition, we introduce the QoS satisfaction index and compare the performance of the proposed schemes with that of the OPA-HE scheme (Kwon and Lee, 2009).

2 System model

We consider an orthogonal frequency-division multiple access (OFDMA) based SFN with K cells, G multicast groups, and N mutually orthogonal subcarriers. Unlike the single cell MBMS, in SFN, BSs transmit common multicast packets with the same time-frequency resource in a synchronized manner and the users aggregate them.

In this SFN, each BS has three antennas, and an existing 1/3 multi-cell orthogonal space-time code reuse pattern (Rege *et al.*, 2008) is employed (Fig. 1). $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are the code vectors of the three antennas, respectively. For each BS, complex data symbols are grouped into a set of four symbols each, and then each such set is transmitted from three antennas over eight time slots. Thus, the rate associated with the code is 4/8=1/2. Assume that the power distributed to all three antennas by each BS is the same. According to Eq. (12) in Rege *et al.* (2008), the rate of user m in group g at subcarrier n is given by

$$R_{gm}(n)=\frac{w}{2}\log_2\left(1+\frac{2}{wN_0}\sum_{i=1}^{3}\left|\sum_{k=1}^{K}\sqrt{P_k(n)}h_{gm}^{k,i}(n)\right|^2\right), \quad (1)$$

where $P_k(n)$ is the power distributed to subcarrier n by each antenna of BS k, w is the frequency bandwidth of each subcarrier, N_0 is the double-sided noise power spectral density level, which is the same for all

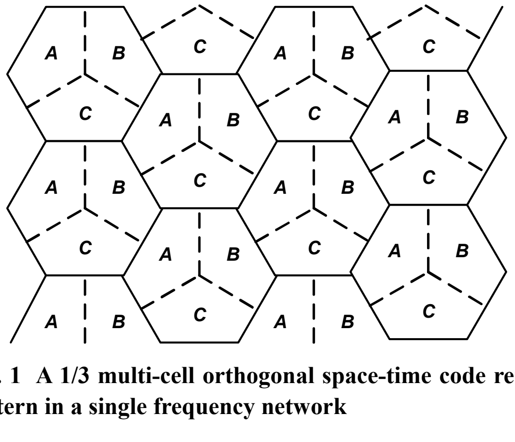

Fig. 1 A 1/3 multi-cell orthogonal space-time code reuse pattern in a single frequency network

subcarriers and BSs, and $h^{k,i}_{gm}(n)$ is the channel coefficient at subcarrier n from antenna i of BS k to user m in group g. The corresponding channel gain can be given by $G^{k,i}_{gm}(n)=|h^{k,i}_{gm}(n)|^2=d^{-\alpha}_{kgm}|g^{k,i}_{gm}(n)|^2$, where d_{kgm} is the transmission distance and α is the pathloss exponent, while $g^{k,i}_{gm}(n)$ is modeled as a zero-mean circularly symmetric complex Gaussian random variable with a unit variance. Because in the SFN a longer cyclic prefix (CP) is designed to decrease inter-symbol and inter-carrier interference, we assume that the delay spread of the channels from different BSs to all users is shorter than this CP. Therefore, Eq. (1) can be rewritten as

$$R_{gm}(n)=\frac{w}{2}\log_2\left(1+\frac{2}{wN_0}\sum_{i=1}^{3}\sum_{k=1}^{K}P_k(n)G^{k,i}_{gm}(n)\right). \quad (2)$$

Since the transmission rate of a multicast group is determined by the most disadvantaged user, the data rate of this group is given by

$$R_g=\sum_{n=1}^{N}\rho_g(n)\min_{m\in U_g}R_{gm}(n)\triangleq\sum_{n=1}^{N}\rho_g(n)R_g(n), \quad (3)$$

where U_g is the set of all users in group g, $R_g(n)$ is the rate at subcarrier n, and $\rho_g(n)$ is an indicator that determines whether or not subcarrier n is used by this group.

We consider two classes of services, RT services and QRT services. QRT services are applications such as mobile paper. They come with a prescribed maximum allowable bit error rate, but pose no requirements on rate guarantees. RT services are for mission-critical and rate-constraint applications such as mobile TV. The multicast groups in the system can be classified into q_1 RT groups with the set of Q_1 and q_2 QRT groups with the set of Q_2. For RT groups, the QoS requirement is

$$\sum_{n=1}^{N}\rho_g(n)R_g(n)\geq C_g,\ \ \forall g\in Q_1, \quad (4)$$

where C_g is the target rate of group g.

Suppose the available power at each BS is P and the set of all BSs is H. Our goal is to maximize the total rate, while guaranteeing the QoS requirements of RT multicast services. Thus, the optimization resource allocation issue can be formulated as follows:

$$\max\ \sum_{g=1}^{G}\sum_{n=1}^{N}\rho_g(n)R_g(n)$$
$$\text{s.t.}\ \begin{cases}\sum_{n=1}^{N}\rho_g(n)R_g(n)\geq C_g,\ \ \forall g\in Q_1,\\ 3\sum_{n=1}^{N}P_k(n)\leq P,\ \ \forall k\in H,\\ \sum_{g=1}^{G}\rho_g(n)\leq 1,\ \rho_g(n)\in\{0,\ 1\},\ \ \forall n.\end{cases} \quad (5)$$

3 Resource allocation

The above optimization problem is a generalized knapsack problem, which is NP hard. Thus, it is impractical to determine the optimal solution directly. In addition, it may be infeasible to provide all instantaneous CSI to BSs. To overcome these drawbacks, we develop a low complexity resource allocation scheme based on a limited feedback. In this scheme, we first design a UFC algorithm to effectively reduce feedback overhead and then distribute subcarriers and power to different multicast groups according to the limited information. To sum up, the resource allocation scheme should consist of three steps: user feedback control, subcarrier allocation, and power allocation.

3.1 User feedback control

It is observed that the large-scale fading has a great effect on the user's channel gain. Most of the signal energy received by a user comes from BSs in the neighborhood. Therefore, a user may be excused from BSs further away. Meanwhile, a user may not be considered in resource allocation either, if it has exceptional high channel gains, as multicast performance is determined by the more disadvantaged users. Thus, we set an interval $[L_\mathrm{w}, L_\mathrm{h}]$ to decrease user feedback.

More specifically, user m in group g can measure the channel gains at all subcarriers from all three antennas of each BS to user m (e.g., through pilot symbols from BSs). It reports $G^{k,i}_{gm}(n)$ and $\eta^{k,i}_{gm}(n)$ is set to 1, only if $G^{k,i}_{gm}(n)>L_\mathrm{w}$ and $\min_{j\in A(k')}G^{k',j}_{gm}(n)<L_\mathrm{h}$, where k' is the index for the BS of the serving cell of the user and $A(k')$ is the set of all antennas of BS k'. Otherwise, $\eta^{k,i}_{gm}(n)$ is set to 0, where $\eta^{k,i}_{gm}(n)$ is an

indicator which denotes whether or not $G_{gm}^{k,i}(n)$ is feedback. In other words, the probability that $G_{gm}^{k,i}(n)$ is feedback is equal to $\Pr(\min_{j\in A(k')} G_{gm}^{k',j}(n) < L_{\mathrm{h}})\times \Pr(G_{gm}^{k,i}(n) > L_{\mathrm{w}} \mid \min_{j\in A(k')} G_{gm}^{k',j}(n) < L_{\mathrm{h}})$, which is less than 1. Therefore, the feedback load can be reduced. Here, the selection of L_{w} and L_{h} is considered as follows.

Selection of L_{w}: We intend to have each user feed back CSI only to its nearest three BSs. Denote the distance between adjacent BSs as L and the desired probability that the channel gain between the user and the antenna of its adjacent BS is more than L_{w} as P_{w}. We know that $g_{gm}^{k,i}(n)$ is a zero-mean circularly symmetric complex Gaussian random variable with a unit variance, so $|g_{gm}^{k,i}(n)|^2$ follows an exponential distribution (with a parameter of 0.5). Then L_{w} can be obtained through solving the following equation:

$$\int_0^{L^\alpha L_{\mathrm{w}}} 0.5\,\mathrm{e}^{-h/2}\,\mathrm{d}h = 1 - P_{\mathrm{w}}. \tag{6}$$

Selection of L_{h}: Assume r is the cell radius, and $\{(r_{gm}, \theta_{gm})\}$ is the location of user m in group g in its serving cell. Users are uniformly distributed over the cell. $f(r_{gm}, \theta_{gm})$ is the user's distribution function. Then the probability that the channel gain between the user and antenna i of its serving BS k' is less than L_{h} is given by

$$\begin{aligned} P_{\mathrm{h}} &= \int_0^r \int_0^{2\pi} \Big\{ \Pr[G_{gm}^{k'i}(n) < L_{\mathrm{h}} \mid \{(r_{gm}, \theta_{gm})\}] \\ &\qquad \cdot f(r_{gm}, \theta_{gm}) \Big\} \mathrm{d}\theta_{gm} \mathrm{d}r_{gm} \\ &= \int_0^r [1 - \exp(-L_{\mathrm{h}} r_{gm}^\alpha)] \frac{2r_{gm}}{r^2} \mathrm{d}r_{gm} \\ &= 1 - \frac{2}{\alpha r} L_{\mathrm{h}}^{-2/\alpha} \Gamma\left(\frac{2}{\alpha}, r^\alpha L_{\mathrm{h}}\right). \end{aligned} \tag{7}$$

3.2 Subcarrier allocation

As mentioned earlier, the computational complexity of the joint subcarrier and power allocation increases exponentially with the increment of G, K, and N. A low-complexity resource allocation strategy is necessary. Therefore, for simplicity, we first distribute subcarriers under the assumption of equal power distribution. Assuming $P_1(n)=P_2(n)=\ldots=P_k(n)$, the received signal-to-noise ratio (SNR) at subcarrier n of user m in group g can be calculated using

$$\begin{aligned} \mathrm{SNR}_{gm}(n) &= \frac{2}{wN_0} \sum_{k=1}^{K} \sum_{i=1}^{3} \eta_{gm}^{k,i}(n) P_k(n) G_{gm}^{k,i}(n) \\ &= \frac{P_1(n)}{wN_0} \sum_{k=1}^{K} G_{gm}^{k}(n), \end{aligned} \tag{8}$$

where $G_{gm}^{k}(n)$ is defined as the equivalent channel gain at subcarrier n from BS k to user m in group g. Let $F_g(n) = \left\{ m \mid m \in U_g, \sum_{i=1}^{3} \sum_{k=1}^{K} \eta_{gm}^{k,i}(n) \geq 1 \right\}$. Then the equivalent channel gain at subcarrier n of group g is $G_g(n) = \min_{m\in F_g(n)} \sum_{k=1}^{K} G_{gm}^{k}(n)$.

3.2.1 Proportional allocation based on QoS (PQ)

The QoS requirements of each group are different; thus, their service priorities are different. In the PQ scheme, subcarriers are distributed to different groups, proportional to their channel conditions and service priorities. For RT services, more subcarriers are distributed to the group with the higher target rate and/or the worst channel condition. A larger number of subcarriers are assigned to the group with the least channel gain for QRT services. The service priority between RT and QRT services is dependent on the predefined priority factor β. Thus, we can formulate the proportional subcarrier allocation issue as

$$\frac{R_1}{C_1} = \ldots = \frac{R_{q_1}}{C_{q_1}} = \beta R_{q_1+1} = \ldots = \beta R_{q_1+q_2}, \tag{9}$$

where β is fixed to $1.5/\min_{g\in Q_1} C_g$.

The subcarrier allocation procedure includes the following steps:

1. Initialize $R_g=0$ $\forall g$. The set of free subcarriers $T=\{1, 2, \ldots, N\}$ and the set of subcarriers assigned to group g, $S_g=\varnothing$. $I_g=R_g/C_g$ for $g\in Q_1$ and $I_g=\beta R_g$ for $g\in Q_2$.

2. While $T\neq\varnothing$, find group $g'=\arg\min_g I_g$ and subcarrier $n'=\arg\max_{n\in T} G_{g'}(n)$, and update $T=T-\{n'\}$, $S_{g'}=S_{g'}+\{n'\}$, $R_{g'}=R_{g'}+R_{g'}(n')$.

3.3 Power allocation

In the above resource allocation with equal power distribution, the limited power cannot be reasonably used. Thus, an effective power allocation strategy is necessary. Currently, the only scheme about power allocation between multiple BSs is OPA-HE, where iterative water-filling is used and each BS has only one antenna. Here we briefly describe the steps of the scheme. Denote the power distributed to each subcarrier by BS k at the tth iteration as $P_k^t=(P_k^t(1), P_k^t(2), ..., P_k^t(N))$. At each iteration, when a BS allocates power, the power distributions of other BSs are considered to be fixed. Suppose that the power allocation $(P_1^t, P_2^t, ..., P_K^t)$ is given at the tth iteration and that subcarrier n is distributed to group g. Then P_k^{t+1} is determined as follows:

$$P_k^{t+1}(n)=\left[\lambda_k-\frac{1+\sum_{l=1,l\neq k}^{K}P_l^t(n)\bar{G}_{gm'}^l(n)}{\bar{G}_{gm'}^k(n)}\right]^+, \quad (10)$$

where $[x]^+=\max(x, 0)$, λ_k is the Lagrange multiplier, and $\bar{G}_{gm}^k(n)$ is the channel gain at subcarrier n from BS k to user m in group g.

3.3.1 Iterative water-filling allocation scheme with the QoS constraint (IWF-Q)

In OPA-HE, only a single antenna is considered at the BS and all CSI is available at the resource manager. However, our system recognizes only partial CSI and each BS has three antennas. Therefore, if iterative water-filling is introduced to this system, user m' in Eq. (10) should satisfy

$$m'=\arg\min_{m\in F_{kg}(n)}\left\{P_k^{t+1}(n)G_{gm}^k(n)+\sum_{l=1,l\neq k}^{K}P_l^t(n)G_{gm}^l(n)\right\}, \quad (11)$$

where $F_{kg}(n)=\left\{m \mid m\in U_g, \sum_{i=1}^{3}\eta_{gm}^{k,i}(n)\geq 1\right\}$. Then, the rate at subcarrier n can be written as

$$R_g(n)=\frac{w}{2}\log_2\left(1+\frac{1}{wN_0}\left(P_k^{t+1}(n)G_{gm'}^k(n)+\sum_{l=1,l\neq k}^{K}P_l^t(n)G_{gm'}^l(n)\right)\right). \quad (12)$$

From the analysis above, we know that if a user receives a high enough signal from other BSs, it is unnecessary to allocate a large power to it. Based on this idea and the QoS requirements of different groups, the IWF-Q scheme is proposed. The allocation process can be summarized as follows:

1. Initialize $P_k(n)=0$, and the remaining power of BS k is $P_{\mathrm{e}k}=P$ for all k.

2. Find group $g'=\arg\max_{g\in Q_1} C_g$.

3. Distribute power to the subcarriers of group g' according to Eq. (10). In each iteration, if the power consumption of this group is less than the remaining power $P_{\mathrm{e}k}$, the constant λ_k is chosen such that $\sum_{n\in S_{g'}}R_{g'}(n)=C_{g'}$. Otherwise, λ_k is computed according to $3\sum_{n\in S_{g'}}P_k(n)=P_{\mathrm{e}k}$. Return to the start of step 3 until convergence.

4. Update $P_{\mathrm{e}k}=P_{\mathrm{e}k}-3\sum_{n\in S_{g'}}P_k(n)$. If $\sum_{k=1}^{K}P_{\mathrm{e}k}=0$, the algorithm ends. Otherwise, update $C_{g'}=0$. If $\sum_{g\in Q_1}C_g\neq 0$, return to step 2.

5. Distribute power to the subcarriers of QRT groups according to Eq. (10). In each iteration, λ_k is obtained according to $3\sum_{n\in S_{q_1+1}\cup\cdots\cup S_{q_1+q_2}}P_k(n)=P_{\mathrm{e}k}$. Return to the start of step 5 until convergence. The algorithm ends.

3.3.2 Power iterative scheme with the QoS constraint (PI-Q)

The IWF-Q scheme can reasonably utilize power. However, its computational complexity is very high, which makes the scheme not suitable for practical implementation. Therefore, we propose a low-complexity power iterative scheme with the QoS constraint.

The RT services have a higher priority. Thus, we first allocate resources to them. To improve the total data rate, we should reduce the power consumptions of the RT services while guaranteeing their rate requirements. However, this is a convex optimization problem, and it is infeasible to obtain the optimal solution directly. For simplicity, we assume $P_1(n)/P_{\mathrm{e}1}=P_2(n)/P_{\mathrm{e}2}=\ldots=P_k(n)/P_{\mathrm{e}k}$ and $P_{\mathrm{e,max}}=\max_{k\in H}P_{\mathrm{e}k}$. $P_{\max}(n)$ is the power distributed to subcarrier n by each antenna of the BS with the largest remaining power. Therefore, the received SNR at subcarrier n of user m in group g is given by

$$\begin{aligned}\mathrm{SNR}_{gm}(n)&=\frac{1}{wN_0}\sum_{k=1}^{K}P_k(n)\sum_{i=1}^{3}2\eta_{gm}^{k,i}(n)G_{gm}^{k,i}(n)\\&=\frac{P_{\max}(n)}{wN_0}\sum_{k=1}^{K}\frac{P_{\mathrm{e}k}}{P_{\mathrm{e,max}}}G_{gm}^{k}(n)=\frac{P_{\max}(n)\bar{G}_{gm}(n)}{wN_0},\end{aligned}\tag{13}$$

where $\bar{G}_{gm}(n)$ is considered the normalized equivalent channel gain at subcarrier n of user m in group g. Based on above identical ratio power allocation assumption, we first compute the power of the BS with the largest remaining power, and then other BSs allocate power proportionally. Then the optimization problem for the resource allocation of RT group g can be formulated as follows:

$$\begin{aligned}&\min\ \sum_{n\in S_g}P_{\max}(n)=wN_0\sum_{n\in S_g}\frac{2^{2R(n)/w}-1}{\min\limits_{m\in F_g(n)}\bar{G}_{gm}(n)}\\&\text{s.t.}\ \begin{cases}\sum\limits_{n\in S_g}R_g(n)\geq C_g,\ R_g(n)\geq 0, & \forall n\in S_g,\\ \dfrac{P_1(n)}{P_{\mathrm{e}1}}=\dfrac{P_k(n)}{P_{\mathrm{e}k}}=\ldots=\dfrac{P_{\max}(n)}{P_{\mathrm{e,max}}}, & \forall n\in S_g.\end{cases}\end{aligned}\tag{14}$$

From Karush-Kuhn-Tucker (KKT) optimality conditions, the solution of Eq. (14) is given by

$$\begin{aligned}R_g(n)=0.5w[&\log_2(\lambda_b\min\nolimits_{m\in F_g(n)}\bar{G}_{gm}(n))\\&-\log_2(wN_0\ln 2)]^+,\quad \forall n\in S_g,\end{aligned}\tag{15}$$

where λ_b is the Lagrange multiplier.

With the above identical ratio power allocation, resources cannot be efficiently used. Thus, to further decrease the power consumption, we appropriately adjust the power distributed to the subcarriers by each BS in the identical ratio power allocation such that the following equation is satisfied:

$$\begin{aligned}&2\sum_{k=1}^{K}\sum_{i=1}^{3}P_k(n)\eta_{gm}^{k,i}(n)G_{gm}^{k,i}(n)\geq wN_0(2^{2R_g(n)/w}-1)\\&\qquad\forall n\in S_g,\ \forall m\in F_g(n).\end{aligned}\tag{16}$$

Eq. (16) is a linear programming problem, which can be solved using a simplex method. However, this method has low calculation efficiency. Thus, we propose the following algorithm with low complexity to obtain a solution for Eq. (16):

1. Initialize the remaining power of BS k, $P_{\mathrm{e}k}=P$. Let $\Delta R_{kg}(n)=\min_{m\in F_{kg}(n)}R_{gm}(n)-R_g(n)$.

2. Find group $g'=\arg\max_{g\in Q_1}C_g$.

3. $\forall n\in S_{g'}$, compute $P_k(n)=wN_0P_{\mathrm{e}k}/P_{\mathrm{e,max}}\times\dfrac{2^{2R(n)/w}-1}{\min\limits_{m\in F_{g'}(n)}\bar{G}_{g'm}(n)}$. If $P_{\mathrm{e}k}\geq 3\sum_{n\in S_{g'}}P_k(n)$, update $P_{\mathrm{e}k}=P_{\mathrm{e}k}-3\sum\limits_{n\in S_{g'}}P_k(n)$ and $\Delta P=0.05\min\limits_{n\in S_{g'}}P_k(n)$. Otherwise, update $P_k(n)=\dfrac{P_{\mathrm{e}k}\cdot P_k(n)}{3\sum_{n\in S_{g'}}P_k(n)}$. The algorithm ends.

4. For BS k=1 to K, find subcarrier $n'=\arg\max\limits_{n\in S_{g'}}\Delta R_{kg'}(n)$. If

$$\begin{aligned}&\min_{m\in F_{kg'}(n')}0.5w\log_2\left(1+\frac{2}{wN_0}\sum_{i=1}^{3}(P_k(n')-\Delta P)G_{g'm}^{k.i}(n')\right.\\&\left.+\frac{2}{wN_0}\sum_{l=1,l\neq k}^{K}\sum_{i=1}^{3}P_l(n')\eta_{g'm}^{l,i}(n')G_{g'm}^{l,i}(n')\right)\geq R_{g'}(n'),\end{aligned}$$

update $P_k(n')=P_k(n')-\Delta P$ and $P_{\mathrm{e}k}=P_{\mathrm{e}k}+3\Delta P$.

5. Repeat step 4 until the remaining powers of all BSs converge.

6. Update $C_{g'}=0$. If $\sum_{g\in Q_1}C_g=0$, the algorithm ends; otherwise, return to step 2.

After distributing resources to RT services, if $\sum_{k=1}^{K}P_{\mathrm{e}k}>0$, we will allocate these remaining powers to QRT services to improve their data rates under the constraints of remaining power of each BS. Based on identical ratio power allocation assumption, the optimization problem for the resource allocation of QRT services can be formulated as follows:

$$\begin{aligned}&\max\sum_{n\in Q_{\mathrm{s}}}\frac{w}{2}\log_2\left(1+P_{\max}(n)\sum_{g\in Q_2}\rho_g(n)\min_{m\in F_g(n)}\bar{G}_{gm}(n)\right)\\&\text{s.t.}\ \begin{cases}3\sum\limits_{n\in Q_{\mathrm{s}}}P_k(n)\leq P_{\mathrm{e}k}, & \forall k,\\ \dfrac{P_1(n)}{P_{\mathrm{e}1}}=\dfrac{P_k(n)}{P_{\mathrm{e}k}}=\ldots=\dfrac{P_{\max}(n)}{P_{\mathrm{e,max}}}, & \forall n\in Q_{\mathrm{s}},\end{cases}\end{aligned}\tag{17}$$

where Q_{s} is a set of subcarriers that are distributed to all QRT services. By the KKT optimality condition, we can obtain the following:

$$P_k(n)=P_{\max}(n)\frac{P_{\mathrm{e}k}}{P_{\mathrm{e},\max}},\quad \forall n\in Q_{\mathrm{s}}$$

$$\text{s.t.}\begin{cases} P_{\max}(n)=\left[\dfrac{w}{\lambda}\ln 2-\dfrac{wN_0}{\sum\limits_{g\in Q_2}\rho_g(n)\min\limits_{m\in F_g(n)}\bar{G}_{gm}(n)}\right]^{+}, \\ 3\sum\limits_{n\in Q_{\mathrm{s}}}P_{\max}(n)=P_{\mathrm{e},\max}, \end{cases} \tag{18}$$

where λ is the Lagrange multiplier.

Similar to the power allocation of RT services, we can further increase the rate by adjusting the power distributed by each BS. The algorithm can be summarized as follows:

1. Initialize $P_k(n)$ according to Eq. (18), and $\Delta P=0.05\min_{k\in H}P_{\mathrm{e}k}/(3|Q_{\mathrm{s}}|)$.

2. Let $R_{\min}(n)=\sum_{g\in Q_2}\rho_g(n)\min_{m\in F_g(n)}R_{gm}(n)$. Find $n'=\arg\min_{n\in Q_{\mathrm{s}}}R_{\min}(n)$. Then find group g' satisfying $\rho_{g'}(n')=1$ and user $m'=\min_{m\in F_{g'}(n')}R_{g'm}(n')$.

3. Let $B_{g'm'}^{n'}=\left\{k\,|\,k\in H,\ \sum_{i=1}^{3}\eta_{g'm'}^{k,i}(n')\geq 1\right\}$ and $M_g(j)=\bigcup_{k\in B_{g'm'}^{n'}}F_{kg}(j)$. Find $j'=\arg\max\limits_{j\in Q_{\mathrm{s}}}\left(\rho_g(j)\times\min\limits_{m\in M_g(j)}R_{gm}(j)-R_{\min}(j)\right)$ and group $\tilde{g}$ satisfying $\rho_{\tilde{g}}(j')=1$. If

$$\min_{m\in M_{\tilde{g}}(j')}\log_2\left\{1+\frac{2}{wN_0}\sum_{i=1}^{3}\left(\sum_{\substack{k\in H\\ k\notin B_{g'm'}^{n'}}}P_k(j')\eta_{\tilde{g}m}^{k,i}(j')G_{\tilde{g}m}^{k,i}(j')\right.\right.$$
$$\left.\left.+\sum_{k\in B_{g'm'}^{n'}}(P_k(j')-\Delta P)\eta_{\tilde{g}m}^{k,i}(j')G_{\tilde{g}m}^{k,i}(j')\right)\right\}>R_{\min}(j')$$

is satisfied, update $P_k(j')=P_k(j')-\Delta P$ and $P_k(n')=P_k(n')+\Delta P$ for all $k\in B_{g'm'}^{n'}$.

4. Return to step 2 until convergence.

4 Simulations results

In this section, we compare the performances of different resource allocation schemes. We assume that the total number of available subcarriers is 32, the bandwidth of each subcarrier is 0.2 MHz, the pathloss exponent is 3, the cell radius is 1 km, and the distance between adjacent BSs is 1.8 km. Each group has M users with the actual positions of the users being uniformly distributed over each cell. For comparison, we additionally consider the non-cooperative (NC) single cell multicast scheme where the same data are transmitted independently in each cell and each BS distributes power equally among the subcarriers, the non-QoS (nQoS) scheme where QoS requirements are not considered and the power iterative allocation is adopted, and the OPA-HE scheme without the QoS constraint (Kwon and Lee, 2009).

In Fig. 2, we compare the total rate of all groups in different schemes. The following conclusions can be obtained from Fig. 2:

1. With more users, the total rate of all schemes decreases, because when the number of users increases, the possibility of the existing bad user also increases, and then more power is required.

2. The rate of the NC scheme is the least. This is mainly due to the fact that, when the NC scheme is used, the received useful signal of the user located at the cell edge is weak and the interference signals from other BSs are strong. The multicast performance will be greatly reduced due to that user. In contrast, when the other schemes are used, the data from different BSs are aggregated at each user, instead of being interfered by each other. The multi-BS diversity gain is obtained and the rate is improved.

3. The rates of both PI-Q and IWF-Q are more than that of OPA-HE. Moreover, their feedback overhead is greatly decreased compared with OPA-HE. This is because OPA-HE considers only a single antenna at the BS and then the multi-antenna diversity gain cannot be obtained. In addition, the rate of PI-Q is slightly less than that of IWF-Q, but the computational complexity of the former is obviously lower than that of the latter. Thus, the PI-Q scheme is more suitable for a practical system.

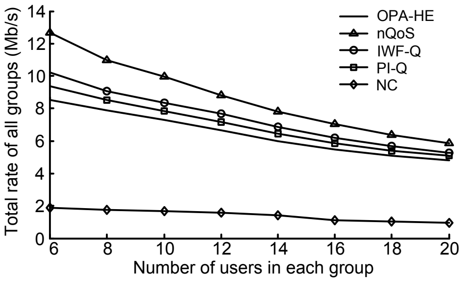

Fig. 2 Total rate of all groups vs. the number of users in each group (K=8, P=10 W, P_{w}=0.8, P_{h}=0.1)

4. The rate of PI-Q is less than that of nQoS. This is because the QoS requirements are not considered and then power is distributed to the best subcarrier in nQoS. In contrast, in PI-Q, the power is first distributed to the RT group, and then to the QRT group. Power resource is not fully used.

Fig. 3 shows the QoS satisfaction results of different algorithms. To evaluate the performance of the scheme supporting different services, we propose a new metric, the satisfaction index (SI), which can be defined as SI=$1/q_1\cdot\sum_{g\in Q_1}\min(R_g/C_g, 1)$, where SI is a number between 0 and 1. SI=1 represents the QoS requirements that all RT services are satisfied. It can be observed that the SI performances of all schemes increase as power increases. At lower power, PI-Q and IWF-Q have greatly improved SI compared with both nQoS and OPA-HE.

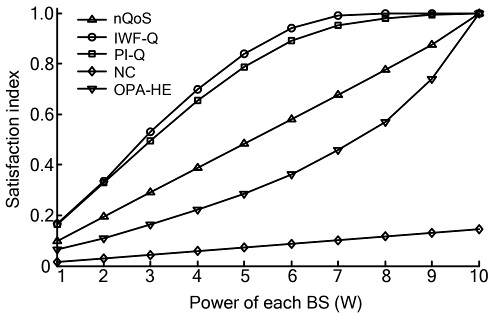

Fig. 3 Satisfaction index vs. the power of each base station (K=8, M=5, P_w=0.8, P_h=0.1)

Fig. 4 shows that the total rate of all schemes increases with the number of BSs. However, the growth rate of the total data rate diminishes as the number of BSs increases. This is because in practical environments, a user may have three to four neighboring BSs. In the range of a small number of BSs, the multi-BS diversity gain increases rapidly. When the number of BSs is large, the number of readily existing BSs located near the users is large enough.

Fig. 5a shows that the average feedback ratio increases as P_w increases. Figs. 5a and 5b also show that when P_w=0.8, the ratio of the users that successfully receive the corresponding multicast services is more than 95%. However, 68% feedback load is reduced compared with the OPA-HE with full feedback. Therefore, the PI-Q scheme significantly reduces uplink feedback while satisfying the multicast performance when P_w=0.8 and P_h=0.1.

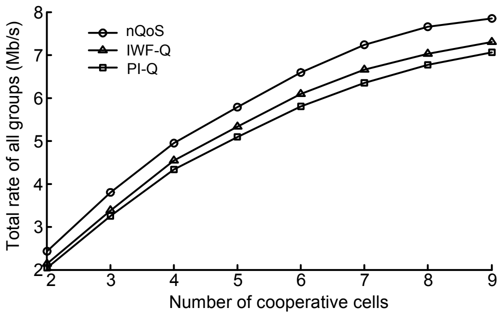

Fig. 4 Total rate vs. the number of cells (M=5, P=10 W, P_w=0.8, P_h=0.1)

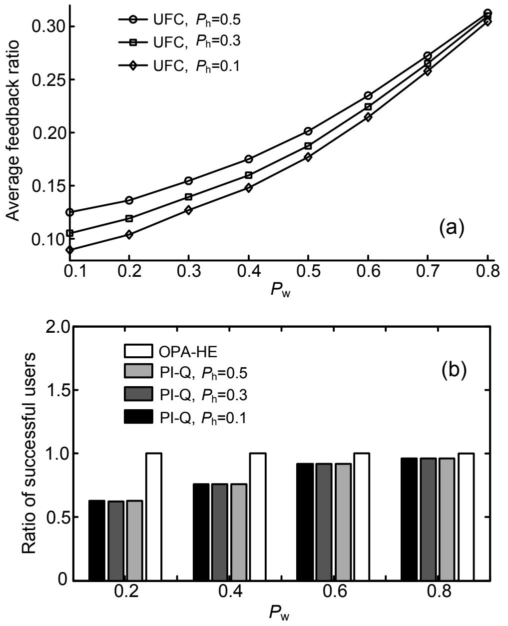

Fig. 5 The average feedback ratio (a) and the ratio of successful users (b) vs. P_w, which is the desired probability that the channel gains between the users and the antenna of its adjacent base station are more than L_w (K=8, M=5, P=10 W)

5 Conclusions

In this paper, we investigate how to improve the total rate while guaranteeing the QoS requirement of real-time services. We formulate the optimal resource allocation issue and find that it has high computational complexity. Moreover, all channel state information should be fed back to base stations for the optimization, which is not feasible from an implementation point of view. Hence, we first develop a user feedback control algorithm to effectively decrease feedback. Next, to decrease the complexity of the optimal solution, we divide the optimization into subcarrier allocation and power allocation and then propose the PQ subcarrier allocation strategy and two power allocation strategies: IWF-Q and PI-Q. Simulation results show that the proposed schemes greatly reduce the feedback overhead while ensuring a low enough ratio of failure users. In addition, the computational complexity of PI-Q is greatly reduced compared with that of IWF-Q at the expense of a small performance loss, which is efficient for practical implementation.

References

3GPP TS 22.146:2006. Multimedia Broadcast/Multicast Service. Stage 1 (Release 6), V6.7.0.

Alay, O., Liu, P., Guo, Z.L., Wang, L.G., Wang, Y., Erkip, E., Panwar, S., 2009. Cooperative Layered Video Multicast Using Randomized Distributed Space Time Codes. IEEE INFOCOM Workshops, p.1-6. [doi:10.1109/INFCOMW.2009.5072122]

Gong, P., Xue, P., Park, D., Kim, D.K., 2011. Optimum power allocation in a nonorthogonal amplify-and-forward relay-assisted network. *IEEE Trans. Veh. Technol.*, **60**(3):890-900. [doi:10.1109/TVT.2011.2108672]

Jin, J., Li, B.C., 2009. Cooperative Multicast Scheduling with Random Network Coding in WiMAX. Proc. 17th IEEE Int. Workshop on Quality of Service, p.1-9. [doi:10.1109/IWQoS.2009.5201384]

Kurjenniemi, J., Vartiainen, V., 2008. MBMS Performance with Single Frequency Network Operation on WCDMA Network. Proc. IEEE Vehicular Technology Conf., p.2379-2384. [doi:10.1109/VETECS.2008.527]

Kwack, S., Seo, H., Lee, B.G., 2007. Suitability-Based Subcarrier Allocation for Multicast Services Employing Layered Video Coding in Wireless OFDM Systems. Proc. IEEE 66th Vehicular Technology Conf., p.1752-1756. [doi:10.1109/VETECF.2007.370]

Kwon, H., Lee, B.G., 2009. Cooperative power allocation for broadcast/multicast services in cellular OFDM systems. *IEEE Trans. Commun.*, **57**(10):3092-3102. [doi:10.1109/TCOMM.2009.10.080196]

Laneman, J.N., Tse, D.N.C., Wornell, G.W., 2004. Cooperative diversity in wireless networks: efficient protocols and outage behavior. *IEEE Trans. Inf. Theory*, **50**(12):3062-3080. [doi:10.1109/TIT.2004.838089]

Li, J., Chen, W., 2008. Joint power allocation and precoding for network coding-based cooperative multicast systems. *IEEE Signal Process. Lett.*, **15**:817-820. [doi:10.1109/LSP.2008.2006330]

Li, J., Chen, W., 2009. Physical layer network coding for wireless cooperative multicast flows. *IEICE Trans. Commun.*, **E92-B**(8):2559-2567. [doi:10.1587/transcom.E92.B.2559]

Liu, J., Chen, W., Cao, Z.G., Ltaief, K.B., 2008. Dynamic Power and Sub-carrier Allocation for OFDMA-Based Wireless Multicast Systems. Proc. IEEE Int. Conf. on Communications, p.2607-2611. [doi:10.1109/ICC.2008.494]

Morimoto, A., Kishiyama, Y., Tanno, M., Higuchi, K., Sawahashi, M., 2009. Performance evaluations of MBMS signals using transmit/receiver diversity with SFN in OFDM based evolved UTRA downlink. *IEICE Trans. Commun.*, **E92-B**(5):1649-1659. [doi:10.1587/transcom.E92.B.1649]

Ngo, D.T., Tellambura, C., Nguyen, H.H., 2009. Efficient Resource Allocation for OFDMA Multicast Systems with Fairness Consideration. IEEE Radio and Wireless Symp., p.392-395. [doi:10.1109/RWS.2009.4957364]

Pitaval, R.A., Rihonen, T., Wichman, R., Blostein, S., 2010. Performance Evaluation of Relay Deployment Strategies in Multi-cell Single Frequency Networks. IEEE Wireless Communications and Networking Conf., p.1-5. [doi:10.1109/WCNC.2010.5506307]

Rege, K.M., Balachandran, K., Kang, J.H., Karakayali, K., 2008. A Multi-cell Space-Time-Coded Transmission Scheme for Single Frequency Networks. IEEE 19th Int. Symp. on Personal, Indoor and Mobile Radio Communications, p.1-6. [doi:10.1109/PIMRC.2008.4699960]

Rong, L., Elayoubi, S.E., Haddada, O.B., 2011. Performance evaluation of cellular networks offering TV services. *IEEE Trans. Veh. Technol.*, **60**(2):644-655. [doi:10.1109/TVT.2010.2091657]

Zhang, H., You, X.H., Wu, G., Wang, H.F., 2010. Cooperative Multi-antenna Multicasting for Wireless Networks. IEEE Global Telecommunications Conf., p.1-5. [doi:10.1109/GLOCOM.2010.5684278]